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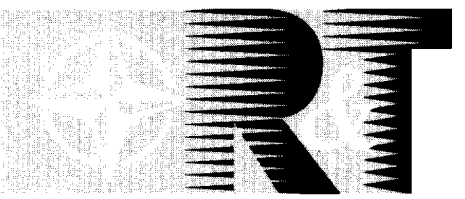

RESEARCH AND TECHNOLOGY ORGANIZATION

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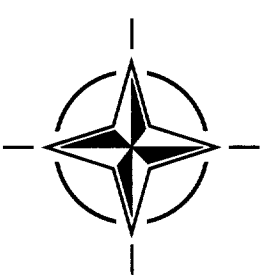
RTO MEETING PROCEEDINGS 12

Sensor Data Fusion and Integration of the Human Element

(la Fusion de données de senseur et l'intégration du facteur humain)

Papers presented at the System Concepts and Integration (SCI) Symposium held in Ottawa, Canada, 14-17 September 1998.



Published February 1999

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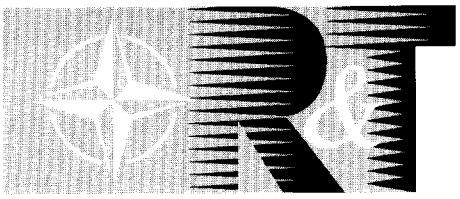

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The Research and Technology Organization (RTO) of NATO

RTO is the single focus in NATO for Defence Research and Technology activities. Its mission is to conduct and promote cooperative research and information exchange. The objective is to support the development and effective use of national defence research and technology and to meet the military needs of the Alliance, to maintain a technological lead, and to provide advice to NATO and national decision makers. The RTO performs its mission with the support of an extensive network of national experts. It also ensures effective coordination with other NATO bodies involved in R&T activities.

RTO reports both to the Military Committee of NATO and to the Conference of National Armament Directors. It comprises a Research and Technology Board (RTB) as the highest level of national representation and the Research and Technology Agency (RTA), a dedicated staff with its headquarters in Neuilly, near Paris, France. In order to facilitate contacts with the military users and other NATO activities, a small part of the RTA staff is located in NATO Headquarters in Brussels. The Brussels staff also coordinates RTO's cooperation with nations in Middle and Eastern Europe, to which RTO attaches particular importance especially as working together in the field of research is one of the more promising areas of initial cooperation.

The total spectrum of R&T activities is covered by 6 Panels, dealing with:

- SAS Studies, Analysis and Simulation
- SCI Systems Concepts and Integration
- SET Sensors and Electronics Technology
- IST Information Systems Technology
- AVT Applied Vehicle Technology
- HFM Human Factors and Medicine

These Panels are made up of national representatives as well as generally recognised 'world class' scientists. The Panels also provide a communication link to military users and other NATO bodies. RTO's scientific and technological work is carried out by Technical Teams, created for specific activities and with a specific duration. Such Technical Teams can organise workshops, symposia, field trials, lecture series and training courses. An important function of these Technical Teams is to ensure the continuity of the expert networks.

RTO builds upon earlier cooperation in defence research and technology as set-up under the Advisory Group for Aerospace Research and Development (AGARD) and the Defence Research Group (DRG). AGARD and the DRG share common roots in that they were both established at the initiative of Dr Theodore von Kármán, a leading aerospace scientist, who early on recognised the importance of scientific support for the Allied Armed Forces. RTO is capitalising on these common roots in order to provide the Alliance and the NATO nations with a strong scientific and technological basis that will guarantee a solid base for the future.

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Printed on recycled paper

Published February 1999

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ISBN 92-837-1-1010-X

Printed by Canada Communication Group Inc.
(A St. Joseph Corporation Company)
45 Sacré-Cœur Blvd., Hull (Québec), Canada K1A 0S7

Sensor Data Fusion and Integration of the Human Element

(RTO MP-12)

Executive Summary

Operators of future military systems in a digitised battlespace will be faced with increasing volumes of data. These data will derive from multiple sources including on-board sensors, other platforms and systems. Sensor Data Fusion (SDF) aims to integrate these data in order to present the simplest and most accurate picture to the operator. Perceived benefits include reduced operator workload, improved mission management and improved decision-making.

The prime purpose of this symposium was to provide an opportunity for the NATO community to explore and discuss the technological and operational issues raised by the need to ensure effective integration of SDF systems and the military operators.

The symposium was structured into sessions as follows:

- Characteristics of Operational Requirements
- System Design Techniques and Technologies
- Integration of Human Operators with Complex Systems
- System Applications
- Lessons learned and Future Trends

The papers presented addressed a broad spectrum of issues for a variety of different platforms and mission types. The main areas covered were:

- Development and implementation of data fusion algorithms
- Design of SDF Human Machine Interfaces
- Methods for evaluating the effectiveness of integrated SDF/crew systems
- Results of trials assessing the performance of integrated SDF/crew systems

The issue of mission responsibility was discussed: was the human or the machine to be held responsible for "decisions" made by an SDF system? What checks should systems incorporate to ensure that the operator could verify or override a fusion decision? In today's increasingly politically sensitive climate, this issue could be critical to the implementation of SDF systems.

There seemed little doubt amongst the attendees that SDF systems could significantly enhance mission effectiveness. However, it was also agreed that integration of the human element was vital. The involvement of crew in the design and prototyping process was felt to be key. The importance of adequate training was stressed. Training must ensure that crew not only understand the capabilities of the system but also trust the information generated.

Dr George E A Reid
Chairman, Technical Planning Committee

La fusion de données de senseur et l'intégration du facteur humain

(RTO MP-12)

Synthèse

Les opérateurs des futurs systèmes militaires sur un champ de bataille en environnement numérisé devront faire face à des volumes grandissants de données. Ces données proviendront de sources multiples telles que capteurs embarqués et autres plates-formes et systèmes. Le fusionnement des données capteurs (SDF) permet d'intégrer ces données afin de présenter la situation à l'opérateur de la façon la plus simple et la plus précise possible. Les avantages escomptés comprennent la diminution de la charge de travail de l'opérateur, ainsi que l'amélioration de la gestion de la mission et de la prise de décisions.

Ce symposium a eu pour objectif principal de permettre aux représentants des pays membres de l'OTAN d'examiner et de discuter des questions technologiques et opérationnelles soulevées par l'intégration effective des systèmes SDF dans l'environnement de travail des opérateurs militaires.

Le symposium a été organisé sous forme de sessions :

- Caractéristiques des besoins opérationnels
- Techniques et technologies de conception systèmes
- Intégration des opérateurs humains dans les systèmes complexes
- Applications systèmes
- Enseignements tirés et tendances

Les communications présentées ont abordé un large éventail de sujets concernant divers types de plates-formes et de missions. Les principaux domaines couverts furent :

- Le développement et la mise en oeuvre d'algorithmes de fusionnement de données
- La conception des interfaces homme-machine SDF
- Les méthodes d'évaluation de l'efficacité de l'intégration des systèmes SDF
- Les résultats des essais de performance des systèmes SDF

La question de la responsabilité de la mission a été discutée : Les « décisions » prises par un système SDF, sont-elles imputables à l'être humain ou à la machine ? Quels sont les tests intégrés à inclure pour permettre à l'opérateur de vérifier une décision de fusion, afin d'en tenir compte ou non. Etant donné la sensibilité du climat politique actuel, cette question pourrait être déterminante pour l'adoption des systèmes SDF.

La majorité des participants semblait convaincus que l'intégration des systèmes SDF pourrait améliorer de façon considérable l'efficacité des missions, en étant cependant d'accord sur le fait que l'intégration de l'élément humain était indispensable et que l'implication des membres d'équipage au stade de conception demeurerait un élément clé. Les participants ont souligné l'importance d'une formation appropriée qui devrait permettre aux équipages non seulement d'apprécier les capacités du système, mais aussi d'avoir confiance dans les informations qu'il génère.

Dr George E A Reid
Président du comité de planification technique

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Theme

The theme is the effective collaboration between crew and the complex, but not entirely autonomous, systems in the context of multiple information sources such as off-board communications, other platforms and multiple sensors on board platforms. The primary components of this theme that merit particular attention are:

(a) Characteristics of operational requirements demanding difficult human-system interactions;

(b) System design and technology for the fusion of mission-related data, information and knowledge in the context of complex missions involving co-operation against multiple targets;

(c) Effective deployment of crew in supervising and interacting with such systems, taking into account cognitive issues including software psychology (addressing human-software interaction).

TOPICS

a) Characteristics of operational requirements requiring difficult human-system interaction, e.g. group operations; C^3I issues; interoperability; uncertainty; survival in battle damage; IFF: consideration of air, sea and land systems.

b) Reliance on human operators to perform the fusion task often creates a prohibitively high workload and can result in an unacceptable reduction in the timeliness of information. This applies particularly to the operation of modern aircraft where one person may be required to assimilate all the sensor information as well as flying the aircraft and managing other systems. Automating the functions of fusion and sensor management offers a potential solution to these workload and timeliness difficulties.

c) New concepts and improving techniques in the integration of crew with complex systems, including: solution of cognitive issues; model-based reasoning for human advisory systems; the psychology of human interaction with complex software systems; virtual reality; de-cluttering in information presentation; the multi-media cockpit including head-mounted, head-up and head-down displays, voice input and output; autonomous machine Vs human-assisted machine; interactions and transitions between system autonomy and human interaction; situation awareness; representation of the human operator for modelling.

Thème

Cette réunion a pour thème la collaboration effective entre des équipages et des systèmes complexes mais non totalement autonomes, dans un contexte de sources multiples d'informations telles que communications terrestres, autres plates-formes et senseurs multiples sur plates-formes. Trois éléments principaux de ce thème méritent une attention particulière à savoir :

(a) les caractéristiques des situations opérationnelles impliquant des interactions homme-système difficiles

(b) la conception systèmes et les technologies permettant le fusionnement des données de mission, des informations et des connaissances dans le contexte de missions complexes requérant des actions coopératives contre des objectifs, multiples

(c) le déploiement efficace des équipages en ce qui concerne la surveillance et l'interaction avec de tels systèmes, compte tenu des questions cognitives y compris la psychologie de l'interaction homme-logiciel.

SUJETS

a) caractéristiques des situations opérationnelles exigeant des inter actions homme-système difficiles par exemple des opérations de groupe; questions C3I; interopérabilité; incertitude; survie après avaries au combat IFF; la prise en compte de systèmes terre, air et mer.

b) le recours à des opérateurs humains pour l'exécution de la tâche de fusionnement crée souvent une charge de travail excessivement lourde et risque d'entraîner une dégradation inacceptable dans l'actualisation des informations. Ceci vaut à plus forte raison pour le pilotage de l'avion de combat moderne où, dans certains cas, un seul homme doit assimiler l'ensemble des informations fourmes par les senseurs, piloter l'avion et gérer d'autres systèmes en même temps. L'automatisation des fonctions de fusionnement et de gestion des senseurs offre une solution possible à ces problèmes de charge de travail et d'actualisation.

c) l'application de concepts nouveaux et l'amélioration des techniques d'intégration des équipages aux systèmes complexes, y compris la résolution de problèmes cognitifs; le raisonnement à partir de modèles pour des systèmes-conseil; la psychologie de l'interaction homme/logiciels complexes; la réalité virtuelle; l'élimination sélective dans la présentation des informations; le poste de pilotage multimédia y compris les viseurs de casque et les représentations tête haute et tête basse, les entrées et les sorties vocales; la machine autonome contre la machine assistée par l'homme; les interactions et transitions entre le système autonome et l'interaction humaine; l'appréciation de la situation; la représentation de l'opérateur humain pour la modélisation.

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ACKNOWLEDGEMENTS/REMERCIEMENTS

The Panel wishes to express its thanks to the Canadian RTB members to RTA for the invitation to hold this Symposium in Ottawa and for the facilities and personnel which made the Symposium possible.

Le Panel tient à remercier les membres du RTB du Canada auprès de la RTA de leur invitation à tenir cette réunion à Ottawa, ainsi que pour les installations et le personnel mis à sa disposition.

TECHNICAL EVALUATION REPORT

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INTRODUCTION

The symposium on Sensor Data Fusion and Integration of the Human Element was initiated by the former AGARD Mission Systems Panel. The theme of the symposium was stated as "the effective collaboration between crew and the complex, but not entirely autonomous, systems in the context of multiple information sources such as off-board communications, other platforms and multiple sensors on board platforms." Particular attention was given during planning to consideration of human-system interactions, system design and technologies, and the effective deployment of crew, taking into account cognitive issues and psychology.

The main topics identified for the symposium can be summarised as:

- The characteristics of operational requirements requiring difficult human-system interaction in air, sea and land systems (e.g. group operations; C³I issues; interoperability; uncertainty; survival in battle damage; IFF).
- The high workload and information delays that can result from reliance on human operators to perform the fusion task, particularly in relation to modern aircraft where multiple sensor inputs may be loaded on to a single operator in addition to the tasks of flying and system management.
- New concepts and evolving techniques for crew-system integration, embracing: cognition, model-based reasoning, psychology, virtual reality, uncluttered information presentation, the multi-media cockpit (combined head-up and head-down displays, head-mounted systems, voice input/output etc.), autonomous vs. human-assisted machines plus interactions and transitions between the two, situation awareness, and human operator model representation.

Dr John Leggatt of the Canadian Department of National Defence, gave a welcome address and introduction in which he outlined the activities of the R&D Branch and its interest in the symposium. He gave examples of relevant Canadian activities such as the design, development and evaluation of a computer-based real time decision support system (DSS) integrated with C³I for the Modern Frigate programme, and synthetic displays for Search and Rescue Helicopters (the latter being one of the highlights of a Technical Tour of the Defence Research Establishment Ottawa (DREO) which took place during the week).

KEYNOTE ADDRESS

In his Keynote Address, "Sensor Data Fusion Technologies for Precision Strike," Eugene L Freeman of the Boeing Company, US, gave an assessment of the enabling technologies for sensor data fusion in the context of precision strike for a 2010 time frame. He emphasised a view of data fusion as a means for adding leverage to the human element rather than replacing it. Precision strike operations make big demands on the operator and, at each stage of an operation, involve a variety of operator actions for which sensor fusion can provide major benefits. He went on to discuss *sensor design considerations* in relation to various military applications, atmospheric and weather effects, the enabling effect of micro-electro-mechanical systems (MEMS), processing capacity and cost improvements, and GPS integration; expected *target sensor attributes* for a range of sensor types, in terms of weather, clutter, automatic target recognition (ATR) discriminants and design, weight, and cost; and *sensor data fusion architecture* with fusion at different levels from the decision-level downwards, including their relative merits, and the ongoing debate regarding sensor-level versus pixel-level fusion in the sensor data fusion community.

He concluded by stressing the importance of objective assessment of alternative systems and described an evaluation study which tries to balance the system level "requirements pull" with the sensor and ATR communities' "technology push."

SESSION I: CHARACTERISTICS OF OPERATIONAL REQUIREMENTS

Two of the papers originally planned for this session had been withdrawn. Mr Jean Bernard Senneville, FR, introduced the session's remaining two papers as snapshots of system concepts driven by requirements.

The first paper of the session, "Intelligent Crew Assistant for Military Transport Aircraft", by Walsdorf and Onken of the University of the Armed Forces, GE, was presented by Anton Walsdorf. It described the requirements for CAMA, the *Crew Assistant Military Aircraft*, and its design principles. Recent accident investigations were stated as evidence of aircrew being overtaxed by current concepts of cockpit automation. Automation – which can lead to increased aircraft performance and extend mission capabilities but still needs crew monitoring and supervision – can make the multitask environment of piloting, navigating, communicating and systems management more difficult in demanding circumstances. A video film illustrated the difficulties involved in a military transport, with minimal ground control assistance, making a steep approach over a hill to a landing strip or a drop zone in order to avoid air defences.

The paper identified the need for a system to assist the pilot in the cognitive process and in decision taking, and went on to analyse the characteristics of a *cognitive assistant system* in which conventional automated features are augmented by knowledge-based or rule-based functions of recognition, identification and decision making, and overlap with more conventional automation of planning, task/state association, and feature formation from sensory inputs. The CAMA design was described in terms of *interpretation of the situation, interpretation of pilot behaviour, situation diagnosis, mission planning, and crew interface*. The paper concluded with a

brief statement of flight simulator trials carried out in 1997/98 and in-flight experiments planned for early 2000 (the co-author, Reiner Onken, pointed out that further description of simulator trials were contained in a paper to be delivered in Session III). In answer to a question from the Session Chairman regarding the effects of human error, the author stated that crew responses were continually reviewed in closed loop simulations and said that the system had never failed to recognise pilot intent.

The other paper in this session, "On the Design of a Decision Support System for Data Fusion and Resource Management in a Modern Frigate", by Bruce A Chalmers of the Defence Research Establishment Valcartier, CA, was concerned with mid-life upgrade of the Command and Control system (CCS) for the HALIFAX Class frigate in the 2005-2010 timeframe. The paper, though including many of the same cognitive issues as the first paper, was more concerned with the underlying theoretical basis for design of the human-system interface and the different perspective of maritime operations in open-ocean and littoral environments (the latter presenting particular difficulties of geographical constraints, increased numbers of threats, sensor and guidance systems degradation, and commercial air and surface traffic congestion).

The author reviewed *the characteristics of shipboard C2*, describing the Combat System Operator (CSO) team in the ship's Operations Room, organised hierarchically with sub-division generally into warfare areas such as air, surface, and sub-surface. He provided a background philosophical analysis of the issues involved, including problems and opportunities related to goals, and a view of C2 as a complex sociotechnical system involving a wide range of operational problems and teamwork. He also noted various navy research efforts in the USA and UK directed towards leaner crewing of future ships. He discussed the *automation issues* of decision aid metaphors (as either prostheses or tools) and *dynamic delegation of authority* (with alternative modes appropriate to changing circumstances), before describing *a cognitive model of C2* and the approach to *a framework for design* based on an abstraction-decomposition hierarchy from the top level functional purpose of the whole system down to the physical form of individual components, and finally a discussion of *design goals*. The work is expected to lead to a specification of a decision support system integrated with existing CCS to support operators with data fusion, situation and threat assessment, and resource management. He confirmed, in answer to a question that the work had not yet proceded beyond the exploration of concepts and development of algorithms.

The two papers in this session provided striking contrasts in system characteristics for maritime warfare and air transport scenarios. The organic command and control system of a frigate and its crew needed to handle a wide variety of missions and tasks is very different from the single-mission but complex task of the individual pilot of a military transport aircraft. Nevertheless the similarities that emerged, in regard to the requirements for cognitive and decision aids for operators faced with the growing magnitude of systems and sensor data, provided an instructive introduction and background to the rest of the symposium.

SESSION II: SYSTEM DESIGN TECHNIQUES AND TECHNOLOGIES

The six papers of this session, which was introduced by Ir Pieter van den Broek, NE, who was also Chairman of the symposium, were concerned with concepts for data fusion in a variety of applications.

The first paper, introduced by Mark Alford and presented by Dale Klamer, was on "Measures of Merit for Collaborative Collection, Connection, and Execution Management" by Kowalski, Stubberud and Klamer of ORINCON Corporation and Alford of the Air Force Research Laboratory, US. The paper described a future technique for information sharing between otherwise independent sensor platforms, using interactive measures of merit (MOMs). The top-level design scheme to be used in individual platforms would use MOMs in data collection and execution of the fusion process, in conjunction with a connection management process utilising a connection agent to execute information requests and responses to and from other platforms. The scheme aims to provide an interactive environment for distributed intelligence agents (e.g. individual platforms/sensors).

A key feature of the scheme is the use of metrics to determine the quality of the *collection plan* generated in the collection process, the quality of gathered information and the quality of connections. The approach offers the potential for efficient theatre-wide surveillance, targeting and tracking by a two-way collaborative process between multiple platforms and sensors. System design and development has reached the stage of individual component testing. In answer to a question on the benefits of dynamic evaluation of MOMs, the authors mentioned the possibility of revising parameters to allow dynamic reconfiguration and its importance in a changing battlefield.

The next paper, "Contextual Information and Multisensor Data Fusion for Battlefield Applications" by Bastière, Chalmeton and Nimier, FR, focused on algorithms for the more specific task of multi-sensor tracking of individual targets. It was presented by Annie Bastière who gave a detailed exposition of the principles involved. Extended Kalman filters are applied independently to each of the sensor measurement coordinates, rather than to the whole cartesian representation of the state variables. This approach was aimed at avoiding global deterioration of the results in the event of individual coordinate degradation. As well as robustness to perturbations, other advantages claimed for this approach included simpler (linear) filters and no need for inversion matrices. The paper presented comparative mathematical analyses of a *classical multisensor tracking method* and a *multisensor tracking method taking context into account* (with contextual parameters enabling sensor validity ranges to be characterised with membership functions relative to fuzzy subsets).

Numerical simulations have confirmed the superiority of the context-sensitive approach. The possibilty of including further contextual information, such as weather and extending the techniques to other scenarios (e.g. multiple targets), was mentioned. The author confirmed, in answer to questions, the possibility of extending the scope of contextual information from other sources and noted the principal application at present to relatively slow-moving targets such as AFVs.

The paper "Image Data Fusion for Future Enhanced Vision Systems" by Döhler, Hecker and Rodloff of the Institute of Flight Guidance, DLR, GE, was presented by Dr Hans-Ulrich Döhler. It included comparisons of competing imaging sensors in the context of the needs of military transport aircraft, as well as the results of recent field trials, and first concepts for the fusion of radar and synthetic images – the basis for the enhanced vision system decribed. The advantages and disadvantages of direct sensor vision and

synthetic vision were reviewed; in particular the difficulties of image interpretation with direct sensor displays and the problems of obstacle detection, reliability and accuracy with synthetically generated displays. The aim of the enhanced vision system was to make use of all the information available in combination with on-board aircraft status and ATC inputs.

The paper reviewed the characteristics of sensor types ranging from UV video and LADAR, through medium and long waveband IR, to active and passive MMW radar bands up to 35GHz; from which it was concluded (not surprisingly) that for military transport aircraft operating in in poor weather conditions, active MMW radar would provide the best all-round solution. Trials were conducted using a MMW FMCW radar of high sensitivity and low detectivity (important for military applications) mounted on top of a DO-228 twin turboprop aircraft. A technique of "data fusion in time and space," using sensor images at different times as well as from different sources was used to generate scene images in a variety of presentation modes, with promising results. The questions that followed were mainly concerned with clutter discrimination and update rates; for which the author cited acceptable experimental results, though (in answer to a question by the Chairman) the system's usefulness during taxying would require further trials.

The fourth paper in Session II, "A distributed System for Command and Control Applications with Programming Language Abstraction" was given by the author, Erhan Saridogan of the Turkish Navy's Software Development Centre. Similar in its application to the paper by Chalmers in Session I, this paper focused on software techniques (particularly the use of object oriented programming) rather than the overall system. The author reviewed the characteristics and requirements of *distributed and real-time computing* including *OOP (object oriented programming) languages, concurrency, process management, communication, inheritance and real-time aspects*, before describing CPL (the CORD Programming Language). This is based on C++ with new keywords and a special layer to handle distributed processors.He also described the CORD-RTS (Concurrent, Object oriented and Real-time Distribution Run-Time System). Performance details were given, in terms of inter-object communication times achieved for three different computer platforms. The command and control system context and its links were mentioned as an introduction to a description of a *proposed solution to C^2 applications*, covering hardware and software architecture, and implementation – with special attention to *track management*, using either a centralized model or a distributed model for sensor fusion. In his concluding remarks, the author reiterated the value of linguistic mechanisms for abstracting real-time constraints and distribution, including simplified programming. The work is still under development at the TNSDC. The author, when asked how well CST compared with Java, was confident in its superiority for the given application.

The paper "Novel Concepts for Identity Fusion in an Air Combat Environment," was presented by Shari Arman of DERA, UK, as an AI approach to augmenting current data fusion algorithms for air combat applications. Fused sensor outputs of target tracks, generated through extended Kalman filters, produce *software objects* which are further programmed with a set of *self beliefs* including variable behavioural response, goals and knowledge of how to achieve those goals. The author described the programme of ongoing work, including the *Sensor Tracking Application Rig (STAR), incorporating HOTAS (hands on throttle and stick)* man-in-the-loop interface, before discussing track identity fusion and the potential – and concepts – for augmentation, and introducing the concept of intelligent *agents* as meta-objects embodying cognitive notions of *beliefs, desires and intentions*. The information agent structure of *self model, acquaintance model, world model and ability model* form the basis for an optimised system architecture with an *agent wrapper* built around a multi-sensor data fusion tracking algorithm. Asked if it might not be better to have separate agents for, say, identification and identity, the author replied that this would lead to a high degree of duplication, when compared to the proven ability to combine them in a single agent wrapper.

The final paper in Session II, "MIDS (Multi-functional Information Distribution System) Triangulation," by Ziegler and Sachsenhauser of Daimler-Benz Aerospace, GE, was presented by Joseph Ziegler. The system's aim is to improve the range spoke of a platform's sensor (especially against jammers) by reference to information on target range or track from other platforms. The triangulation and de-ghosting process described assumed direction spokes from MIDS (a NATO system to provide for data exchange among airborne, land and sea forces). An exposition of *the triangulation mathematics* was given, including *extrapolation of ownship data, derivation of the intersection equations* (of spokes from the platform's own sensor and from MIDS) and *alignment*. Individual analyses were given of the credibility of MIDS range, visibility, height, vertical velocity, manoeuvre and velocity, leading to the credibility of the intersection point itself, and alternative association tests were described.

Results were shown of simulations of the triangulation algorithms (using a PC), carried out mainly for the purpose of fine tuning constants. It was interesting to note that 88% of processing time was taken up by the algorithm, transformations, and range and range rate calculation, and only 12% by credibility and association tests. It was confirmed, in answer to questions, that time histories were not determined (or used), only variances; and, despite the notoriously poor accuracy of aircraft ESM sensors, useful results had been achieved.

SESSION III: INTEGRATION OF HUMAN OPERATORS WITH COMPLEX SYSTEMS

This session, chaired by Dr-Ing Luigi Crovella, IT, was originally planned to include five papers, one of which was moved to Session IV.

The first paper of the session, "Subjective Information Given by Users in Bearings-only Target Motion Analysis," by Spigai and Grandin of Thomson-CSF-RCM, FR, was presented by Jean-François Grandin. It addressed a similar problem to that of the final paper of the previous session – determining the position and velocity of a target from sensors in more than one location – but with more limited information, and including a subjective human element. In the *Bearings-only Target Motion Analysis* (BTMA) scheme described, two observers on the ground measure bearings of manoeuvring air targets which are used in a trajectory estimation algorithm based on *Hidden Markov Models* that allow the use of subjective information. The paper contained a review of the limitations of the extended Kalman filter for non-linear or non-Gaussian problems and the alternative *interacting multiple models* (IMM) based on multiple extended Kalman filters. There followed a statement of the principles of the *hidden Markov models* (HMM). *Subjective information* from the human observer, typically in the form of estimates of possible target position, is input to a map display which also

provides additional aids such as geodesic information, type of target, etc. A fairly simple algorithms is employed to provide a best estimate of target position. Simulation has demonstrated smooth and accurate results for HMM (subject to the quality of the subjective inputs) when compared to the more mechanistic IMM. As a next step, it is intended to develop an automatic learning process to aid the user.

The next paper, "Fusion and Display of Data According to the Design Philosophy of Intuitive Use," was by Goetz Ardey of the Technical University of Braunschweig, GE. His historical survey showed how the ad hoc development of avionics systems had led to severe demands on aircrew, with worrying implications for safety, particularly in the field of General Aviation. Examples of past and present cockpits illustrated the growth in the number of displays and controls confronting pilots, (who may be of widely varying backgrounds and abilities). In addition, he pointed out that equipments developed for large commercial aircraft were generally unsuitable (too big, too complex, too expensive) for GA aircraft. The author went on to describe the *COSIMA programme*. COSIMA (Cockpit and Simulator for General Aviation) aims to integrate new technologies to provide an intuitive user interface based on operational analysis of cockpits. The system, installed in a Cessna C-172 testbed, consists of two PC-like computers with inputs from sensors (engine instruments, GPS, etc.) and controls (keyboard, trackball) and outputs to three side-by-side colour-LCD screens. The centre display shows the *Aircraft Monitoring System, AMS* (essential engine, fuel, and time data) with optional levels of information controlled by keyboard input. The side-displays show *Flight Planning and Navigation System (FPNS)* information in the form of moving maps, together with indicated air speed, altitude (and rates of change) heading, ground track, etc. The cockpit layout aims to achieve a well-balanced presentation with variable operational modes and minimal distraction from the flying task. On a question of pilot acceptability, the response of those who had tried it was said to be, "when can we have it?" Other questions were concerned with IFR capability (not practical in its present form) and multiple AMS fault display (handled by prioritization of the different levels).

The paper "Enhanced and Synthetic Vision System Concept for Application to Search and Rescue Missions," by Swail and Jennings of the Institute for Aerospace Research, CA, was presented by Carl Swail. Search and Rescue by helicopters is an important issue for Canada, given its size and need to access remote areas, often in poor weather (down to 100 ft ceiling and 1/8 nm visibility). The system described by the author is intended to augment pilot's situational awareness in four phases: descent in a search area without external aids; search for crash site, survivors and wreckage; transition to, and maintenance of hover during rescue; and safe egress from the rescue area. Constructed largely from COTS components, it includes a *camera platform* with infrared and visual band sensors, an *image generation system* incorporating a terrain database and with inputs from a range sensor, and a *digital image processing unit* which fuses video and synthetic images to provide an output to the pilot's *helmet-mounted display*, plus a *head tracker* which controls the camera platform, HMD display and the DIPU.

A prototype system is due to be incorporated in a Bell 205 by 2000: whilst an ongoing research programme has been addressing the questions of field-of-view, camera platform roll compensation, system delays, display symbology, image fusion techniques, true binocular vs bi-ocular trades, and synthetic image scene content. In answer to a question, the author stated that a range sensor was not being incorporated initially but eventually an infrared sensor was envisaged.

The final paper in Session III, "Evaluation of the Cockpit Assistant Military Aircraft CAMA in Simulator Trials," by Schulte (ESG Elektroksystem- und Logistik-GmbH) and Stütz (Universität der Bundeswehr), GE, was presented by Peter Stütz. The CAMA system is that described in the paper by Walsdorf and Onken in Session I. The flight simulator has primary flight displays either as standard ADI (for IFR phases) or 3-D perspective format (for low level flight), plus a multi-mode interactive navigation display with a touch-sensitive screen input for mode selection, etc. Speech recognition/synthesis is used in parallel with the manual/visual input/output.

Ten German Air Force transport pilots took part in the trials, with various *scenarios and tasks*, between Autumn 1997 and Spring 1998. Subjective ratings were given by the pilots in terms of *evaluations of flight simulation, CAMA philosophy, situation awareness, assistance quality, and advice and warning philosophy*. The pilots were also asked to rate the *handling qualities and acceptance of CAMA*. Finally they were asked to provide a general evaluation, with ratings of CAMA's influence on *flight safety, mission efficiency, and survival probability*. Overall, the system was rated as "very good". Objective evaluations in the form of reaction times in response to events such as appearance of a threat, change of destination, and corridor change, were given, showing a dramatic improvement – the result, it was stated, of reduction in mental workload. The trials were also effective in indicating improvements in display formats. Further work planned includes: flight trials (scheduled for 2000) and integration of imaging sensor information into the 3-D flight guidance display to achieve an enhanced vision system. In answer to questions, the author said that objective tests to back up all of the subjective evaluations were not possible (for example, situation awareness). He conceded that the use of operational pilots may not be ideal when compared with professional test pilots' critical appraisal of new technology, but had been the only practical trials approach.

SESSION IV: SYSTEM APPLICATIONS

This session, chaired by Mr Paul Sergent, FR, contained five papers, including one (the last paper) transferred from Session III.

The first paper of the session, "Fusion and Display of Tactical Information Within Battlefield Helicopters," by Watts and Silvester of DERA, UK. Presented by Anna Watts; its subject was the trials by the Defence Evaluation and Research Agency of alternative forms of Tactical Situation Displays (TSD) for the WAH-64 attack helicopter. The author described the *HOVERS* man-in-the-loop mission simulator, the *cockpit configuration* (appropriate to a possible 2010 timeframe for introducing TSD), *TSD configurations*, trial *scenarios and threat environment* (defined by the Army Air Corps), *and trials procedure* (with 72 AAC-crewed missions). Results were shown for three TSD configurations. The "baseline" case assumed on-board sensor data available at the in-service date overlaid on a digitised map containing tactical information. The "improved" and "fused" cases have different degrees of integration of on-board sensor and tactical information.

The trials results were illuminating. Although the probability of being killed by ADUs reduced dramatically and progressively with the improved and fused cases, overall survival was only slightly improved, due to an increase in the

probability of being killed by threat helicopters. This result was ascribed to commanders focusing their attention on the map displays – used successfully to improve use of terrain to avoid ADUs – to the detriment of survival against threat helicopter missiles. It was nevertheless concluded that the simpler tactical display made possible by fusion of on-board sensor data improved crew planning and survivability. It was also concluded that: comprehensive training will be needed to realise the full benefits; appropriate enhanced information should be provided to both the pilot and the commander to improve communication; and further benefits would be gained from on-board planning capability and additional display functionality. Questioned on timeliness and validity of the data displayed, the author replied that human factors experts had been consulted regarding display of threat error circles but their size would render them of doubtful utility.

The second paper in the session, by Roschmann and Wacker of Daimler-Benz Aerospace, GE, was on "The Multi-Sensor Integration System for NATO E-3A Mid-Term Modernisation" and presented by Ulrich Pietzschmann. The paper described an integrated programme of work embracing hardware and software, starting with the *historical background*, and *a programmme overview*. The E-3A mid-term modernisation programme reflects the changed – and more fragmented – geo-political situation that has arisen since NATO AWACS was first introduced. This makes greater demands on the system, in terms of quickly-changing situations and an increased number and variety of inputs. It will introduce new equipments for communications, navigation (including GPS) and identification, as well as the integration of all available sensor data, state-of-the-art flat panel displays, and new COTS-based computers with open systems architecture and future upgrade capacity.

The MSI system is required to provide a unique display object from all the inputs related to each single target. Its software, coded in Ada95 and C/C++, is executable on a SUN/SPARC compatible computer with Solaris 2.x OS, and is required to communicate with the AWACS mission control (AMC) computer via a Gigabit Ethernet. Outline descriptions of the *multi-sensor tracking and identification systems, and the MSI manager*, were followed by a review of the test philosophy which utilizes a DASA *MSI Software Test Bed* which permits testing independently of the Boeing AMC. In answer to questions on the approach to identification and data fusion, it was stated that a rule-based, rather than probabilistic approach was followed, with updates based on operator indications. Although it was agreed that this does not follow current STANAGs, it was nevertheless accepted by the user.

The next paper, "Environmental Perception Process in Maritime Command and Control," by Paradis and Roy of the Defence Research Establishment, Valcartier, CA, and Treurniet of TNO, the Hague, NE, was presented by Stéphane Paradis. It was complementary to the paper by Chalmers and Bosse in Session I, being concerned with the same subject matter of maritime C^2 but concentrating on situation awareness and data fusion. The *environment perception process (EPP)* was presented as a step towards defining an integrated architecture for data fusion and a basis for higher levels of abstraction. A conceptual model provided by Boyd's Observe-Orient-Decide-Act (OODA) loop was given as a means of capturing the command and control process, onto which could be mapped the elements of *multi-sensor data fusion, situation and threat assessment, plan creation, and plan implementation*. This provided the background for a discussion of a *situation awareness perspective for data fusion* and an exposition of the *environment perception process* (EPP) itself, representing the first two levels of Endsley's three-level model of situation awareness (*perception, comprehension, and projection*). An *EPP framework* was presented, supported by examples, the first of which illustrated a situation in which three targets are tracked, whilst a third target track – inferred from a knowledge of doctrine – may be constructed, with inferences for the total situation. The author concluded with a discussion of *uncertainty and potential pitfalls* – for example, the danger of data looping where information from higher data fusion levels may be fed back into the fusion process as if it were independent information. Questions were mainly concerned with the issue of identity uncertainty raised in the final part of the paper, the author replying that it was not clear whether this should be output. The Session Chairman commented that too much information can make decision making more difficult, a problem that an integrated data fusion system ought to be trying to avoid.

The last of the papers originally scheduled for this session, "Tactical Missions of Transport Aircraft: an Approved Low Level Guidance Concept Reduces Crew Workload," by Lerche, Schoder and Mehler of Daimler-Benz Aerospace, was given by Dipl-Ing H-D Lerche. The difficulty of flying transport aircraft at low altitude for long periods (up to 500nm), led to the system concept described in this paper. The author reviewed the tactical and delivery reasons for low-level flying and the problem of terrain avoidance coupled with freedom of spontaneous lateral manoeuvre, which demand an exceptional degree of concentration on the part of the pilot. The *Low Level Flight Guidance Demonstrator* concept design is based on a *rolling stone algorithm* in which flight path radius is overlaid on the terrain profile generated from a digital data base, to generate a *flyable altitude profile*. Energy management is also included in the algorithm.

Experimental equipment for flight demonstration and validation, consisting of a guidance computer, HUD and HDD, has been implemented in the ATTAS (Advanced Technology and Testing Aircraft System) with the aim of demonstrating pilot's increased situation awareness, optimizing the man/machine interface, and testing handling qualities. The pilot interface emphasises *care free moding* with pilot selection between *fixed track* (fully automatic 3-D pre-planned track with auto-throttle), *free track* (automatic altitude and throttle with pilot lateral control), *and standby track* (pilot steering with synthetic vision and ground proximity warning). Support to the programme is also provided by the parallel *Reliable Autonomous Precise Integrated Navigation (RAPIN)* C-160 Transall flying testbed – which has demonstrated data fusion of navigation sensors LINS, GPS and radar altimeter/TRN. In reply to questions, the author stated that the display was selected on the basis of pilots' preferences from a study by Darmstadt University. This work confirmed the differences in display options – and needs – compared to Tornado.

The final paper in this session, "Integration of the Human Operator into Complex Air Systems using Alternative Control Techniques, by Dr Graham Rood of DERA, UK, was carried over from Session III. Demands on the pilot, in addition to an ever-increasing complexity of avionics systems and the quantity of information input, include the frequent need for *eyes-out* operation, which places limits on the practicability of head-down displays and switches. Helmet-mounted displays and HOTAS (hands on throttle and stick) improve pilot response in such situations, but the large number of functions and control modes remains a problem. Controls and switches per crew member have grown in number from single digits in

the 1920s up to several hundred today, a trend which is being repeated in HOTAS switching (up to 40 functions on the hand controls of some aircraft), with associated increase in the probability of error. Further problems arise from variations in physical attributes – for example, gender differences in the average size of hands.

Alternative Control Technologies to alleviate these problems were discussed, including *head pointing*, *eye tracking*, and *voice control*. Direct voice input (DVI), though not as well developed as the foregoing technologies, can provide a quicker and more natural interface and has proven effective in simulator trials. Longer term possibilities are *biopotential and gesture-based* control, using electromyographic (muscle impulse) or electroencephalographic (brain impulse) inputs. Finally, the development of unmanned air vehicles (UAVs) was mentioned, which would profoundly change the nature of the human operator interface. To a question on the "best" combination, the author replied that it depended on the type of aircraft – fast jets for example, required speed of input/response for which DVI had proven popular in tests with pilots – though attention had to be paid to noise discrimination. Other questions concerned: the areas of the brain responsible for different tasks (on which work was being carried out) and differences in the needs and environment of UAV operators and aircraft pilots.

SESSION V: LESSONS LEARNED AND FUTURE TRENDS

Chaired by Robert Campbell, US, this session of the symposium contained two papers(two papers were withdrawn).

The first paper, by Balti (Turkish Navy Department of Software Development) and Kuru (Bogazici University), TU, was on "Utilizing CORBA Concepts for Command and Control Systems" and presented by Metin Balti. The paper described an evaluation of the CORBA (Common Object Request Broker Architecture) as a platform-and-operating system-independent architecture for large systems such as naval C^2. A background description was given of the requirements for *a military C^2 system* and *its software architecture*, leading to *an overview for distributed systems*, particularly *CORBA and common object services* built on the *object management architecture* introduced by the Object Managemant Group (OMG), and defined in an *interface definition language (IDL)* which is mapped onto other programming languages such as C, C++, Java, Ada and COBOL.

An *architectural evaluation* was made in a comparative review of CORBA and alternative distributed systems (DCOM, RMI, DCE) against a number of criteria. *Performance assessments* were carried out in two test environments, the latest of which consists of four Ultra-60 machines with 155MB ATM connections. In summarising the evaluation, it was concluded that CORBA, as currently specified, though superior to the alternatives considered, was inadequate for reliable large-scale C^2 systems; leading to the decision to build an intermediate layer on top of a CORBA infrastructure. Related research on CORBA by other organisations was also reviewed, noting particularly OMG's plans for fault-tolerant improvements. The *proposed architecture for C^2 systems* applies the lessons learned from the evaluation and will be implemented in prototype form using COTS products as far as possible, including Java-based programs (especially for the user-interface). The author, in answer to questions, provided clarification of the architecture and of the CORBA working group (representing government and university interests) which will lead to its commercialisation.

The final paper, "The Effects of Image Resolution on the Utility of Target Recognition Aids," by Jan Stiff of the US Naval Air Warfare Center, China Lake, was concerned with imagery-based target recognition aids (IBTRAs) provided to a pilot from off-board sources. A console, used by the thirty participants in the experiments, was based on a 166MHz Pentium computer, with digitised imagery displayed on a 17 inch monitor at a resolution close to that of a tactical aircraft display. Two kinds of imagery were presented: *FLIR imagery* from exercise and training flights; and *reference imagery* which was derived either from a commercial, SPOT source (low resolution – 10m) or from US Geologic Survey aerial reconnaissance information (high resolution – 1m). Two images were presented, the FLIR image (close, medium or far) and the reference image with a box round an object which the test subject was required to identify in the FLIR image.

Results were given in terms of response time (no time limit imposed) and accuracy (percentage of correct responses) for trials at the three ranges and varying IBTRA cross-range coverage. Earlier work, showing the beneficial effects of matching cross-range extent of the IBTRA to the sensor image, was confirmed, whilst the effect of resolution – the main purpose of the present study – appeared to be more ambiguous. It was concluded that beneficial effects of high resolution-derived IBTRAs were most likely for missions involving weapon release close to the target.

SESSION VI: ROUND TABLE

The round table discussion which concluded the symposium, was conducted by the Chairman, Ing Pieter van den Broek, as an open forum for all those present. He got the discussion under way by posing the question: how important is integration of the human element? There exists a wide divergence of views and, as he pointed out, it was important to recognise that the human element has its own failure modes. Several authors had commented that crews involved in trials of sensor fusion systems felt very confident with them but could be frustrated when a fault did occur. The problem was usually handled by providing extra degrees of freedom, but that gave rise to the possibility of even more faults. In general, he asked, might it not be better to have inadequate information rather than false information? Other contributors agreed that it should be inherently possible for systems to provide *no ident* or *low probability* indications. In the end however, decisions must be taken by the system with – ultimately – human operator decision on appropriate action. There seem to be no ideal solutions as yet but the requirements of users must define the system (including considerations of fratricide and political issues). At present it seems best to continue treating fusion systems essentially as operator aiding devices, though recognising that in situations where time is vital, the system might have to be taken at face value.

Joseph Ziegler noted that lack of total operator confidence could lead to a desire to know which sensor(s) are contributing, though it would be difficult to present all the information simultaneously in view of the large number of symbols required. It may therefore be necessary to persuade and/or train operators to accept such systems on trust. From a Navy point of view, Metin Balci was concerned that even a single failure would make it difficult to trust the system, but it was pointed out that, in a situation when, say, three sensors produced agreed results supported by an expert system, that ought to be sufficient. Also, it was reiterated that system

failures could be detected in most cases. Graham Rood observed that operators' reaction to aiding systems was generally, "when we can see it works better than we do, we will accept it!" For example, terrain avoidance radar, when first introduced, was accepted only gradually; it was, he agreed, a training issue.

Luigi Crovella raised a second significant question: how far can fusion systems adapt to the crew? Graham Rood pointed out that voice input systems are already a two-way process and Ziegler mentioned that systems such as MIDS do have initialisation inputs from the human operator. Human input to modify system behaviour is also a desirable feature of NATO AWACS where operators want to apply relative weightings to identification inputs – evidence, Crovella remarked, that when engineers talk of certainty, operators feel uneasy. Balci pointed out that there were differences between ground and ship uses for AWACS information and on-board confidence was necessary in both cases, by AWACS as well as by the end-user.

The Chairman returned to the issue of operators' confidence and their natural scepticism regarding the reliability of new systems and wondered why it was necessary to have an expensive pilot at all if an aircraft were fitted with an all-glass cockpit. He rounded off the discussion by commenting that operators may use new systems in ways that were not envisaged by those (as represented by the round table participants) who developed them.

CONCLUDING REMARKS

A general impression was that the papers presented were not only relevant to the symposium's stated theme and topics but also extremely wide-ranging. They embraced discussions of the basic principles of sensor data fusion and operator behaviour at one extreme, to presentations of results from trials of complete systems at the other. This was perhaps reflected in answers to the questionnaire circulated to participants; more than half of the respondents replying positively to the question: *has the symposium provided valuable new perspective in your work?* An even greater number agreed that the symposium had a substantial impact on *expanding personal contacts for potential future collaboration;* indeed this was listed as the highest priority aspect of the symposium by most participants. This view can be expected, since professional peer inter-communication is generally regarded as a primary reason for holding symposia. More to the point, the overall value of the symposium was assessed by the majority as at least "*important – return equals contribution*" with an average score of 72 (on a scale of 0 to 100).

The essential technical concerns of the symposium – the fusion and presentation of information in a form that can be easily assimilated, and the interaction of fusion systems with the human operator – was well covered, as was the fact that advanced sensors and communications can produce a deluge of information as well as opportunities for improved performance. The problems of assimilating large amounts of information and using it to make correct decisions, were shown to be particularly acute in the case of command and control systems, as was evident in several papers. These ranged from analysis of basic C^2 structures, to computer and software requirements.

The opportunities that sensor fusion provides for new or enhanced mission capabilities were also shown in a variety of papers, covering applications as diverse as multiple target tracking, and helicopter search and rescue in adverse weather. Sensor data fusion, to enable the operator to make sense of multiple sources (or combined with optical sensors in enhanced vision systems), was an essential element in all of them. It was also salutary to hear of an approach in the field of general aviation which, though constrained by considerations of size and cost of equipment, was attempting to rationalise cockpit layout so as to reduce pilot workload. For more complex applications, several papers described the development of operator aids based on cognitive analysis and applications of machine intelligence in automated or semi-automated systems.

The round table discussion sounded a note of caution on the need to persuade and train operators, who were recognised to be naturally cautious of new technology until proven. Participants also recognised the importance of two-way interaction between system and operator, to provide flexibility of response.

In conclusion, the symposium provided a wide-ranging and comprehensive review of this important area of technology and demonstrated its potential for major improvements in operators' situation awareness, mission effectiveness, and survivability.

Defense R&D in Canada

Following are the viewgraphs of the opening address for the symposium presented by Dr. John Leggat. This presentation not only highlighted the research and development activities in the host country, but emphasised also some of these activities related to the subject of the symposium. Because of this the presentation is included in the proceedings of this symposium in the form of these (self-explaining) viewgraphs.

Pieter Ph. Van den Broek

Acting symposium chairman.

Paper presented at the RTO SCI Symposium on "Sensor Data Fusion and Integration of the Human Element", held in Ottawa, Canada, 14-17 September 1998, and published in RTO MP-12.

DEFENSE R&D
R&D POUR LA DÉFENSE CANADA

John Leggat
Chief Research and Development
Chef - Recherche et développement

Content

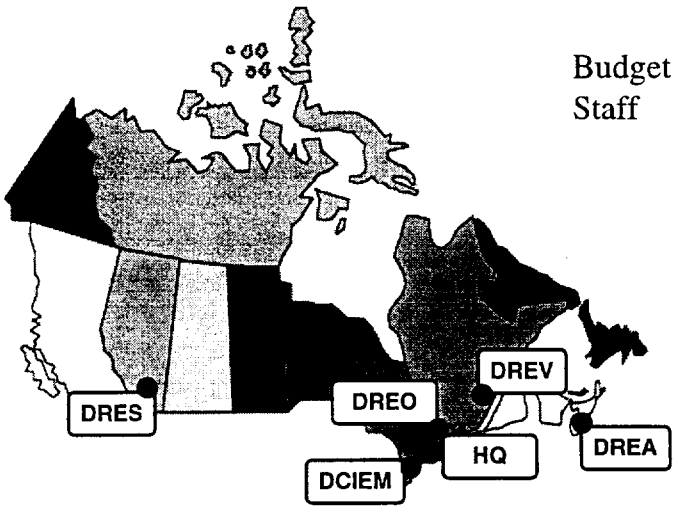
- The Defence R&D Branch
  - The R&D Program
  - The Strategy
- The R&D Network
- Some Studies Related to this Symposium
  - Environment Perception Process in Maritime C&C
  - Tactical Information Fusion Prototype
  - Decision Support System in Modern Frigate
  - Synthetic Displays for SAR Helicopters
  - Landmine Detection
  -

The Defence R&D Branch

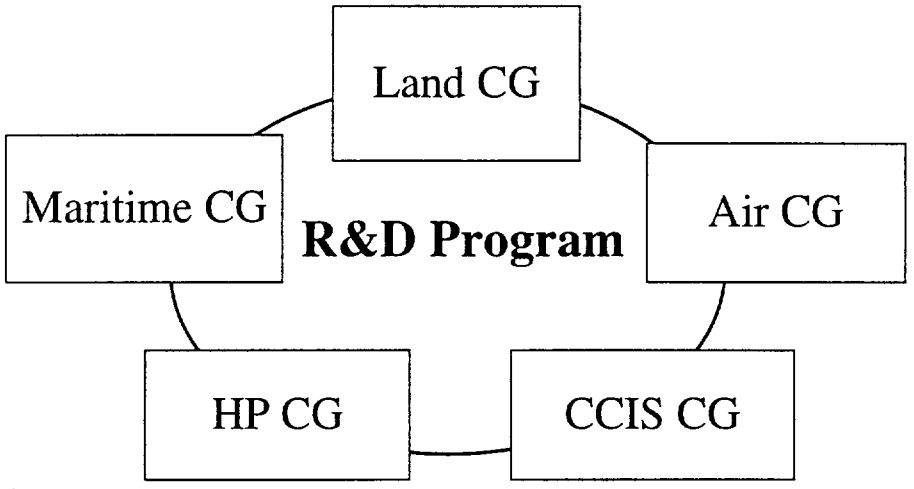
- Centre of Canadian Defence Technological Expertise
- Mission:
  - Provide expert S&T advice for decision making
  - Contribute to the success of military operations
  - Enhance the preparedness of Canadian Forces
  - Facilitate a Canadian defence S&T industrial capability

Laboratories/Establishments

Budget $160M
Staff 1023



R&D PROGRAM



Keeping the Sharp End Sharp

- What Blunts the Sharp End:
  - Weapons proliferation
  - continuing advances in technology
  - Expansion of the battle space
  - Revolution in military affairs
  - Expansion of the spectrum of conflict
  - Nature of Coalition operations
  - Assymetric Threats

THE STRATEGY

Delivery Strategy

- In-house focus on technologies unique to defence
- balanced in-house effort and extramural partnerships for dual-use technologies
- capability to adapt commercial technologies for defence purposes

Current Core Technologies

- Surveillance and Target Acquisition
- Electronic Warfare
- Command Information Systems
- Air Vehicles
- Naval Platforms
- Combat Systems
- Human Systems Integration
- Life Support Systems
- Space Systems

Areas of Increasing Emphasis

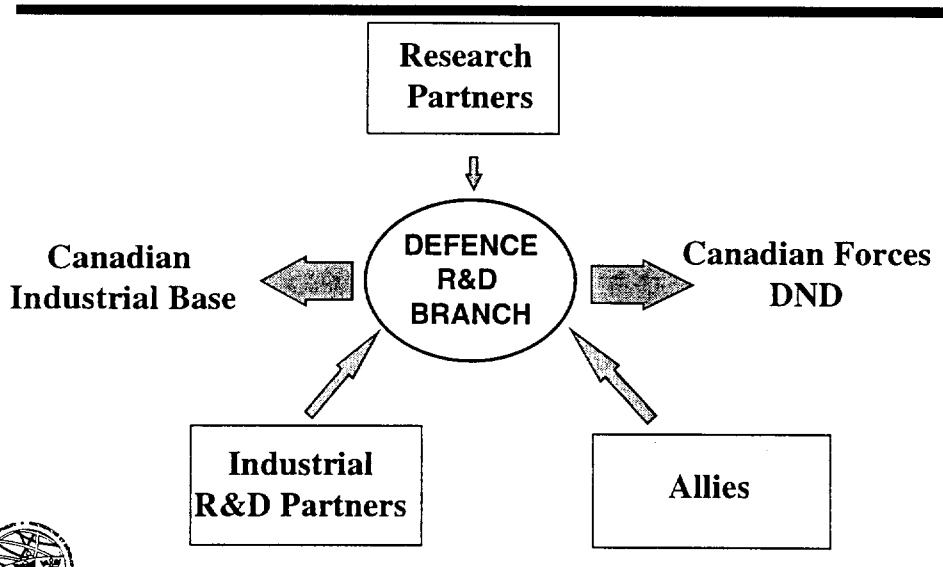
- Distributed Interactive Simulation
- Information Warfare
- Signature Reduction
- Non-Lethal Weapons
- Advanced Materials
- Biotechnology
- Robotics

Technology Investment Strategy

- TIS Projects forward to 2010
- an attempt to:
  - define technology competencies we must maintain, withdraw from or develop;
  - identify human resources and skill sets to support these competencies;
  - identify a framework to oversee and manage competency developments to realise optimal benefits for clients

THE R&D NETWORK

Redefining the R&D Network



Defence R&D Branch as a creator, integrator and enabler in the areas of new technology

Partner Programs

- International Agreements
  - The Technical Cooperation Program (TTCP)
  - NATO Research and Technology Board
  - Bilateral Memoranda of Agreement
- Other Canadian Public Sector Institutes
  - National Research Council
  - Canadian Space Agency
  - Provincial Research Agencies
- Industries/Universities

Partner Programs

- Benefits of Partnership
  - Leveraged Resources
  - Maintenance of critical mass
  - Enhanced quality
  - Quicker progress
  - Stable working relationships
  - Commercial exploitation

SOME STUDIES RELATED TO THIS SYMPOSIUM

Environment Perception Process in Maritime Command and Control

- Definition of an architecture for data fusion with emphasis to situation awareness in the context of dynamic human decision making
- This architecture facilitates the proper conceptualisation and design of decision support system according to the human role in the command and control cycle
- Environment Perception Process is the foundation of the architecture for data fusion

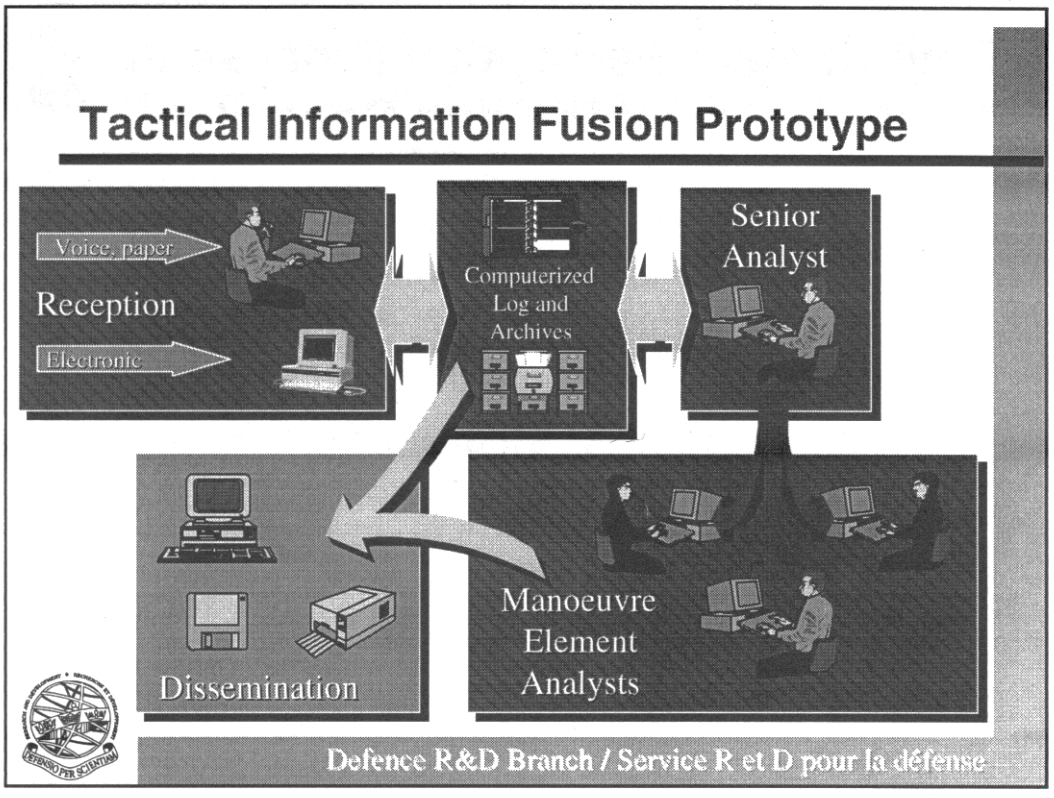
Defence R&D Branch / Service R et D pour la défense

Various operational trends in naval warfare, such as technological advances in threat technology and an ongoing shift to littoral warfare, put the shipboard decision making process under pressure. Data must be processed under time-critical conditions and as a consequence, the risk of saturation in building the tactical picture and of making the wrong decision increases.

The aim of this study is to explore an aspect of the problem of *dynamic decision making* in the context of naval command and control. One must realise that the human plays an essential role in the command and control cycle. *Situation awareness* is essential for commanders and their staff to conduct decision-making activities. *Data Fusion* is seen as an essential process to enable operators to achieve situation awareness.

The study is a step towards the definition of an architecture for data fusion giving emphasis to situation awareness in the context of dynamic human decision making. This architecture facilitates the proper conceptualisation and design of decision support system according to the human role in the command and control cycle.

A presentation will be made by Mr Stephane Paradis (DREV). He will discuss *environment perception process* as the foundation of this architecture for data fusion. The environment perception process is aimed at achieving a first level of situational awareness, which forms the basis for the other more abstract levels of situation awareness. Thus the quality of the results of this level is of utmost importance for the situational awareness that can be gained at the higher levels.


Tactical Information Fusion Prototype
Voice, paper
Reception
Electronic
Computerized
Log and
Archives
Senior
Analyst
Manoeuvre
Element
Analysts
Dissemination
Defence R&D Branch / Service R et D pour la défense

Decision Support System in Modern Frigate

- Exploration of Concepts for

  design, development, investigation, and evaluation of computer-based, real-time decision support system (DSS) to be integrated into the ship's C2 Systems to assist operator in conducting tactical C2

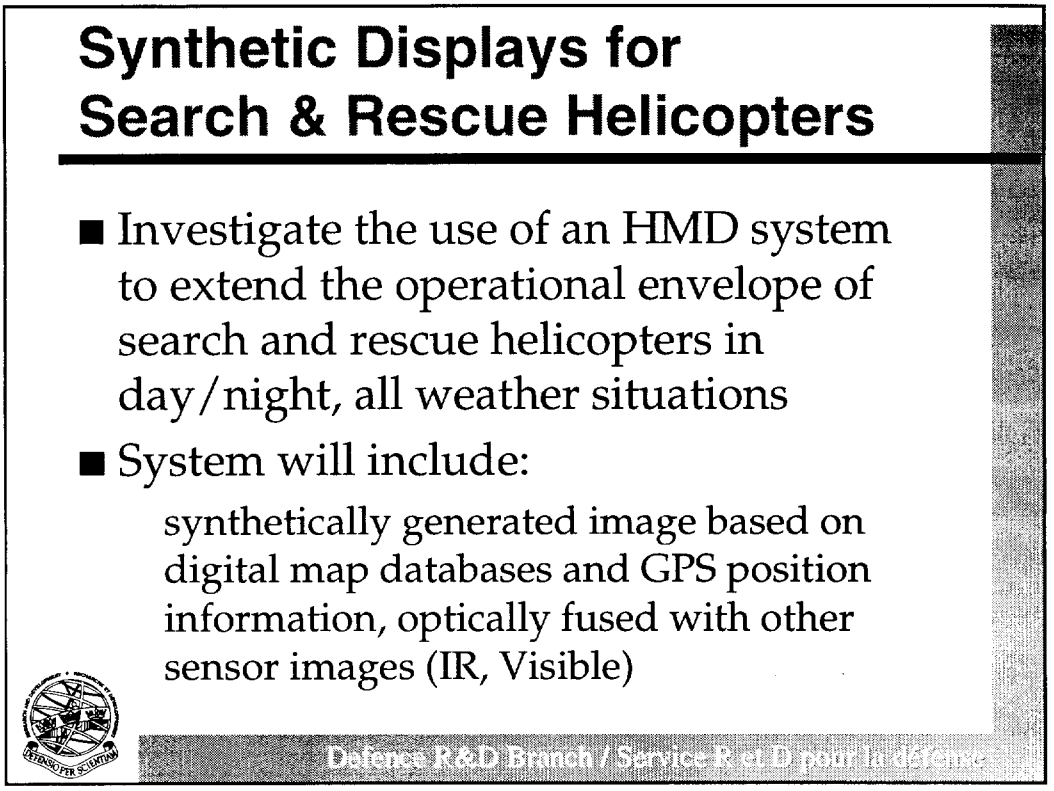
  Operator Serves 3 roles in the C2 Process:

  - situation interpreter
  - decision maker
  - effector

Defence R&D Branch / Service R et D pour la défense

DREV is exploring concepts for the design, development, implementation, and evaluation of a computer-based, real-time decision support system (DSS) that can be integrated into the ship's CCS to assist operators in conducting tactical C2. The operator serves three primary roles in the C2 process: situation interpreter, decision maker and effector. The purpose of the DSS is to support operators in each of these roles for data fusion and resource management related activities in Above-Water Warfare (AWW). A key goal is the design of a joint system, comprised of both operators and automated decision aids, that optimises overall mission performance, leading to improved operational effectiveness.

Developing this type of decision support system is a challenging task. A key problem is that it must be capable of operating in a highly dynamic and open environment that imposes variable and unpredictable demands on operators. Operators must be able to effectively handle the demands of new and unanticipated situations that have not been addressed by the system designer or by doctrine. The system must certainly support operators so that they can follow established principles and recommended procedures. Yet it must not overconstrain them so that they are hampered from taking advantage of their abilities to reason, improvise, and respond, while at the same time calling on the system for the support they need.



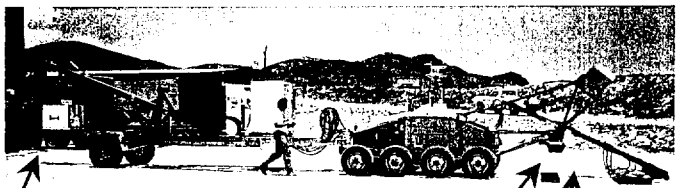
Research into the use of helmet mounted displays (HMD) is being carried out at the Flight Research Laboratory (FRL) of the National Research Council (NRC). They work on a collaborative project with the Canadian Armed Forces, CAE Electronics and the Canadian Marconi Company to investigate the use of an HMD system to extend the operational envelope of search and rescue (SAR) helicopters in day/night, all weather situations (100 ft ceiling, 1/8th nm visibility). The final enhanced and synthetic vision system (E/SVS), planned for testing in the year 2000, will include a synthetically generated image based on a digital map database and GPS position information, optically fused with other sensor images. The sensor images could include an IR image or enhanced, low-light level video. Range information will be provided by a laser range-finding system. The system must provide good situational awareness to the pilot to allow operation in low visibility conditions for search and rescue operations to be carried out.

Research is being carried out at FRL into the system requirements of HMD systems in helicopter flight. A presentation by Mr. Carl Swail will include results to date and a description of the final system. He will discuss human factors issues related to the integration of the different sources of information. The present research system consists of two colour video cameras on a head-slaved platform mounted on the roof of NRC's Bell 205 helicopter and two video projection systems inside the helicopter projecting images through fibre optic bundles to the helmet mount display optics. Baseline handling-qualities investigations have been carried out to determine the effects of using an HMD on the pilot's workload and performance while performing standard manoeuvres.

Landmine Detection

- The major problem is to detect plastic buried antitank landmines reliably
- Multiple sensors are used to find the mine while rejecting the numerous false alarms produced by buried objects like rocks, roots, conductive soil, etc.

Improved Landmine Detection System (Technology Demonstrator)



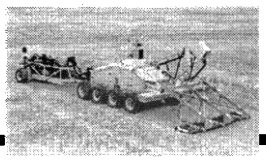
Thermal Neutron Activation System (detects N_2)

Ground Penetrating Radar

Infrared Camera

Metal Detector

Important Points



- Multi-sensor landmine detection system was shown to reduce false alarm rate while retaining acceptable Probability of Detection
- Temporal and spatial correlation of data is crucial
- Sensors must be "orthogonal" - i.e. measure independent properties for data fusion to work
- Datasets are very expensive to generate
- Difficult to develop surrogate targets (ie which test all sensors at same time)

SENSOR DATA FUSION TECHNOLOGIES FOR PRECISION STRIKE

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SUMMARY

This paper provides an assessment of the enabling technologies for sensor data fusion. The assessment is conducted in the context of precision strike for the year 2010 time frame. Emphasis is given to the sensor data fusion technologies that reduce the workload and improve the performance and safety of the human element. Technology advances are projected for C4ISR, sensors, electronics, and weapons that enable sensor data fusion, with the operational considerations of weather and clutter.

Preferred sensors are synthetic aperture radar (SAR), passive imaging millimeter wave (mmW), active imaging infrared (IIR), and passive IIR.

Examples are shown of robust sensor data fusion architecture for high detection and low false alarm.

Follow-on system-level studies to assess sensor data fusion concepts and technologies are outlined.

INTRODUCTION

Sensor data fusion has numerous military applications, including the precision strike mission area. Precision strike requires human elements such as image analysts and mission planners involved in command, control, communication, computers, information, surveillance, reconnaissance (C4ISR) and pilots involved in weapon delivery. Benefits of sensor data fusion for the human element include reduced workload, improved throughput, and improved accuracy. Sensor data fusion also improves safety of the pilot and friendly forces/civilians in the target area. Figure 1 shows the benefits of sensor data fusion for the precision strike mission area.

Although an autonomous system does not have the human frailties of fatigue or variation in performance over time, autonomous systems are not foolproof. In the foreseeable future, sensor data fusion algorithms are unlikely to embody the capability of the human element to resolve ambiguities and errors in target identification. Image analysts, mission planners, and pilots will provide oversight monitoring to ensure that correct targets are selected. Sensor data fusion will provide a leveraging of human efficiency, rather than a replacement of the human element.

Figure 2 illustrates the need for an automated system to conduct the image analysis used in C4ISR. For a non-automated system, the number of image analysts required to conduct daily area coverage of a threat country the size of Iran would be unrealistically large. As an extreme example, more than 100,000 image analysts, examining a full frame of 1/3 meter resolution data every two minutes, would be required to evaluate daily coverage of Iran. An impossible task! In this case the image analyst is drowning in data but starved for information. The desired analysis for a data rate of 3 Gbps can be accomplished only by automating the system. Figure 2 also shows the search and the spotlight data rates of the Global Hawk unmanned air vehicle (UAV). Note that improvements are also required in data rate, due to the limited size of the UAV force.

Benefit of Sensor Data Fusion	Precision Strike Event (Time →)							
	C4ISR	Mission Planning	Threat Warning	Weapon Targeting	Weapon Navigation	Weapon ATR	Target Track	BDA
• Human Element Workload	●	○	–	●	○	●	–	◒
• Accuracy	●	○	●	○	◒	●	●	●
• Safety	–	–	●	–	◒	●	◒	–

Note: ● Very High Benefit ◒ High Benefit ○ Moderate Benefit – Relatively Low Benefit

Ottawa_98_030

Figure 1. Benefits of Sensor Data Fusion for Precision Strike

Paper presented at the RTO SCI Symposium on "Sensor Data Fusion and Integration of the Human Element", held in Ottawa, Canada, 14-17 September 1998, and published in RTO MP-12.

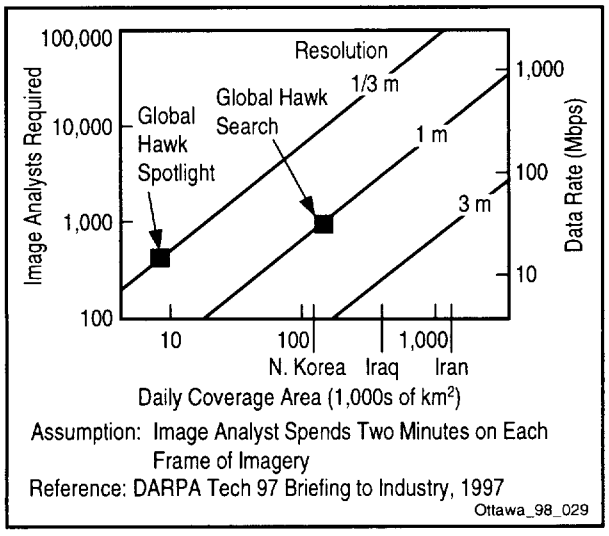

Figure 2. Automated Systems are Required for C4ISR Image Analysis

An example of the importance of timely, high-resolution data is the problem of countering threat theater ballistic missiles (TBMs). TBMs have characteristics of short timelines, low signature, and high mobility associated with a "hide-scoot-shoot-hide" doctrine. Events such as leaving a camouflage/concealment site, moving to a launch site, preparing for launch, tearing down after launch, and moving to a camouflage/concealment site are often not observed or they are observed too late to provide an effective counterforce response. New sensor data fusion technologies are required to expedite the C4ISR process for time critical targets such as TBMs.

Sensor data fusion also enhances pilot safety. Some missions, such as low altitude weapon delivery, may be too dangerous to put pilots at risk and may be best handled by autonomous weapons such as cruise missiles. The problem is illustrated in Figure 3, which shows the anti-aircraft artillery (AAA) fire over Baghdad during the first night of Operation Desert Storm.

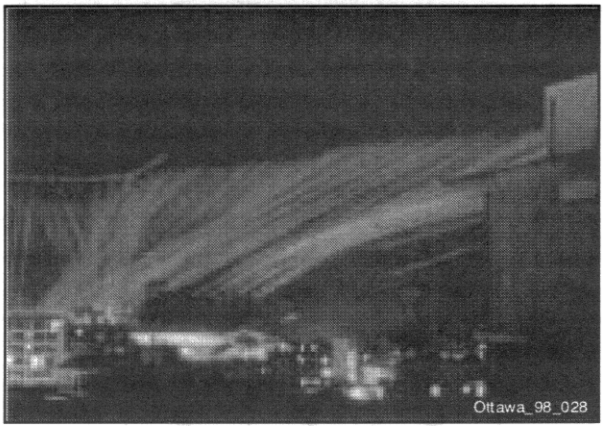

Figure 3. Automated Systems Avoid Putting Pilots in Harm's Way

Although the U.S. Department of Defense (DoD) does not have a technology area dedicated to sensor data fusion, the technology areas associated with sensor data fusion receive high emphasis in the DoD technology funding. The DoD top-three military technology areas are the following: information systems, weapons, and sensors/electronics (Figure 4). The funding for these areas is greater than the combined total of the other military related technologies. Sensor data fusion is emphasized in the information systems, weapons, and sensors/electronics technology areas.

An example of the increased application of sensor data fusion is combat aircraft avionics. Combat aircraft avionics have been increasing in emphasis each year. Avionics has now become the dominant consideration in combat aircraft. In the 1960s, aircraft such as the F-4 had relatively low consideration of avionics, with only about 10% of the flyaway cost allocated to avionics (Figure 5). The dominant costs for the F-4 aircraft were engines and airframe. Although the aeromechanics performance of combat aircraft has had only evolutionary advancements, the advancements in avionics have been revolutionary. Each new aircraft has brought an increasing emphasis in avionics, due primarily to improvements in the DoD Top 3 technology areas of information systems, weapons, and sensors/electronics. An emerging market for older aircraft is the periodic updating of their avionics. As shown in Figure 5, the cost of future aircraft will be primarily driven by their avionics.

An application of sensor data fusion is the use of ATR to accurately detect and identify targets in a computationally efficient and timely manner. Challenges include weather, clutter, and changes in the target signature. Changes in the target signature could include target wear, orientation, and camouflage. Although no ATR system is perfect, sensor data fusion provides robustness in false alarm rate and detection.

Examples of a broad range of alternative systems that use sensor data fusion are shown in Figure 6. Going clockwise around the figure, the sensor systems tend to have decreasing range, sophistication, and cost:

- Predator unmanned air vehicle (UAV) surveillance system. Predator has synthetic aperture radar (SAR), passive imaging infrared (IIR), and visible electro-optical (EO) sensors.

- Low Altitude Navigation and Targeting Infrared for Night (LANTIRN) targeting pod for combat aircraft. LANTIRN fuses passive IIR and laser detection and ranging (LADAR) sensor data.

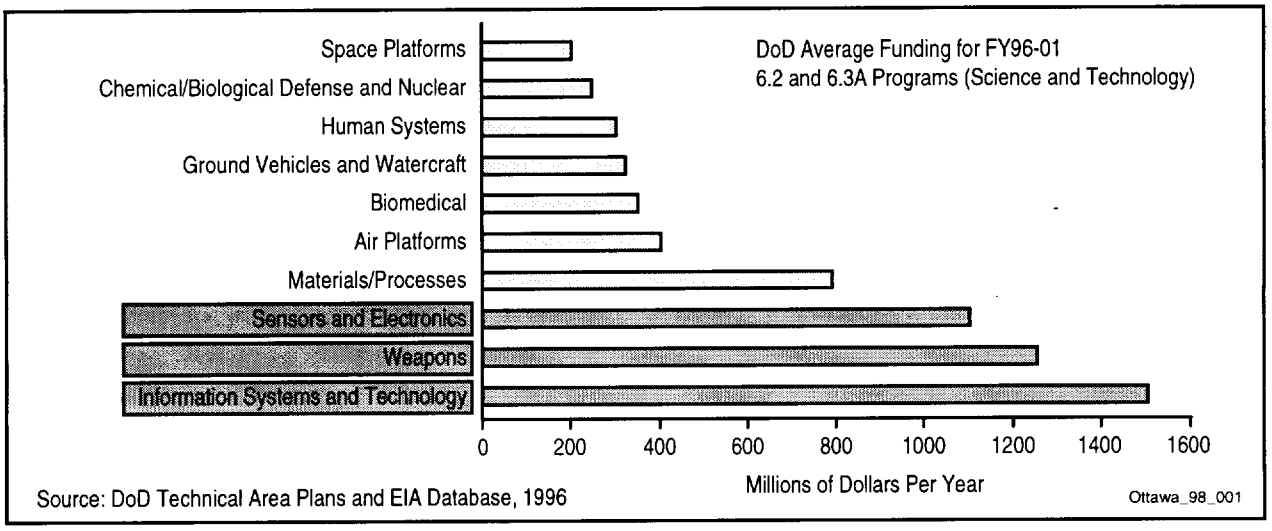

Figure 4. Sensor Data Fusion is Reflected in the U.S. DoD Top 3 Technology Areas

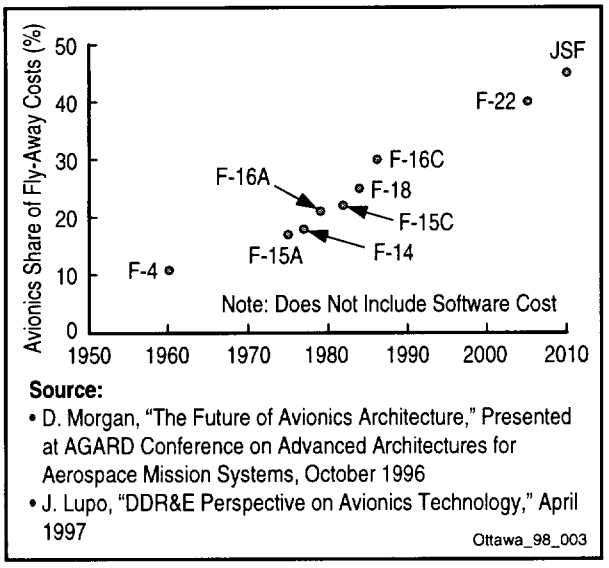

Figure 5. Avionics Has Become Very Important to Fighter Aircraft

- AGM-130 missile guidance and control. AGM-130 fuses global positioning satellite (GPS) receiver/inertial navigation system (INS) and passive IIR seeker sensor data for precision guidance.

- Brilliant Anti-Tank (BAT) guided submunition. BAT fuses acoustic and passive IIR sensor data for autonomous acquisition and strike of mobile targets.

The above sensor systems use a wide field of view (FOV) sensor for target detection and a narrow FOV sensor for target identification and targeting. The wide FOV sensor cues the narrow FOV sensor.

Sensor data fusion was defined in 1987 by the Joint DoD Laboratories (JDL) subpanel on Data Fusion as "the process dealing with the association of sensor data and the estimation of entity kinematics, attributes, and identity to achieve assessments and projections of a situation." Sensor data fusion combines different sets of data from one or more sensors. Fusion can occur over multiple wavelengths, space, or time. As the data channels are combined, the processing evolves from signal processing to information processing, resulting in information of higher value to the human element.

SENSOR DESIGN CONSIDERATIONS FOR PRECISION STRIKE

The precision strike design considerations of weather, clutter, C4ISR, target set, sensor/processor performance and cost, and navigation accuracy will be discussed in this section.

Weather, including cloud cover and rain, is a driving consideration in the selection of sensors. As an example of the effect of weather on IR sensors, IR sensors are blocked if a cloud masks the target and IR sensor performance is degraded by rain.

Clouds are pervasive in the world wide weather. The average global annual cloud cover is about 61 percent (Figure 7), with an average cloud cover over land of about 52 percent and an average cloud cover over the oceans of about 65 percent. Clouds tend to occur at a height between 3,000 and 20,000 feet. Due to the frequency of low cloud cover, airborne IR sensors are often limited in their applications to flight at heights of less than 3,000 feet.

Figure 8 shows the signal attenuation versus wavelength for a representative cloud, rain rate, and humidity level requirement. Note that although passive EO sensors have

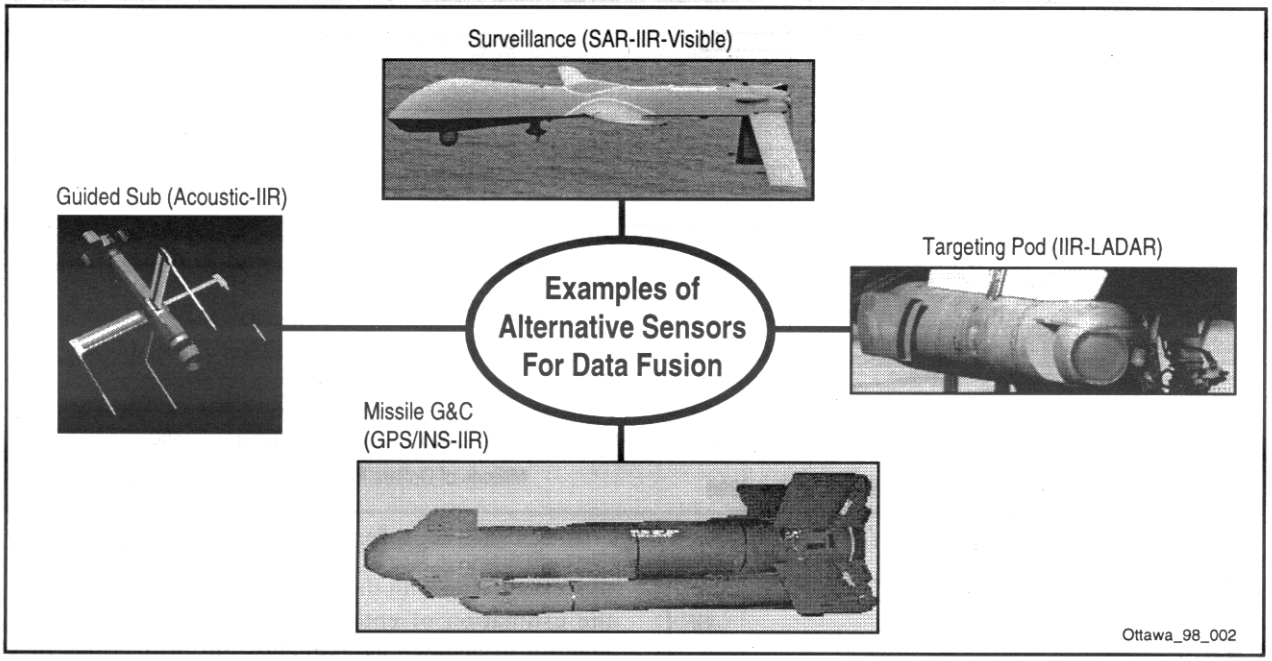

Figure 6. Example of Alternative Sensors for Data Fusion

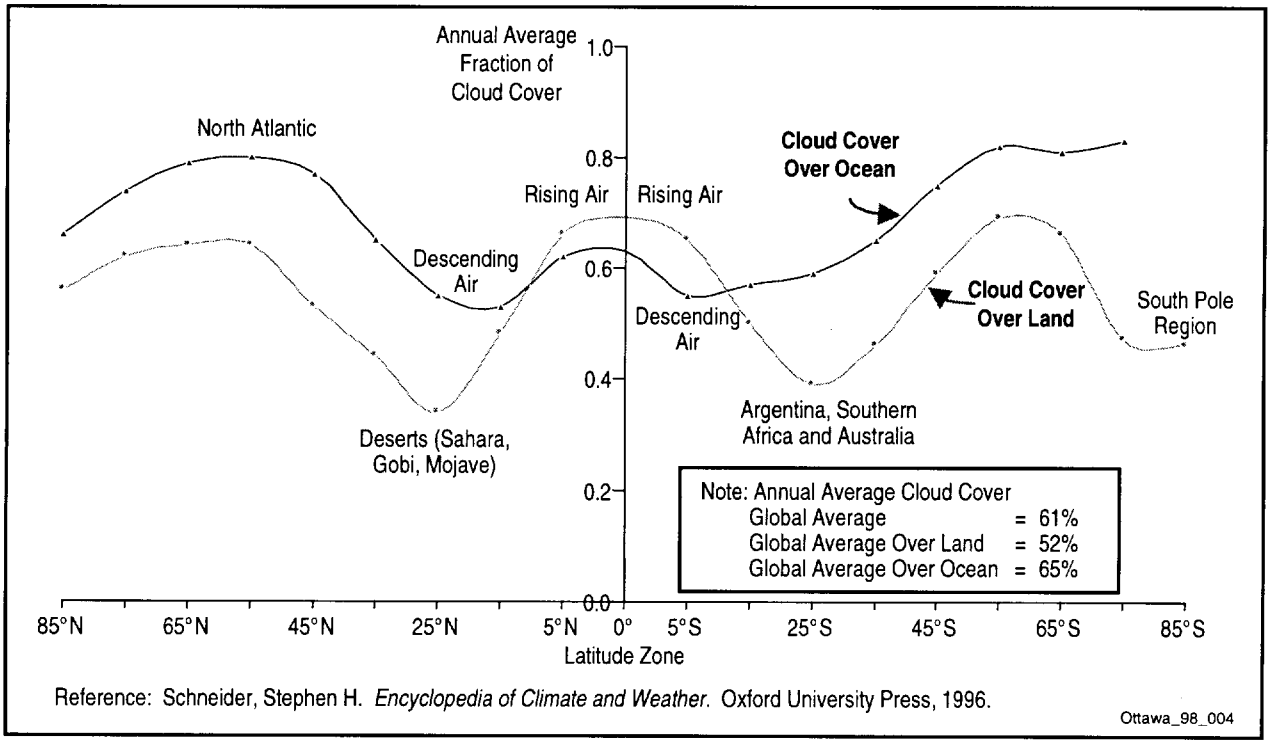

Figure 7. Cloud Cover is Pervasive

one-way transmission through rain of about 50 percent per km, there is almost no transmission of an EO signal through clouds. Cloud droplets are small - about 5 to 20 microns in diameter, with dimensions comparable to the EO wavelength. The concentration is high—about 50 to 500 droplets per cubic centimeter. EO wavelengths are strongly diffracted around cloud droplets due to Mie electromagnetic scattering. However, raindrops are about 2-6 mm in diameter (much larger than EO wavelengths) and cause less attenuation to an EO signal. Rain rate attenuation is due primarily to optical scattering. EO transmission through rain is a function of the size of the

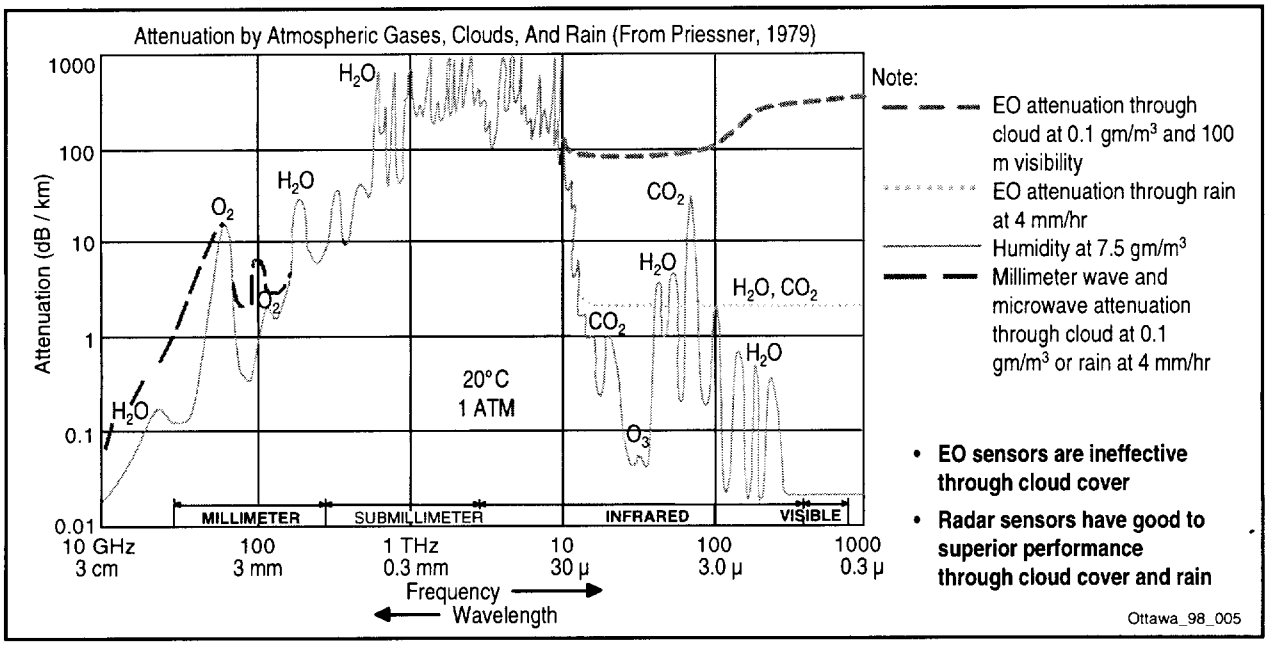

Figure 8. Signal Attenuation Due to Weather

raindrops, rain rate, and the path length through the rain. EO passive sensors are limited from about 2 to 5 km of path length through rain.

The best sensors in looking through clouds and rain are radar sensors. Radar sensors have negligible attenuation at frequencies below 10 GHz. At higher frequencies, millimeter wave sensors operating in clouds and rain are limited from about 2 to 5 km length of path through the clouds and rain, with the same implications as those discussed in the previous paragraph. Cloud droplets, which are much smaller than mmW wavelengths, absorb mmW radiation (much like a microwave oven). A different mechanism is responsible for the attenuation of a mmW signal through rain or snow. Raindrops and snowflakes are comparable in size to mmW wavelengths and cause Rayleigh and Mie electromagnetic scattering attenuation. Lower frequency, longer wavelength Ku-band sensors are less affected by cloud cover and rain/snow.

The second consideration to be discussed for the precision strike mission is clutter. Like weather, clutter is pervasive— everything that is not part of the target is clutter. There are two types of clutter, natural clutter and man-made cultural clutter. Natural clutter includes terrain, lakes, rivers, trees, bushes, plants, and grass. Cultural clutter includes buildings, roads, and vehicles. Clutter complicates ATR because clutter can look like a target, and targets can be partially or completely obscured by clutter. A benefit of sensor data fusion is that clutter for one type of sensor or discriminant may be less limiting to another type of sensor or discriminant. For example, a low frequency ultra wide band SAR sensor has foliage penetration that is not possible with higher frequency, shorter wavelength sensors.

In high clutter areas (e.g., urban, villages crowded together, forests, mountains, jungles, brown water), the threat may rely on the exploitation of confusing clutter. In an urban area, targets may be at street level, on roofs and the upper stories of buildings, and below street level in bunkers, sewer systems, subways, and other underground structures. A particular concern is precision strike for military operation in urban terrain (MOUT). MOUT has a risk for confusion of civilian and friendly force assets with the threat military assets. Figure 9 illustrates a MOUT environment.

A third design consideration for precision strike is the C4ISR architecture. Figure 10 illustrates an example of C4ISR architecture of the year 2010 time frame. It

Figure 9. Example of MOUT Clutter

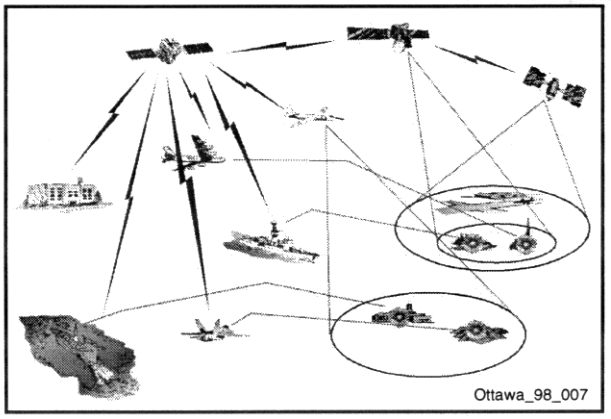

Figure 10. Example of C4ISR Targeting

includes a ground station, overhead low cost tactical satellite sensors (e.g., Starlite/Discoverer II), satellite relays, and overhead UAV sensor platform elements. The C4ISR architecture of the year 2010 is projected to have a capability of detecting targets in clutter, target location error (TLE) of less than 1 meter (1 sigma) and off-board sensor-to-shooter connectivity time of less than 2 minutes (1 sigma). This capability will enable a counterforce response against time critical targets, such as TBMs.

Target sensors of the year 2010 time frame will use real-time ATR for precision targeting. ATR performance will be enhanced through multidimensional orthogonal discriminants. The best overall target sensors for precision strike in adverse weather and clutter are considered to be X-band or Ku-band SAR sensors and passive imaging mmW sensors. Other sensors for precision strike, listed in order of their expected application in the year 2010, include active imaging IR based on LADAR, passive imaging IR, active nonimaging radar, active nonimaging LADAR, passive nonimaging IR, visible, UV, and acoustic/seismic. Sensors are available that cover the range of acoustic-to-visible. However, due to the importance of standoff in adverse weather, radar and mmW will be the primary sensors considered for the precision strike mission area. Multidimensional orthogonal discriminants that are likely to be used in sensor data fusion include angular resolution, range resolution, contrast, polarization, temporal (e.g., vibration, movement), multispectral, and gas composition signatures of the target.

Until recently, most UAVs had relatively unsophisticated sensor suites that typically consisted of a forward looking infrared (FLIR) sensor, a television (TV) camera, and a data link. However, the more recent UAVs, such as Predator, are beginning to carry sophisticated sensor payloads, including multiple IR sensors and SAR sensors, that broaden the range of missions and mission performance. Improvements in sensor capability are expected to continue into the next-generation multimission UAVs. Drivers for the next-generation UAVs, which will result in improved sensor capability, include a broader range of missions, enhanced survivability, wide area/continuous coverage of the target area, real time ATR, low False Alarm Rate (FAR), and real-time precision targeting.

The General Atomics Predator UAV is an example of recently introduced UAVs. Developmental UAVs such as Global Hawk and Dark Star will be more sophisticated than Predator. The Predator sensor payload includes an EO sensor suite, a Ku-band SAR sensor, Ku-band and UHF-band satellite communication (SATCOM), a C-band line-of-sight data link, and a GPS/ INS navigator.

The Predator's SAR sensor is the Northrop Grumman (Westinghouse) Tactical Endurance Synthetic Aperture Radar (TESAR). TESAR provides continuous, near real time strip-map transmitted imagery over an 800 meter swath at slant ranges up to 11 km. Maximum data rate is 500,000 pixels per second. The target resolution is 0.3 meters. TESAR weight and power are 80 kg and 1200 watts respectively. A lighter weight, lower cost SAR is currently in development for Predator.

The Predator's EO sensor suite is the Versatron Skyball SA-144/18 quartet sensor. It consists of a PtSi 512 x 512 MWIR FLIR with six fields of view, a color TV camera with a 10X zoom, a color TV 900 mm camera, and an eyesafe pulsed erbium: glass laser range finder. The diameter of the EO sensor turret is relatively small – 35 cm. The turret has precision pointing with a line-of-sight stabilization accuracy of 10 μrad.

It is anticipated that high performance UAVs of the year 2010 will have a broad range of missions, including surveillance, reconnaissance, communication, intelligence gathering of threat electronic emissions, target designation for weapons attacking moving targets, and communication relay. The system flight performance is expected to be greater than present UAVs, with higher velocity providing a larger area of coverage and faster response in getting to the target area. Higher cruise altitude, above 60,000 feet, will provide a longer line-of-sight data link (Figure 11) and safer operation above commercial aircraft. As an example of the current state-of-the-art (SOTA) in data rate, Global Hawk has a data rate of approximately 1.6 million pixels per second at a resolution of 1 meter. The daily data rate is approximately 30 Mbps in a 1-meter-resolution search mode and approximately 10 Mbps in a 1/3-meter-resolution

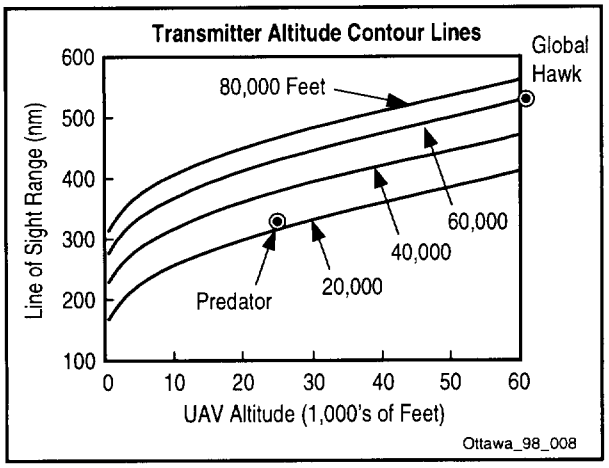

Figure 11. High Altitude UAVs Provide Long Range C4ISR and Safe Operation Above Commercial Aircraft

spotlight mode (Figure 2). However, this does not provide full daily coverage of a large country such as Iran. Year 2010 UAVs will have higher data rate and the implication of automated image analysis and sensor data fusion for ATR. Finally, the precision pointing and line-of-sight stabilization accuracy of future UAVs will be improved to about 5 μrad, to accommodate longer standoff.

Advancements in sensor capability for C4ISR will provide new capabilities of near real time ATR, orders of magnitude reduction in FAR, an order of magnitude improvement in targeting accuracy, and an order of magnitude improvement in data rate. The advanced sensors will leverage the current advanced development (category 6.3A funding) activities that are presently under way.

There is emphasis to reduce the logistics cost by producing multipurpose systems that cover a broad range of targets. An example is the Joint Standoff Weapon (JSOW). JSOW is a neck-down replacement of Walleye, Skipper, Rockeye, laser guided bombs, Maverick, and other precision strike weapons. A multipurpose weapon system for precision strike must consider a broad target set (Figure 12). Challenges include targets with low signature (e.g., command and control bunkers), small size (e.g., trucks), small vulnerable area (e.g., armor), mobility (e.g., artillery), time urgency (e.g., missile transporter/erector/launcher), and weapon cost effectiveness (e.g., cost per kill versus target value) considerations. ATR for a multipurpose weapon system against the broad range of targets is enhanced through sensor data fusion, exploiting the unique characteristics of each target.

The revolutionary advancement of high performance, low cost processors is an enabling technology for sensor data fusion. The capability to process mutidimensional discriminants at low cost, small size, and low power is just beginning to emerge. Figure 13 shows the history of processing capability of commercial chips, with a projection to the year 2010. Note that for the last twenty three years the processing capability has been doubling about every two years, going from 2,300 transistors on the 4004 chip in 1972 to 5.5 million transistors on the Pentium Pro chip in 1995. There is no sign that the growth rate will slow down. A projection to the year 2010 predicts a capability of over 1 billion transistors on a chip. Processing capability is ceasing to be a limitation for the application of sensor data fusion to precision strike. The limitations for precision strike are now focused on ATR algorithms, cost effective sensors, and sensor data fusion architecture.

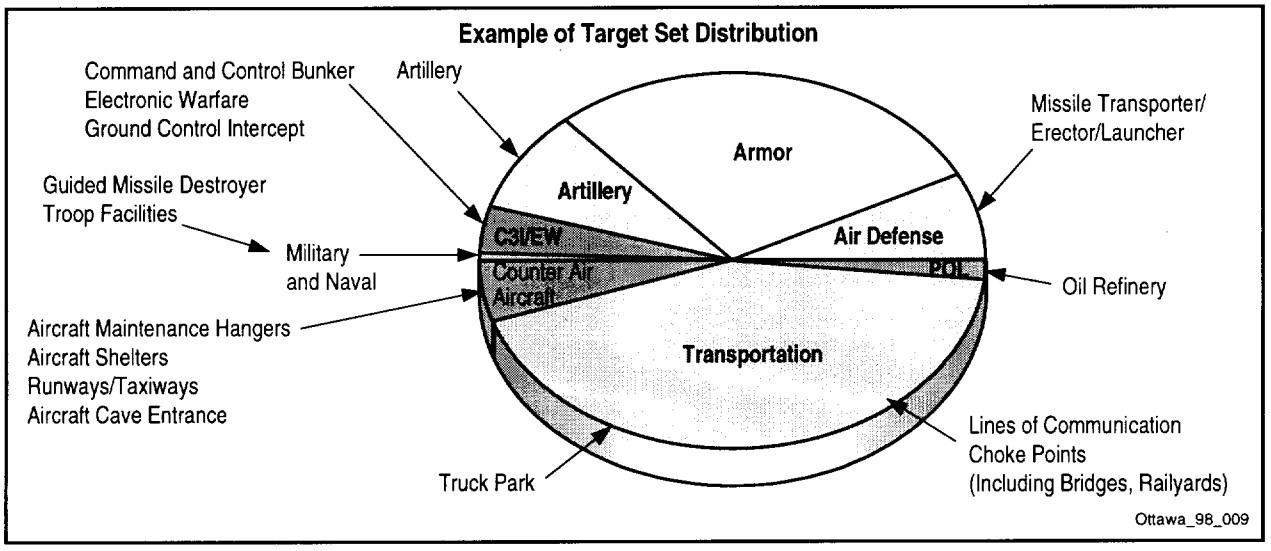

Figure 12. Precision Strike Addresses a Broad Range of Targets

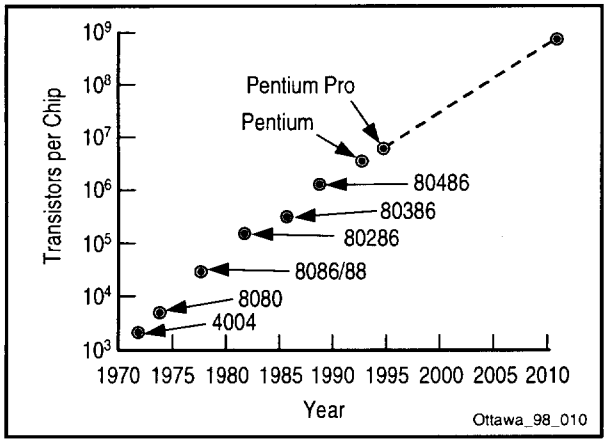

Figure 13. Revolutionary Advances in Processing Enables Sensor Data Fusion

The revolutionary advancement described above in the performance of low cost commercial chips has led to the recent movement to incorporate commercial parts into military products. Figure 14 shows the decreasing presence of military parts in the integrated circuit (IC) market and the decline of military procurement. The military IC presence has diminished to where it is now less than 1 percent of the IC market. At this level, the military exerts almost no influence on IC manufacturers to supply the technology needed for military electronic parts. The relatively low level of military chip procurement has caused several traditional high-reliability IC manufacturers to leave the military market. The result is less selection of military-type parts. As this trend continues, military electronics will use low-cost commercial plastic parts as the norm. The low-cost commercial plastic parts will have to be cocooned for protection against the harsher military environment (temperature, vibration, acoustics, moisture, dust, salt, etc.). New technology is required to develop cocoons for the commercial off the shelf (COTS) parts. Another consideration is the rapid introduction of new commercial products. Due to the relatively long development time of military products compared to commercial products, the military electronics are often one-to-three generations behind the commercial state-of-the-art (SOTA) by the time the military product is introduced. In addition, the military product may not have a logistical support base due to obsolete parts. This requires the consideration of a robust architecture to handle frequent upgrades of the commercial parts. The frequent upgrades will require a streamlined process for military qualification tests, to make the more frequent qualification tests affordable.

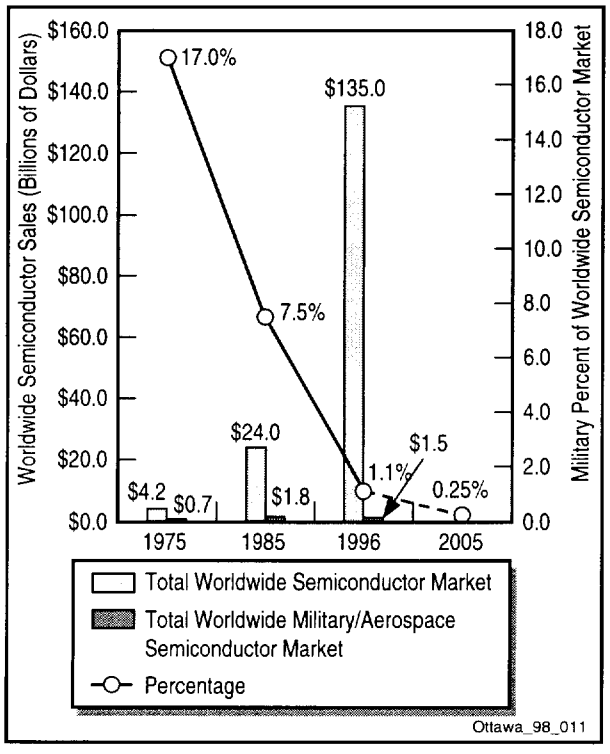

Figure 14. COTS Electronics Are Low Cost Because Commercial Sales Are Driving Semiconductors

Another example of a commercial-type technology that is reducing sensor cost is Micro Electro Mechanical Systems (MEMS). With MEMS technology, inertial measurement units (IMUs) may cost $2,000 to $3,000 in the year 2010 time frame. MEMS devices are fabricated from a single piece of silicon by commercial-type semiconductor manufacturing processes, resulting in a small, low-cost package (Figure 15). The compatibility with high rate production and broad range of applications (military and commercial) are enablers for low cost. Between 2,000 and 5,000 MEMS gyro devices can be produced on a single five-inch silicon wafer.

Precision GPS/INS guidance is an enabling consideration for sensor data fusion in high clutter. The current GPS receivers operating in a military P(Y) code have an accuracy

Figure 15. MEMS is Small, Lightweight, and Low Cost

of approximately 6 meters. Recent advances in using GPS in the Wide Area GPS Enhancement (WAGE) mode, differential mode, or relative mode, combined with SAR precision mapping, provide errors less than 3 meters.

Figure 16 illustrates the benefit of precision GPS/INS guidance for a bridge target in a high clutter environment consisting of a river and rolling terrain. In this example, a high-resolution (640 pixels x 480 pixel) IIR sensor is used for terminal homing for precision strike of the center pier of the bridge. Note that even for a relatively large target such as the bridge in the figure, there is a large amount of clutter at a seeker lock-on range of 850 meters. The 20-degree FOV seeker provides a 300 meters x 230 meters scene with high resolution (1 pixel = 0.47 meters). The GPS/INS error is assumed to be 3 meters, resulting in a 6 pixel correction error for a seeker lock-on range of 850 meters. The maximum acceleration to correct the 3-meter initial heading error is small, about 1.0 g. Fortunately, the GPS/INS precision accuracy (3 meters) allows delay of seeker lock-on and terminal guidance until the missile is closer to the target. As the missile closes on the target at the seeker lock-on alternative ranges of 500 meters and 250 meters, note that there is less and less clutter. The maneuveracceleration to correct the 3-meter initial heading error is 1.7 g's and 3.5 g's respectively. Finally, at a range-to-go of 125 meters, note that there is almost no clutter within the seeker FOV. Relatively high maneuverability is required (7.1 g's) to correct the GPS/INS initial heading error of 3 meters. The GPS/INS accuracy of 3 meters is comparable to the tracking accuracy of the seeker, resulting in a relatively smooth transition in handing off from midcourse navigation GPS/INS guidance to terminal seeker guidance. For a typical closing velocity of 300 meters per second and a guidance update rate of 60 Hz, there are 25 guidance updates available to conduct ATR for a seeker lock-on range-to-go of 125 meters. The terminal accuracy is more a function of the airframe response (assumed to be 0.1 second) than that of seeker tracking error. As a result

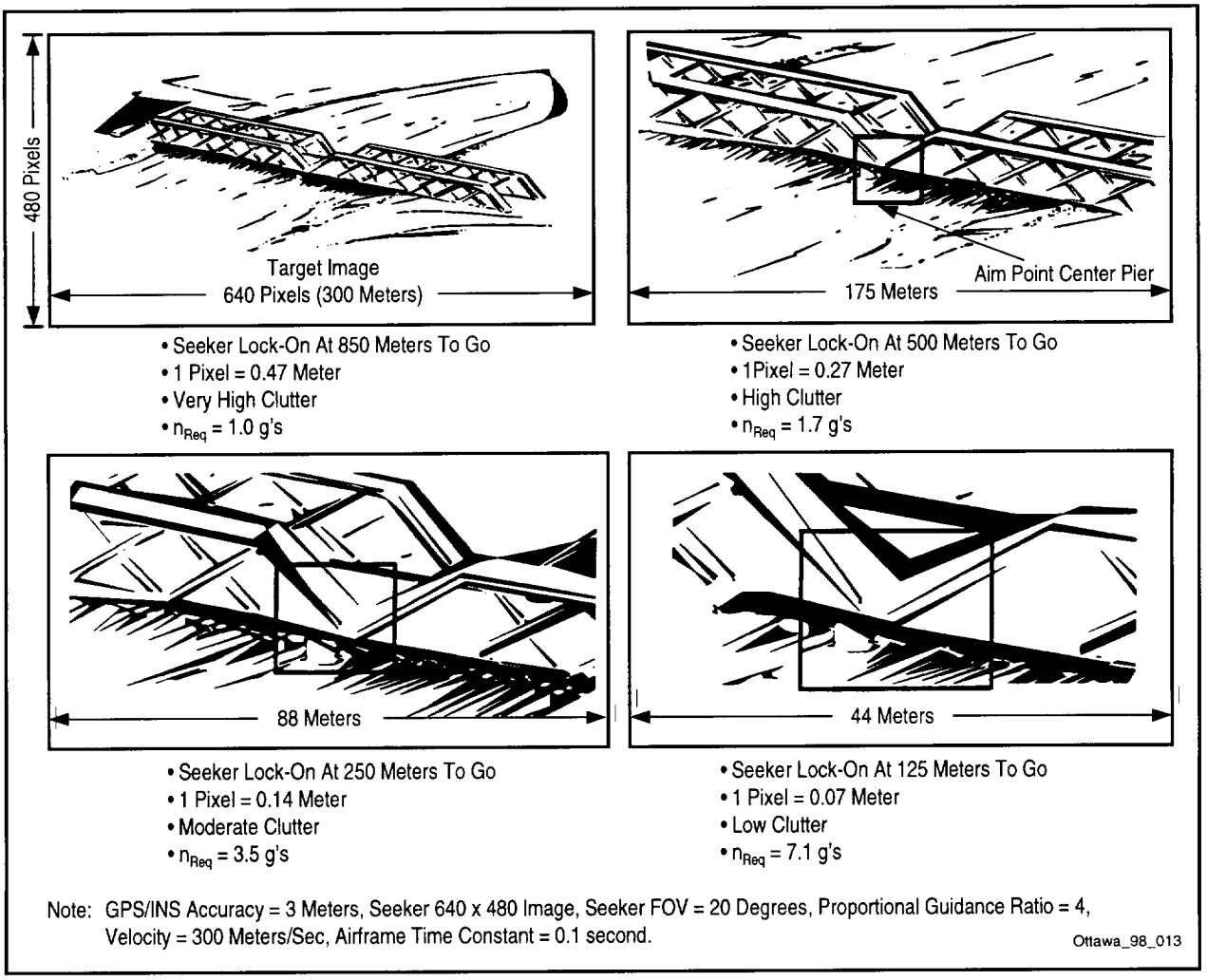

Figure 16. Precision GPS/INS Facilitates Targeting in a Clutter

of the GPS/INS precision guidance, the missile has higher probability of hitting the center pier aim point and dropping the center span of the bridge. The GPS/INS guided missile can be treated almost like an artillery projectile of low ballistic dispersal, with high probability of impacting in the target area and low probability of collateral damage.

Benefits of tightly coupled integration of INS with GPS include high-precision position and velocity measurement and reduced jamming susceptibility. The availability of GPS to continuously update the inertial system allows the design trades to consider a lower precision and less expensive INS, while maintaining good navigation accuracy and anti-jam (A/J) performance.

Future GPS/INS receivers will be based on a centralized Kalman filter that processes the raw data from all of the sensors (e.g., SAR, GPS receiver, INS). Tightly coupled GPS/INS is more robust against jamming because it is able to make pseudo-range measurements from three, two, or even one satellite if one or more of the satellites are lost.

The conservative 6-meter GPS standard accuracy can be significantly improved. An example shown in Table 1 is a Conventional Air Launched Cruise Missile (CALCM) demonstration based on Precision On-Board GPS Optimization (POGO). POGO demonstrated precision accuracy using GPS-aided inertial navigation. POGO uses smart algorithms to reduce satellite clock errors and satellite ephemis errors. The use of an all-in-view GPS receiver and the implementation of a 61-state tightly-coupled Kalman filter for INS error calibration provide further accuracy enhancement and increased performance in a jamming environment. For the flight demonstration, Wide Area GPS Enhancement (WAGE) was used, which improved the GPS signal measurement accuracy. The missile flew for 4-1/2 hours and impacted 2.4 meters from the target center (Figure 17). A projected capability for POGO guidance, based on GPS IIF satellites other improvements, and a guidance accuracy contribution of 1 meter, is 2.0 meters circular error probable (CEP).

Figure 17. CALCM Precision Strike Demonstration Against 3-Meter Target

TARGET SENSOR ATTRIBUTES FOR PRECISION STRIKE IN THE YEAR 2010

A summary comparison of sensor alternatives is given in Figure 18. The measures of merit selected are sensor performance in an adverse weather environment (cloud cover and rain), sensor performance in clutter, ATR discriminants, ATR design considerations, and weight/cost. The sensor performance through adverse weather of clouds and rain and operating in clutter were discussed previously. Figure 18 is based on the assumptions of a cloud thickness of 6,000 feet, a cloud base height of 20,000 feet, rain rate of 4 mm/hr, and moderate urban clutter. Alternative sensor capabilities for the ATR discriminants of angular resolution, range resolution, contrast, polarization, temporal (e.g., vibration, motion), multispectral, and gas composition are shown in the figure. The comparison of other ATR design considerations is based on sensor noise, uniformity, and

Table 1. CALCM POGO Demonstrated GPS/INS Precision Guidance

Error Sources	Standard GPS	POGO Demo	Source of Improvement
User range error Satellite ephemeris = 4.0 m Satellite clock = 3.0 m	5 m	URE = 2.0 m 1.8 1.0 1.0	• WAGE Phase 1 • Accuracy improvement initiative (All) • WAGE – complete • Block IIF satellites
Ionosphere	2.3	1.0	• Dual-frequency receiver • Special algorithm based on phase
Troposphere	2.0	0.5	• Real-time pressure and temperature measurements • Accurate modeling
Multipath	1.2	0.4	• Low missile multipath • Phase use as well as code
GPS receiver	1.5	0.5	• New technology
RSS total	***6.2M***	***1.7-2.4 m***	• URE dependent

URE = user range error
Advanced GPS provides precision navigation for targeting

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Target Sensor	Weather	Clutter	ATR Discriminant: Angular Resolution	Range Resolution	Contrast	Polarization	Temporal	Multispectral	Gas Comp	ATR Design Considerations: Noise	Uniformity	Wide FOV Latency	Weight & Cost
SAR	●	◒	●	◒	○	●	○	◒	–	◒	–	●	○
Passive imaging mmW	○	◒	○	–	●	–	○	○	–	●	◒	◒	◒
Active imaging IR	–	●	●	●	●	●	●	◒	●	◒	○	–	◒
Passive imaging IR	–	●	◒	–	◒	○	○	●	○	●	◒	●	◒
Active nonimaging RADAR	●	–	–	◒	○	●	◒	–	–	–	–	●	◒
Active nonimaging LADAR	–	○	–	●	◒	○	●	○	◒	◒	○	–	●
Passive nonimaging IR	–	–	–	–	–	–	–	○	–	●	●	–	●
Visible (TV)	–	●	●	–	○	○	–	◒	–	●	●	●	●
Ultraviolet (UV)	–	●	●	–	●	–	–	–	–	●	●	●	●
Acoustic/Seismic	●	–	–	–	○	–	●	●	–	–	●	●	●

Note: ● Superior ◒ Good ○ Average – Poor

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Figure 18. Target Sensor Attributes for the Year 2010

latency to cover a wide FOV. Finally, a comparison is made of weight and cost of the alternative sensors.

The best overall sensor in adverse weather and clutter is probably a SAR sensor operating at a frequency of either the X-band (~10 GHz) or the Ku-band (~17 GHz). These bands permit a small antenna size while also providing a capability to penetrate clouds and rain. SAR sensors have the flexibility required to cover an area search (e.g., 5 km by 5 km) for single-cell target detection, then switch to high resolution (e.g., 0.3 meter) for target ID and targeting in clutter. SAR sensors can also provide high-accuracy profiling of the known terrain features around the target and derive GPS coordinates of the target. An image of the high resolution SAR imagery from the Northrop Grumman TESAR is shown in Figure 19.

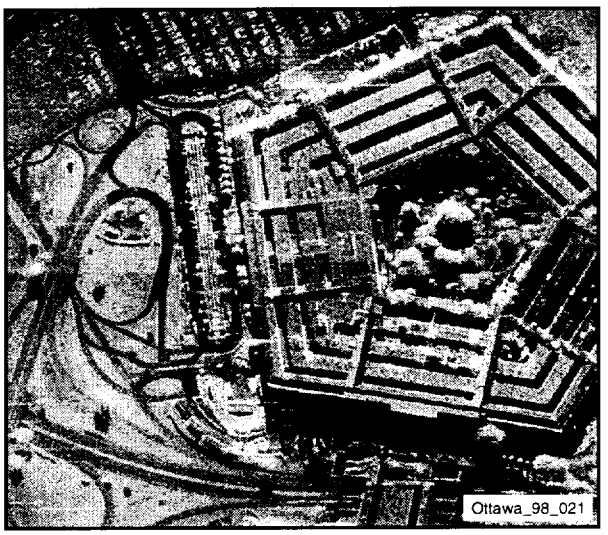


Figure 19. TESAR Image of U.S. Pentagon

Although today's SAR sensors have good imagery performance, their current ATR and FAR performance is much worse than the performance of a human. As discussed previously, present SAR sensors require post-flight human analysis of the SAR imagery in order to identify/confirm targets and eliminate false alarms. This time consuming process will be alleviated in the next-generation ATR, which will include other orthogonal discriminants, such as polarization. The additional discriminants will be fused with the SAR imagery as well as data from other sensors, to greatly enhance ATR.

Polarization provides a SAR sensor with the capability to extract information on the physical shape characteristics of each target pixel. Full-polarization (transmit left: receive left/right, transmit right: receive right/left) algorithms are under development by Boeing that allow complex targets to be decomposed into elemental scatterers such as dihedrals, trihedrals, cylinders, helices, and dipoles. Nine different target scatter types and their physical attributes are shown in Figure 20. These attributes are robust over relatively wide observation angles. The application of full-polarization algorithms provides more than 10 times the information for ATR algorithms than conventional single-polarization and significantly improves the probability of detection while reducing FAR. Conventional single-polarization SAR algorithms simply exploit imagery based on the intensity or amplitude of the return signal and

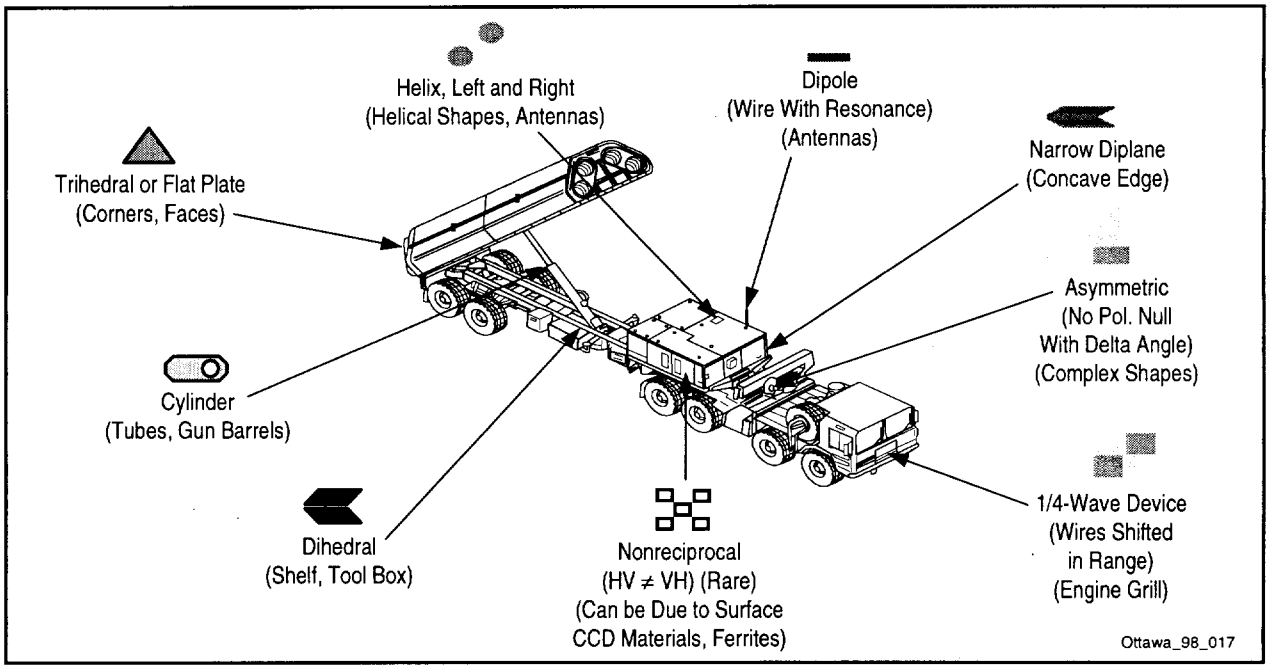


Figure 20. SAR Full-Polarization Scatter Physical Basis

object shape. Other discriminants that also improve the ATR performance of SAR sensors include motion detection and 3D imagery. SAR detection of a moving target and estimation of its velocity is based on the temporal correlation of SAR consecutive images. The correlation of doppler in consecutive images resolves the doppler ambiguity by associating it with the moving target. In the obtained sequence the background is static, while the moving target changes position from image to image.

Figure 18 also addresses the strengths and weaknesses of passive imaging mmW sensors. Passive imaging mmW sensors have an advantage over EO sensors in their capability to see through cloud/fog cover. Advantages of passive imaging mmW sensors over active nonimaging radar sensors include better performance in clutter, high contrast, better angular resolution, and low noise. Figure 21 illustrates the high contrast discriminant of passive imaging mmW sensors. The cold sky (about 35K) is reflected at mmW frequencies by the metal object in the image (i.e., Queen Mary), while the temperature of the terrestrial clutter and the fiberglass dome in the image is much higher, about 300K. Current radiometers can typically detect differences in temperature of 1K. Radiometers are in development that will detect differences in temperature of 0.1K, providing a very high signal-to-noise ratio of more than 300 to 1.

Passive imaging mmW sensors similar to video cameras have been developed by TRW. Array sizes up to 40 x 26 elements have been produced, with apertures ranging from

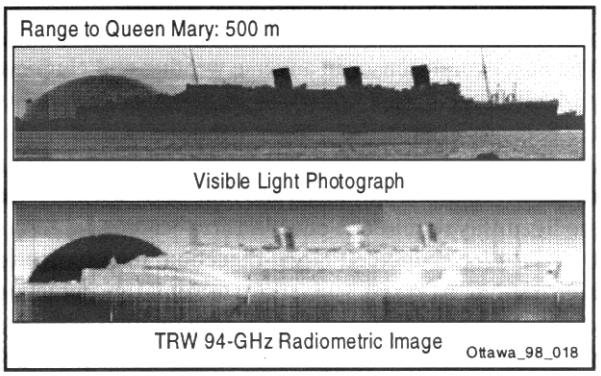


Figure 21. Passive Imaging mmW Sensors Provide High Contrast

0.4 to 1.2 meters in diameter. The frequency and frame rate demonstrated to date are 89GHz and 17 Hz respectively. An airborne flight demonstration of a TRW passive imaging mmW sensor was successfully conducted during Fall 1997.

A disadvantage of passive imaging mmW sensors is relatively low resolution compared to EO and SAR sensors. As noted previously, at heavy rain rates above 4 mm/hr, passive imaging mmW sensors are highly attenuated. However, passive imaging mmW technology is relatively immature. Sensors of the year 2010 time frame will have higher performance and resolution due to the lower noise from indium phosphide semiconductor substrate technology and the use of distributed apertures as high-resolution interferometers. As an example, ten widely spaced apertures could provide an effective

aperture that would be comparable to the wing span of a UAV, providing more than an order of magnitude improvement in resolution.

Referring back again to the Figure 18 assessment of sensor alternatives, the third priority sensor for precision strike is active imaging IR based on LADAR. Active IIR has high performance in clutter and provides unique three-dimensional images at high resolution and other discriminants such as temporal (e.g., skin vibration, exhaust gases), exhaust gas composition, and multispectal that complement the other sensors of a multidimensional sensor suite. Figure 22 illustrates the high resolution 3D imagery of a Lockheed Martin active IIR sensor. The laser transmitter is usually bore-sighted to a passive IIR sensor that acquires and tracks the target. The capability to fuse the target IR signature with the reflected laser signature enhances the ATR performance.

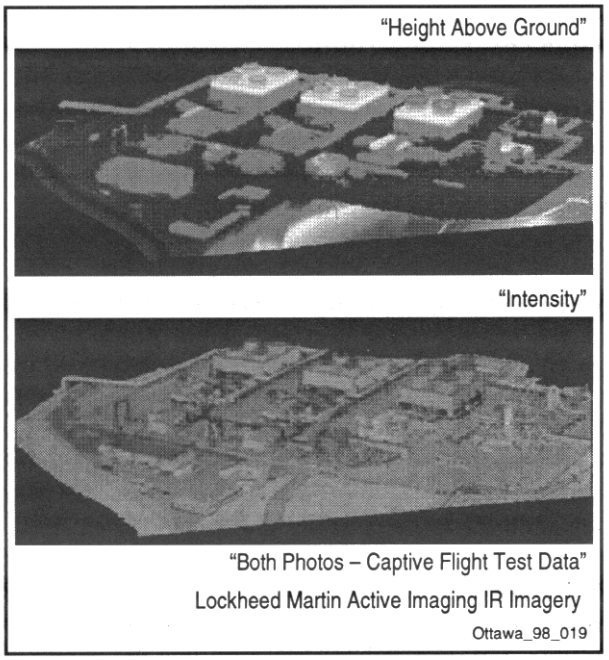


Figure 22. Active Imaging IR Sensors Provide High Resolution 3D Imagery

A technology currently in development that will enhance the application of active IIR sensors is tunable lasers. Tunable lasers provide a multispectral discriminant for ATR.

Active IIR sensors have the capability to provide high-accuracy profiting of the known features around the target and derive GPS coordinates of the target.

Target designation is a mission that can be addressed by an active IIR sensor. It is postulated that UAVs of the year 2010 time frame could carry low cost laser guided weapons and self-designate their targets.

Disadvantages of active IIR sensors are their performance in adverse weather and the latency required for a wide FOV search. Guided submunitions such as Low Cost Autonomous Attack System (LOCAAS) minimize the problem by operating at low altitudes under clouds and flying at low velocity. The "under the weather" operation is effective under most conditions except for fog, heavy rain, and obscurants. Search capability could be improved by adding an additional wide FOV sensor, such as passive imaging IR. The wide FOV sensor cues the LADAR sensor for fine tracking and designation.

Referring back again to the Figure 18 summary comparison of sensor alternatives, note that a passive imaging IR sensor complements the baseline SAR sensor. Passive IIR sensors have attributes of good performance in clutter, low noise, multispectral discrimination, and wide field of view. The passive IIR multidimensional discriminants (such as angular resolution, contrast, and multispectral) at their shorter wavelengths complement the baseline SAR sensor. There is a relatively small increase in the sensor suite cost and weight to incorporate a passive IIR sensor.

Passive IIR focal plane array (FPA) detectors have good capability to sample multiple wavelengths, providing a multispectral discriminant across a broader wavelength. Multispectral passive IIR sensors have been produced with up to four colors, based on either filter wheel or stacked FPA technologies. Figure 23 is an example of the unique two-color IR signature of a missile plume in the MWIR spectrum. Note that the average target intensity of Color A (4.5 to 4.9 micron region) is approximately seven times the average target intensity of Color B (region less than 4.1 microns). Also shown is the typical terrain clutter intensity represented by a 300K blackbody and the typical solar clutter intensity from sun glint at 5900K. The

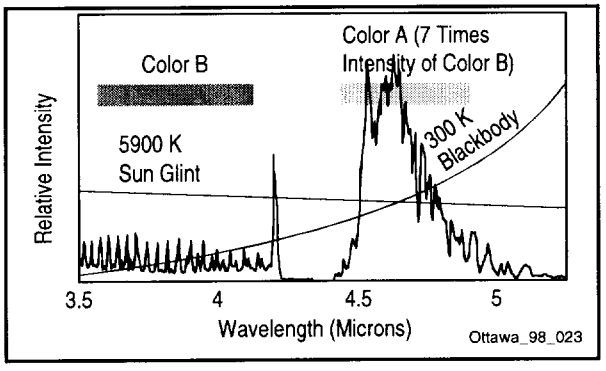


Figure 23. Example of Unique Two-Color IR Signature of Missile Plume

Color A/Color B MWIR intensity is a unique discriminant of the missile plume.

EO FPAs cover the wavelength range from ultraviolet (UV) through long wave infrared (LWIR). In the IR wavelengths, a number of detector materials are available. The production of most IR FPAs is based on mating the detectors to a silicon readout circuit, through indium columns. This provides a sandwich or hybrid sensor. However, there is a potential problem from a mismatch in the thermal coefficient of expansion, since high performance FPAs operate at cryogenic temperatures. Large IR FPAs tend to have lower yield than the simpler, more easily produced monolithic silicon based FPAs that are used in visible light TV cameras.

In the MWIR wavelengths (3 to 5 microns), the leading high performance FPA detectors for the year 2010 time frame are InSb, HgCdTe, and Quantum Well Infrared Photodetector (QWIP) detectors.

InSb and HgCdTe FPAs of 640 x 480 size are currently in production. In development are array sizes up to 1024 x 1024 with pitch (detector-to-detector spacing) as small as 18 microns. Figure 24 illustrates the SOTA advancements of Boeing's MWIR HgCdTe FPAs. It is postulated that by the year 2007, HgCdTe MWIR FPAs will be in production in a 2048 x 2048 size with 10 micron pitch-performance, providing resolution that is comparable to that of the present SOTA of TV cameras.

QWIP FPAs are based on stacked thin layers of materials that form quantum wells sensitive to a broad range of wavelengths. A layer is only a few molecules thick, creating energy sub-bands where quantum effects respond to the IR incident radiation. QWIP MWIR FPAs have high detector uniformity and yield. Disadvantages are relatively low quantum efficiency and relatively high dark current.

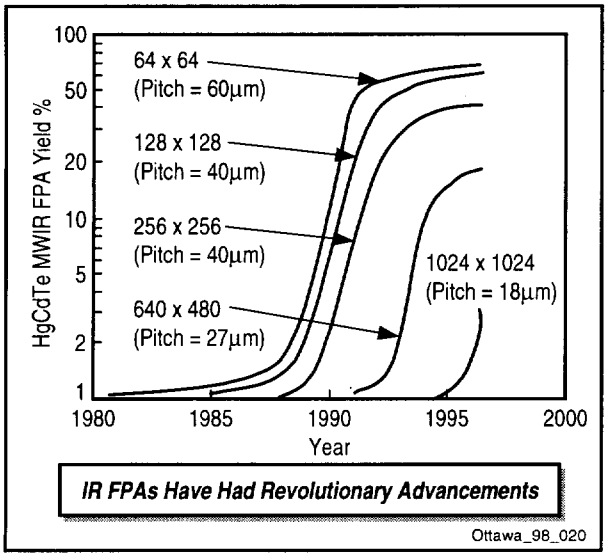


Figure 24. Example of Advancement in SOTA of IR FPAs

LWIR (8 to 12 microns) high performance tactical FPA detectors include HgCdTe and QWIP. HgCdTe LWIR devices that are currently in production have array sizes up to 256 x 256, with a pitch of about 40 microns. It is projected that by the year 2000, HgCdTe LWIR FPAs will be in production in array sizes up to 640 x 480. The problem of producing HgCdTe LWIR FPAs in large array sizes has been alleviated by the use of a balanced composite structure. The balanced composite structure mitigates the differences in the coefficient of thermal expansion of the FPA. Also in development are HgCdTe multispectral FPAs capable of simultaneous detection in both the LWIR and MWIR bands.

LWIR FPAs based on QWIP are currently in development. QWIP FPAs have advantages of uniformity, low thermal stress even in large size arrays, and suitability for multispectral applications. Disadvantages of QWIP LWIR sensors are a requirement for cooling down to less than 77 Kelvin, higher dark current, and lower quantum efficiency. Cryogenic cooler engines based on helium are available that operate at temperatures below that of liquid nitrogen (77 Kelvin). However, there are disadvantages of shorter lifetime, less temperature control, and longer cool down time. The higher dark current and relatively low quantum efficiency of QWIP FPAs will be alleviated by technology advancements for this relatively immature technology and the effective use of the multispectral discriminants that provide enhanced detection at longer range.

The other sensor alternatives (active nonimaging radar, active nonimaging LADAR, passive nonimaging IR, visible, UV, and acoustic/seismic) that are shown in Figure 18 are less likely to be used in precision strike, due to their combined limitations from factors such as weather, clutter, and angular resolution.

SENSOR DATA FUSION ARCHITECTURE FOR PRECISION STRIKE

As discussed previously, improvements in the SOTA for sensor suites and sensor data fusion will be required to meet the precision strike performance requirements for the year 2010. The sensor data fusion architecture must be sufficiently robust to provide a high probability of selecting the correct target while also satisfying the latency and cost constraints. As an example, the traditional features for ATR are based on 2D images of the

target, such as treads of a tank target compared to a wheeled vehicle. Adding additional target 2D image features, such as the tank gun barrel provides enhanced confidence. However, greater payoff is achieved by also combining unique features from multidimensional independent discriminants. Multiple independent discriminants tend to have correlated target detection with noncorrelated false alarms. Thus, a 20 percent FAR for a single discriminant would be greatly reduced in combining two discriminants (resulting in 4 percent FAR), while a 90 percent probability of detection for a single discriminant would be only slightly reduced in combining two discriminants (resulting in 81 percent probability of detection). Another example is combining SAR sensor 2D imagery with the additional orthogonal feature of SAR polarization.

Orthogonal features in this context have noncorrelated false alarms. Orthogonal features often provide higher performance with less required data bandwidth than the traditional approach of using higher and higher resolution imagery. By expanding the number of orthogonal features, more difficult targets can be correctly identified. A limiting consideration is the cost trade of the alternatives of (1) increased resolution for a single sensor, versus (2) the fusion of other orthogonal discriminants from the same sensor, versus (3) the fusion of other orthogonal discriminants from other sensors.

Figure 25 is an example of sensor data fusion architecture that is robust, based on seven combinations of classifying the features of three sensors. In the far-left classification channel, common features of sensors A, B, and C are classified. In the case of a sensor suite consisting of three imaging sensors in different wave bands, the target pixels of the bore-sighted sensors would be registered to obtain a common image in each wave band. The unique features of the target (e.g., tank treads, tank gun barrel) are classified for common features. Other common features, such as polarization at different wavelengths, are also classified. The advantage of the serial configuration of the far-left classification channel is that false alarms and decoys are likely to be rejected. The common features must be measured in all three wave bands to be accepted as a target. A disadvantage of the serial fusion in the far-left channel is lower detection probability, particularly for low signature targets in clutter. The next three classification channels provide combinations of the common features from two sensors. These channels tend to have higher detection but also higher false alarms. Finally, the three classification channels on the far right individually classify the features of the individual sensors A, B, and C. The classification is based on the data fusion of discriminants (e.g., image features, polarization) for each individual sensor. These channels tend to have the highest detection but may also have the highest false alarms. Above the seven classification channels is the decision level fusion.

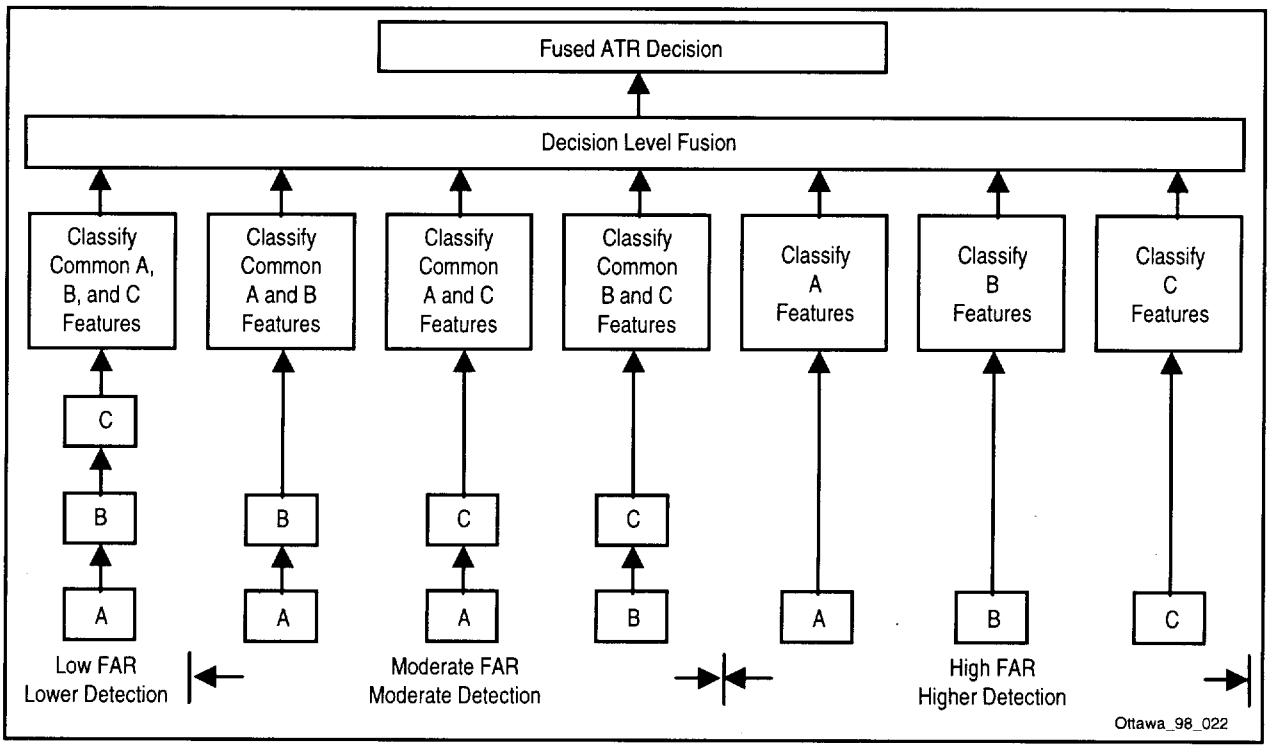


Figure 25. Example of Robust Sensor Data Fusion Architecture for Low FAR and High Detection ATR

The decision level fusion processes the results of the seven individual channel classifications to yield a fused, optimized target identification decision. Decision level fusion of multiple sensors is a relatively immature technology, and is currently more of an art than a science.

Figure 26 is an example of sensor data fusion based on an allocation of discriminants for ATR. The example is based on three sensors – Sensor A: SAR, Sensor B: passive imaging mmW, and Sensor C: active imaging IR. Two-dimensional imagery from an angular resolution discriminant was selected as a common discriminant for all three sensors. This information could be used in the far-left classification channel of Figure 25. Requiring a classification of target image features (e.g., tank treads, tank gun barrel) for three different wavelengths (e.g., X-band, mmW, IR) mitigates the problem of false alarms. An example of the other classification channels in Figure 25 is the assumed common discriminants of Sensors A and B (2D image, temporal), Sensors A and C (2D image, polarization), Sensors B and C (2D image, contrast), as well as the individual discriminants of Sensors A, B, and C.

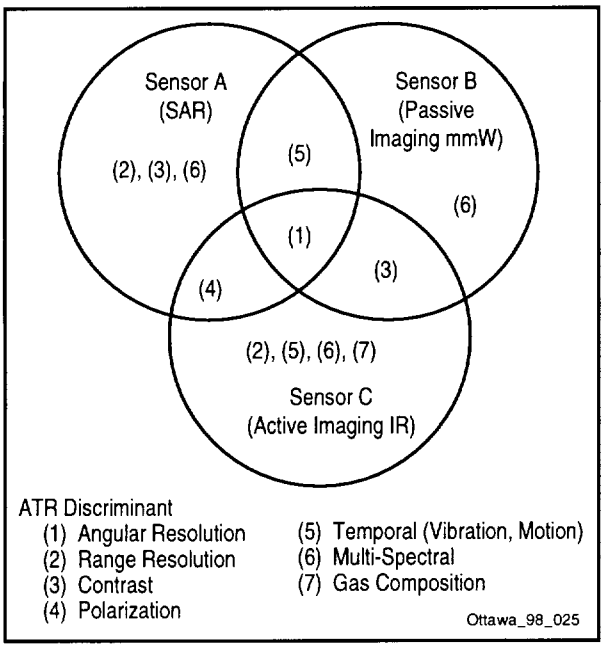


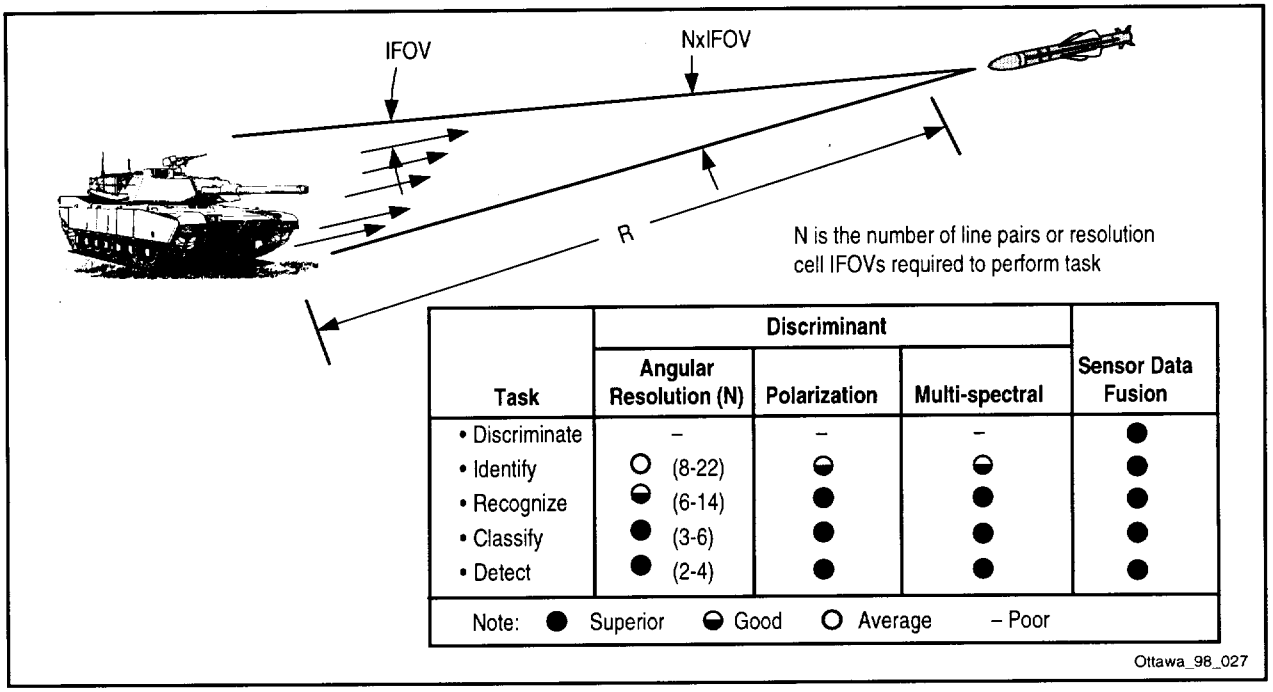
Figure 26. Example of ATR Discriminant Allocation for Sensor Data Fusion

Figure 27 illustrates how sensor data fusion provides higher confidence to discriminate and identify the target, over the traditional approach of using only image resolution. The traditional approach to ATR of a target in clutter is based on statistical pattern recognition of the 2D image features such as height-to-width ratio, unique components (e.g., tank treads, tank gun barrel), and contrast (intensity of the target resolution cells [pixels] compared to the background). An ATR task (e.g., detection, classification, recognition, etc.) can be related to the number of sensor resolution cells or line pairs across a maximum dimension of the target. A line pair is the instantaneous field of view (IFOV) resolution of the sensor. NxIFOV is a maximum dimension (e.g., width, length) of the target. For a square target, there are N^2 resolution cells imaged by the sensor. In the case of detection, 2-4 line pairs are required to indicate that an object is present in the clutter. In the case of classification, 3-6 line pairs are required to classify the target in a broad class of object types, such as tracked vehicles. In the case of recognition, 6-14 line pairs are the traditional criteria to put the object into a subclass, such as a tank. In the case of identification, 8-22 line pairs are the traditional criteria for a specific object type within a class of objects, such as a T-72 tank. Finally, discrimination involves distinguishing real targets (e.g., a real T-72 tank) from decoys (e.g., a replica of a T-72 tank). A problem with single sensor monochrome imagery is the point of diminishing return where the confidence in ATR does not improve with increased resolution. In the example of Figure 27, a SAR sensor could avoid the problem by fusing 2D imagery, polarization, and multispectral discriminants for enhanced ATR performance. Sensor data fusion not only provides higher confidence in each task, but also provides a capability for the more difficult ATR tasks, such as discrimination, that may not be achievable using traditional imaging-only ATR.

The previous discussion has focused on sensor level and decision level fusion. A potential disadvantage is the discarded information associated with the same pixel data correlations between sensors. However, the alternative of pixel level fusion at the raw data level may also have problems, due to differences in pixel size, resolution, field-of-view, and boresighting. The issue of sensor-level versus pixel-level fusion is an on-going debate in the sensor data fusion community.

CONCLUDING REMARKS

Sensor data fusion technologies will have high payoff for precision strike in the year 2010. Benefits include reduced workload for the image analyst, mission planner, and pilot; improved safety for the pilot and friendly forces/civilians; higher lethality; and the potential to reduce the cost per target kill. There is no doubt that sensor data fusion provides higher performance over traditional 2D imaging ATR that uses a single wavelength from a single sensor.



Task	Discriminant: Angular Resolution (N)	Discriminant: Polarization	Discriminant: Multi-spectral	Sensor Data Fusion
• Discriminate	–	–	–	●
• Identify	○ (8-22)	◒	◒	●
• Recognize	◒ (6-14)	●	●	●
• Classify	● (3-6)	●	●	●
• Detect	● (2-4)	●	●	●

Note: ● Superior ◒ Good ○ Average – Poor

Figure 27. Example of Benefit of Sensor Data Fusion

ATR development should consider sensor alternatives that capture the most important target features and efficiently run the ATR algorithms. Similarly, the sensor development should consider ATR algorithm alternatives that exploit sensor performance and capture the most important target features. A problem is that the ATR community is typically funded independently from the sensor community and there is little incentive to work together. Unless the ATR and sensor communities communicate more on system level trades, the system level result will be nonoptimum (Figure 28).

Selection of the best approach for sensor data fusion requires an assessment of alternative concepts and technologies to provide a traceable path from system-level requirements to technology requirements. However, developers of sensors and ATR algorithms usually have a conflict of interest in conducting technology assessments. The sensor community may advocate sensors that are based more on what they wish to sell and not by reasoned consideration of enhanced ATR. Similarly, the ATR community may advocate favorite algorithms that are not optimized for sensors. The assessment of alternatives for sensor data fusion concepts and technologies should be conducted by an "honest broker" that is not biased by prior investments in either sensors or ATR. Figure 29 illustrates a study to evaluate alternatives for sensor data fusion concepts and technologies. The study duration is typically 3 to 6 months and the scope is approximately 2 to 4 person-years. Typical study tasks are mission analysis/ scenario definition; sensor data fusion requirements, trade studies and sensitivity analysis; assessment of the physical and avionics integration of the sensor on the aircraft/UAV/weapon platform; sensor data fusion concept design synthesis; and technology assessment and development roadmap. The recommended system concepts and technologies are a system-level "requirements pull" for sensor fusion technologies that balances the "technology push" advocacy from the sensor and ATR communities.

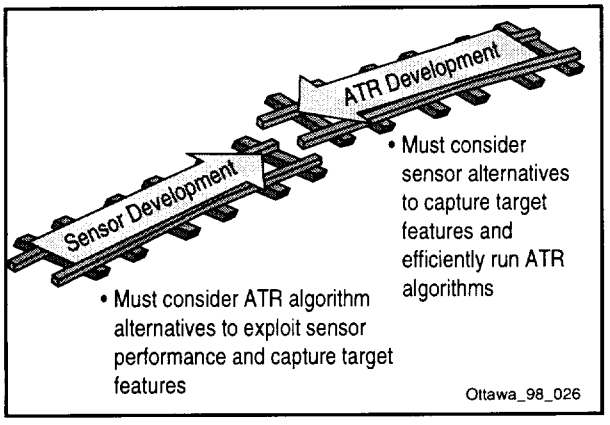


Figure 28. Sensors and ATR Need to be Developed in Concert

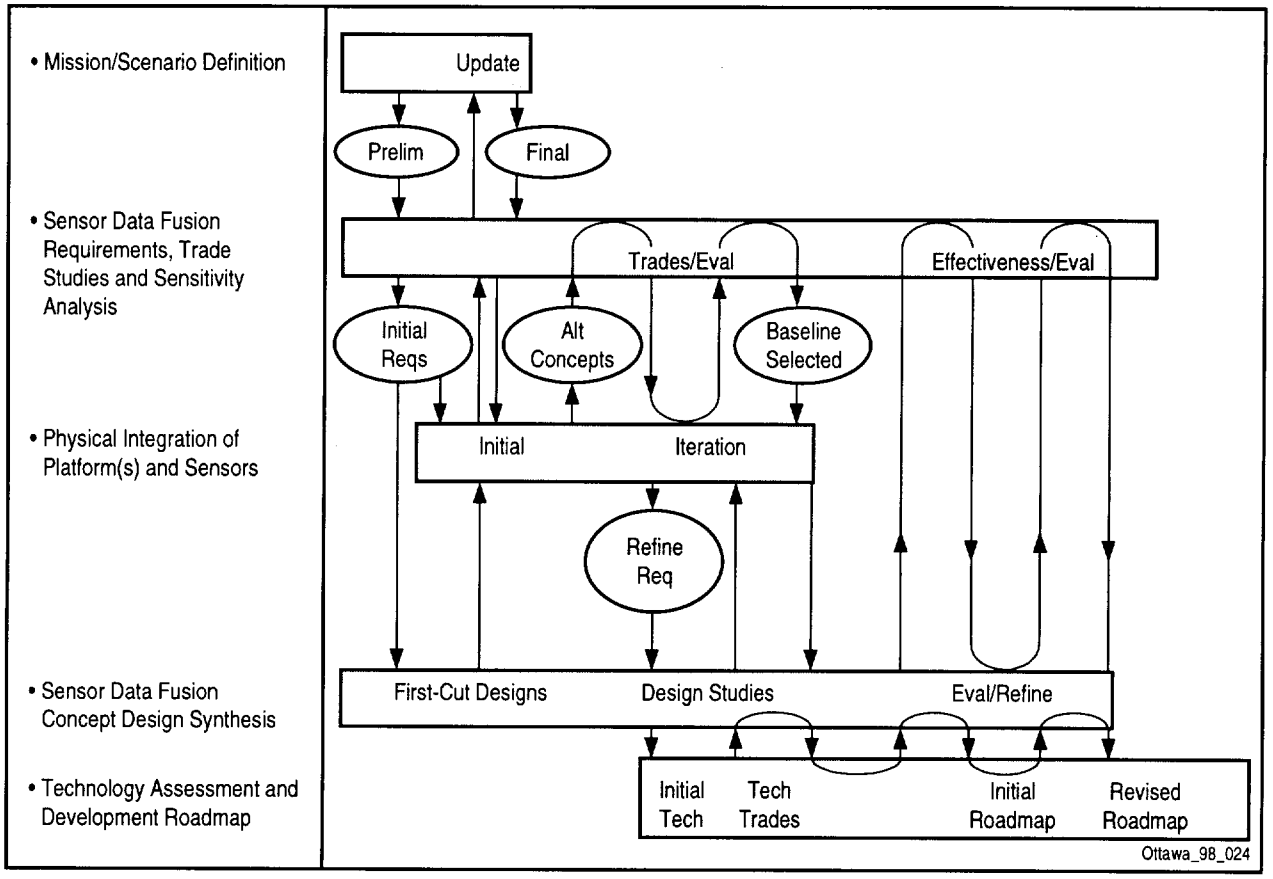


Figure 29. Example of an Assessment of Alternative Sensor Data Fusion Concepts and Technologies

QUOTATIONS

- "When I see a bird that walks like a duck and swims like a duck and quacks like a duck, I call that bird a duck."
  ~ Richard C. Cushing ~
- "A pile of facts is no more a science than a pile of bricks is a house."
  ~ J. Henri Poincare ~
- "Where is the wisdom we have lost in knowledge? Where is the knowledge we have lost in information?"
  ~ T.S. Elliot ~
- "He can run but he can't hide."
  ~ Joe Louis ~

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Intelligent Crew Assistant for Military Transport Aircraft

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ABSTRACT

Modern cockpit environments, covering highly integrated and complex automatic functions, pose various demands on the crew. In unusual situations the crew often is overtaxed and acts erroneously. "Clumsy automation" is considered to be a major reason for deficiencies concerning the interaction between cockpit crew and aircraft systems. Cognitive systems appear to be a promising approach to overcome these deficiencies in future cockpits. They are being developed covering human-like capabilities in the interpretation and diagnosis of the situation, planning and decision making and the execution of a plan. In this paper a general survey on the principals of cognitive cockpit assistance will be given. Demands and requirements for an appropriate automation and a generic functional structure of a cognitive assistant system will be introduced. A prototype system, CAMA, the *Crew Assistant Military Aircraft*, its capabilities and functional units (modules) are presented and described in detail. In future combat transport aircraft, constraints created by low level flying in a high risk theater, the high rate of change of information and short reaction times required will produce physiological and cognitive problems for pilots. CAMA is designed taking into consideration the approach of human-centered automation.

INTRODUCTION

Automation technology in the past improved significantly flight-safety, mission-effectiveness (satisfying multiple goals) and efficiency (e.g. fuel economy, timelines). However, recent accident investigations reveal that the human operator might become overcharged by the current concept of cockpit automation.

The modern cockpit is a multitask environment, comprising four task categories:

- to aviate,
- to navigate,
- to communicate and
- to manage systems.

Executing these tasks, the crew is permanently trying to comply with a number of concurrent, sometimes competing, often conflicting objectives. Multiple actions have to be performed to accomplish them. The allocation of operator tasks to automatic devices is often seen as the appropriate design strategy to reduce workload. However, the crew remains still responsible for operating the aircraft. Complexity and autonomy of automation, the coupling between or among automated functions and the inadequate feedback have been identified as leaks in the system's concept [1]. Monitoring and supervising requirements become more prevailing and that may increase the pilot's workload in unusual situations. Managing the automatic devices and being aware of their behavioral features becomes more and more difficult.

Automation increases the aircraft's performance and by that its mission capabilities. The complexity of planning and decision-making tasks increases correspondingly and takes pilot's mental capacity. Aircraft manufacturers and flying organizations try to reduce crew decision-making as much as possible. This is done by means of automation and by establishing standard procedures and checklists to cover anticipated failures or emergencies [2][3]. Natural decision making environments can be turbulent, with time-varying goals and requirements. Pilot's tasks alter with increased automation as to decreasing physical activities and increasing cognitive activities. The human being is well equipped with cognitive capabilities concerning his natural tasks. However, flight guidance provides quite different challenges. The crews have to make many different kinds of decisions, but all involve situation assessment, choice among alternatives, including risk assessment. Effective crews are characterized by [2]:

- Good situation awareness.
- High levels of metacognition.
- Shared mental models (based on explicit communication).
- Efficient resource management.

Assisting the pilot in his flight guidance task by a technical system should compensate humans deficencies in the cognitive process and improve decision-making in any situation.

Paper presented at the RTO SCI Symposium on "Sensor Data Fusion and Integration of the Human Element", held in Ottawa, Canada, 14-17 September 1998, and published in RTO MP-12.

COGNITIVE ASSISTANT SYSTEMS

The human information processing comprises

- Monitoring of the Situation,
- Diagnosis of the Situation,
- Planing and Decision Making and
- Plan Execution/Activation.

Situation monitoring comprises the determination of situational attributes, based on the perception of the relevant objects. The situation diagnosis completes the picture of the situation by evaluation of the situational attributes against the governing objectives, plans and actions, thereby identifying problems. Conflict resolution is performed by planning and decision making. Planning comprises the generation of alternatives for interim-goals, plans, tasks and actions. Selection and instantiation of the most appropriate alternative subject to the governing goals is performed within the decision making process which is entailed by the execution of the plan.

Rassmussen [3] distinguishes human's cognitive capabilities by the three levels of knowledge-based, rule-based and skill-based behavior (see Figure 1)

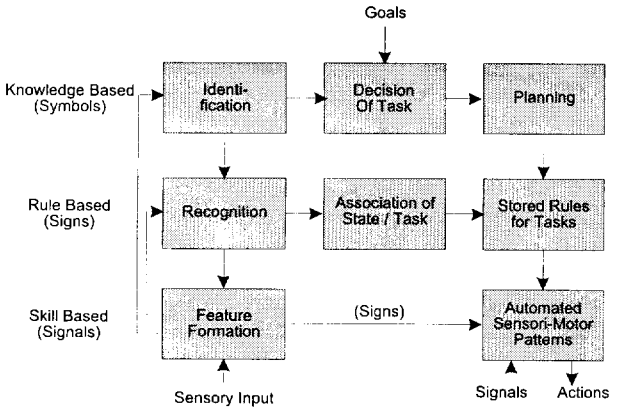

Figure 1: Human's Level of Cognitive Behavior [3]

The cognitive process passes all levels of human-behavior. Situation interpretation starts on a skill-based level by the extraction of features. The diagnosis of the situation, with regard to identification and resolution of conflicts can become a knowledge-based process. Plans and tasks are executed in the rule-based level resulting in various actions.

Current automatic devices provide good performance within their specified restricted functional scope. The representation of the situation within these devices is restricted to, consequently. This provides fundamental implications and resulting problems [4]:

- Automation performs tasks without knowledge of the complete situation, current goals, plans and further parallel tasks.
- The assessment of the situation remains by the pilot, who has to determine wether the current situational scope fits the specification of the activated automatic device.
- The pilot has to ensure that all automatic devices are supporting the current goals the pilot tries to comply with.

This is the reason why increasing of cockpit automation complexity, managing the systems becomes more and more prominent.

Cognitive assistant systems cover all of the human-like capabilities in Figure 1, using the representation of the complete picture of the situation over all levels of behavior (see Figure 2).

These systems work in parallel to the pilot as to assessment of the situation and resolution of conflicts and support mutual assistance. The underlying concept for the interaction between assistant and pilot is the human-centered approach, with the following fundamental design criteria [1][5]:

- Human operators must be actively involved.
- Human operators must be adequately informed.
- Human operators must be able to monitor the automation assisting them.
- The automated system must also monitor the human operator.
- Automated systems must be predictable.
- Every intelligent system element must know the intent of other intelligent systems elements.

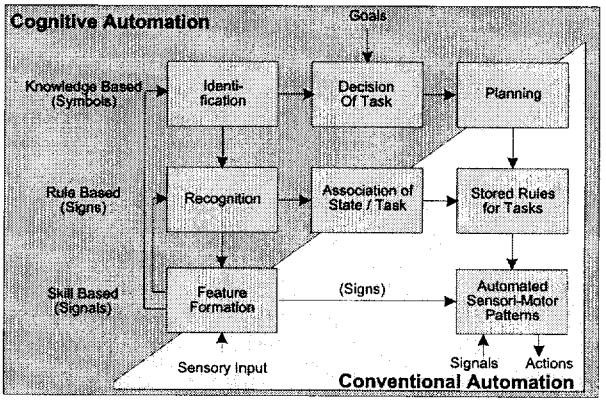

Figure 2: Conventional vs Cognitive Automation

Onken [6] stated two basic functional requirements for the behavior of a cognitive assistant system, which are in line with the design criteria of the human-centered approach:

(1) "Within the presentation of the full picture of the flight situation it must be ensured that the attention of the cockpit crew is guided towards the objectively most urgent task or sub-task of that situation."

(2) "If basic requirement (1) is met, and if there still comes up a situation with overcharge of the cockpit crew (in planning and execution), then this situation has to be transfered – by use of technical means – into a situation which can be handled by the crew in a normal manner."

These requirements lead to the functional structure of the cognitive assistant system as depicted in Figure 3. For a comprehensive understanding of the situation, the process of *situation analysis* comprises both perception of objects and pertinent features in a number of levels of abstraction as well as the process of *situation diagnosis* which based on the perception, recognizes and predicts conflicts, caused by events

in the domain of either aircraft, pilot or environment. This closely resembles the human way of situation analysis

In order to recognize potential opportunities in addition to conflicts alternatives are generated for goals, plans, tasks and actions, including that one, which represents the given flightplan. Only the conflict-free alternatives are passed to the 'Decision Finder of How to Proceed'. The conflict solving process is ranking these alternatives on the basis of the mission success criteria.

The *Dialogue Manager* insures effective communication with the crew. This is the front-end of an assistant system. It presents all necessary and useful information in a way, that is easy to comprehend. Messages to the cockpit crew should be tuned and tailored to the current situation, especially with respect to minimize the demands on crew resources. Inputs to the system should allow initialization of services and decision support without tedious or distracting input actions.

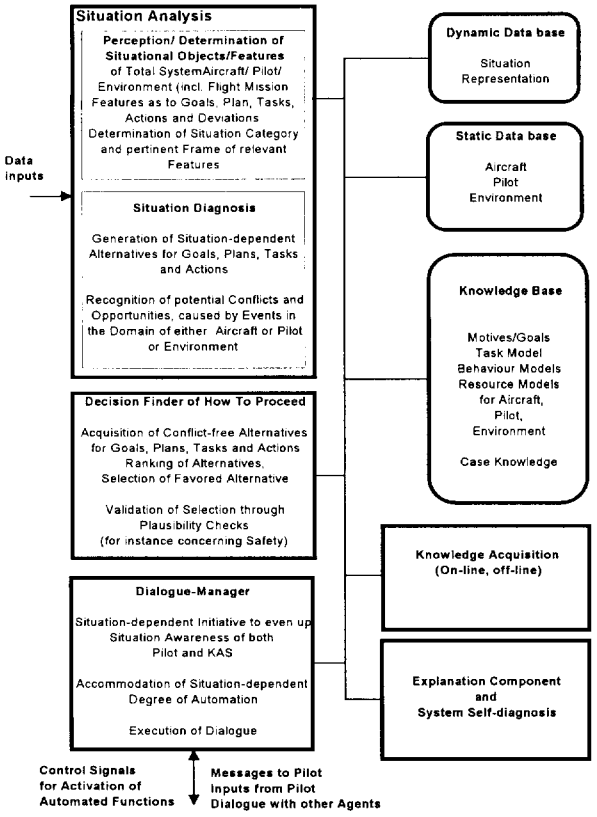

Figure 3: Structure of a Cognitive Assistant System.

Knowledge processing needs a *dynamic object-orientated representation* of the situation-describing objects. The representation covers sensor data on the lowest level as well as very abstract objects like a whole flight plan or for instance the recognized intent of the crew.

Other *knowledge bases* are needed to express and enable access to domain knowledge and to permit inferencing. Models about motives and goals, task selection, execution knowledge and demand for resources as well as behavior models are important examples of this kind of knowledge, executed by additional information about the crew member.

Static data bases for navigation purposes or threat data bases can already be considered as standard, keeping in mind, though, that incompletness, incorrectness and aging effects have to be coped with.

The expert knowledge embodied in the system has to be obtained in a systematic way.

Knowledge acquisition appears as a potential bottle neck during development of the knowledge-based assistant system. Well-defined and efficient algorithms and methods have to be used to cope with the ill-structured and uncertain real world.

In order to increase user acceptance, it is desirable that the system contains a justification or *explanation component*. First of all the user should be conscious of the rules that are applied in the algorithm to obtain a solution or system state. This will provide confidence in the system outputs.

System *self-diagnosis* makes sure that the hints and services to the crew will be really useful. The system must be able to realize, if information concerning the actual situation might be insufficient to assist the crew, or that the system itself is not working all right and needs to be corrected.

CAMA – Crew Assistant Military Aircraft

In future combat transport aircraft, low level flying in a high risk theater, the high rate of change of information and short reaction times required will create physiological and cognitive problems for pilots. From the cognitive point of view, low level flying over rapidly changing terrain elevation coupled with complex and dynamic tactical environment will result primarily in difficulties to maintain situation awareness. It still seems impossible to ensure the pilot's situation awareness as the dominating requirement for high level mission performance and safety.

CAMA, the *Crew Assistant Military Aircraft*, is a cognitive cockpit assistant system (see also [7][8]). It is being developed and tested in close cooperation between the Daimler-Benz Aerospace AG Ottobrunn, Deutsches Zentrum für Luft- und Raumfahrt Braunschweig, Elektronik- und Logistiksysteme GmbH München and Universität der Bundeswehr München. The system is divided into several functional units (modules), each supporting the execution of a specific task category (see Figure 4).

Interpretation of the Situation

The perception and determination of situational objects and features comprises the following modules:

The *Environment Interpreter* (EI) provides information concerning the actual weather and the technical environment. Thunderstorms, areas of turbulence, the atmospheric conditions as well as objects of special interest (e.g. airborne vehicle) are recognized and located relative to the aircraft's current position.

The airspace surveillance task is performed by the *Traffic Alert and Collision Avoidance System* (TCAS). In the case of a potential traffic conflict, four levels of information and advisories are issued respectively. Visual and acoustic advises and recommendations are given. CAMA monitors and supports the execution of the conflict resolution.

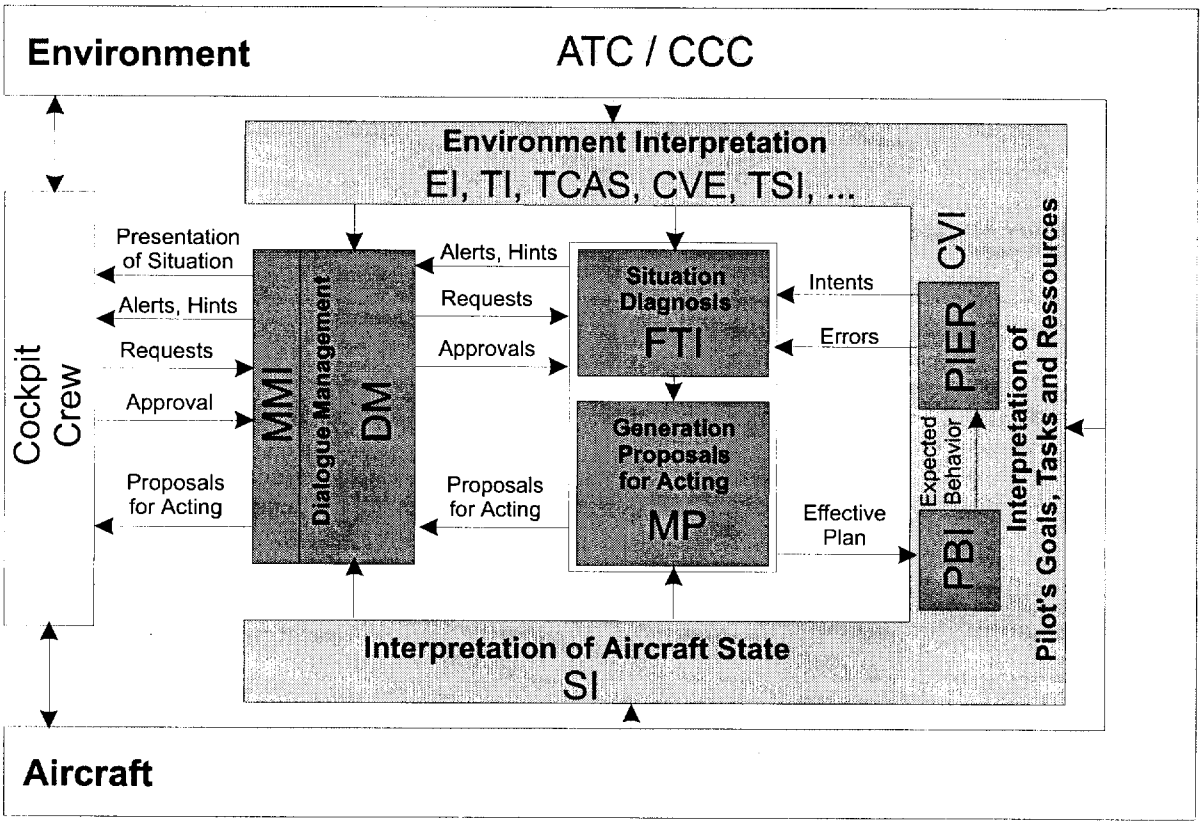

Figure 4: Functional Structure of the Crew Assistant Military Aircraft.

Ground proximity is detected by the *Terrain Interpreter* (TI). A hyperplane of possible flight trajectories, achievable by full exploitation of the aircraft's performance capabilities is calculated and checked for intersections with the terrain, using a terrain database.

The aircraft's state is monitored by the *System Interpreter* (SI) [9]. In the case of a detected malfunction the module initiates a system diagnosis to resolve the reason for the failure occurred.

The module *Computer Vision External* (CVE) [10] serves the interpretation of the surrounding environment using its computer vision capabilities. Determination of aircraft's actual state in respect to the environment. The module supports approach and landing even on unequipped airfields. In addition obstacles on the runway are recognized.

The *Tactical Situation Interpreter* (TSI) [11] computes a threat map. A digital terrain elevation map and the present tactical scenario (e.g. hostile SAM stations) are taken into consideration. The threat model comprises the maximum range, operationability, efficiency along range and respective models for threat area overlapping.

The module *Computer Vision Internal* (CVI) [12] provides information concerning the pilot's point of gaze. A bifocal camera is installed in the cockpit's front-panel for this purpose. The information, for instance the moving line of sight to a control device or to a certain indicator, could be used to confirm the need for a warning or a hint. This information can also lead to a better assessment of the pilot's resources [13]

Interpretation of Pilot Behavior

Monitoring of the pilot flying by a pilot non-flying in the multi-crew cockpit is one of the reasons that air transport is as safe as we are used to. In the same way pilots monitor the actions of air traffic controllers, and in the turn, controllers monitor the behavior of the aircraft they control. The assistant system should have the same kind of capability.

With specific attention to potential failure points (e.g. those documented in aviation operations) and by the application of information technology and the support of the various aircraft systems more comprehensive and effective monitoring of both pilots and controllers is applicable. Within the human-centered approach automation can and should be thought of as a primary monitor of human behavior in exactly the same way that humans are the primary monitors of machine behavior [1].

The *Pilot Behavior Interpretation* (PBI) generates the expected pilot behavior in two ways depending on the behavioral pilot model used. A *normative model* [14] describes deterministic pilot behavior as documented in pilot handbooks and air traffic regulations. Primarily rule-based behavior is considered. The modeling is done for all flight segments (taxi, takeoff, departure, IFR-cruise, tactical flight, drop, approach, landing) and the following tasks:

a) situation analysis

- Recognition of actual flight segment.
- Recognition of process of plan execution related to flight plan procedures.

b) pilot actions / performance

- Primary flight guidance (altitude, course, airspeed, power setting, climb/descent rate, pitch attitude).
- Operation of flaps, speed brakes and gear.
- Drop procedure.
- Operation of ramp.
- Radio navigation.

An *adaptive model* [15] covers behavioral parameters of the individual pilot, when specifically differing from the normative model.

The expected pilot behavior as provided by the PBI is compared with the pilot's actual behavior by the *Pilot Intent and Error Recognition* (PIER) [16][17]. In case of detected deviations the module PIER tries to figure out, wether the deviation was initiated erroneously or intentionally. Detected errors are issued to the *Flight Situation and Threat Interpreter*. Error detection will help the pilot to correct slips and to focus his attention on most important or critical events.

By monitoring pilot actions as well as the mission context, the system is able to compare the pilot's action to a set of behavior hypotheses. In case of an intentional deviation from the flight plan, the module checks, if the behavior fits to one set of a given set of intent hypotheses.

These hypotheses represent behavior patterns of pilots, for example, when commencing a missed approach or avoiding a thunderstorm. With the intention recognized, support like re-planning is initiated, and the overall loop could be closed without further inputs of the pilot.

In the more tightly integrated system of the future, such cross-monitoring between man and machine and vice versa will be the key to improved system safety.

Situation Diagnosis

Mission-oriented goals are derived from the mission order. The mission order comprises instructions and constraints, which are to be kept (e.g. entrance-corridors to gaming area, drop-point, TOT, etc.). The recognition and prediction of potential conflicts and the initiation of suitable measures for conflict resolution are the primary tasks of the *Flight Situation and Threat Interpreter* (FTI).

The FTI initiates the module *Mission Planner* (MP) to generate a complete, conflict-free flightplan. If the mission order leads the aircraft into an area with hostile radar coverage, the *Low Altitude Flight Planner* [10] is started additionally for the calculation of a low altitude flightplan as well as the pertinent trajectory. FTI controls the planning parameters. They are provided to the planning modules and comprise origin and destination, corridors to be planned through, civil and tactical waypoints as well as detailed drop procedures.

Crew constraints, e.g. individual route preferences are included as well. Generated routes are proposed to the cockpit crew, and are accepted, modified or refused respectively.

Erroneous crew intents and other crew errors, recognized by the module PIER are monitored and hints and warnings to the crew will be initiated. Sensible deviations from the flight plan, intentionally carried out by the crew are incorporated in the actual flightplan.

Monitoring of the flightplan and evaluation against the situation is done permanently. Conflicts within the planned route, e.g. new threats popping up within the operation area or corridors, weather deterioration en-route or at the destination, etc., will be recognized and suitable mission planning routines will be triggered.

Mission Planning

CAMA comprises two flight planning agents, serving the knowledge-based conflict resolution task. Both are coordinated and controlled by the FTI via a set of various parameters.

The *Mission-Planner* (MP) [18] calculates a flightplan for the purpose of a civil IFR flight. The module creates and maintains a 'take off'-to-landing mission flight plan, including routes, profiles, time estimates and fuel-planning, taking into consideration the mission constraints, gaming area, ATC instructions, aircraft state (e.g. fuel contingency, system failures), environmental data, etc. Two lateral route alternatives – a standard IFR routing as well as a radio-navigation route – are calculated and proposed to the crew. Acceptance, modification and rejection, all of those pilot reactions are possible.

The task of the *Low-Altitude Flight Planner* (LAP) [11] is the calculation of a 3D trajectory with a maximum probability of survival in a hostile environment. This is achieved by avoiding threatened areas if possible, minimizing the exposure to unknown threats and keeping clear of the terrain. Therefore, the planning constraints, the tactical elements and the resulting threat map, the terrain elevation data and the aircraft performance data are taken into consideration.

Crew Interface

Communication between CAMA and the cockpit crew plays an important role. The kind of information to be transmitted in either direction varies with respect to the different situations and demanded tasks. The information flow from CAMA to the crew and vice versa is controlled exclusively by the module *Dialogue Manager* (DM) [13][19].

Pilot's inputs are:

- Requests of new flightplan proposals.
- Activation or rejection of proposal.
- Activation of actions related to warnings.
- Retrieval of information (e.g. ATIS, navigational aids, reconnaissance information, mission progress).
- Autopilot operations.
- Configuration of the man/machine interface (e.g. heading-up, range, display modes).

CAMA outputs are:

- Presentation of calculated flightplan proposals.
- Situation presentation (e.g. weather, tactical situation, terrain, airports)
- Warnings about detected conflicts.

- Recommendation of explicit actions.
- Messages in reply to requests.
- Acknowledgment of speech-input.
- Presentation of complex actions (e.g. approach briefing)

The *Dialogue Manager* coordinates the following interface components:

- Moving map display (see Figure 5) providing various information and map-layers (e.g. low level flying chart, terrain, calculated threat).
- Secondary display for e.g. flight-log, ATIS, horizontal scenario overview, briefings.
- Speech output systems.
- Context sensitive speech recognition system.

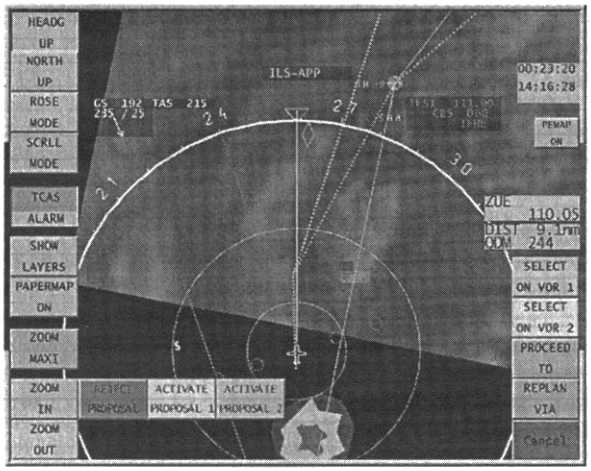

Figure 5: Moving Map Display of CAMA.

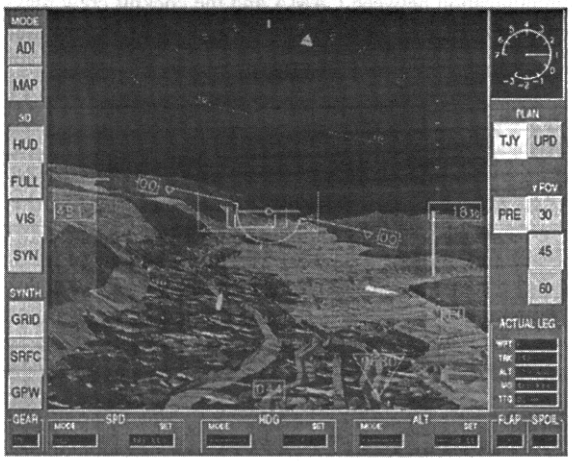

Figure 6: Primary Flight Display in 3D-mode.

Additional man-machine-interface devices provide support for the flight-guidance task. For flying in low altitudes under demand of visual flight rules, a primary flight display (see Figure 6) provides a 3-dimensional presentation of the surrounding environment. The calculated trajectory is presented as a tunnel.

Flight Simulator Trials and In-Flight Experiments

CAMA is integrated in the flight simulator of the Universität der Bundewehr München (University of the German Armed Forces Munich). In November '97 and May '98 flight simulator test runs were conducted with 10 military transport pilots. Each pilot conducted two tactical missions of 1 hour. The results of these flight simulator tests are also presented at this symposium [20].

Currently CAMA is being integrated in the in-flight simulator ATTAS of the DLR (German Aerospace Research Establishment Braunschweig) and will be demonstrated in flight experiments scheduled for the early year 2000.

Further Research

At this point, interactive planning in terms of dealing with specific pilot request at any time, is not developed yet to an extent which will be desirable in an operational system. Although there is no principal difficulty to achieve this on the basis of the CAMA system structure, it seems still to be worthwhile for the sake of completeness to demonstrate this in a prototype system.

Also the modeling of the pilot's resources and behavior will be further completed in order to further improve timeliness and goal-conformity of the aiding actions of the system.

Another aspect of further research is the integrity issue with respect to cognitive assistant systems. It turns out that knowledge-based systems with situation analysis capability bring with the capability of self-diagnosis, which can be exploited for integrity purposes. This capability provides the potential to get rid of the necessity of abundant test runs for most part of the system, which could be inevitable to prove for sufficient flawlessness in software and data bases.

Conclusion

Allocating pilot tasks to automatic devices and improving aircraft performance and mission capabilities by increasing use of computing power and resulting system complexity pose new demands on the cockpit crew.

CAMA has demonstrated, that cognitive capabilities within a technical system, behaving in a manner similar to an additional crew member, improve the effectiveness of the cockpit crew as well as the mission effectiveness. Aiding functions for better situation interpretation as well as planning and decision-making provide a safer and more effective conduction of the flight. The benefit of the human-centered approach, the cross-monitoring between man and machine are shown even in the environment of complex, highly automated modern flight decks of transport aircraft for military missions.

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ON THE DESIGN OF A DECISION SUPPORT SYSTEM FOR DATA FUSION AND RESOURCE MANAGEMENT IN A MODERN FRIGATE

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1. SUMMARY

Decision support has been identified as a focus of attention for the mid-life upgrade of the Command and Control System (CCS) of the HALIFAX Class frigate, anticipated in the 2005-2010 timeframe. To support this effort, we are exploring concepts for the design of computer-based decision aids that can be integrated into the CCS to assist operators in their tactical Command and Control (C2) activities. To date, the emphasis has been on investigating algorithms for aiding operators with their decision making tasks, including picture compilation, situation and threat assessment, and resource management. To support this effort and develop an integrated set of aids, a systematic framework is now needed to identify the requirements that an effective computer-based decision support system (DSS) should satisfy. Determining support interventions in the work environment of tactical C2 is a challenging problem due to a number of its characteristics (e.g., time-critical decision making under uncertainty, high risk, dynamism, social cooperation, large amounts of data, unanticipated variabilities) that are similar to those observed in other complex sociotechnical systems in the civilian world, while introducing new ones (e.g., organised, intelligent threats to the mission, limited advance knowledge of threats). Whatever the chosen analysis and design framework, it should be tailored to the unique demands imposed by these factors. This paper reviews a range of concepts being explored for the design of the DSS, focusing on automation, cognitive and methodological issues. Automation concepts address principles and paradigms for decision support. Cognitive concepts deal with the cognitive behaviours which the DSS must exhibit and/or support. Methodological issues are concerned with a specific framework for determining DSS requirements known as Cognitive Work Analysis. It is a constraint-based approach to modeling a complex sociotechnical work system that provides an overarching framework and a variety of flexible conceptual tools for systematically investigating the space of design interventions in the joint human-machine system. The paper also identifies a high-level framework for the immediate design goal, a DSS that can support operators with data fusion, situation and threat assessment, and resource management.

2. INTRODUCTION

Tactical decision making requires a number of data and information processing tasks to be continually performed in real time in a complex dynamic environment. This calls for a high degree of coordination among combat system operators to achieve the various objectives in a timely manner. Unfortunately, there are a number of factors that will increasingly challenge operators to perform effectively. Examples include technological advances in threats (e.g., higher speeds, smaller signatures, multimode guidance), the increasing tempo and diversity of open-ocean and littoral scenarios, and the growing volume of data and information pertinent to a ship's area of interest that needs to be processed under time-critical conditions. The littoral environment, in particular, imposes a number of difficulties [1], including significant reductions in the size of the battlespace due to geographical constraints, increased numbers of threats, sensor and guidance system degradation, and congestion from commercial air and surface traffic which results in increased uncertainties in identification and deconfliction.

Such developments increase scenario complexity and impose higher processing demands on operators, while reducing the time available for decision making. Operators could be forced into the unmanageable situation of having to make extremely rapid, complex decisions, based on a limited understanding of the tactical situation, for which they are accountable. For example, a key difficulty for the ship's commander is: failure to resolve situation uncertainty and hesitation to act may lead to a missile hit; however, rapid reaction to what appears to be a threat may lead to undesirable consequences.

The purpose of the CCS is to support human operators in best utilising the fighting capabilities of the ship. An inevitable conclusion from developments in modern warfare is that future shipboard CCSs must provide better or new kinds of support. Unfortunately, current

Paper presented at the RTO SCI Symposium on "Sensor Data Fusion and Integration of the Human Element", held in Ottawa, Canada, 14-17 September 1998, and published in RTO MP-12.

operational systems generally provide little decision support in complex, highly dynamic scenarios. For example, one can envisage computer-based tools that automate tracking to speed up reactions; provide context dependent cues to help focus attention; provide planning and threat analysis tools to assist in decision making; present a common force-level tactical picture; and assign weapons under human veto.

The Data Fusion and Resource Management Group at Defence Research Establishment Valcartier (DREV) have for several years investigated algorithms to augment or enhance existing CCS capabilities. The emphasis has been put on automating various functions associated with picture compilation, situation and threat assessment, and resource management, with the operator assumed to play a mostly passive, supervisory or monitoring role. As a result, operator-in-the-loop issues and their impact on system design have not previously received detailed consideration. DREV is now exploring concepts for the design of a computer-based, real-time DSS that can be integrated into the ship's CCS. Importantly, this extends the scope of the problem to include human-machine interaction and team-machine collaborative issues, particularly where higher level cognitive processing requiring human judgement and decision making is involved.

While our concern here is only with concepts for computer-based decision support, there are a number of other areas, related to decision support interventions, e.g., training, selection, manning levels, organization and layout, where improvements can also be expected to positively impact tactical C2 performance. In fact, the evident interdependencies of the various approaches indicates that they need to be jointly analysed to establish trade-offs and shortfalls.

This paper reviews a range of concepts being investigated for DSS design. It is organised as follows. Section 3 describes the work environment of shipboard C2. Section 4 examines a wide range of automation issues related to providing computer-based decision support in this work environment. A cognitive model of Command and Control is presented in Section 5. Section 6 exposes the model-based framework for design. Section 7 discusses the current version of a high-level framework for a decision support system for shipboard Command and Control. Finally, Section 8 provides conclusions. Various concepts are only treated briefly due to a lack of space. A fuller treatment appears in [2].

3. CHARACTERISTICS OF SHIPBOARD C2

Most tactical decision making in a modern frigate is performed within the ship's Operations Room. There, a team of combat system operators (CSOs) interact with a CCS through consoles and effect action by means of various ship combat subsystems (Fig. 1). They perceive and interpret information available from ownship sensors (organic data) or data linked from other cooperating platforms (non-organic data), and plan and conduct mission operations.

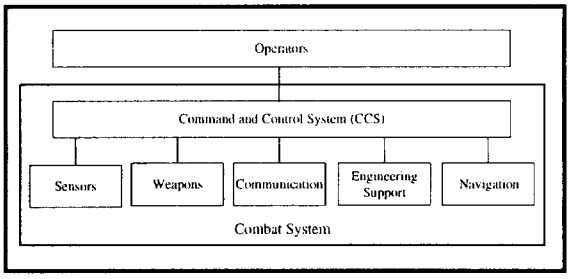

Figure 1. Interaction with ship's combat system

We give a brief description in this section of various elements of shipboard C2, concentrating primarily on situation representation. This is to expose key elements of the domain's complexity.

3.1 Overview

A ship's command structure is typically organised hierarchically. The CSO team is divided into sub-teams, generally along warfare areas (e.g., air, surface, sub-surface), with immediate control exercised by a sub-team supervisor, and with the Commanding Officer (CO) being responsible in all respects.

Operators monitor information disseminated to and from other units at sea and ashore, communicate with each other and provide feedback by means of headphones. In addition, stateboards disseminate current information on perceived threats and assist in activating pre-planned responses to highly time-stressed events such as the sudden detection of an anti-ship missile (ASM) flying towards the ship.

C2 tasks require demanding perceptual and cognitive processing (monitor, detect, assess, diagnose, plan, act) to be continuously performed. For example, with respect to the event sequence from "birth" to "death" of a single contact (track), operator activities span the moments from first contact detection, its investigation and evaluation in the context of the current mission, development of one or more courses of action, to a course of action decision, potentially involving an engagement and monitoring of that engagement.

Data from sensors and other sources are continually processed to determine a contact's kinematics (position, velocity, etc.), classify it at various levels of specificity (e.g., surface combatant, name of contact), and evaluate it to decide whether it is a neutral, a friend, or a threat. A given contact may undergo several changes in evaluation over its lifespan - pending, unknown, assumed friend, friend, neutral, suspect, hostile [3] - as new pieces of evidence are acquired and integrated.

Contact evaluation may require a variety of investigative actions to resolve uncertainty (e.g., send a helicopter for closer surveillance; manoeuvre the ship

and observe the contact's response; request additional information from a participating unit). This may involve trading off seeking additional information against the time available for implementing a specific action. A potentially hostile platform must be evaluated for its capability to detect, track, mount an attack or play a role in an attack, and defend itself or be defended. Its status and behaviour must be monitored, its assessed intentions understood, and various anticipatory decisions and/or actions taken in readiness for an attack.

Even if it is evaluated as a threat, a contact may never be engaged. For example, it may be deploying its weapons outside the engagement range of ownship's weapons. Even if it does come within the ship's engageability envelope there could still be a conscious decision not to engage, for example, because of rules of engagement, risk to a friend or neutral in the line of engagement, or a desire to remain covert in some way.

Beyond these snapshots related to processing a single contact, at any moment numerous contacts may have been detected, and, in addition to dividing their attention between them, operators may need to identify, monitor and interpret a variety of intercontact relations. For example, functional, spatial or temporal groupings of contacts allow structured representations of the tactical picture at different levels of abstraction. The operator can use this to ease information processing load by zooming in or out in the level of detail in his or her mental situation picture. Threats can be prioritised for processing and resolving weapon contention.

Additional processing demands arise from the need to continuously fuse data from a variety of organic and non-organic sources (radar, electronic support measures, infrared search and track, identification friend or foe transponder responses, data links, and intelligence). The resulting information is used to build a coherent Maritime Tactical Picture (MTP) of the ship's region of interest. Difficulties with picture compilation are related to the imperfect nature of the data (which can be uncertain, incomplete, imprecise, inconsistent, or ambiguous, or some combination of these, due to limited sensor coverage, report ambiguities, report conflicts, or inaccuracies in sensor data [4]), its quantity and its timeliness. The amount and quality of data and information is also affected by deliberate interference and deception by the enemy (e.g., by using decoys).

3.2 Problems and Opportunities

While the above focused exclusively on contact related problems in the tactical picture, there is in fact a variety of other situation features that may alert a commander to other types of pending "threats" in the environment, both internal and external to the ship, and which may also need to be "tracked" and assessed.

Context independent examples include: the operational status of the ship's equipment and fighting resources (e.g., inventory of missiles and shells, status of sensors and weapons); logistics and personnel status; social and political status. Another example is related to plan execution which must be monitored for execution error, action outcome uncertainty, or unanticipated variability in the action environment. Context-dependent examples include geographical and environmental constraints of the littoral environment that can significantly reduce the size of the battlespace or degrade weapon and sensor performance [1] (e.g., an increase in the number of false alarms of a sensor unless its detection threshold is lowered, limits in ship manoeuvrability that impact feasibility of a particular countermeasure).

These examples indicate that an operator may need to understand the impact of a host of potential problems on the mission. We define a *problem* to be a feature of the situation that has the potential to negatively impact the achievement of one or more *goals* or which should at least alert a decision maker to consider a change in the way these goals are being, can be, or should be achieved. A problem therefore represents an important goal-relevant property of the environment in that it can shape some aspect of an operator's behaviour. The detection of a problem signals a possible need for corrective measures to avoid or resolve the problem.

Another important type of goal-relevant property for an operator interacting with a complex, dynamic environment is related to opportunities. An *opportunity* is defined as a feature of the situation that represents a possibility to achieve one or more goals, or to accelerate their achievement, or to resolve the obstacles to their achievement. Opportunities may present themselves fortuitously and unexpectedly, or they may be planned for as part of purposeful action. Whereas a problem can be thought of as a behavioural constraint, recognition or identification of an opportunity is an event that offers potential for enlarging the degrees of freedom for that behaviour. For example, a particular geographical or environmental feature may offer an opportunity for concealing detection from the enemy. In some cases, there may be a cost attached to taking advantage of an opportunity (e.g., manoeuvring the ship from a pre-planned course to take advantage of terrain masking to hide from a threat, which intelligence sources have suddenly signaled, uses fuel but increases the chances of ship survivability). This cost may need to be estimated as a precursor to a decision.

We suggest in Section 5.2 that the three dynamic elements, consisting of *goals, problems* and *opportunities*, along with their dynamic *relations*, provides a basis for hierarchically structuring a situation representation for tactical decision making that has psychological relevance and offers cognitive processing efficiencies for the operator. This structuring also

underlies our cognitively based C2 model presented later.

3.3 C2 as a Complex Sociotechnical System

We have seen that tactical C2 involves complex, dynamic, real-time, data- and goal-driven multi-tasking. Goals are continually created, prioritised and steps taken toward their achievement. C2 possesses many features that usually characterise a complex sociotechnical system. Such work systems are generally characterised by (e.g., see [5-6]): uncertainty; dynamism; team work; stress; risk; an open environment that imposes variable and unpredictable demands; large amounts of data to process and high potential for sensory overload; imperfect data; human interaction mediated via computers; complex multi-component decision making. Military C2 rates highly highly in each of these dimensions. It also possesses other characteristics that seem to distinguish it from civilian sociotechnical systems (e.g., nuclear power plants, air traffic control). These differences stem from the harshness of the environment in which it operates (e.g., having to deal with an intelligent threat with a goal of denying information, or conveying false information).

It is evident that an open system like the C2 work domain must be highly responsive to variabilities which are very difficult, if not impossible, to completely anticipate or predict. Problems or opportunities can be detected at indeterminate times, resulting in the need for dynamically shifting, multiple goals. Such work systems must inevitably be highly adaptive. Rasmussen *et al.* [7] claim that the modeling an adaptive work system depends on identification of its behaviour-shaping constraints. Our decomposition into goals, problems and opportunities is a step in this direction. We shall return to this observation in Section 6.

In practice, of course, complexity can vary, depending on the specific context and nature of the conflict (varying from low to high intensity levels in open-ocean and littoral areas). Also, complexity in a given situation is likely to be perceived differently by individual operators depending on their role, the nature of their individual processing tasks, workload, and experience.

Finally, with increasing pressure to reduce the through-life costs of future naval platforms, coupled with demographic data suggesting a reduction of available personnel, we note that various navy research efforts in the US and UK are already examining the problem of leaner operator manning of ships (cf., for example, [8]). Reduced manning may have the effect of further increasing complexity as there will be fewer people to share the processing load.

4. AUTOMATION ISSUES

4.1 Overview

Natural questions to ask concerning computer-based aids for improving operational effectiveness of decision making in the Operations Room are: which operator activities and positions need to be aided, why, when, and how? Answers should be based on an appropriate system development philosophy.

It appears from our discussion in Section 3 that computer-based support should be highly beneficial, if not a must, for most, if not all, CSO positions. For example, human information processing is subject to a number of limitations and deficiencies, such as finite cycle time, limited working memory, limited ability to perceive and process information and cognitive biases [9]. It is also negatively impacted by environmental factors or stressors and almost random mistakes (errors of judgement) or slips (errors of execution) [10]. However, there is ample evidence in the literature that designing truly supportive technology is a very challenging problem, particularly at the level of aiding the human's cognitive processing (cf. [5,11-15]). As examples, the burden associated with supervising automation as it performs an offloaded task can outweigh the benefits to improved performance [13]; performance decrements can result from automation-induced complacency (over-trust) [14]; a partially automated system can induce more errors in cases where its knowledge is incompetent than if the user is left in the loop and the system simply critiques the user's performance [15]. It has been suggested that when tools dominate, rather than constrain, the joint human-machine system, the designer runs a strong risk of solving the wrong problem, and of creating new problems and undermining existing work strategies [5].

The form and variety of computer-based support evidently needs to be carefully tailored to an operator's role, depending on the nature and mix of the perceptual and cognitive processing involved, and ideally be capable of personal adaptation to suit the variability in support requirements of the position. The various processes of an operator's tasks need to be established, decomposed into sub-processes, and decisions made about which of these are candidates for receiving some kind of support. An important consideration is the relative capabilities of humans and machines for performing various tasks [16] (e.g., the human is generally considered better at inductive or common-sense reasoning tasks, whereas the machine is better at deductive reasoning).

4.2 Aiding Metaphors

An aiding metaphor is concerned with how support is provided. The aid acting as a prosthesis or as a tool are two extremes that lead to two very different metaphors.

The differences are related to the role of the aid in the decision process.

The prosthetic approach focuses on decision outcomes. The aid essentially replaces the operator in some way or compensates for human deficiencies in reasoning or problem solving. It does this by prescribing the "correct" decision or output given its inputs. Expert systems that provide advice or decision outcomes typically fall into this category. The operator is largely out of the loop and plays a mostly passive role. A frequent criticism of this approach is that it leads to brittle systems, because of limitations in their encoded domain knowledge and assumptions that narrowly bound their model of real-world complexity. This makes them prone to poor performance in the face of environmental variability that has not been anticipated by the system designer. There is a large literature in the cognitive engineering and naturalistic decision-making communities [5,17] arguing for an alternative approach.

In the decision-aid-as-tool metaphor, focus is on the decision-making process itself. The aid is considered a tool in the hands of a competent but resource limited agent [18]. There is sufficient flexibility, however, for it to adapt to a novice, with limited experience (or maybe just a battle-fatigued expert!). Importantly, the operator plays an active role and the tool assists in accordance with his/her support requirements. Design emphasis is on supporting the strengths and complementing the weaknesses of the operator. Moreover, support is provided for the operator's naturally preferred strategies (instead of enforcing a normative or prescriptive approach).

To better appreciate the difference between the two approaches in supporting an operator's situation assessment processes, consider the following two types of aid: one that builds and displays a situation picture using normatively based automated reasoning processes; and another that acts as an intelligent alarm system, monitoring the situation and alerting operators to the occurrence of problems in the mission and opportunities for achieving mission goals which they have requested the automated system to track. In the former aid, automation is playing a prosthetic role, effectively replacing the operator. Of course, it may be necessary to take this approach for selective situation elements in certain instances simply because the operator is (temporarily) inundated by a large number of contacts and cannot cope. The second aid acts as a tool only. Its purpose is to aid the human's limited attentional resources. The design challenge in this latter system is to ensure that it does not generate so many false alarms that it becomes totally ignored and is simply tuned out or turned off.

Given the wide range of expected task loads in a ship's Operations Room and the variety of types of processing involved (monitoring, detection, assessment, planning, etc.), there appears to be a place and need for both metaphors, or some adaptable hybrid of these extremes, in aiding operators, depending on situation context, the specific nature of the processing, and the role of the operator. For example, a prosthetic mode would seem appropriate in situations where the operator is momentarily overwhelmed and incapable of effective participation. However, both designer and operator need to understand how the aid's performance degrades in such circumstances to avoid the problem of "the blind leading the blind". Also, the operator's involvement must be determined to avoid, or at least limit, the effects of "the out-of-the-loop performance problem" [19]. These effects leave the operator handicapped in the ability to resume control in case of automation failure or once the cognitive demands of the situation have diminished to an acceptable human level. In less demanding situations, a decision-aid-as-tool mode would keep the operator in the loop.

The "out-of-the-loop performance problem" has been linked to loss of situation awareness (SA) and skill decay [19]. The former suggests a number of questions: When situation complexity increases, leading to operator overload, what aspects of their environment do they continue to need to maintain an understanding of? If operators are withdrawn from a decision loop in stages, as a means of lightening load, what support for maintaining SA should the computer-based system provide at each stage to permit judgements and decisions that remain part of their role (i.e., not part of automation's)? How should the operator be able to influence the behaviour of support components and how much does the operator want or need to understand about their processing (e.g., models and algorithms used; assumptions made)?

4.3 Dynamic Delegation of Authority

Section 4.2 dealt with how automated support is provided once the decision has been made to aid a given (sub-process of a particular) decision process. Related issues include: mechanisms for delegating authority to the system for making a decision about the outcome or result of an automated (sub-)process; dynamically triggering a change in delegation based on changing situational factors; an override capability when the operator and the system have overlapping responsibilities; and a capability to influence system behaviour when operators have delegated or lost authority.

Two approaches to task delegation are adaptive automation and providing a fixed variety of operator-system modes. Adaptive automation involves a computer-controlled, adaptive allocation, depending, for example, on which party has at the moment more resources or is the more appropriate for performing the task [20]. A potential problem is that it requires operators to keep up with who is doing what as the allocation changes.

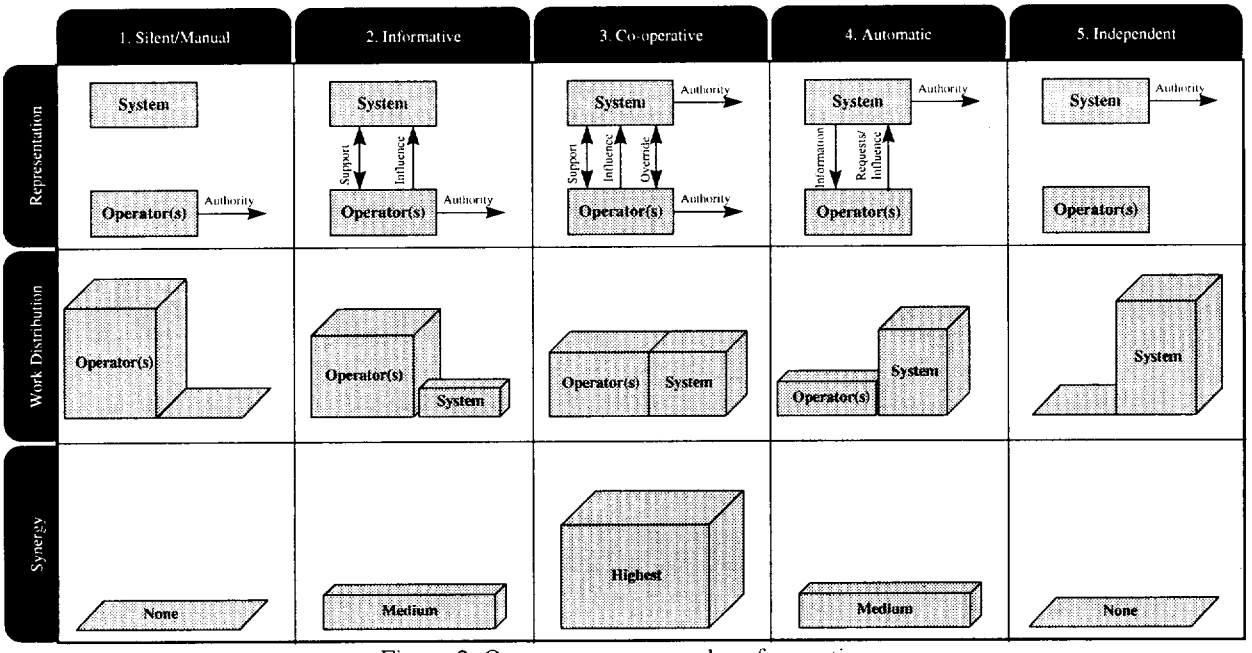

Figure 2. Operator-system modes of operation

One possible version of providing various modes of operator-system delegation, which resembles that currently implemented in the HALIFAX for threat evaluation and weapon assignment (TEWA) related tasks, is illustrated in Fig. 2. Five operator-system modes of operation are shown, along with variations in the levels of work distribution and synergy between automation and the operator in these various modes. The human selects the mode, which applies until mode transition is triggered by a new selection. If these modes are applied at the system level (instead of at the level of particular decisions), each mode implies a fixed delegation of authority for all the various sub-processes for which automated support is available. The bi-directional support arrows in Fig. 2 indicate that the support paradigm in a specific mode could involve the operator in an active processing role (decision-aid-as-tool paradigm). The actual support paradigm used in a given mode is fixed, but it does not have to be the same for each mode.

In the *silent/manual mode*, the operator has total authority. Moreover, the system is completely passive and provides no support whatsoever to the operator. In *informative mode*, the system only provides support, some of which may be a consequence of a request from the operator; authority again rests solely with the operator. The operator can also influence characteristics of the support provided. In *cooperative mode*, the system and the operator both have authority to decide and act. This authority may be divided (e.g., responsibilities for some judgements, decisions and actions allocated to the operator, the rest to the system, depending on type) or shared by the two parties. However, in the shared case, one of the two parties (operator or system) has ultimate authority to override the other. This requires an override protocol. For example, suppose that the operator decides to retain overriding authority for some types of decisions but is supported in these decisions by the system's processing. Two possibilities are: the system processes, decides and acts accordingly only if the operator first concurs; and the system processes, decides and acts automatically unless the operator vetoes. The operator can also influence the system's processing in sub-processes for which authority has been allocated entirely to the system (e.g., by requesting that a specific algorithm be used). There is maximum synergy between the system and the operator in cooperative mode. In *automatic mode*, the system has total authority, but the operator can influence its behaviour and request information. Otherwise, the system operates in complete autonomy. The *independent mode* completely excludes the operator. It processes information and acts autonomously without consulting the operator.

The division of roles between the system and the operator in the various modes is summarised in Table 1.

Mode	Operator's Role	System's Role
1. Silent/Manual	Decide and act	Passive
2. Informative	Decide and act	Support
	Influence system behaviour	
3. Co-operative	Decide and act	Decide and act
	Influence system behaviour	Support
	Override system	Override operator
4. Automatic		Decide and act
	Request information	Provide information
	Influence system behaviour	Respond to operator influence
5. Independent	Passive	Decide and act

Table 1. Roles in the various modes of operation

Hybrid approaches encompassing aspects of the two described above can also be formulated [2].

5. A COGNITIVE MODEL OF C2

5.1 Overview

Command and Control (C2) is the process by which commanders plan, direct, control and monitor any operation for which they are responsible. The cognitive model of C2 briefly reviewed here should be applicable to a wide range of settings, involving one or several operators interacting with a dynamic environment. For example, we anticipate its application in situations from a single operator in front of a console to a team of operators, as in our shipboard application [2]. There is an abundance of C2 models in the literature (cf., for example, [21]). Our model is distinguished by its emphasis on psychologically relevant problem structuring components and the inclusion of both data- and goal-driven behaviours, modulated by a meta-level. Additional motivating details appear in [2].

This type of model should play a role in applying a model-based approach to DSS design (see Section 6). For example, it permits structuring verbal protocols from operators according to a conceptual framework and provides assumptions about the nature of cognitive activities to guide data collection in field studies.

5.2 Structuring the Environment

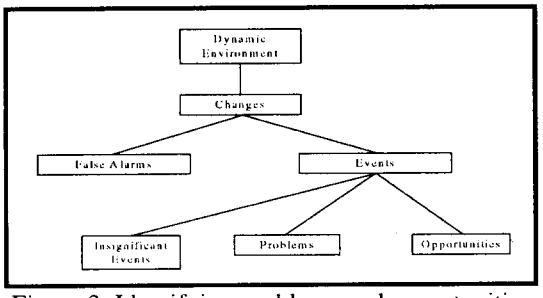

Figure 3. Identifying problems and opportunities

We first present a framework for structuring changes in a dynamic environment that, on the grounds of cognitive plausibility at least, appears psychologically relevant to a decision maker interacting with the environment. It represents a personalised structuring, *from some frame of reference considered relevant by the decision maker.* For example, the frame of reference could be his own, a participating unit's, or his enemy's. It assumes that what the decision maker wishes to *comprehend* at any given time can be phrased in the language (see Section 3.2) of the *problems* or *opportunities* the environment poses, given the *goals* and the state of various *relations* that the decision maker deems relevant among these problems, opportunities and goals at that time. In short, they are specific, time-dependent, goal-relevant properties of the environment that can shape the decision maker's behaviour. We call them *situation structures* because they provide a structured representation for understanding the environment as a prelude to action.

The decision maker could be interested in a variety of relations among goals, problems and opportunities, including: enabling relations (between an opportunity and a goal); causal and subset relations (between pairs of problems or opportunities); value relations (for prioritising goals, problems and opportunities); and impediment relations (between a problem and a goal).

The separation of events into insignificant events, problems and opportunities, shown in Fig. 3, is not really an event partition. An event could represent both a problem and an opportunity. For example, the presence of a particular geographical or environmental feature in a ship's vicinity, which route planning could avoid, might represent a problem (reduced sensor detection envelope) for achieving one of the decision maker's goals (optimise detection) but an opportunity (increased chance of concealment) for another (optimise survivability). This arises from conflicting goals. There is also a potential for duality between problems and opportunities. For example, a problem in one frame of reference (e.g., his own) could represent an opportunity in another (e.g., his enemy's). This structuring in a variety of frames of reference should be an important element of a decision maker's need for simultaneous, multiple perspectives in understanding the situation in some cases as a precursor to a decision.

5.3 Description of the Model

The model decomposes the C2 process into two levels: a lower level involving the three processes *Perception*, *Situation Representation* and *Action Management*, and a higher level consisting of various *Command Meta-Processes* (Figs. 4-6).

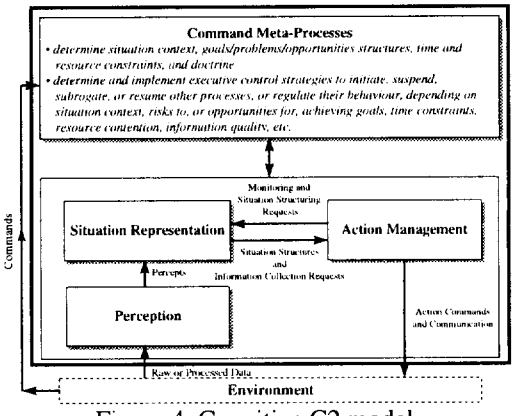

Figure 4. Cognitive C2 model

The Command Meta-Processes in Fig. 4 dynamically manage the goals and choice of situation structures, and control various parameters (like frequency with which to monitor for changes in a specific environmental feature) and the sequencing and cognitive control level (in the sense of Rasmussen's skills, rules, knowledge (SRK) taxonomy [7]) of lower level processes. Suspension and subrogation control strategies serve to shift the focus of attention between various processes.

For example, a process might be suspended during its execution because a higher priority process suddenly demands the decision maker's attention or simply because it cannot be performed to completion at the moment.

Feedback from the lower level can cause new goals and situation structures to be generated and old goals and structures to be removed from consideration, as well as new control strategies to be employed. Commands originating from higher-level C2 echelons can also induce changes in these processes.

Situation Representation and Action Management are uncertainty reduction processes, but in different senses. The first (Fig. 5) reduces uncertainty in understanding the situation. In this case, it involves judgements about where there is uncertainty, incompleteness, etc., in data/information (short-term knowledge) and in the resolution of such problems. Where it is deemed worthwhile to reduce this uncertainty by obtaining more data/information, it can issue an information collection request to Action Management (e.g., send a helicopter for closer surveillance). Action Management reduces uncertainty in the selection of actions.

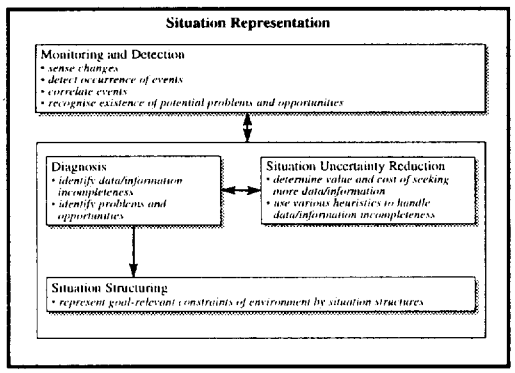

Figure 5. Situation Representation

In either case, it is possible to add the need to reduce uncertainty due to incomplete long-term knowledge (purposeful learning behaviour), by first evaluating benefits and costs of seeking this knowledge and the likelihood of being successful in doing so. Situation Representation would issue a request to Action Management which would handle its own needs and those of Situation Representation with subsequent feedback to Situation Representation. However, these various considerations are not fleshed out in the figures.

Situation Representation generates descriptions of a dynamic environment. The particular descriptions are in terms of situation structures (defined previously) which the decision maker (via the Command Meta-Processes) dynamically determines to be relevant for determining and managing action. Situation Representation generates these structures either at the request of Command Meta-Processes or at the request of Action Management when it needs to better understand specific situation elements for planning or managing the coordination and execution of its actions. Situation Representation is analogous to the human situation assessment process described in the naturalistic decision-making literature [17]. It combines the situation assessment and threat assessment processes of the technologically centred JDL data fusion model [22], but from the perspective of the human. An important nuance, which distinguishes our approach from previous efforts, has to do with the way the model handles situation projection (i.e., extrapolation of the current tactical situation into the future). While a given situation element (goal, problem, opportunity, relation) may well involve an aspect of the future (e.g., the problem related to a contact might be "Time to ship intercept is less than 30 seconds"), we use the term projection in an action-oriented sense in that its need is determined within Action Management to support knowledge-based planning. Process sequencing in Situation Representation essentially follows the identification strategy suggested by Fig. 3, with feedback loops arising from the need to resolve problems of incomplete data, information or knowledge.

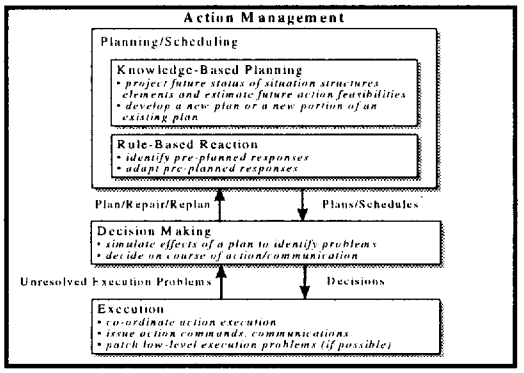

Figure 6. Action Management

Action Management handles all processes related to determining feasible courses of action, action selection, and management of action execution. Action commands are commands to physical actuators (sensors, weapons, navigation, etc.) or lower levels in the organisational hierarchy. We also include as part of Action Management decisions related to sharing information or requesting information from other parties in the environment. This leads to the communication shown in Fig. 4.

The presence of both rule-based and knowledge-based processing (in the sense of the SRK taxonomy [7]) in Action Management should be noted. This is also the case for Situation Representation. For example, diagnosis could be entirely rule-driven or employ, in addition, various knowledge-based heuristics to make judgements that reduce uncertainty in situation understanding. Evidence of both types of behaviour have been found in the naturalistic decision-making literature. For example, [23] reports findings of a study in which they interviewed officers in the Combat Information Centre of an AEGIS cruiser and found that the primary situation diagnosis strategy was essentially rule-based feature matching. However, in situations of

insufficient information or when the situation was novel and unfamiliar, the officers used a knowledge-based strategy of story generation.

Finally, we draw attention to a couple of additional omissions in Fig. 4. First, the complex process of human perception has not been elaborated. Second, a direct processing path between perception and action that would correspond to Rasmussen's notion of skill-based behaviour [7] of an operator is not shown.

6. TOWARDS A FRAMEWORK FOR DESIGN

This section describes key ideas of a framework for designing a DSS to support operators in the tactical C2 process. The approach uses concepts from a model-based framework pioneered by Rasmussen, known as Cognitive Work Analysis (CWA) [6-7]. Ongoing DREV work aims to establish the degree of fit of this approach generally to the C2 work environment and to the specific design goal in Section 7.

6.1 Rationale: Designing for Adaptation

We have already noted that tactical C2 can be viewed as a complex sociotechnical system. As in any open system, command personnel and their staff have to deal with a large variety of situations or events both internal and external to the ship, from familiar ones that they encounter routinely, to unfamiliar, but anticipated ones, to both unfamiliar and unanticipated ones. The designer seeking to support CSOs must therefore be able to alleviate the cognitive demands posed by each of these event types.

Unfortunately, the unfamiliar and unanticipated event poses a particularly difficult problem. How does one design for the unanticipated? Automated solutions to replace the human in such situations do not appear to be on the near horizon. Moreover, in this approach, humans are inevitably left to supervise automation which is prone to failure in the face of variabilities unaccounted for by the designer. This requires the human to monitor the situation for problems and develop solutions on the spur of the moment, usually without support for this automation-induced role. A simple example of this in the shipboard context is an automated TEWA that automatically engages threats under certain (quick reaction) conditions. It is impossible for the designer to delineate a complete set of automatic engagement contingencies. The operator must therefore remain in the loop to monitor automatic engagements for problems (e.g., a friend in the line of engagement) and apply immediate corrective measures (e.g., exercise a firing veto).

There is increasing evidence that poorly engineered automated solutions can lead to substantial performance decrements of the joint system and potentially catatastrophic results. We suggest that a more achievable and realistic solution can, however, be found in the design philosophy underlying CWA: create computer-based tools that help workers adapt to unexpected and changing demands in their environment [6]. In fact, CWA argues that the primary value of people in the human-machine system is to play an adaptive role in their work space, with the necessary freedom to flexibly change their behavioural patterns, both as individuals and as members of a team, as, and when, the situation demands. Such adaptation can occur at several levels, including the levels of tasks, strategies and social organization. Rasmussen [7] argues that to do this designers need an intimate understanding of the behaviour-shaping features of the domain that remain invariant even with its unanticipated variabilities. This approach is consistent with the "decision-aid-as-tool" metaphor (see Section 4.2), but extends it by emphasising adaptation to handle the demands of a complex sociotechnical system.

6.2 Behaviour-Shaping Constraints

CWA provides a framework for supporting a variety of levels of adaptation by adopting a model-based approach to work analysis and DSS design. The framework is based on identifying behaviour-shaping or intrinsic work constraints [6-7]. These constraints delimit the set of productive behaviours (human or machine) without overconstraining such behaviour, unless required (e.g., by doctrine), to specific trajectories. As Vicente [6] puts it, "constraints specify what should not be done, rather than what should be done".

DSS design for a sociotechnical system is fundamentally an ill-defined problem, likened to solving a jigsaw puzzle consisting of uncertain pieces and an uncertain goal picture. It would appear that the only approach is to engage in many iterative, bottom-up design probes, with continual technology assessment and user evaluation and feedback at each step to direct the search from one prototype to the next. However, its consistent application is problematic. It is potentially very ad hoc, expensive in both time and cost, and can result in much wasted effort; e.g., [25] cites one example where features in a medical DSS that were most strongly rejected at field tests were those included in the prototype at the specific insistence of doctors involved in development. While a search of the design space that actively involves user participation is both advisable and essential, the problem is primarily that this process alone does not incorporate any mechanism but feedback and developer intuition to guide it [18]. CWA provides an approach to overcoming the task-artifact cycle associated with pure prototyping [6].

CWA is a top-down approach that derives power from the use of a variety of models that effectively help explore the design space efficiently. By focusing on explicitly representing behaviour-shaping constraints in the system, these models have both descriptive and

predictive capabilities. Their descriptive abilities permit understanding current behaviour in the C2 system. In a qualitative sense, their predictive abilities allow the designer to identify and anticipate the consequences of design interventions. Naturally, it will be difficult in applying CWA to make the claim that all behaviour-shaping constraints have been modeled or modeled with sufficient fidelity. However, modeling must be seen as a process of iterative refinement. The key point is that explicitly representing models of work constraints provides a structured way of recording what has been included [6] and making design improvements in a consistent (i.e., not ad hoc) manner. Vicente [6] contrasts this approach with other normative or descriptive approaches to work/task analysis.

6.3 CWA Framework

We sketch here the CWA framework. Full details can be found in [6-7]. CWA identifies five different layers of behaviour-shaping constraints in a sociotechnical system, each layer related to a different aspect of the work done in the system. They are illustrated in Fig. 7.

In the *work domain* layer, work space constraints are identified, in a device-, event-, goal-, task- and actor-independent manner. These constraints generally define the work space's content and structure or its field of action. The *control tasks* layer is a product or input-output representation of the work goals to be accomplished in the work space in an actor-independent manner. Special attention is paid to identifying processing short cuts as a means of capturing variabilities in processing sequences among actors. The *strategies* layer represents information processing in the system. It models the category of generative mechanisms or processing procedures that can be employed by domain actors, as well as the constraints that govern strategy adoption and switching, depending on context, subjective task formulation and performance criteria. The *social organization and cooperation* layer models organizational constraints and content and form constraints (workload sharing, social organization, etc.) underlying human-human and human-machine cooperation and social communication. Finally, the *competencies* layer models the constraints associated with the operators themselves, including their generic capabilities and performance limitations and more specialised competence requirements of their various information processing activities. It is worth noting that the various constraint levels have far-reaching work space design implications. While several directly impact computer-based DSS design, some are also related to other design interventions (e.g., training, selection, sensors) (see [6,26]).

As Fig. 7 indicates, the degrees of freedom in the design space (i.e., the space of feasible design interventions) are reduced as each new layer of constraint is added. The ordering of layers, from work domain to competencies, is related to an ecological orientation underlying CWA. The ecological approach argues that in work domains that impose dynamic, external constraints on the goal-directed behaviours of its workers, it is necessary that work domain constraints (ecological compatibility) be dealt with before cognitive constraints (cognitive compatibility) [6].

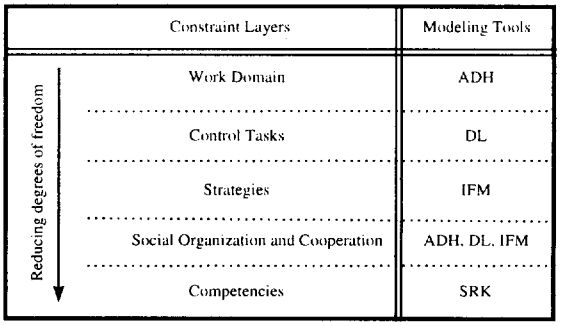

Figure 7. Constraint layers in CWA

Rasmussen has also pioneered a set of generic, conceptual modeling tools for representing constraints in each layer [6-7]. These are shown in Fig. 7, where ADH is the abstraction-decomposition hierarchy, DL is the decision ladder, IFM are information flow maps, and SRK is the skills, rules, knowledge taxonomy.

6.4 An Abstraction-Decomposition Hierarchy

The first phase of DREV's CWA work is focusing primarily on the work domain layer. This involves developing an ADH for tactical C2. We provide a brief sketch here of some highlights of the work. More detail appears in [27], along with some examples illustrating the anticipated use of the ADH for representing the mental model of an operator engaged in knowledge-based processing for situation representation and action management. This establishes the link with the cognitive model of C2 presented in Section 5.

It is worth noting that information hierarchies have already proved useful in previous developments in the maritime environment. For example, with the goal of establishing maritime tactical display coding standards, NATO STANAG 4420 [3] developed a tactical information hierarchy (taxonomy), organized in a tree, as a means of defining "the full range of tactical information required by the operational user at the command level". A variety of relationships link tree nodes in the taxonomy, including classification, attribute values, and generalisation/specialisation.

However, the ADH that we are constructing in this work belongs to a quite different class of hierarchy. Its unique defining characteristic is that it represents functional relationships between work domain elements and their purposes, as well as part-whole relationships, in a hierarchy (Fig. 8). Rasmussen [7] makes the case that this type of hierarchy can be used in modeling both causal and intentional systems. Certainly, the C2 work domain comprises both causal elements (e.g., weapon

and sensor systems) and intentional elements (e.g., threats). Important benefits of this purpose-, function-, and decomposition-oriented description stem from the fact that: it exposes the work space information necessary for dealing with unanticipated events by presenting structural constraints for "proper" operation of domain elements (via structural means-ends links); and it provides a psychologically relevant representation for problem solving, varying in the level of abstraction at which the work space is viewed and the resolution or level of decomposition at which system components are under attention (via part-whole links) [6]. Figure 8 uses the five levels of abstraction Rasmussen has identified to describe process control systems: functional purpose, abstract function, generalised function, physical function, and physical form [6-7].

What might an ADH for tactical C2 look like? While the work needed to provide a substantive answer to this question is still in progress, some general characteristics of the ADH and the process for deriving it are nonetheless evident.

First, it is apparent from our previous discussion of the tactical C2 work domain (problems, opportunities, etc.) that the work space can benefit from being partitioned into a variety of entity types, differing in purpose or intention (e.g., domain of threats, domain of countermeasures). Developing an ADH for each separate purpose and combining these ADHs should simplify the analysis (cf. [6]). Second, in view of the need for multiple perspectives in understanding a tactical situation (see Section 5.2), it should be useful to develop a separate ADH for each likely perspective. Inevitably, an ADH for the threat from an own force perspective will be less complete than that for own forces due to knowledge limitations.

For illustrative purposes only and to help the reader appreciate the nature of the ADH, Fig. 9 provides a simple abstraction hierarchy only for contacts in the tactical environment. It is based on Rasmussen's five levels of abstraction for process control.

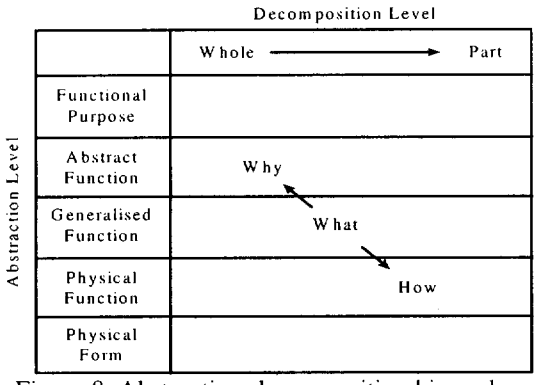

Figure 8. Abstraction-decomposition hierarchy

To conclude this section, we mention that an iterative process is being followed in developing the ADH. Preliminary knowledge acquisition sessions will use a variety of operational level documents dealing with the principles and procedures of maritime warfare. This will be followed by interviews of subject matter experts (SMEs) in doctrine, training, and engineering, and by observations in a training simulator. This will be further augmented by a field trip on a HALIFAX Class ship. Initial CWA models constructed in this manner will be evaluated by SMEs to correct misconceptions and fill in gaps in the models. Finally, data will be collected in a training simulator to test the validity and completeness of the CWA models. Although this work deals only with the first CWA layer, a plan for conducting a full CWA is also being developed.

Abstraction level	Description
Functional Purpose	Mission
Abstract Function	Functional roles and coordination relationships
Generalised Function	Tasks
Physical Function	Process behaviours in conducting tasks
Physical Form	Observable attributes and behaviours of contacts that permit their recognition and identification

Figure 9. An abstraction hierarchy for contacts

7. DESIGN GOAL

At present, in the HALIFAX, computer-supported situation representation is limited essentially to threat evaluation in the form of threat ranking. As a very simple example, the capability for operators to request the CCS to monitor a specific contact or group of contacts for a certain potentially threatening behaviour while attention is shifted to a more immediately threatening part of the tactical picture does not exist.

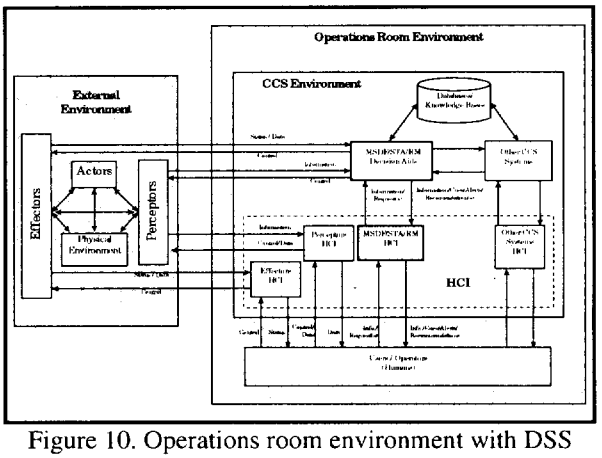

Figure 10. Operations room environment with DSS

There is some automated support in the CCS for reactive action management related to the allocation of the fighting resources (weapon allocation) in terminal engagement. However, there are a number of areas

where additional support should be highly beneficial, particularly in complex littoral scenarios. These include support for: planning at both the operational and tactical levels; doing "what-if" analyses of options to permit keeping ahead of the current tactical situation, including visualization of options; and co-ordinating the use of weapon and sensor systems or evaluating their effectiveness in the current environment.

DREV's work is expected to lead to a specification of a DSS to support operators at least in: (i) the integration or fusion of data from the ship's sensors and other sources; (ii) the formulation, maintenance and display of an accurate dynamic situation picture, leading to enhanced situation awareness; (iii) the identification and selection of courses of action in response to anticipated or actual threats to the mission; and (iv) action implementation once a decision to act has been made and is being carried out. With respect to particular DSS capabilities, item (i) relates to its Multi-Source Data Fusion (MSDF) capability. It will support perception activities in Fig. 4, for example by enhancing the quality and coverage of the processed data that feeds perception. Item (ii) relates to its Situation and Threat Assessment (STA) capability. It will support the situation representation process in Fig. 5. Finally, items (iii) and (iv) relate to its Resource Management (RM) capability. This will support the action management process in Fig. 6.

A high-level framework of the DSS integrated with the existing CCS is shown Fig. 10 [24].

8. CONCLUSIONS

This paper examined a wide range of issues currently being investigated for the design of a decision support system to assist combat system operators of a modern frigate in their tactical decision making and action execution activities as part of the Command and Control process. Automation, cognitive and methodological issues were highlighted.

Fundamental issues in providing computer-based decision support are related to the questions of which operator roles and positions need assistance, why, when, and how. These are very complex questions that require a coherent methodology to be followed if a joint system, comprised of both operators and computer-based aids, is to lead to improved operational effectiveness in conducting shipboard Command and Control. A key problem for the design of such aids is that they must be capable of operating in a highly dynamic and open environment that imposes variable and unpredictable demands on operators. Operators must be able to effectively handle the demands of new and unanticipated situations that have not been addressed by the system designer or by doctrine. The system must certainly support the operators so that they can follow the established principles and recommended procedures. Yet it must not overconstrain them so that they are hampered from taking advantage of their abilities to reason, improvise, and respond, while at the same time calling on the system for the support they need. This paper proposed Rasmussen's Cognitive Work Analysis as an appropriate framework for achieving these design objectives. Work is ongoing at DREV to investigate its applicability to the design of a computer-based system to support operators with data fusion, situation and threat assessment, and resource management.

9. ACKNOWLEDGEMENT

The author wishes to thank Professor Kim Vicente of the Cognitive Engineering Laboratory, University of Toronto, for many helpful discussions and inputs, as well as comments on a previous version of some of the material in this paper.

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MEASURES OF MERIT FOR COLLABORATIVE COLLECTION, CONNECTION, AND EXECUTION MANAGEMENT

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SUMMARY

One of the most important aspects of any combat engagement is the effective gathering of intelligence information. To accomplish this information gathering in modern battlefields, many sensor platforms are deployed. These platforms are typically stovepiped systems that operate independently of each other and require considerable operator intervention to interpret collected information and adjust the collection plan accordingly. With automated methods, these sensor platforms could collaborate with each other and share information. As a result, the effort needed to collect information would decrease and the gathered information could be fused together to increase understanding of the overall picture of the battlefield.

We are developing a system that facilitates this interaction among platforms. This system of Measures of Merit (MOMs) implements metrics across platforms at various levels of the fusion and data gathering process. When additional information is needed, the metrics are aggregated to measure the value added that an additional platform can make to the mission and to the overall battlefield perspective. Intelligent agents distributed among the platforms prioritize the requesting and gathering of information from other platforms as well as from the host sensor suite.

We are applying MOMs to the collection, connection, and execution chain of events for intelligence surveillance and reconnaissance (ISR). Our development focuses on the interaction among platforms and on the MOMs algorithms. In this paper, we describe the MOMs system and its primary components.

INTRODUCTION

In today's battlefield environment, many sensor platforms of varying capabilities are deployed to gather intelligence information. The process of planning, tasking, and executing these missions is currently performed using sequential, serial, and manpower-intensive methods, with experts in one discipline vaguely aware of capabilities of other disciplines. As a result, platforms are optimized singly and operate independently of each other.

Current information gathering operations need to be more efficient and flexible. For example, when new information arrives, mission goals may change and require retasking of assets. Collection assets may be incapacitated, leaving holes in information. Since platforms often have overlapping coverage areas and carry sensors with similar capabilities, platforms may duplicate effort by gathering the same or similar information. If platforms would share their information, it stands to reason that information gathering would be optimized across platforms, improving resource management, and freeing resources to gather additional useful information they were otherwise unable to gather.

Figure 1 illustrates the concept of collaborative platforms. In the figure, two sensor platforms have a view of a Transporter Erector Launcher (TEL). In one case, platform 2 automatically pushes information about the TEL to platform 1. However, the value of a particular piece of information may be of little worth and the use of platform 1's communication bandwidth would not be justified. In another case, platform 1 may ask the other platform to look at the TEL from a different aspect angle. If platform 2's mission plan does not include looking for TELs, and it has too many other higher priority tasks to accomplish, platform 2 would deny such a request. Yet, if platform 1 could in turn relay information beneficial to platform 2's mission, the second platform may negotiate an exchange and accept retasking to honor the request.

While information sharing among platforms is beneficial, current platforms have some limitations that require an enhanced methodology for them to handle this sharing. For example, platforms have their own priorities that may take precedence over gathering data for another platform. Therefore, rather than automatically retask platforms, it is desirable to allow them to consider requests and refuse them. Before requesting information from off-board sources, platforms should consider the capabilities, such as sensor and communications capabilities, of these sources. Platforms also require enhancements to store, access, and reason about the capabilities of other platforms, as well as enhancements to promote robust communications.

In this paper, we overview the design of a system for interactive Measures of Merit (MOMs), whose purpose is to provide an automated technique to share information among platforms. This system consists of MOMs that evaluate results of each of the functional components in the ISR collection process and

Paper presented at the RTO SCI Symposium on "Sensor Data Fusion and Integration of the Human Element", held in Ottawa, Canada, 14-17 September 1998, and published in RTO MP-12.

distributed intelligent agents (DIAs) that facilitate interactivity among the platforms. This is followed by a discussion of specific MOMs for each of the functional components. Finally, we overview the benefits of this system implementation.

OVERALL SYSTEM DESIGN

The MOMs system is designed to make decisions based on the value of off-board information and to broker with other platforms to obtain information from them. The concept is to provide metrics at different levels of the data gathering and fusion process for each platform. These measures can then be used to make decisions for requesting data, sharing data, and honoring requests.

We divide the gathering and fusion process into three main functional components: collection management (CLM), connection management (CNM), and execution management (EXM). Each of these functional components resides on each platform. CLM manages resources at all levels, to schedule platforms and sensors in accordance with mission priorities. CLM MOMs measure the quality of the collection plan, i.e., the allocation and scheduling of tasks among multiple ISR assets. Contributions to CLM MOMs include the probability of successful collection and the timeliness of collected information. CNM manages communications assets, based on the demands of EXM and CLM, and encompasses communication issues between platforms as well as communications to the fusion system itself. CNM MOMs assess connectivity paths among collection platforms and to users. Contributions to CNM MOMS include bandwidth, links between platforms, communication errors, the optimal use of connection paths, and the ability to adapt interconnections. EXM controls the actual data collection and fusion process. EXM MOMs evaluate the effectiveness of a platform's collected information to contribute to satisfying mission needs for a well-defined fused picture of the battlespace. Contributions to EXM MOMs calculations include quality of target track localizations and classifications as well as ambiguity and errors in associating new measurements to tracks.

Figure 2 illustrates the top-level design and process flow for MOMs in the collection, connection, and execution chain of events for a sensor platform. This design, which is replicated for each platform, shows the main system components and their interaction, as well as interfaces to external platforms and functions. To assist operators with complex analyses across platforms and disciplines, the EXM, CNM, and CLM components contain MOMs that assess the quality of the collection plan, connectivity paths, and collected information. DIAs facilitate collaboration and communication, while feedback loops provide multiple opportunities to adjust the collection process based on the assessments and improve results.

In the design, the Connection Agent handles the communications among the platform components and external interfaces. The Connection Agent receives the initial task allocation and passes it to CLM, which locally optimizes its collection plan against its task allocation. The CLM MOM system evaluates the collection plan and CLM makes improvements to the plan. CLM sends the plan via the Connection Agent to EXM, which controls the asset sensor suite to execute the collection plan. EXM fuses the collected information and the EXM MOM system evaluates the effectiveness of the fused information with respect to the asset mission objectives. Based on that evaluation, EXM determines information shortfalls, or gaps. The Execution Agent determines whether the platform can fill the information gaps, generates new collection tasks, and passes them to CLM via the Connection Agent. When the platform cannot fill the gaps, the Execution Agent evaluates capabilities of other platforms, estimates the value added of obtaining information from these platforms, and directs CNM to request the information from other assets. The CNM determines connection paths and the CNM MOM evaluates the planned connection paths and makes improvements. Then CNM requests the information from other platforms, which may fulfill or deny the request.

Similarly, CNM receives information requests from other platforms and relays them to EXM. The Execution Agent evaluates the requests in light of the platform's own priorities and determines whether or not to honor the requests. If the Execution Agent determines it is better to deny the request, it then considers opening negotiations with the requesting platform to fulfill the request in exchange for needed information the other platform could supply.

When evaluating the value added of requesting another platform to gather information, the Execution Agent considers the following capabilities of that platform:

1. Automatic retasking. The effectiveness of retasking assets based on changes in observed events or a reassessment of collection priorities.
2. Cooperative multiple asset management. The effectiveness of cooperating to optimize multiple sensor resource management, data sharing, and distributed fusion.
3. Multiple asset synchronization. The effectiveness of coordinating coverage of the battlefield while feasibly meeting collection and priority requirements.
4. Platform resource management. The effectiveness to optimize multiple sensor resource management and centralized fusion within a single platform.

SYSTEM INTERACTIVITY VIA DISTRIBUTED INTELLIGENT AGENTS

DIAs are essential to achieving collaboration among the sensor platforms. DIAs are the mechanism that supports the interaction among multiple distributed sensor platforms by providing an infrastructure of small, stand-alone processes that are flexible, modular, robust, understandable, and cost-effective. These processes have many advantages over standard software processes:

- *Social ability* to interact with information sources, each other, and humans
- *Pro-activity and reactivity* to initiate action based on their own reasoning, as well as perceive their environment and quickly respond to changes in it
- *Task driven and data driven* to operate in both a goal-directed manner (e.g., working to achieve a task) and in a data-directed manner (e.g., initiating an action based on processing results)
- *Embedded domain knowledge* about methods for performing tasks and knowledge about the context
- *Explicit knowledge representations and procedural knowledge* to explain an agent's behavior, both in terms of *what* it is doing and *why*

These characteristics make it easy to upgrade DIAs to incorporate new knowledge and capabilities that evolve over time.

In our design, each participating platform has the following three DIA functions:

- *Pull:* requests data from other platforms needed to optimize fusion performance (as opposed to receiving a fixed set of information)
- *Push:* sends pertinent data to other platforms by anticipating their data needs (as opposed to simply broadcasting data)
- *Refusal:* considers and negotiates requests from other platforms based on its own priorities and cost

Figure 3 illustrate the interaction of the pull and refusal functions between two platforms.

In the design of Figure 2 above, the Execution Agent reasons about information gaps and the capabilities of other platforms, then determines which information to pull, push, and refuse. The Connection Agent performs the communications functions needed to pull, push, and refuse the information. Specifically, the Connection Agent handles task messages among platforms, as well as among functional components of each platform. These task messages include allocated tasks, task acknowledgments, and requested data. The Connection Agent also provides routing, flow control, and error control.

EXECUTION MEASURES OF MERIT

EXM MOMs have been the primary focus of our MOMs development thus far. The purpose of these MOMs is to reduce the operator load by determining which targets immediately need to receive a measurement update, estimating how well a new measurement would improve the target track, and measuring the actual level of improvement. In a battlefield environment, an operator would be quickly overwhelmed with such computation.

The challenge in creating such metrics is two-fold. As an element of a real-time system, the metrics depend solely on measurements and calculated results. Truth is considered an unobtainable quantity. Therefore, if not developed properly, the metric may routinely provide high quality scores even though the results vary significantly from truth. The second challenge in developing EXM MOMs is that they need to provide reports on current track quality, estimated track quality, and resulting track quality. These reports identify which tracks need to receive new information, which sensor reports would be of value, and the accuracy of our estimates.

To meet these challenges, we are using three metrics that when implemented together determine instantaneous track quality, comparisons over time, and a performance evaluation over time. Our metrics, entropy [Hamming], the Gap [Stewart], and order statistics, rely only on measured and computed values and provide the information necessary for the calculation of the desired track quality scores.

The instantaneous track quality is provided by entropy. Entropy is defined as

$$H(\mathrm{X}) = \frac{1}{2}\log(2\Pi\det|\Sigma|e)$$

for Guassian density functions, and

$$H(X) = -\sum_{x} P(x)\log P(x)$$

for discrete density functions. Entropy provides a measure of the degree of uncertainty for each solution. We use it to measure localization and classification quality as well as measurement-to-track ambiguity. For example, in Figure 4, a platform using a multi-hypothesis tracker is tracking five targets. The localization of a target is represented as a Gaussian distribution. The classification is described in a Bayesian taxonomy [Pearl], which can be interpreted as a discrete probability density function as can the hypothesis scores. From this information we can determine which tracks are well localized and classified, and the ambiguities that exist in measurement-to-track associations and can be quickly computed.

While this instantaneous information is very useful for providing elements of all three track quality scores, we are also interested in determining how well we are tracking targets over time. The ability to compare results eases determination of the value added of new information. While new data can change all of our results, its benefit needs to be measured. For instance, an improvement of half a percent in accuracy may be too little to warrant reassigning assets and processing their results. The way we monitor the benefit of new data is through the Gap metric, which measures the distance between subspaces. This distance is measured by the canonical angles between vector subspaces. By defining our entropy results as sets of subspaces, we can determine in which direction the greatest amount of change has occurred. From this measure, we determine the quality of the data used as well as which parameters are most affected by a particular sensor's measurements.

One of the key elements of EXM MOMs is the ability to predict how well a measurement can improve a target track. A platform's DIA estimates another platform's sensor suite and the tracking system processes the information. By interpreting the change in entropy, we determine whether or not the measurement is useful. However, we need to compare our estimated improvement with the actual improvement. These errors over time can provide a useful bound on the accuracy of the DIA and its estimation system. We are using order statistics to create these bounds. Order statistics are a distribution free method of ranges of values, in this case error of prediction to actual results, with a given confidence. If the bounds are tight, the predictions are accurate. Larger bounds indicate that prediction results are suspect. This information is then used by the DIAs to determine reliability of given platforms and estimation systems.

EXM MOMs provide information on how well the current data fusion system is performing. They also can indicate the potential usefulness of new information. Our basic implementation procedure is to measure the amount of uncertainty in the targets' localizations, classification, and measurement association ambiguity using the entropy measure. We then use the Gap metric to measure behavior of the data fusion system over discrete time intervals. By using measurement estimates, we can predict behavior. Finally, we use order statistics to measure the accuracy of our predictive capability. This automation provides a wealth of additional information and conclusions that operators are unable to provide given their current workload.

COLLECTION MEASURES OF MERIT

The purpose of CLM MOMs is to measure the quality of the collection plan, which typically consists of resources that have

tasks allocated to them and a schedule for achieving these tasks. In contrast to EXM MOMs, which are concerned with the quality of the actual collected information, CLM MOMs are concerned with the *plan* to collect information. By evaluating the collection plan, we can optimize the use of collection assets, reduce duplicate coverage, and close coverage gaps by tasking alternative assets to collect information. By starting with a higher quality plan, collection will be more efficient and timely and reduce the extent of revisions that operators need to make.

Our approach for developing CLM MOMs differs greatly from our approach for EXM MOMs. For CLM, we define a top-level MOM, decompose it into lower level MOMs, and decompose those into measures of performance (MOPs), measures of effectiveness (MOEs), and measures of robustness (MORs). When evaluating the collection plan, we evaluate low level contributing factors to MOPs, MOEs, and MORs and aggregate these measures to produce the top-level measure.

Figure 5 shows this CLM MOM decomposition and characteristics that contribute to the calculations. The individual metrics are combined through a Bayesian network and accommodate factors that change, such as priorities, through a simple weighted average according to

$$MOM_{CM} = w_{EPA}\, MOM_{EPA} + w_{MAC}\, MOM_{MAC} + w_{DRP}\, MOM_{DRP},$$

where the weights are selectable and must satisfy

$$w_{EPA} + w_{MAC} + w_{DRP} = 1.0$$

with each individual weight in the interval [0, 1].

CONNECTION MEASURES OF MERIT

The purpose of CNM MOMs is to measure the quality of communications between platforms and ground stations with respect to the goals of

- *Optimal connectivity*
- *Value added of an additional connection*

While CLM MOMs assess the collection plan and EXM MOMs assess information as it is collected, CNM MOMs are valuable in both the planning stages and in real-time management of the communication networks. With respect to planning, CNM MOMs evaluate the adequacy of the planned communication networks, the value of adding an additional data link, the degradation due to anticipated communication delays, and the impact of losing a communication path.

During real-time collection, the foremost impact to the user is the timeliness of receiving information. Transmission delays, alternative communication paths, bandwidth, and compression affect the timeliness of getting information to the user. In addition, the frequency of updating a scene, target density, target type (air, land, or stationary) and message formats also drive the timeliness. In order to obtain optimal system performance during collection, the communication processing loads must be balanced and messages must be dynamically routed.

Communication effectiveness determines the success of coordinating data collection between platforms and provides the means for real-time retasking. The evaluation of communications connections during both planning and execution frees operators from performing this tedious analysis. We can incorporate more details into an automated evaluation, to achieve higher quality results, and provide more timely information for real-time communications management.

To assess connectivity paths among collection platforms, we are again using entropy. This key information theory technique can handle both continuous and discrete information, as well as both types of information combined.

An example is a decentralized communication network for target tracking that uses entropy as an information fusion metric. As a scalar, entropy provides a direct comparison between alternatives and is applicable to continuous (e.g., position, speed, and course), discrete (e.g., classification such as air, land, friendly, hostile), or joint mixed probability density functions. The objective is to maximize the information, or equivalently, to minimize entropy. The global entropy is given by

$$H(global) = H(local) + H(received) + H(communicated)$$

where the local communications decide which information to communicate by determining the global impact of communicating track information represented by H(communicated).

CONCLUSIONS AND RECOMMENDATIONS

In this paper, we presented technologies for a next-generation system of interacting sensor platforms that share information with each other. We introduced the three main components in the information gathering process: CLM, CNM, and EXM; and overviewed an approach for determining when it is beneficial for platforms to share information.

A key aspect of this approach is the use of metrics to measure the quality of the collection plan, gathered information, and connections. These metrics are used to determine the value added of tasking additional assets to collect more information, as well as to optimize asset utilization. Another key aspect is the use of DIA technology to evaluate platform capabilities and their value added, negotiate information exchange among platforms, and facilitate communications with other platforms. We also discussed a variety of technologies for implementing the MOMs, including entropy, the Gap, order statistics, and weighted sums.

The information sharing discussed here provides several benefits for the ISR community. First, this sharing facilitates theater-wide tracking, targeting, and surveillance capabilities. The automation reduces operator workload for performing these complex analyses across platforms and disciplines. The collaboration among platforms optimizes asset use, since assets can share information rather than collect duplicate information. Another benefit is better coverage, since platforms can fill information gaps and obtain supplemental information. The result is that resources can be freed to obtain other useful information that they were otherwise unable to obtain. The end result is better quality, more timely information that contributes to an improved overall picture of the battlefield.

This system has been designed and individual components have been tested to demonstrate their capabilities. Our next step is to incorporate EXM MOMs and DIAs into a multi-platform testbed simulation system and demonstrate the interactive capabilities.

ACKNOWLEDGMENTS

We thank the Air Force Army Research Laboratory for funding this research and development under contract F30602-97-C-0010. We thank the following for their excellent contributions to the MOMs system concept: Dr. Ivan Kadar (Northrop-Grumman Corp.); Dr. Charles Morefield, Dr. Chris Donohue, and Mr. O. Patrick Kreidl (all Alphatech, Inc.); and Larry Nelson (Integrated Sensors Inc.).

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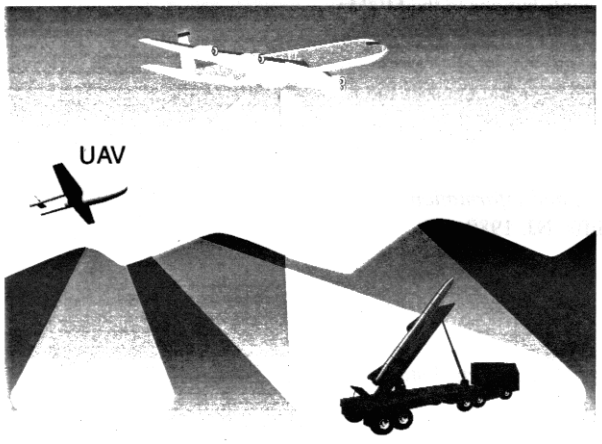

Figure 1. Sensor platforms share information to more efficiently cover the area of interest

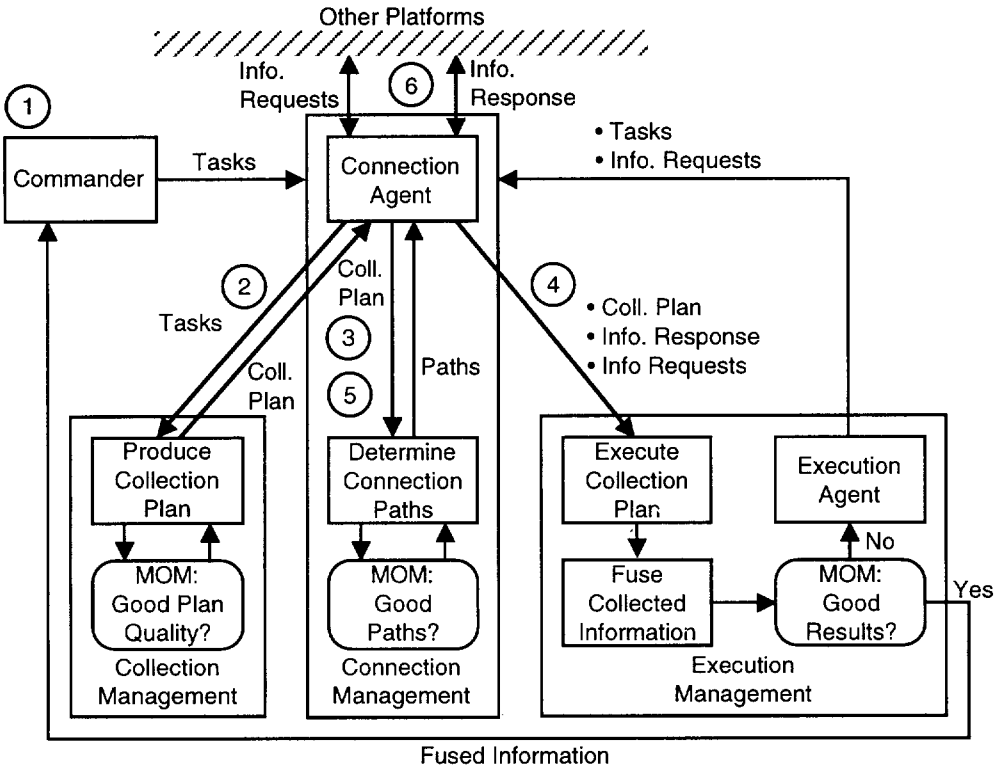

Figure 2. Top-level design for Measures of Merit (MOMs), showing main components and their interaction to assess collection quality and adjust the collection plan to improve results

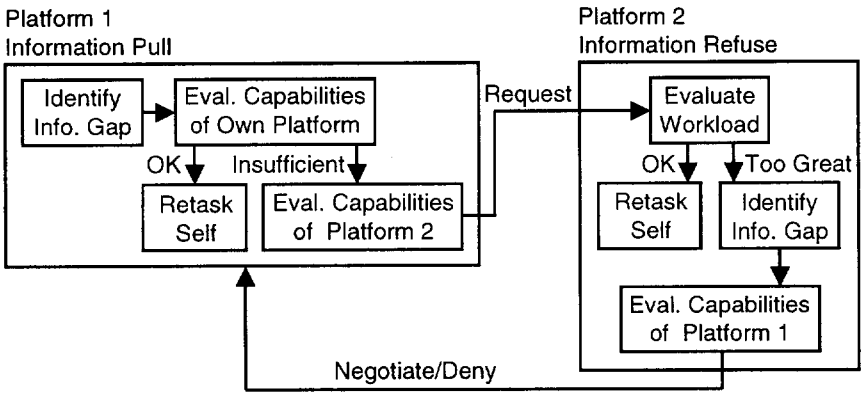

Figure 3. Push, pull, and refusal agents dynamically reason about the ability of sensor platforms and interact with platforms to share information

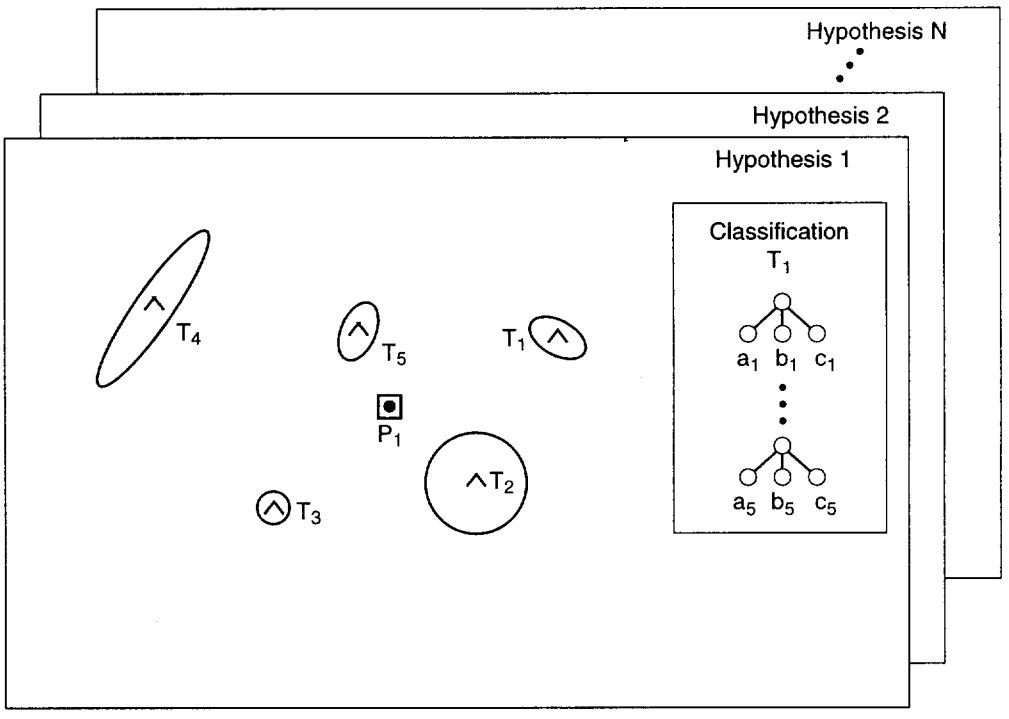

Figure 4. EXM MOMs are based on information for target error ellipses, hypotheses, and classification

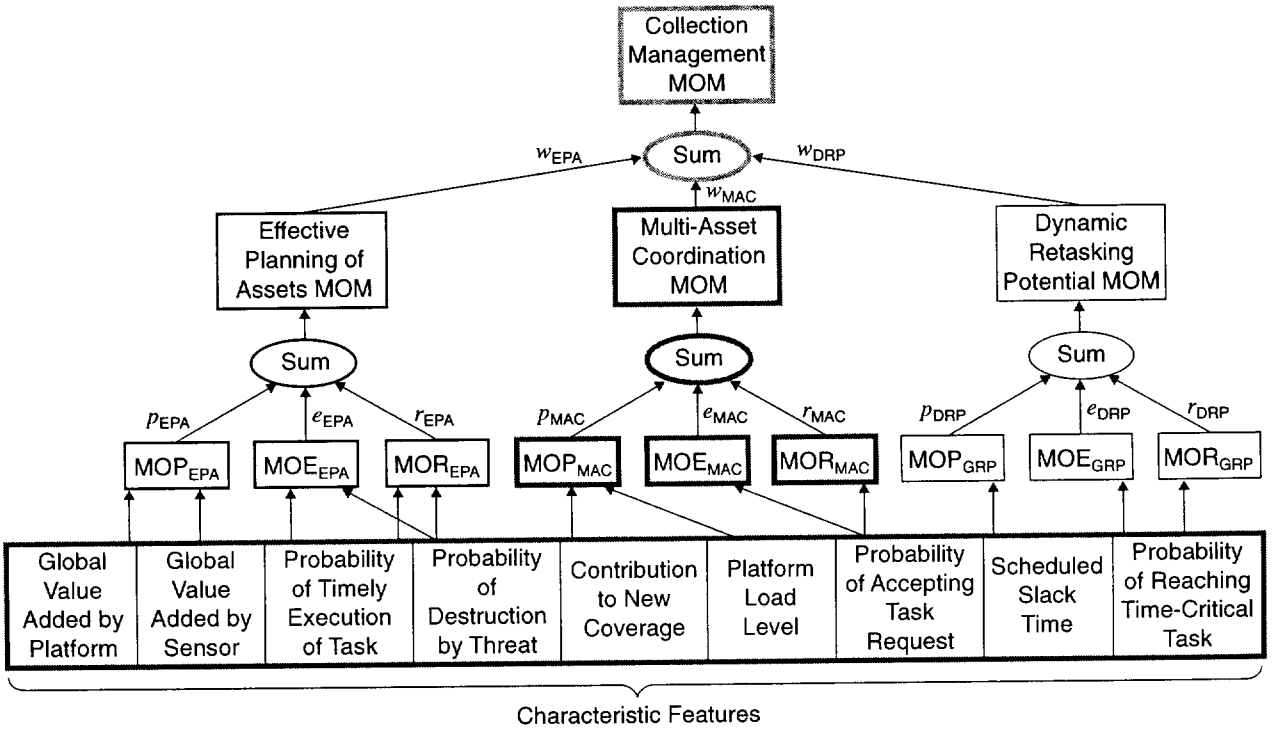

Figure 5. Lower level measures are aggregated to form an overall Collection Management MOM

Contextual information and Multisensor data fusion for battlefield applications

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1. SUMMARY

We propose in this article several multisensor tracking algorithms for battlefield applications. Generally, the context is never taken into account in the multisensor systems. Moreover, it can have an influence on the performance of the sensors. Contexts can be for example hidden zones, jamming, or meteorological conditions. The main interest of the presented research is to describe a multisensor tracking method which takes context into account and to use it for battlefield applications. By analysing the context, the relative confidence in the sensors is taken into account in the tracking algorithm. A ponderation coefficient is defined which represents a very simple way to handle and a very flexible tool to modulate the relative confidence levels of sensors depending on their own characteristics, their environment and those of the observed targets. This method avoids that the measurements of no reliable sensors disturb the result of the global fusion. The objective is to have a robust system which always conserves the target track. In the last section of this article, we present results of numerical simulations based on realistic battlefield scenarios in which a ground target moves behind hidden zones. The proposed algorithm is compared with a classical tracking algorithm. This parallel study emphasizes a better performance of the suggested method.

2. INTRODUCTION

The interpretation of increasing amounts of battlefield information by both operator and systems is more and more difficult. Therefore, data fusion, i.e. combining data from several sources in order to obtain a global and coherent view on (a part of) the battlefield at sensor level (multisensor data fusion) becomes very important.

In this paper we focus on the multisensor tracking problem. In multitarget tracking applications [1], [2], [5], the algorithms proposed for data fusion are Kalman filters and extensions IMM (Interacting Multiple Models), PDAF (Probability Data Association Filter), JPDAF (Joint Probability Data Association Filter). The assumption that the characteristics of the sensors are known is always made. Moreover, the context is never taken into account, that supposes it is always in favour of the sensor concomitant use. It is obvious this fact is seldom verified. Especially, hidden zones, jamming, E.M. interferences, meteorological conditions, are all contexts which influence the performance of the sensors. A multisensor system can work in all conditions only if the context is analysed and if the fusion process takes it into account in the algorithms. The main aim of the presented research is to focus on the way in which different factors can modify the conclusion of classical filtering algorithms.

In this context, this paper is composed of two important sections. The first section describes two different methods: a classical multisensor tracking algorithm and a more sophisticated multisensor tracking algorithm which takes context into account [3], [4]. The second section describes the validation of multisensor tracking methods for battlefield applications. In this part, we present results of numerical simulations based on realistic scenarios in which a ground target moves behind hidden zones. A comparative study of the proposed algorithm and classical tracking algorithm is made and demonstrates the benefice of the suggested method.

3. MULTISENSOR TRACKING METHODS

3.1 Choice of coordinates system

The first difficulty in the implementation of a tracking algorithm is to choose the coordinates system. This problem has been little studied for the multisensor systems compared with monosensor systems. As we will see it later, there are two possible approaches for resolving it. A first one consists in adopting a cartesian coordinates system for the representation of state variables. Such a model permits to represent with precision the target dynamic and requires to use an Extended Kalman filter (EKF) because resulting observation equations are not linear. But for the degenerated cases, this approach is limited. The loss of one coordinate, like radar range, can lead to an important global deterioration of filtering results. The other approach consists in adjusting an independent filter to each coordinate. If it's necessary, polar to cartesian coordinates transformation can be realized after filtering. This last approach has been selected in this paper because it presents two main advantages: used filters in this one are simple (linear Kalman filter) and need no inversion matrices; it is more robust to perturbations.

Paper presented at the RTO SCI Symposium on "Sensor Data Fusion and Integration of the Human Element", held in Ottawa, Canada, 14-17 September 1998, and published in RTO MP-12.

Subsequently, we consider a multisensor system composed of two sensors. Filter equations are written in considering only one of the coordinates (range or azimuth) because the method is exactly the same for each coordinate.

3.2 Description of a classical multisensor tracking method

3.2.1 *Synchronous case*

In this section, the considered system is synchronous and the described algorithm is sequential [6], [7]. For a system composed of two sensors, state equations can be split up into two sub-systems:

$$\begin{array}{ll} \text{Dynamic} & x_k = F\, x_{k-1} + v_k \\ \text{Sensor 1} & y_k^1 = H_1\, x_k + b_k^1 \end{array}$$

$$\begin{array}{ll} \text{Dynamic} & x_k^1 = x_k \\ \text{Sensor 2} & y_k^2 = H_2\, x_k^1 + b_k^2 \end{array}$$

where x_k is the target state (position, velocity, acceleration), F is the transition matrix, v_k is the state noise whose covariance is defined by $E(v_i v_j^t) = Q\,\delta(i,j)$ with Q constant, δ the Kronecker symbol. At time k, sensor 1 measurement is designed by y_k^1 and sensor 2 measurement by y_k^2 . Measurements are connected to state with observation matrices H_1 and H_2. Measurement noises of each sensor are not correlated and are noted b_k^1 and b_k^2. Their variance are respectively defined by $E(b_i^1 b_j^{1t}) = R_1\,\delta(i,j)$ and $E(b_i^2 b_j^{2t}) = R_2\,\delta(i,j)$. Consequently, this decomposition suggests making treatment in three successive steps: one prediction process and two estimation processes.

Step 1

With current state $\hat{x}_{k-1/k-1}$ and covariance $P_{k-1/k-1}$, estimated at time k-1, prediction is:

$$\begin{aligned} \hat{x}_{k/k-1} &= F\,\hat{x}_{k-1/k-1} \\ P_{k/k-1} &= F\,P_{k-1/k-1}\,F^T + Q \end{aligned}$$

where $\hat{x}_{k/k-1}$ is the state prediction at time k and $P_{k/k-1}$ the associated covariance.

Step 2

The updated state estimate and the associated covariance are calculated:

$$\begin{aligned} \hat{x}_{k/k}^1 &= \hat{x}_{k/k-1} + K_1(k)(y_k^1 - H_1\,\hat{x}_{k/k-1}) \\ P_{k/k}^1 &= (I - K_1(k)\,H_1)\,P_{k/k-1} \end{aligned}$$

where $K_1(k)$ is the Kalman gain for sensor 1 measurement and is given by the formula:

$$K_1(k) = P_{k/k-1}\,H_1^T\,(H_1\,P_{k/k-1}\,H_1^T + R_1)^{-1}$$

Step 3

In this third process, we identify the predicted state with the estimated state at the previous step and the state prediction covariance with the updated state covariance calculated before. So, the second estimation leads to the following expressions:

$$\begin{aligned} \hat{x}_{k/k}^2 &= \hat{x}_{k/k}^1 + K_2(k)(y_k^2 - H_2\,\hat{x}_{k/k}^1) \\ P_{k/k}^2 &= (I - K_2(k)\,H_2)\,P_{k/k}^1 \end{aligned}$$

where $K_2(k)$ is the Kalman gain for sensor 2 measurement and is given by the formula:

$$K_2(k) = P_{k/k}^1\,H_2^T\,(H_2\,P_{k/k}^1\,H_2^T + R_2)^{-1}$$

In the synchronous case, it's also possible to use a specific Kalman filter [8] which is more suitable for a multisensor system. But, this method presents an important drawback: it requires to inverse the covariance matrices R_1 and R_2 for the Kalman gain's calculation. It's the reason for which we have retained the above sequential algorithm.

3.2.2 *Asynchronous case*

In this section, the considered system is asynchronous. Each measurement arrives to the fusion centre with its acquisition date. We note, t_k, the acquisition date of the current measurement and, t_{k-1}, the acquisition date of the preceding measurement. Each data can be obtained independently by the first sensor or the second sensor. The system takes the following form:

$$\begin{array}{ll} \text{Dynamic} & x_{t_k} = F(t_k,t_{k-1})\,x_{t_{k-1}} + v_{t_k} \\ \text{Sensor i} & y_{t_k}^i = H_i\,x_{t_k} + b_{t_k}^i \quad \text{avec } i \in \{1, 2\} \end{array}$$

where $y_{t_k}^i$ is sensor i measurement at time t_k. $F(t_k,t_{k-1})$ is the transition matrix which depends on the last acquisition time and the present time.

Prediction equations are very close to those obtained in the synchronous case. The difference is that a prediction is realized each time a measurement arrives to the system and the transition matrix varies as the time difference between the present acquisition date and the preceding acquisition date. With state $\hat{x}_{t_{k-1}/t_{k-1}}$ and associated covariance $P_{t_{k-1}/t_{k-1}}$, estimated at iteration k-1, prediction is:

$$\hat{x}_{t_k/t_{k-1}} = F(t_k,t_{k-1})\,\hat{x}_{t_{k-1}/t_{k-1}} \qquad (1)$$

$$P_{t_k/t_{k-1}} = F(t_k,t_{k-1})\,P_{t_{k-1}/t_{k-1}}F(t_k,t_{k-1})^T + Q(t_k,t_{k-1}) \qquad (2)$$

where $\hat{x}_{t_k/t_{k-1}}$ is the predicted state at iteration k and $P_{t_k/t_{k-1}}$ the associated covariance. At each time, the system uses only one measurement. So, estimation equations are

classical but depend on the sensor which gives the measurement. If the measurement results from sensor i at time t_k, the equations are the following:

$$\hat{x}_{t_k/t_k} = \hat{x}_{t_k/t_{k-1}} + K_i(k)\,(y^i_{t_k} - H_i\,\hat{x}_{t_k/t_{k-1}}) \quad (3)$$

$$P_{t_k/t_k} = (I - K_i(k)\,H_i)\,P_{t_k/t_{k-1}} \quad (4)$$

where $K_i(k)$ is the Kalman gain for sensor i measurement and is given by the formula:

$$K_i(k) = P_{t_k/t_{k-1}}\,H_i^T\,(H_i\,P_{t_k/t_{k-1}}\,H_i^T + R_i)^{-1} \quad (5)$$

This algorithm is almost identical to the sequential algorithm mentioned above. The difference is the use of each measurement's acquisition dates in the prediction process. Then, the state is changed in taking the noise characteristics of the sensor which delivers the current measurement into account.

3.3 Description of a multisensor tracking method in taking context into account

If we want to make the performance of a multisensor system optimal, it's necessary to study the operational context and to adjust to this last. That is the reason why we propose in this section a multisensor tracking method that takes context into account. With this aim in view, the suggested algorithm is based on two treatment levels: the first level consists of filtering the measurements and is almost identical to the asynchronous fusion algorithm described above; the second level makes the analysis of the context and permits to define a confidence coefficient which is taken into account in the first level (tracking system). This coefficient represents a very simple way to handle and a very flexible tool to modulate the relative confidence levels of two sources depending on their own characteristics, their environment and those of the observed targets. This method avoids that the measurements of no reliable sensors disturb the result of the global fusion. The objective is to have a robust system which conserves always a track of the target.

3.3.1 *Study of the context*

In the second treatment level, it's necessary that each context in which the system can work is identified. A particular context can be defined by p contextual parameters, noted z_j with $j \in \{1, ..., p\}$. Each contextual parameter permits to characterize the sensor validity range with membership functions relative to fuzzy subsets. We give an example of such a function on figure 1. Here, the variable z_1 represents the rainfall rate in ml by m^2 and $\mu_1(z_1)$ the sensor 1 validity range: if $\mu_1(z_1) = 1$, the sensor works nominally, and if $\mu_1(z_1) = 0$, the sensor doesn't work any more.

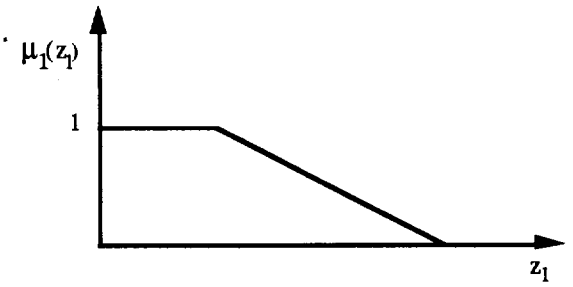

Figure 1 - Definition of a membership function

The sensor i validity relative to the contextual variable z_j is represented by the fuzzy event C_i whose the probability is defined by the following formula [9]:

$$P(C_i) = \int \mu_i(z_j)\,p(z_j)\,dz_j$$

If the context is identified with p contextual variables, this expression becomes general and is defined by:

$$P(C_i) = \int \mu_i(z_1) \wedge .. \wedge \mu_i(z_p)\,p(z_1, .., z_p)\,dz_1..dz_p$$

where $\wedge$ is the conjunction operator of fuzzy subsets. Generally, we choose the min operator. If the probability $p(z_1, ..., z_p)$ is identified to one Dirac $\delta(z\text{-}z_1, ..., z\text{-}z_p)$, the probability $P(C_i)$ is comparable to the conjunction of elementary membership functions. Subsequently, this probability will be noted β_i and takes its values in the interval $[0,1]$. It measures the sensor i reliability relative to identified context.

3.3.2 *Context taking into account in the fusion process*

Here, we present the tracking algorithm which takes context into account only in the case asynchronous. At each time, a sensor i measurement y_i arrives to the fusion centre with its acquisition date t_k and its confidence level β_i. Prediction is identical to the one defined by equations (1) et (2). The estimation results from a compromise between the two following alternatives:

- the measurement is completely reliable and the state estimation is realized with equation (3);
- the measurement is not reliable and the estimated state is identified to the predicted state at the previous step.

So, the new estimation is given by the formula [4]:

$$\hat{x}_{t_k/t_k} = \hat{x}_{t_k/t_{k-1}} + \beta_i\,K_i(k)\,(y^i_{t_k} - H_i\,\hat{x}_{t_k/t_{k-1}})$$

where the Kalman gain $K_i(k)$ is equivalent to the preceding expression (5). This estimated state is obtained in making the weighted average between the two previous states and the associated covariance is lightly different from the expression (4) because equal to:

$$P_{t_k/t_k} = (1-\beta_i)\, P_0 + \beta_i\, P_1$$

with:

$$P_0 = P_{t_k/t_{k-1}} + (\hat{x}_{t_k/t_k} - \hat{x}_{t_k/t_{k-1}})(\hat{x}_{t_k/t_k} - \hat{x}_{t_k/t_{k-1}})^T$$

$$P_1 = P^1_{t_k/t_k} + (\hat{x}_{t_k/t_k} - \hat{x}^1_{t_k/t_k})(\hat{x}_{t_k/t_k} - \hat{x}^1_{t_k/t_k})^T$$

and

$$P^1_{t_k/t_k} = (I - K_i(k)\, H_i)\, P_{t_k/t_{k-1}},$$
$$\hat{x}^1_{t_k/t_k} = \hat{x}_{t_k/t_{k-1}} + K_i(k)(y^i_{t_k} - H_i\, \hat{x}_{t_k/t_{k-1}}).$$

We can easily verify the two following facts: when β_i is equal to 1, the global estimate is identical to the estimate obtained without taking context into account; when β_i is equal to 0, only prediction is taken into account.

4. SIMULATIONS

4.1 Introduction

This new section suggests to validate the two preceding tracking multisensor algorithms which have been described in the asynchronous case. Numerical applications on which we focus in this paper consist in tracking a ground target on the battlefield with a multisensor system composed of two asynchronous and co-located sensors. The two systems which have been studied here are the following: a system on ground associating a MTI radar and an IR camera; a system on ground associating a MTI radar and a TV camera. Data used for algorithms validation are the following: a terrain numerical model which contains hidden or/and forbidden areas; trajectory data relative to a fictive target and generated with a simulation tool developed with MATLAB.

Figure 2 gives terrain numerical model's representation. This model is composed of a river, three hidden areas and a road network. Filtering is realized with polar coordinates and uses two linear Kalman filters working in parallel on range axis and azimuth axis. Each filter considers a state model with constant velocity. Before being filtered, the simulated measurements must be changed and the mentioned transformations are the following:

- position target information are converted in polar coordinates;
- we add to different measurements an observation noise which characterizes the considered sensor.

Subsequently, we suggest to adopt the following notations:
Δ_1 and Δ_2 are respectively the sampling periods of sensors in seconds;
D_t is the treatment time in seconds;
Δ_s is the wished output period;
σ_{d1} is the noise standard deviation relative to radar range (in meters);
σ_{a1} is the noise standard deviation relative to radar azimuth (in radians);
σ_{a2} is the noise standard deviation relative to IR camera azimuth (in radians);

The performances of the algorithms are evaluated with the mean absolute error. This last one is designed by erm_{xy} and is the difference between the true trajectory of the target and the estimated one. We'll design by erm_1 the mean absolute error relative to range filter and by erm_2 the one relative to azimuth filter.

4.2 Numerical application 1

The first battlefield scenario on which we focus is represented on figure 3. It's composed of a target whose trajectory is rectilinear at the beginning and which takes a bend to 90° at a given time on several seconds. The target moves behind hidden zones. We suppose the MTI radar is only disturbed by areas presence.

The sensor characteristics are known and defined by:

$\Delta_1 = 4$ s, $\sigma_{d1} = 40$ m and $\sigma_{a1} = 3.10^{-3}$ rd for the MTI radar;
$\Delta_2 = 2$ s and $\sigma_{a2} = 10^{-3}$ rd for the IR camera.

Concerning the state noise variance, we'll take at each test $\sigma^2_{e1} = 0.1$ for the first filter, and $\sigma^2_{e2} = 0.1$ for the second filter. We'll suppose also that: $D_t = 800$ s and $\Delta_s = 2$ s for each filter. Radar disturbance relative to hidden areas is simulated with an additional Gaussian noise which is defined by parameters:

$\sigma_{dc1} = 320$ m for range,
and $\sigma_{ac1} = 0.0245$ rd for azimuth angle,

and which is added to radar measurements. In the classical tracking algorithm, all measurements are filtered but in the second algorithm, we take context into account with the confidence level β which can take the two following values:

- $\beta = 0$ if radar measurement isn't reliable;
- $\beta = 1$ if radar measurement is reliable.

In the first case, state isn't updated with radar measurement and in the second case, it is updated.
Table 1 gives different absolute error rates obtained from the two algorithms. Case 1 is relative to the first algorithm test and case 2 to the second algorithm test. This table shows that the second method gives the best performance. It's obvious that the integration of contextual information permits to improve effectively the target tracking. Even if the first algorithm yields worse results than the second method, the obtained precision in the case 1 is nevertheless very acceptable.

	erm_{xy}(m)	erm_1(m)	erm_2(rd)
case 1	32.914	41.686	$9.67.\ 10^{-4}$
case 2	17.919	20.205	$7.96.\ 10^{-4}$

Table 1 - Mean absolute errors obtained from the two algorithms

Figure 4 presents the variation of parameter β according to time. We see that this coefficient is zero when the radar measurements are perturbed by the hidden areas and is equal to one in the other case. Finally, figure 5 is composed of two different curves: the first one is designed by a dotted line and gives the absolute error variation according to time, obtained from the classical method; the second one is described by a continuous line and presents the absolute error variation obtained when we take context into account. The comparison of the two curves on this last figure reveals that the difference between the true trajectory and the estimated trajectory is on average slighter with the second method than with the first one. Consequently, we can say that the tracking algorithm in taking context into account is more satisfactory than the classical tracking algorithm.

4.3 Numerical application 2

The second simulation is relative to battlefield scenario which is presented on figure 6. This last is composed of a target whose trajectory is rectilinear. The main aim of this application is to compare the two tracking methods in validating the second algorithm with a variable context coefficient β which can take any value in the interval $[0,1]$ and in using the Monte Carlo method. The contextual variable on which we focus here can characterize for example a jamming radar level. We suppose that the two sensors have a sampling period equal to 4 seconds, the wished output period is equivalent to 4 seconds and, finally, the treatment duration is equal to 400 seconds. We know also that precision of different sensors is defined by:

$\sigma_{d1} = 40$ m and $\sigma_{a1} = 3.10^{-3}$ rd for the MTI radar;
$\sigma_{a2} = 0.5.10^{-3}$ rd for the IR camera.

We'll fix at each test the state noise variance at $\sigma^2_{e1} = 1$ for the first filter, and $\sigma^2_{e2} = 10^{-7}$ for the second one. Figure 7 gives the variation of coefficient β according to time used at each test. In other respects, when radar measurements are not reliable, we add to them an additional Gaussian noise which is characteristic of the disturbance importance. The two tracking algorithms are compared with the Monte Carlo method in using 100 different realizations of measurement noise. The mean result, which is relative to absolute error and obtained for each algorithm on all realizations, is the following:

Method 1 ------> $\overline{erm}_{xy} = 64.963$ m
Method 2 ------> $\overline{erm}_{xy} = 44.378$ m .

On figure 8, we compare the absolute errors which are obtained from the two methods for one particular realization of measurement noise.

As in the first application, we observe again that the tracking algorithm taking context into account is the one which gives the best performance on average. We can say that the using of contextual information in tracking involves to eliminate unreliable radar measurements in the filtering and permits to have a robust tracking system.

5. CONCLUSION

In this paper, two multisensor tracking algorithms have been studied and validated for battlefield applications. The first algorithm is quite classical but the second algorithm is the more interesting method because it takes context into account in tracking. Several numerical simulations based on realistic battlefield scenarios have been described and have permited to make a comparative study of the two proposed algorithms. This analysis demonstrates that the algorithm taking context into account gives the best performance and yields to a very robust multisensor tracking system. An other advantage of this method is that it's easy to implement because it involves only to make the analysis of the operational context and to define a fuzzy confidence coefficient which is integrated in the tracking system. This parameter is a simple way to handle and to modulate the relative confidence levels of two sensors depending on their own characteristics, their environment and those of the observed target. Several further steps of work might be considered: taking other contextual information sources into account as for example weather forecast, vegetation or jamming; global fusion of several not located sub-systems (association of sensors) for determining contribution of such an architecture faced with the masking problem; study of multitarget scenarios and finally, taking false alarms into account in the multisensor tracking.

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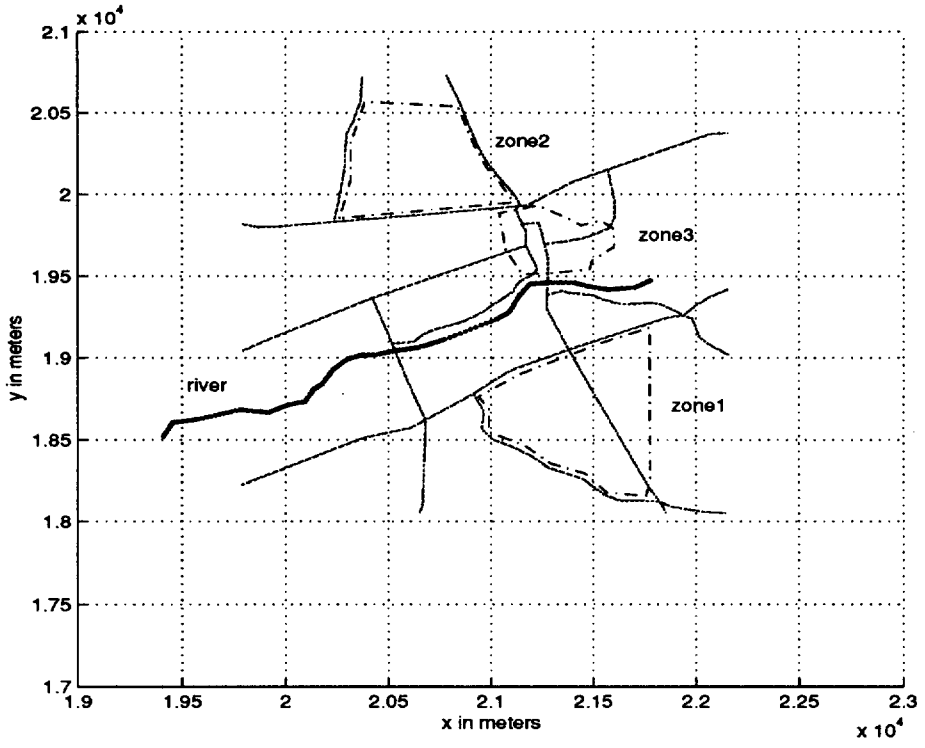

Figure 2 - Representation of the terrain numerical model

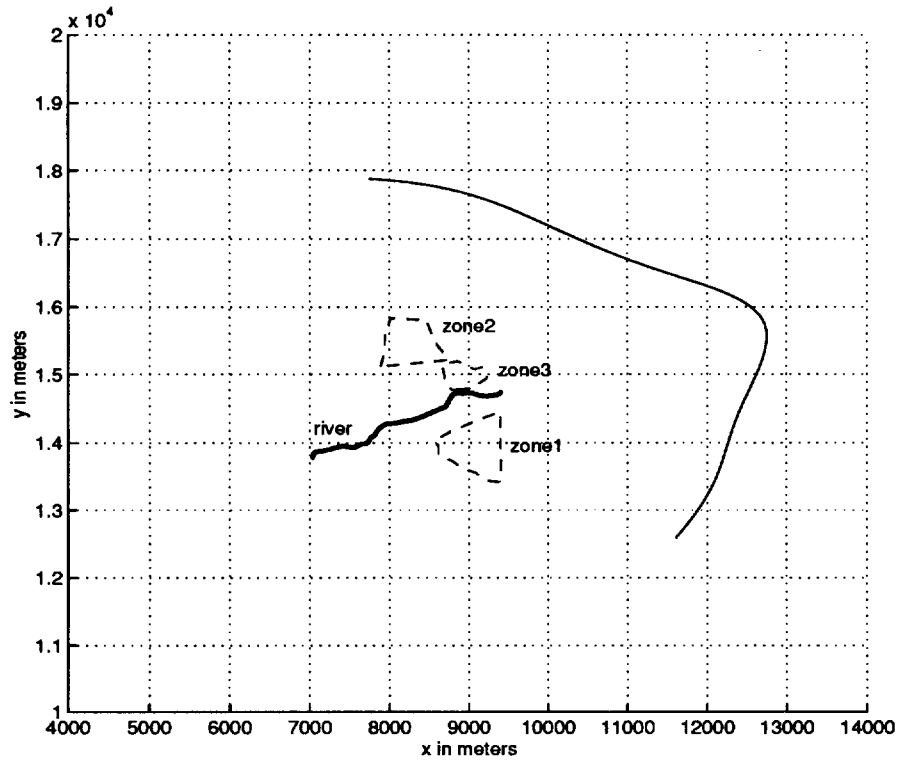

Figure 3 - Scenario 1 of battlefield

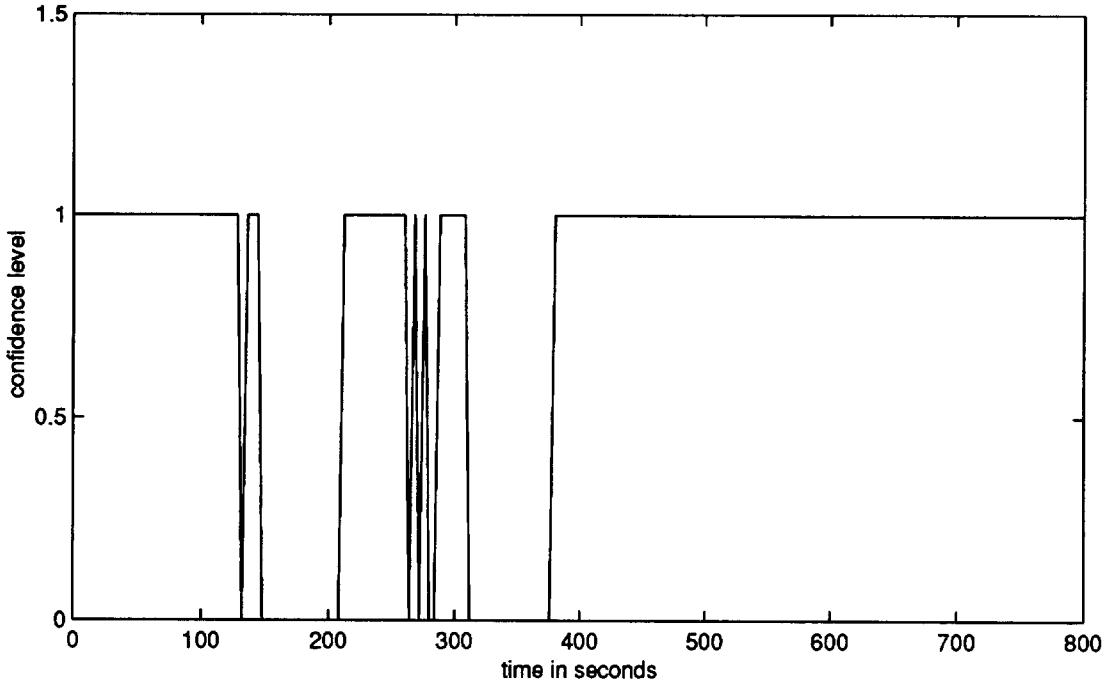

Figure 4 - Variation of coefficient β according to time used in application 1

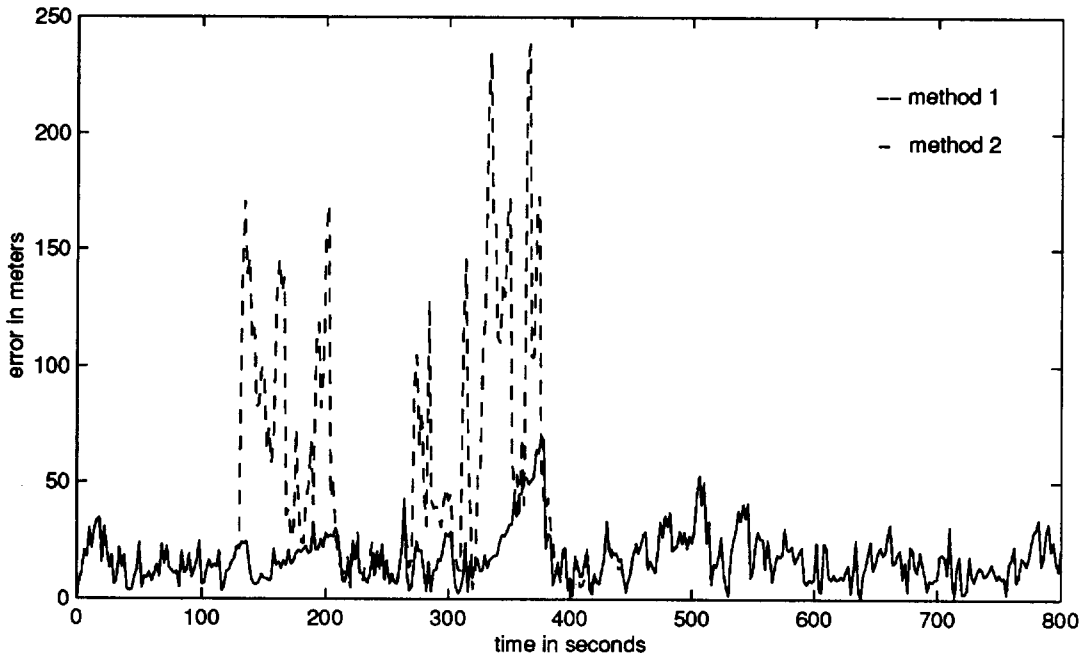

Figure 5 - Absolute error of estimated trajectory in application 1

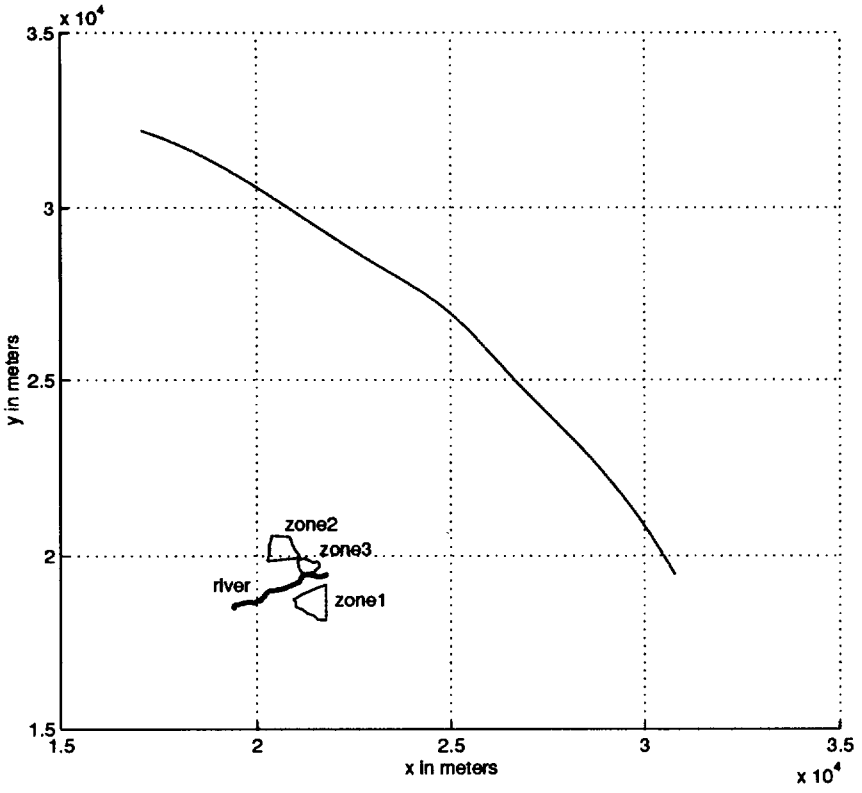

Figure 6 - Scenario 2 of battlefield

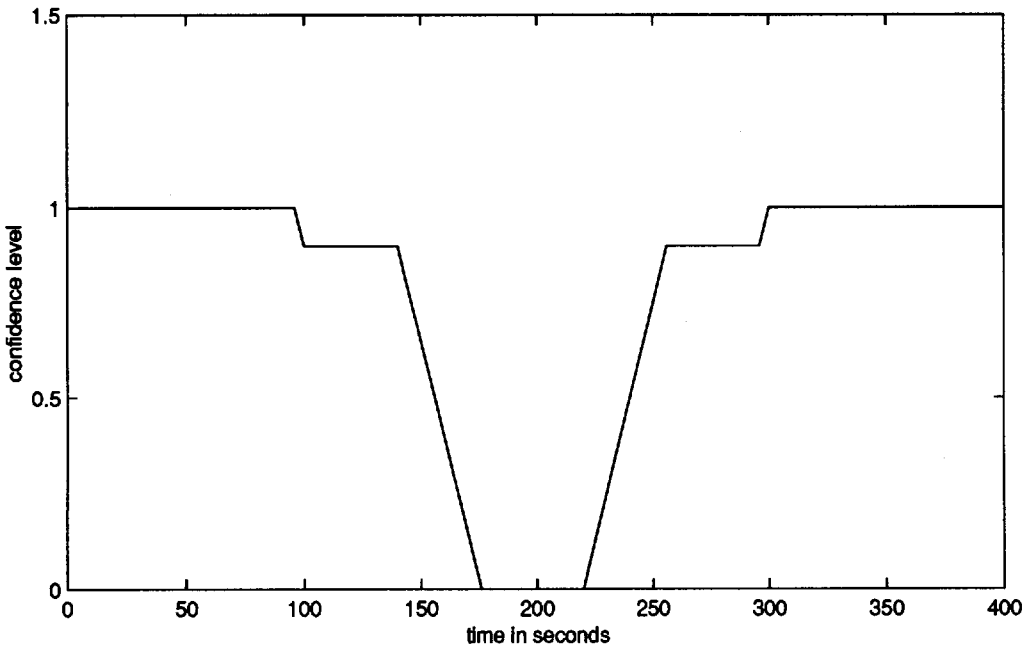

Figure 7 - Variation of coefficient β according to time used in application 2

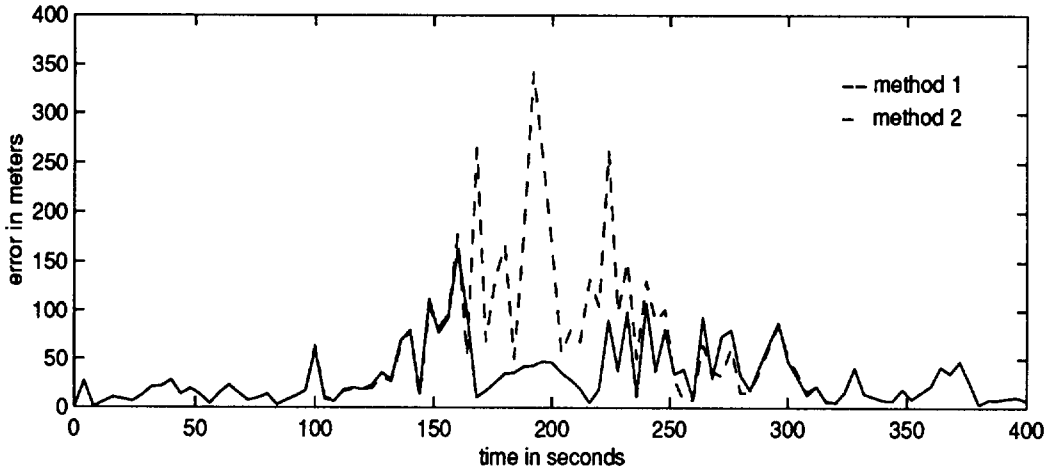

Figure 8 - Absolute error of estimated trajectory in application 2

Image Data Fusion for Future Enhanced Vision Systems[1]

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Summary

New imaging sensors and high performance computer graphics systems have a great impact on the design of the human machine interface of novel cockpit systems. The improvement of aircraft safety and operational qualities under adverse weather can be achieved by so-called enhanced vision systems, which consist in principle of a combination of sensor- and synthetic-vision. The following contribution describes the enhanced vision concept which has been developed at the Institute of Flight Guidance of the German Aerospace Center (DLR). Benefits of competing imaging sensors are compared, results of recently conducted field tests are shown, and first concepts for a fusion of radar and synthetic images are presented.

1. Introduction

Actual investigations on new cockpit technologies are focused on improving the situational awareness of the cockpit crew, especially during approach, landing, take-off and taxiing. The role of this key element is emphasized by the following quotation of the Human Factors Team (SA-1) of the FAA:

> *"The FAA should require operators to increase flightcrews understanding of and sensitivity to maintaining situation awareness, particularly: ... position awareness with respect to the intended flight path and proximity to terrain, obstacles or traffic."*

Particularly future military transport aircraft have to cope with new requirements such as autonomous, non-cooperative landing at unsupported (without D-GPS, MLS, ILS) airstrips down to CAT-I (minimum) or better, low level flight operations, ground mapping, precise air dropping, search and rescue missions. In most cases these requirements have to be established under adverse weather conditions, without being detected by hostile observation.

Within this context visual information provided by fusion of image data from onboard multispectral sensors with synthetic vision, supported by an ATC-interface and aircraft state data (position, attitude, speed, etc.), will become an important and helpful tool for aircraft guidance. The development of these so called "Enhanced Vision Systems" (EVS) is an interdisciplinary task, which requires a wide spectrum of different information technologies:

- modern data link technology for transmission of guidance information;
- complex data bases to provide terrain data and high performance computer graphics systems to render synthetic images in real time;
- a new generation of onboard imaging sensors, like solid state infrared and especially a new kind of imaging radar, providing a real view through darkness and adverse weather;
- knowledge based image interpreters to convert sensor images into a symbolic description.

This paper presents the DLR concept for an integrated enhanced vision system. After the description of the basics in section 2 the image sensor characteristics are compared with the requirements of an Enhanced Vision System in section 3. First results concerning the experiments with the DASA HiVision radar and data fusion techniques are given in section 4.

Sensor Vision	• no single sensor will really cover all possible weather situations • what happens if the imaging sensor fails? • multispectral images are difficult to interpret
Synthetic Vision	• unmodelled obstacles are not detectable • how can the integrity of the data base be monitored and what happens if data base errors occur? • how can such a data base be certified? • position accuracy and reliability of the synthetic image depends on the accuracy and reliability of the reference system.

Table 2.1: Problems of Sensor Vision and Synthetic Vision as isolated technologies.

[1] This work was sponsored by the German Ministry of Defense under the title: *"Bildverarbeitung zur Pilotenunterstützung"*

Paper presented at the RTO SCI Symposium on "Sensor Data Fusion and Integration of the Human Element", held in Ottawa, Canada, 14-17 September 1998, and published in RTO MP-12.

2. The DLR Concept for Enhanced Vision

Looking a little closer to the meaning of the terms "Enhanced Vision Systems" (EVS) and "Synthetic Vision System" (SVS), we find a rather indistinct situation: sometimes the whole field concerning "obstacle detection", "sensor simulation", "4D flight guidance display", "enhanced vision", etc. is subsumed under the headline "Synthetic Vision" [20,8] and sometimes the same term is strictly reduced to computer generated images [17].

It's amazing to see that the terms "EVS" and "SVS" are very often discussed in parallel, - sometimes even treated as competing concepts. But as long as EVS and SVS are considered as isolated technologies, they have to face some critical questions, such as shown in Table 2.1.

Another somewhat restricted but quite interesting definition concerning the field of EVS-, SVS-terminology was coined by the Air Transport Association (ATA) :

> "*... means to safely increase airport capacity and reduce runway incursions in low visibility conditions, without significant expansion of ground facilities.*"

This definition seems to be mainly influenced by civil needs, but the renunciation of supporting ground facilities makes EVS- and SVS-technology also very interesting for military requirements.

To avoid the drawbacks of the isolated EVS and SVS technologies and to maintain the benefits of both, it seems to be absolutely necessary to integrate them into one system which should be treated as a part of an artificial pilot assistant.

In order to avoid any confusion concerning the terms used throughout this paper, it seems to be worthwhile to define them :

"*Sensor Vision*" = Sensor generated images; (replaces the term "Enhanced Vision" in the conventional meaning).

"*Synthetic Vision*" = Computer generated images based on navigation inputs, map information and/or terrain data bases.

"*Enhanced Vision*" = A concept which integrates

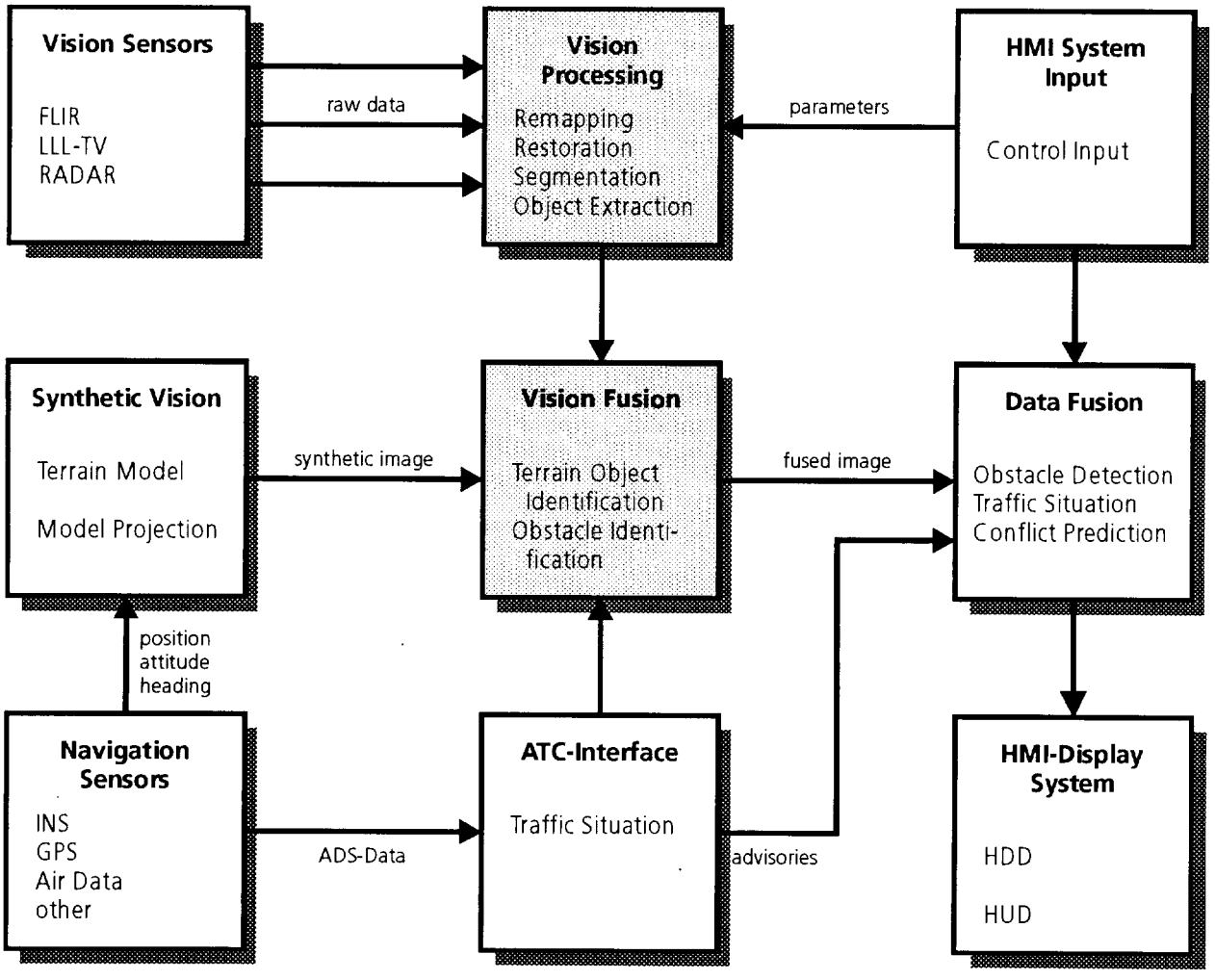


Fig. 2.1: Block Diagram of the DLR "Integrated Enhanced Vision System".

		Advantage	Disadvantage
	Synthetic Vision	easy image interpretation	no obstacle detection reference system necessary depends on data base reliability
+	**Sensor Vision**	obstacle detection no reference system necessary no data base necessary	difficult image interpretation
+	**Aircraft status**	already available	single sensor information
+	**ATC data**	identification of other aircraft	needs data link technology
=	**Integrated Enhanced Vision System**		

Table 2.2: Definition of the Integrated Enhanced Vision System.

"Sensor Vision", "Synthetic Vision", aircraft state- and ATC-data.

Figure 2.1 shows the basic idea of an integrated Enhanced Vision concept [7,12]. Key elements are functional subblocks which are interacting through defined interfaces: The "Sensor Vision" block includes the imaging sensor(s) and possibly some image data preprocessing. The "Vision Processing" block is responsible for a image processing concerning signal restoration like noise reduction and various filtering techniques, scaling and transformation to convenient perspectives and as a most challenging topic: feature- or object extraction. The block "Synthetic Vision" represents all necessary technologies to set up a synthetic image derived from terrain data bases and navigational information.

The core part of the integrated Enhanced Vision System is represented by the block "Vision Fusion". A first and simple possibility for "Vision Fusion" could be an integration of sensor images and flight status data on the primary flight display, using a Head Down Display (HDD) or a Head Up Display (HUD) in order to increase the crew's situation awareness, but other possibilities are just as important:

- incompatibilities between sensed data and terrain data can be used for obstacle detection;
- a conformity check between sensed vision and synthetic vision can be used as an "Integrity Monitor" for the navigation system and the data bases.

This concept should be regarded as part of a pilot assistant system, which will not be discussed in this paper. But it is obvious that obstacle detection carried out within the "Vision Fusion" subblock can be improved to an obstacle or vehicle identification, if ATC information is included. The pilot assistant may condense these data to a representation of the traffic situation and - if the need arises - to a conflict prediction.

Table 2.2 summarizes the concept of an integrated Enhanced Vision System. It is obvious that the disadvantages of "Synthetic Vision" and "Sensor Vision" cancel out each other and the advantages are increased. In the sense of a synergetic effect both sum up to a new system quality in the fields of:

Crew Assistance in connection with:
- adverse weather,
- obstacle detection,
- non-cooperative landing systems.

Integrity Monitor for:
- navigation,
- GPWS,
- taxi guidance system.

Automatic Flight Guidance in terms of :
- image based navigation,
- collision avoidance,
- avoidance of terrain and CFIT.

3. Imaging Sensors - Characteristics and Requirements

The requirements for suitable imaging EVS sensors depend strongly on the application. In the following table the civil requirements and the resulting sensor characteristics should be interpreted as the minimum performance and the military features are meant as an add on.

With the background of the requirements shown in table 3.1 we should be able to qualify different types of sensors in terms of their EVS capability. A rather convenient method to distinguish between all possible sensor types, is to refer to the operating wavelength, because this parameter allows a rather easy estimation for two of the most important sensor parameters: the penetration through the atmosphere (especially under foggy conditions) and the image quality in terms of resolution. The rule of thumb is rather simple: increasing wavelength improves the penetration and decreases the image resolution. But of course there is no rule without exception: if the wavelength is much smaller than the water particle size (1-10 microns), the penetration increases again. This effect is used for the so called "FogEye" - receiver, which is

	operational requirements	resulting requirements for imaging sensors
civil	• reduction of minimum approach RVR • reduction of minimum takeoff RVR • safe taxi operations • obstacle warning in critical phases • CFIT warning • integrity monitor for GPS supported navigation • search and rescue	⇒ weather independent ⇒ sufficient resolution ⇒ image rate > 15 Hz ⇒ image delay < 200 ms ⇒ coverage minimum = HUD coverage
military	• low level flights • landing on unsupported forward operating strips • precise air dropping • air surveillance • ground mapping for surveillance	⇒ passive or "silent" sensor ⇒ autonomous; ground facilities not necessary ⇒ reconnaissance capability

Table 3.1: Requirements for imaging EVS-sensors for civil and military applications. (RVR=Runway Visual Range; CFIT=Controlled Flight Into Terrain)

optimized for UV wavelengths between 0.2–0.275 microns [9]. Table 3.2 compares the characteristics of sensors which might come into consideration for EVS applications.

A valid comparison of the all-weather capability is nearly impossible, because the technical realizations of image generation are too different. First of all, it seems quite clear that the active kind of sensors are more successful penetrating a foggy or rainy atmosphere than the passive ones. "Active" in this context is not only an illuminating kind of device, such as the active radars (LADAR, MMW, PBMMW), but also those sensors which need an emitting source to overcome the signal to noise barrier, as for instant the UV sensor "Fog Eye" [9] and to a certain extent the "passive"-MMW (PMMW) camera, whose range of visibility can be significantly enlarged, if additional MMW-reflectors are positioned nearby the target. [14]. If we take operational requirements into account we can define:

> *Active sensor systems make use of additional means to increase the emission at or nearby the observed object.*

From this point of view the UV-, LADAR-, MMW- and PBMMW-sensor are purely active, the others are optional active depending on the usage of illumination or emission increasing devices, such as IR-emitting lamps or MMW-reflectors, etc.

On the other hand a "passive" sensor is not necessarily the same as a "silent" one. For example: the active MMW–sensor, as it is proposed by DASA Ulm [11], has a greater range than the hostile ESM detection range. This is an example for an active but silent sensor; and it turns out that the meaning of term "silent" is a matter of mission.

But let's return to the "all weather" capability: A rather convincing method to define the "all weather" characteristic of a sensor was proposed by W.F. Horne et.al. [8]. Here the difference of received power from the runway and the surrounding grass as a function of distance and various weather conditions had been measured. The variation of the received power between grass and runway was used as a measure for the contrast and a 3dB difference was defined as threshold for sufficient visibility. The results of these investigations for a 35GHz MMW-sensor and an IR–sensor is given in table 3.2.

Although the visibility data of the other types of sensors are not completely comparable we can state, that the MMW-sensor technology seems to be the most successful one.

Another very important feature of the above listed sensors is the type of imaging: UV-, IR-, Video- and PMMW-sensors generate a perspective 2D kind of image, which the human visual-perception-system is evolutionary trained to process into a 3-D-representation of the "outside world". The MMW–sensor on the other hand delivers primarily an information about the range and the angular direction of a certain object. This range-angle information can be transformed into a view "out-of-the-window", but there is still a lack of information about the objects height or its vertical position [5]. The presentation of such images needs knowledge about the surrounding elevation, which often is estimated by the so-called "flat-earth-assumption"[10]. On the other side a MMW-sensor delivers a direct information about the distance to certain objects, which is extremely valuable for navigation, traffic analysis and obstacle detection and obstacle avoidance respectively.

sensor type	wave-length [micron]	kind of image	active / passive	ground facility	angular resolution [degree]	range resolution [m]	rate [Hz]	delay [sec]	FOV HxV [degree]	visibility range [km]
UV [9]	0.2–0.3	2-D optical	passive	yes [1])	0.05	[2])	[5])	[5])	30x22	0.8
Video	0.4–0.8	2-D optical	passive	no	0.05 [4])	[2])	25	[5])	variable	[8])
LADAR [21]	1.54	2.5-D range-angle-angle	active	no	0.35x0.20	1	2-4	[6])	32x32 range 1km	[8])
IR [8]	3–5	2-D optical	passive	no	0.05 [4])	[2])	25	[5])	variable	[8])
IR	8–12	2-D optical	passive	no	0.05 [4])	[2])	25	[5])	variable	[8])
MMW 94GHz [8,3]	3190	2-D range-angle	active	(no)	[6])	3	10	[6])	30x22	[6])
MMW 77GHz [4]	3900	variable [9])	active	(no)	0.25	1.2	[9])	[9])	[9]) range 250 m	[6])
MMW 77GHz [13]	3900	variable [9])	active	(no)	1.00	1	[9])	[9])	[9]) range 100 m	[6])
MMW 35GHz [8,11]	8570	2-D range-angle	active	(no)	0.25-0.80 [7])	6	16	<0.2	40x28 range 3-10km	3.0
MMW 35GHz [6]	8570	2-D range-angle	active	(no)	0.70	7-15	10.5	<0.2	30x26 range – 7.5km	3.0
PBMMW 35GHz [1]	8570	2.5-D range-angle-angle	active	no	2.5	5-10	0.5-1.0	1-2	50x20 range 1-3km	3.0
PMMW [14,2,15]	3190–8570	2-D optical	passive	(no)	0.15-0.50	[2])	17	[6])	15x17	0.7

Table 3.2: Characteristics of potential EVS-sensors under adverse weather.

UV	Ultra Violet
LADAR	LAser raDAR
IR	Infra Red
MMW	MilliMeter Wave radar
PBMMW	Pencil Beam MilliMeter Wave radar
PMMW	Passive MilliMeter Wave sensor

[1]) UV-source on the ground necessary,
[2]) direct range information not available,
[3]) 1m antenna square aperture [2]
[4]) calculated for field of view (FOV) of 40°
[5]) specific values are not available, but problems are not expected,
[6]) data not available,
[7]) numerical resolution 0.25°, beamwidth: 0.8°,
[8]) no improvement,
[9]) depends on scanning method.

	UV	Video	IR	LADAR	MMW	PBMMW	PMMW
weather independent	●	-	-	-	+	+	●
sufficient resolution	●	+	+	+	-	-	-
image rate > 15 Hz	+	+	+	-	+	-	+
image delay < 200 ms	+	+	+	-	+	-	?
coverage (azimuth x elevation)	+	+	+	+	+	+	●
passive sensor	yes	yes	yes	no	no	no	yes
"silent" sensor	no/yes	yes	yes	no	yes	no	yes
autonomous	no	yes	yes	yes	yes	yes	yes/no
reconnaissance capability	no/yes	yes	yes	yes	yes	no/yes	yes

Table 3.3: Matrix of EVS-requirements and sensor characteristics (+: good ; ●: fair; -: poor).

But whatever conclusions are drawn from these different kinds of image generation, it seems to be impossible to claim a general advantage for one of them. In connection with the above used definition of the term "Enhanced Vision" as a fusion of "Synthetic Vision" and "Sensor Vision", the type of imaging is an important part of the system philosophy.

On the basis of the sensor requirements (Table 3.1) and the sensor characteristics (Table 3.2) we should be able to correlate sensor characteristics and requirements (Table 3.3).

Simply counting the "+" and "yes", Table 3.3 gives the impression, that the infrared sensors and the simple video cameras should be the most promising sensors for EVS applications. They offer nearly all features, which might be valuable, except one: the ability to penetrate fog, snow and rain.

Horne et.al. [8] stated in their paper:

> *"During approaches and landings in actual weather for 50 foot ceilings and 700-1000 foot visibility the millimeter wave image was not noticeable degraded. During these same in-weather approaches, the IR sensor was not able to provide an image any better than the human eye."*

If EVS-technology is mainly justified by an increase of the crew's (visual) situation awareness under adverse weather conditions the all weather capabilities of the sensors will become the most important characteristic. From this point of view the UV-, the MMW- and the PMMW-sensor should be taken into account. The UV-sensor and the passive MMW-sensor need some additional ground facilities (UV-sources and MMW-reflectors), the first one in general and the latter one in adverse weather conditions. [9,14]. Additional ground facilities might be no problem, especially if they are cheap and easy to install, but they restrict the EVS technology to certain scenarios with a ground based infra structure, which might be not always available, especially for military applications.

These are the reasons why DLR decided to use the "HiVision" MMW-radar from DASA Ulm as the main sensor for EVS research. Technical descriptions are given in several papers [11,19]; therefore a short summary might be sufficient: "HiVision" radar uses continous wave (FMCW) technology with a frequency scanning antenna which covers an azimuth sector of 40°. Table 3.4 summarizes the parameters which were achieved during recent tests.

A very promising feature of this sensor, especially for military applications, is the ESM range, where the radar could be detected. With an output power of 100mW/500mW a high performance ESM receiver with a –80dBm sensitivity would detect the radar

waveform	FMCW
scanning principle	frequency scanning
centre frequency	35 GHz
scanning (image) rate	16 Hz
emitted power	500 mW
resolution (angle)	0.26° (157 pixel/41°)
azimuth beamwidth	0.8°
azimuth coverage	41°
range resolution	6 m (512 pixel/3300m)
Instrumented range	3.5 km
detection range against a person	10 km
weight (radar head)	approx. 15 kg
antenna size	86x15x30 cm^3

Table 3.4: Characteristics of the DASA "HiVision" radar.

within a distance of 2.3/5.2km. On the other hand: the radar range against a person (radar cross section approx. $1m^2$) is 6.9/10km, which means that the hostile detection range is much smaller than the detection range of the radar itself [11]. Or in other words: the aircraft with an active HiVision radar can be detected earlier by "ears" than by an ESM receiver.

4. Results

The following chapter describes results concering driving trials and flight tests and some aspects of radar image processing and fusion.

Fig. 4.1: Multi sensor test van, equipped with the MMW-radar (aluminium box on the top), a video- and an IR-sensor.

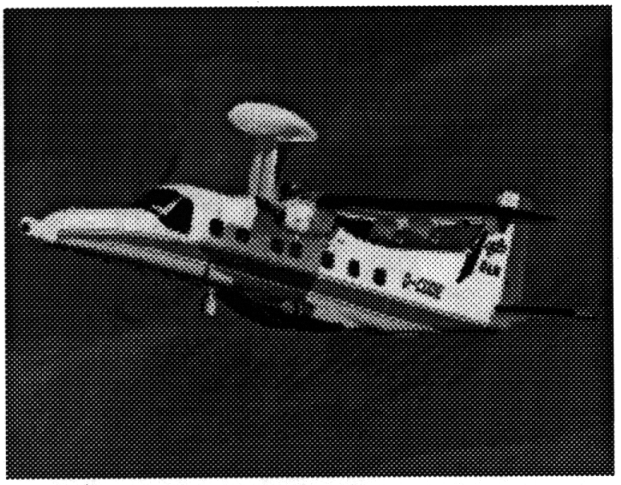


Fig. 4.2: DASA HiVision radar mounted on top of a DO-228.

4.1 Experimental Setup

The DASA HiVision radar is a rather new development which was first investigated within a static environment [19]. The Institute of Flight Guidance at DLR Braunschweig started to take the first step from static scenario to a dynamic one in 1996. In order to establish a rather quick experience, a Mercedes Benz van (Fig. 4.1) was equipped with a differential GPS receiver, with a Litton inertial reference unit (to determine the exact trajectory during the test) and a set of forward looking imaging sensors for the visible and the infrared channel. The visible channel was covered

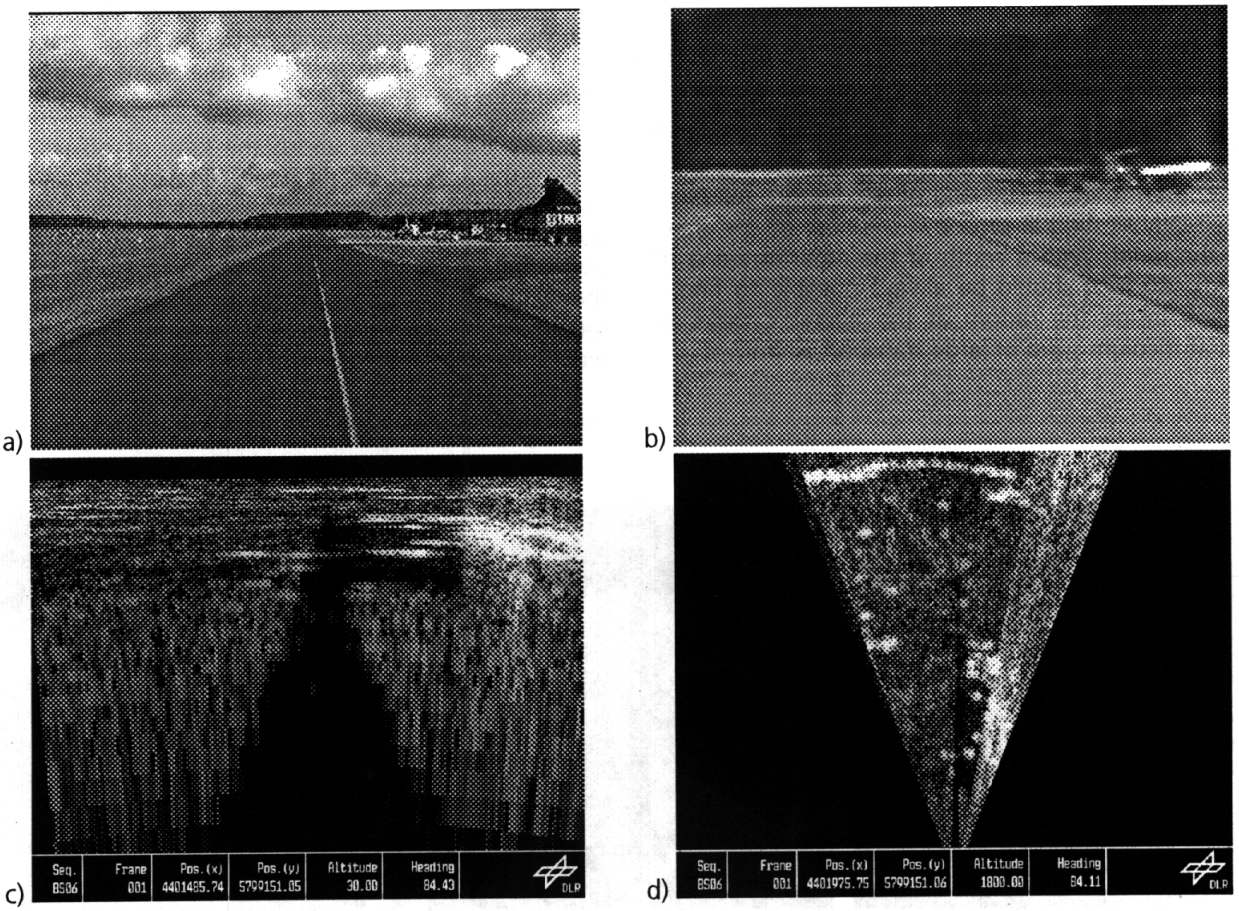


Fig. 4.3: A set of typical multispectral images of a Braunschweig airport taxi way. a) visible channel, b) IR channel, c) Radar "out-the-window-view", d) Radar map view.

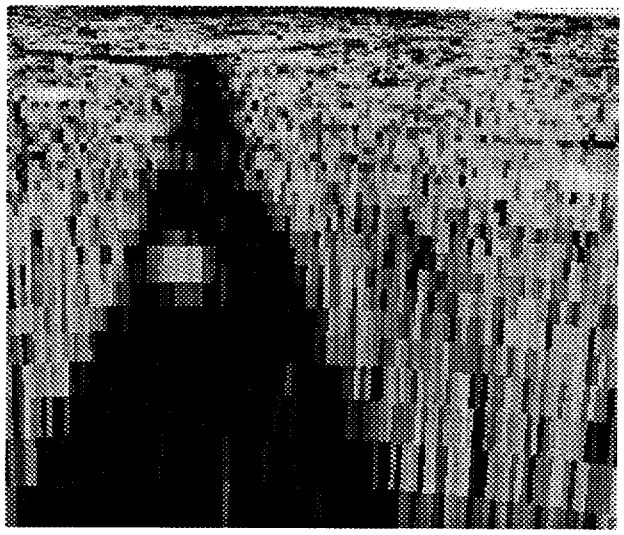


Fig. 4.4: C-scope radar image with "obstacle".

with a video camera type FA 871 (0.4–1.0 micron wavelength) and a resolution of 581x756 pixel manufactured by Grundig. For the infrared channel the AEGAIS – camera manufactured by AIM Heilbronn (former AEG) for the 3-5 micron wavelength and a spatial resolution of 256x256 pixel was used. A set of typical images are shown in Fig. 4.3.

In parallel DASA and DLR developed an airborne version of the HiVision Radar for the DO 228 (Fig. 4.2) . First flight tests are planned for the autumn of 1998.

To avoid any misunderstanding: the "AWACS–like" position of the radar on top of the aircraft (Fig. 4.2) was chosen to avoid any kind of disturbance between the already existing IR-sensor at the nose of the plane and the radar. With a width of the radar antenna of approx. 80cm it should be always possible to find a position inside the radom at the aircraft's nose, at least at medium sized or large transport aircraft.

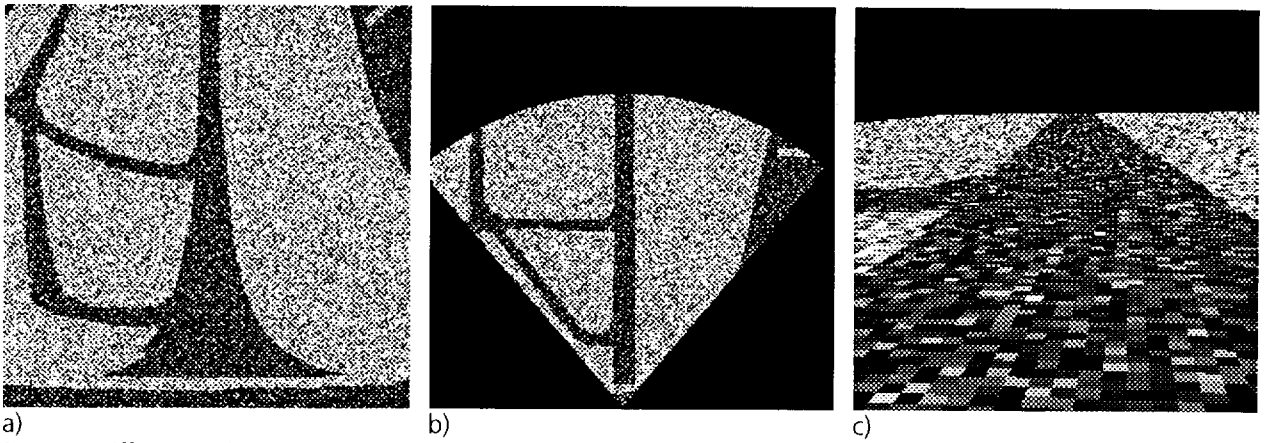
4.2 Experiments with DASA HiVision Radar

Sensor data sets were recorded on Braunschweig airfield driving a well defined course along taxi- and runways. The experiments were repeated at different times of the day (even at night) and under different weather conditions , such as sunny and cloudy sky, rain and fog. Furthermore some artificial obstacles like other vans were placed on the track and natural obstacles (Fig. 4.4) appeared by random.

Fig. 4.3 shows a set of images acquired during a typical test run looking along a concrete runway towards an area with parking airplanes. While Fig. 4.3 a) and b) show unprocessed images of the visible and the IR-channel, images c) and d) show a radar-out-the-window-view (C-scope) and a radar-map-view (PPI-scope) calculated from the raw radar data, which are available in a range angle (B-scope) format.

A very interesting example of the MMW-radar capability for obstacle detection is presented in Fig. 4.4 This image shows the same taxi-way on Braunschweig airport as Fig. 4.3 c), but this time a certain obstacle was located in the region of the taxi-way. Fig. 4.4 also emphasizes some problems which are connected with the interpretation of a radar image: the poor image resolution and the kind of image generation (range angle) which contains no information about the object's height or its vertical position. The only information which is really transmitted by the radar image of Fig. 4.4 is a reflex in a part of the scene (taxi way) where no reflex would be expected.

The pilot has no idea about the kind of object and due to the way of image generation he has also no information about the object's height and the vertical position. In this special case the pilot would identify a bird sitting on the taxi-way, simply by looking out of the window. That's of course not the idea for an EVS-sensor, but from the pure radar information nobody would really be able to decide whether the "obstacle" is under, ahead of or above the own position. This problem of radar-image interpretation is still open.



a) b) c)

Fig. 4.5: Different radar image representations of the same scene. a) range-angle (B-scope), b) radar-map (PPI-scope), c) "out-the-window-view" (C-scope).

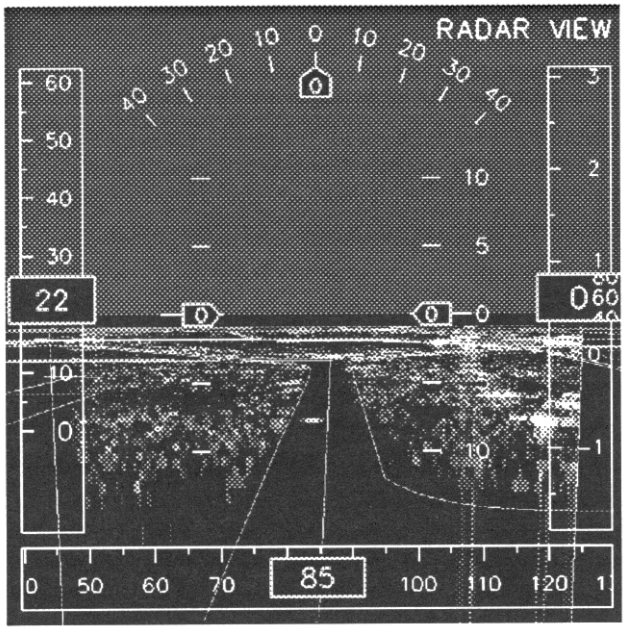


Fig. 4.6: Design example for a fused EVS-display: perspective radar view with overlaid terrain data and PFD-symbology.

4.3 Data Fusion

An integrated Enhanced Vision System, as it is defined in chapter 2, requires the fusion of several data sources. In order to achieve that, all data has to be transformed into the same level of representation.

Especially a radar image data can exist in different formats:

1.	range-angle	B-scope	Fig. 4.5 a)
2.	map	PPI-scope	Fig. 4.5 b)
3.	out-the-window-view	C–scope	Fig. 4.5 c)

Of special interest for radar images is the range- angle, or B-scope representation. This type of image contains two basic information: the distance (range) of a certain object relative to the radar head and the direction in terms of the azimuth angle. These "range-angle"-images use the x-axis for the angle representation and the y-axis for the object (i.e reflector) distances.

Figure 4.5. shows some examples for these different types of image data representations.

A first, rather simple realization of an Enhanced Vision System deals with the fusion of radar images, which might be available in the "PPI-scope"-format or as "out-the-window-view" with a terrain data base.

Position and attitude delivered by the vehicle's navigation system and a 3-D terrain model are used to compute a wire frame overlay of terrain elements which can be presented in combination with the radar image. The fused radar images are a rather natural supplement to the type of information which are carried by the primary flight display (PFD). A tentative example how to integrate such a fused image into a PFD is shown in Fig. 4.6.

Fusion techniques, especially in the field of image data fusion, are often devoted to the fusion of several image sources with different spectral sensitivity [16]. In a first step the emission of all objects and radiation sources are transformed into the same spectral region in order to make them visible or detectable with a common tool, which is in many cases the human eye.

Disregarding the possibility of data reduction which might be achieved with an image fusion technique, the main reason for image data fusion is to improve the situational awareness of the pilot and the observer respectively. In [18] the authors demonstrate a dramatic increase in reliability of target detection and observer performance if visible and thermal images are fused either grey or color.

If we concentrate for a moment on the EVS-technique as a possibility to increase the pilot's or crew's situation awareness - again disregarding requirements for reconnaissance or remote control - we have to compete with a very famous "vision system": the pilot's eyes! In terms of situation awareness the EVS-technology should "enhance" the ability of the human operator, but not replace him. With this background the design of an enhanced vision system, especially the applied fusion philosophy, has to be examined very carefully :

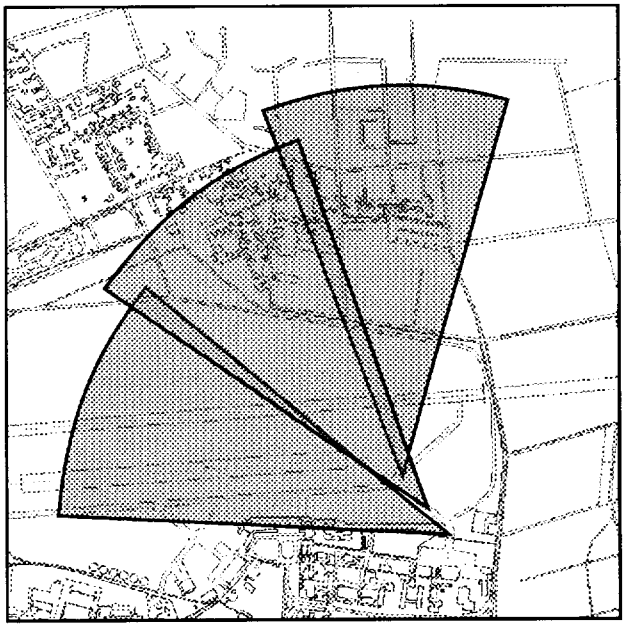
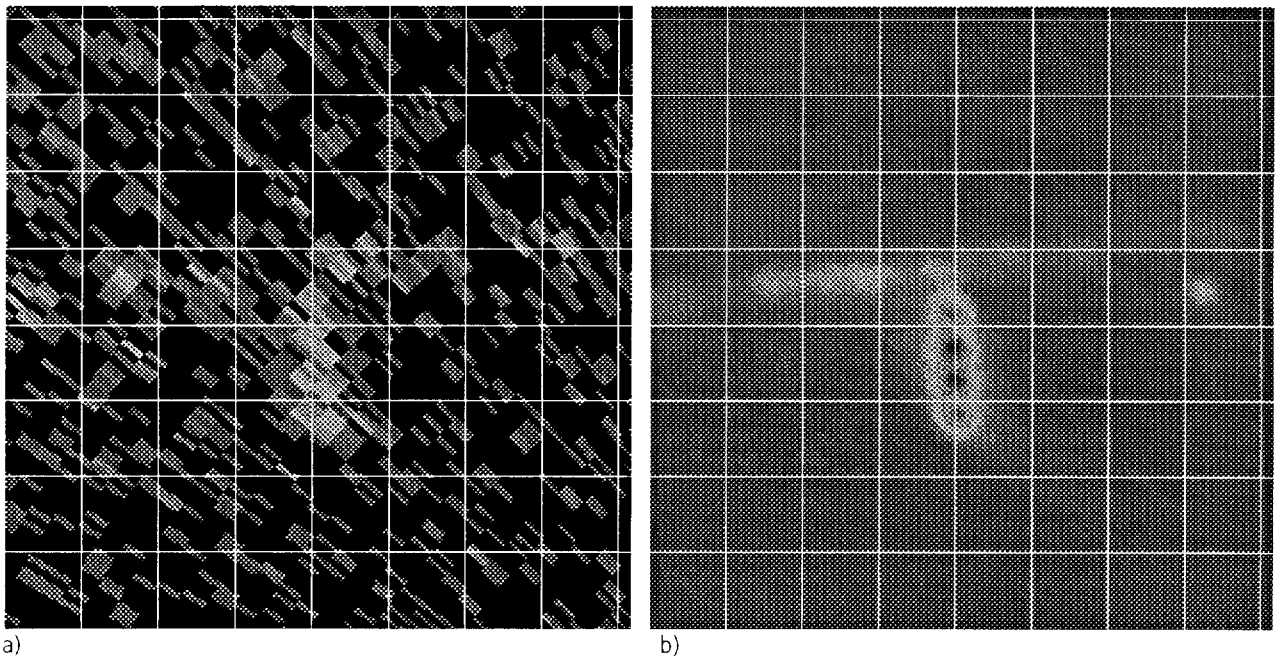


Fig. 4.7: Fusion of radar images to an overall view of Braunschweig airfield (fusion in space, with a moving vehicle).



a) b)

Fig 4.8: Noise reduction in a PPI-scope image (grid-size 20 m). a) detail of single radar image, b) the same part after fusion of 50 single images (approx. 3 seconds of data).

- What kind of additional sensor really enhances the human cognition?
- How useful is a sensor which covers the same, or a similar spectral range as the human eye?
- What kind of representation (map or "out-the-window-view") in what situation should be used?
- What type of images , symbols, synthetic- or sensor vision, should be displayed on a HUD?

Another rather important type of data fusion, especially for radar images, is related to a technique which could be called "data fusion in time and space". Beside the fusion of different data (images) from different sources, it is also possible to fuse different images from one sensor, taken from different positions and at different times . The SAR-technique or computer tomography are good examples how to improve the information of one sensor using data "fusion in space". For EVS applications this approach offers the following advantages:

- (determination of objects height and vertical position by displacement vectors),
- reduction of background noise,
- integration of single snapshots to an overall view.

The first point is set into brackets, because the authors feel that this advantage doesn't really exist, although it is mentioned in the literature [10]. Because this type of radar measures only the distance to certain objects, an information about their vertical position (and height) is not available. A possible solution of this problem could be a series of distance measurements which are taken from the moving radar, because the slant distance is a function of the objects vertical position relative to the radar head. This is the idea to overcome the lack information about the vertical axis, but for the actual available radar systems this procedure fails, due to the rather large range errors, which are in the order 3–6m [12].

The other above mentioned data fusion techniques, fusion in time and fusion in space, are rather promising, particularly for the range-angle images of a radar. The wire frame map in Fig. 4.7 represents the Braunschweig airfield and the shaded segments indicate those parts of the map which are covered by the radar (PPI-scope) during taxiing. Using the information about the vehicles position, which is given by an inertial reference unit, or by means of GPS, every single radar image can be assembled to an overall view of the whole airfield. (For this special fusion technique

reference system	type of image	Result
cockpit	C-scope	noise reduced "out-the-window-view"
geographic system	PPI-scope	overall map-view

Table 4.1: Fusion in time and space for different reference systems.

the "map-like" information of a radar image is very advantageous.)

The image rate of the DASA HiVision radar is 16Hz, which leads to a large overlap of the PPI-scope images. If the vehicle's velocity is rather slow compared with the frame rate, which is a typical situation during taxiing, the overlap between consecutive radar images covers a large common area. This feature can be used for noise reduction and to eliminate or to detect moving targets by means of an averaging technique, adding up weighted grey scale values. The effect of such a motion compensated fusion technique is threefold:

- noise reduction,
- enlargement of image coverage,
- increase of spatial resolution.

The result is shown in Fig. 4.8: a) presents a detail of a raw PPI-scope image. After fusion in space and time, the image noise was nearly completely eliminated and the object itself can be identified as a row of lamps.

The fusion of radar images shown in Figure 4.7 refers to a situation with a fixed map and moving vehicle. In this case the fusion procedure eliminates all moving objects and of course the noise. These features qualifies this type of fusion as a "map generator".

The same fusion technique can be applied to a "out-the-window-view" (C-scope) with a fixed vehicle and a moving map. Unfortunately moving objects are also suppressed, but the visibility of fixed objects will increase. Table 4.1 compares these different fusion techniques.

5. Conclusion

The integrated enhanced vision concept as it is investigated at DLR demands the fusion of sensor vision, synthetic vision and additional information of the inner and outer status of the vehicle. In order to meet most weather situations DLR decided to use the HiVision radar from DASA Ulm, which is a forward looking active, but from the military viewpoint a "silent", MMW imaging sensor. Radar sensors are very promising in the field of weather penetration, but on the other side they are a great challenge concerning noise and resolution, (angle and range) and they fail completely delivering the vertical position of the depicted object. Data fusion techniques, such as an overlay with terrain data, or fusion in time and space may be applied to overcome the former difficulties. The restriction of the MMW-technology to a range-angle information and the impact on the architecture of the overall Enhanced Vision System is still a topic for research.

A very promising imaging technique in this field would be the total 3-D reconstruction of the outside world from 2-D (range-angle) radar images. This would require the adoption of signal reconstruction methods, as they are known from computer tomography (CT) by fusing radar images with different scanning directions. These image data could be acquired for example by at least two orthogonal mounted radar antennas or by a rotating one.

First experiments with the DASA HiVision Radar as an enhanced vision sensor show some very promising results concerning range, image rate and resolution.

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A Distributed System for Command and Control Applications with Programming Language Abstraction

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1. SUMMARY

As processing and time requirements of computer systems increase over borders of single processor architectures, it is becoming more attractive to use distributed computing with additional real-time capabilities. In several cases, traditional programming languages have become insufficient to build such systems easily, especially when basic software quality factors such as reliability, correctness, robustness, ease of design, development, testing and maintenance are concerned. In this paper basic issues relevant to distributed systems are discussed, similar systems and languages are compared, a new language with its supportive run-time system is introduced. The new system provides a solution that hides implementation details from the programmer by embedding distribution and real-time issues within the programming language structure. In order to demonstrate the usage of the new language, basic requirements of distributed naval command and control systems are touched and a simple naval application design and part of the implementation is briefly explained.

2. INTRODUCTION

Real-world systems consist of many distributed components that are asynchronously interacting with their environment. When distributed computing and concurrent processing are considered, it can be seen that conventional programming languages have become insufficient due to the lack of convenient structures for inter-process and inter-node communication. These languages may be efficient for software architectures that use single processor. However, when it is necessary to distribute an application over a network, they tend to become a burden on the programmers due to inconvenient facilities of the underlying operating system and hardware. Therefore it becomes essential to use a *middleware* for decoupling.

Generally, applications are developed using a classical language and several user defined libraries. In this case, the importance of software characteristics, methodology and development issues get the focus. One of the most suitable programming styles is to use object-orientation. The distributed form of this approach requires communication between distinct objects on different nodes. Tightly or loosely coupled computer systems may be used depending on the inter-object communication load. Real-time applications that require critical input and output operations and processing on different nodes are especially difficult to design and implement. Such systems are also required to have important features like high reliability, efficiency, scalability, expansibility, portability and ease of maintenance. Therefore, distributed programming languages have evolved to meet the new requirements within the language constructs, leaving only the design part to the programmer. Since object-oriented programming (OOP) has several important capabilities, adapting them onto a distributed environment with real-time properties has become an important area of research, which has resulted into the evolution of a number of object-oriented, concurrent, distributed and real-time programming languages.

One important domain for research is the command and control systems (C^2) that facilitates a real-time middleware. The system introduced in this paper proposes a solution without an explicit middleware approach, but a programming language.

3. DISTRIBUTED AND REAL-TIME COMPUTING

A distributed and real-time system is desired to be concurrent, fault-tolerant, reliable, fast and efficient, in both computing and communication. Programming languages that are used to develop such systems should have some extra features, in addition to software engineering properties, like modularity, extensibility and reusability. Some of these features are discussed below.

3.1 OOP Languages

OOP languages have special constructs which divide programs into smaller portions called objects. These objects can only be accessed via methods that are

Paper presented at the RTO SCI Symposium on "Sensor Data Fusion and Integration of the Human Element", held in Ottawa, Canada, 14-17 September 1998, and published in RTO MP-12.

defined in their interface. Common properties of OOP languages are specified in (Meyer 1988). A program must be built using separate modules that help designers to produce software systems made of autonomous elements connected by a coherent simple structure (Modularity). Objects are defined as abstract data types encapsulating data elements and operations on them (Data abstraction). Objects using system resources are deallocated automatically when they are finished with (Memory management). Nonsimple types whose instances are objects define classes (Class). A class may be derived from another class inheriting some or all of the properties of the base class (Inheritance). Finally, polymorphism refers to the ability of an entity to refer, at run-time, to instances of various classes. Pure OOP languages meet all these criteria, providing multiple and repeated inheritance. Having the first four properties and all properties are called object-based and object-oriented respectively. When these properties are applied to distributed environments, it becomes essential to define objects either as activities or data. Many concurrent languages like RTC++ (Ishikawa and Tokuda 1992), Mentat (Grimshaw 1993), Concurrent Smalltalk (Yokote 1990) and Eiffel have chosen to use objects for processing elements that are subjected to distribution. On the other hand, Linda (Robinson and Arthur 1995) and SR (Andrews 1982) use data objects.

3.2 Concurrency

Concurrent languages use special constructs for creating processes depending on the underlying operating system. A process is usually defined as Unix-like processing elements that have separate contexts with distinct address spaces coexisting on the same processor. Some systems allow *threads* to be used within a process to support higher level of concurrency. Mutual exclusion and synchronization must be provided when concurrent accesses to critical resources are considered. Although operating systems can provide such facilities, it is usually the programmer's responsibility to implement shared data protection and process synchronization. In distributed systems, processes communicate by message passing or remote procedure calls. Maximum parallelism can be achieved by providing asynchronous message communication that lets the sender continue without having to wait for reply. Some concurrent languages let the programmer specify the concurrency with the language constructs, while others manage it implicitly. Processes and data storage areas can be distributed over the network. These objects can be moved, or migrated, from one node to another.

3.3 Process management

When parallel computing is considered, process management requires special attention as it is necessary to manage them different than ordinary objects. For example, in C++, objects are created by their constructors and deleted by their destructors. Calling a class constructor that creates a process and a destructor that kills the process is not a suitable solution in concurrent environment due to extensive overhead of process management. Therefore, some concurrent programming languages create or terminate processes explicitly, while others create them implicitly, but terminate explicitly. Process granularity is another design parameter in concurrent programming. If communication to processing ratio of a program is small then coarse or large granularity must be selected. If this ratio is high, then small or fine granularity can be used. Threads may also be used to obtain finer granularity. Coarse granularity typically implies one task per object, requiring less communication.

3.4 Communication

In a concurrent environment, objects that are implemented as processes use interprocess communication facilities of the underlying operating system. Concurrent languages like Mentat, ES-Kit C++ (Smith and Chatterjee 1990) and Pearl (Stoyenko and Halang 1993) have constructs that provide this communication in synchronous or asynchronous manner. Ada, which is not a distributed language, uses rendezvous mechanism, like SR, to exchange information between tasks. In a distributed environment, objects communicate using messages that are passed through various network layers. Distributed operating systems hide the network level communication so that all programs seem to execute on a single machine.

When objects are implemented as distinct processes or shared memory segments, they have to be identified specifically at the operating system level, even at the network level. Therefore a global name resolution with kernel or run-time system support for message communication has to be used. Some systems use direct communication method, in which messages are sent to the receiver whose name and location is known by the sender. This approach increases object dependency as each object must have sufficient and consistent information about other objects.

3.5 Inheritance

Many concurrent, object-oriented languages have problems with inheritance. Some languages such as

Eiffel, ES-Kit C++, Java, though, eliminate multiple inheritance where some languages, like Orca, POOL-T (America 1987) do not allow even single inheritance. Other approaches like delegation, static, dynamic and on-demand inheritance and recipe-query method are also used by some languages.

3.6 Real-time aspects

Some mission critical systems require real-time constraints to provide fast response to events occurring at non-regular rates. Real-time systems can be separated into three groups: Soft real-time systems do not fail in case response time constraint is not met, only performance is degraded. Hard real-time systems have to meet deadlines, otherwise system failure occurs. Firm real-time systems are somewhere in between, where low probability of missing a deadline can be tolerated. Generally, hard real-time systems are designed to work with special hardware because of the importance of deadlines. Timing constraints for such systems are predicted off-line and sufficient resource is always left for unpredictable events. Therefore resource allocation, pre-emption and priority issues are very important to meet the real-time requirements.

Languages used for building real-time systems are desired to have some important characteristics such as strong typing, dynamic memory management, fast parameter passing techniques, exception handling, abstract data types and modularity.

4. RELATED WORK

A number of concurrent, distributed and real-time systems as well as programming languages have been examined. Of these, RTC++ and Mentat are emphasized as they have more similarities with the proposed approach. Several common points are noted and the language structure with its run-time communication facilities are considered.

RTC++ introduces temporally constrained active objects which are distinguished from ordinary C++ objects. Timing constraints may be specified as part of method declarations. The language also allows timing constraints to be specified in commands within methods. RTC++ uses a multi-threaded model to describe real-time applications which means multiple operations can be invoked on an object and alter its state. Asynchronous communication is not supported due to the difficulty of recovery. The language employs priority inheritance distribution facilities.

Mentat is an object-oriented, parallel processing system using MPL, an OOP language based on C++, masking the complexity of the parallel environment from the programmer. The underlying Mentat run-time system provides a virtual machine abstraction for easy portability to new architectures. Mentat extends C++ in three ways: the specification of Mentat classes, the *rtf()* value return mechanism, and the select/accept statement. The programmer uses Mentat objects just as any other C++ object. Independent Mentat objects have a distinct address space, a system wide unique name, and a thread of control.

Java from Sun Microsystems is a pure object-oriented language specially designed to work on heterogeneous internet nodes executing byte code. A large class library is provided for several purposes. Concurrency, portability, polymorphism and dynamic linking is emphasized, but due to byte code interpretation, real-time efficiency is reduced.

CORBA (Common Object Request Broker Architecture) is a widely excepted architecture standard utilizing a special Interface Definition Language (IDL). Even though CORBA uses IDL for interfaces, programmers have to use a common language like C++ or Java for implementation.

5. CORD PROGRAMMING LANGUAGE: CPL

The available research work has been examined and it is concluded to combine several features into one programming language as an extension to C++ with new keywords. Since a higher level of abstraction to logically interconnect distributed processors considering real-time requirements is needed, a special layer running on top of the operating system has been built. This layer is called the CORD-RTS standing for *Concurrent, Object-oriented and Real-time Distribution Run-Time System.* Therefore the language is given the name *CPL* (The CORD Programming Language).

5.1 The CORD System

The CORD System framework is designed to allow application development that is independent of hardware, operating system and network topology, facilitating a programming language.

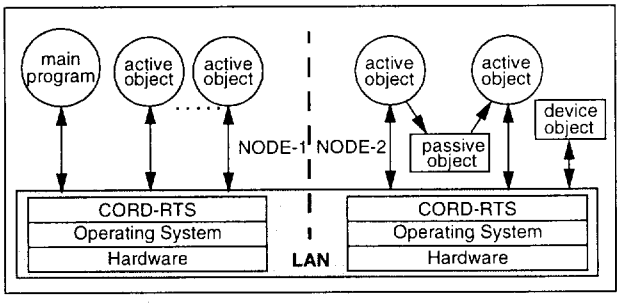

Figure 1. The CORD system architecture

The system has less interaction with the underlying operating system. Therefore, the entire system, together with applications, can easily be ported to a new environment by modifying only those parts that are in interaction with the operating system. Figure 1 shows the system architecture which consists of the following parts:

The CORD Run-Time System (RTS) : The RTS running on each node has four active elements: *Object Manager* is the general object controller which maintains a distributed database of the running programs, classes and their instances. It also manages the nodal data storages in shared memory, handles prioritized messages, controls the publish-subscribe mechanism and reports node availability. *Net Manager* handles network access by considering the logical CORD network. *Device Manager*, which is executed optionally, keeps track of devices on the node and provides multiple access to them. *Error Manager* collects reported errors in a specific format and displays or writes into a disk file. An interactive command shell is also provided to execute programs and objects individually in addition to obtaining system information. These elements with their interactions are shown in Figure 2.

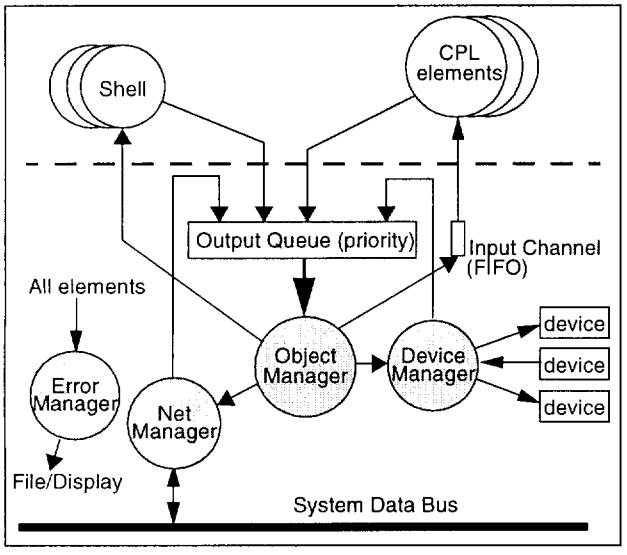

Figure 2. The CORD system infrastructure

Main program : A program is defined as a collection of executables which will later construct the global, distributed program. Therefore, each CPL program must have a main module, like a conventional program, which ultimately is executed on the RTS. This part registers the program itself and its classes to the RTS, and then creates the necessary objects. Those objects later create other objects over the network. Terminating the main program results in the termination of all its classes and objects, independent of their location.

Class Servers : In order to create objects as processing units, a server is used from which child processes are forked. There are as many active class servers as the number of active classes declared in a program. Each node has a copy of each server, ready to create an object.

Objects : There are three basic types of objects in CPL. Active objects are the processing elements, passive objects are plain, shared data storage areas. Device objects control the hardware part of the node and are kept inside the RTS of a node.

5.2 Classes

CPL introduces three new types of classes in addition to regular C++ classes. These are active, passive and device classes, from which active, passive and device objects are created respectively. CPL also supports multiple inheritance in a way similar to C++, provided that the classes are of the same type. Inheritance is achieved statically by the CPL compiler.

Active class : Active classes are implemented using Unix-like processes and act as primary processing elements. Instances of this type of classes are capable of calling methods of other objects. Methods of these objects are accessed by only special messages generated by the compiler, however the programmer just issues a method call. Instances of active classes may have static or dynamic data parts that are specified in the class definition. Dynamic data are stored in a reliable storage on the node. Static data elements are stored inside the object context. During object migration, the dynamic data part is copied to a new location in the destination node and a new active object is created initializing from the data copied to that location. Active objects can be accessed from any node of a distributed environment provided that the necessary naming and scope resolution is achieved.

Passive class : Instances of passive classes are used as a means of data storage and are not capable of calling methods of other objects. These objects can easily be accessed within the context of an active object, providing fast read or write functions. Passive objects can only be accessed by an active object located on the same node and cannot be migrated.

Device class : A device class defines a coherent interface for input and output devices. The class definition specifies only the necessary parts for a programmer to access a physical device. All controls are done by the Device Manager existing on a node. The manager can also provide active object

subscription mechanism for read access. An active object that wants to be triggered by a device input subscribes for that device object data with its own method. When new data is read, the manager calls the registered method of the active object.

5.3 Communication

Inter-object communication can be synchronous, asynchronous or broadcast. These modes are set by the CPL compiler. Actually, programmers never use messages, instead, method calls specified in the class definitions are used. All method calls, replies and published methods are converted into system level messages having priority, destination and time stamp. Therefore all method parameters have an indicator, *in*, *out* or *inout*, to specify the type of communication. If a method has only *in* parameters or no parameter, it causes a one-way call. If there is at least one *out* or one *inout* parameter, then the call is said to be two-way and blocked. Subscription is a way of asynchronous method invocation without having to know the destination objects.

Interdependency between objects is reduced by allowing communication only between active objects and the RTS. Thus, an object prepares a message for a specific method call indicating the destination and sends it to the RTS. The sender object does not have to know where the receiver object is located, or in what state it is. The RTS finds the location of the destination object and forwards the message either to the object itself (if it is located on that node) or to the RTS of the node on which the object resides. The RTS on the destination node transfers the message to the object. The destination object may be in a blocked state waiting for a method invocation or a reply to a specific call. It can also be in a running state doing its work. In any case, the incoming call is accepted implicitly by the object, and the message is put into a queue inside the object context, waiting to be processed according to its priority. No preemption takes place inside the object.

5.4 Real-time aspects

CPL and its supportive run-time system is designed to develop soft real-time systems easily. Therefore, some basic timing constructs are defined in CPL for specifying real-time constraints at statement level. Prioritized message handling, timed loops, time-triggered method calls in millisecond domain are provided and process scheduling is left to the existing operating system. Language structures also enable the programmer to specify actions in case time limit for a statement or for a method call are exceeded. Fast access to shared data is achieved using passive objects.

All active objects send their messages carrying method calls to the RTS with an assigned priority ranging from 1 to 10 and a time-out value defining the validity of the message. The programmer should assign suitable priorities and time-out values to method calls explicitly for efficient resource utilization, otherwise, system defaults are used. Unless otherwise is stated, active objects send their messages with their own scheduling priority. Since messages are subjected to communication delays, in some cases, programmers can assign priorities to method calls higher than the active object's.

Priority inversion feature is provided for the objects that are running with lower priority. When a high priority call is received, the receiving object increases its scheduling priority up to the priority of the incoming call. After the method is executed, the priority is lowered again. Low priority calls do not cause an object to reduce its scheduling priority.

Real-time filters are used inside the CORD system. Each manager in the RTS checks the time-out value of an incoming message to decide if there is sufficient time for communication delay and processing. If not, it does not forward the message and sends a system reply back to the sender. The sender object then raises an exception to be handled by the programmer.

5.5 Distribution

The CPL objects can be created on any node within the network. Object creation is performed in a similar way used in C++ constructors. Objects use three level naming convention. Of these, the first level uses program identification which enables multiple copies of the same distributed program run simultaneously. The second level is the class identification, and the third level is the object identification. In order to speed up processing, numeric representation of logical names are used within the system transparently.

Migration of active objects is performed by stopping the process, copying the contents of the dynamic data and starting a new process at the new location. For this purpose active classes specify if they want to use dynamic data storage which is in a safe memory area. Necessary communication and control of messages during migration are handled by the RTS.

CORD objects do not communicate directly with each other. The caller object only issues a method call with appropriate parameters and waits for reply from the RTS. If fast information transfer in the same node is needed, passive objects can be used without interacting with the RTS.

5.6 System Characteristics

The CPL compiler generates C++ source code modules to be compiled with the target compiler. The resultant distributed program consists of a number of executables for the main module and each active class. These program components are loaded into the disk locations which are accessible by all the nodes. The software structure of an application developed in CPL is shown in Figure 3. Application is isolated from the operating system, underlying computer hardware and local area network. However, standard C++ libraries as well as operating system calls, can directly be used in addition to the CORD Interface in C++.

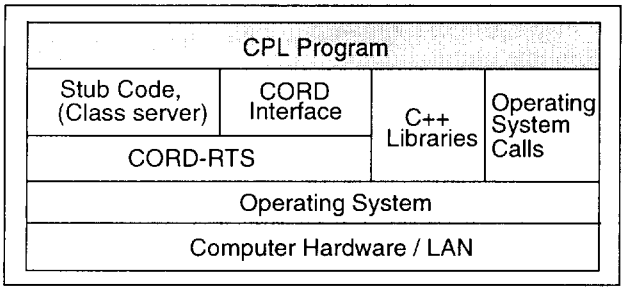

Figure 3. Software architecture

Generally, a good OOP practice dictates an efficient use of scope resolution. That is, objects must be visible to only those objects that are in the same block. An active object is a process managed by the operating system of that processor. It can be accessed by any other active object within the same network. This seems in contradiction with some of the software engineering rules like abstraction and information hiding. However, CPL classes use the same visibility rules as C++. Even though created objects are global to all nodes the CPL compiler manages the scope rules considering files, functions and blocks.

CPL enables programmers to be able to develop a distributed program without concentrating on communication and the physical layout of the system. Programmers write CPL modules as if writing a regular C++ module, either using full capabilities of C++ or CPL specific keywords and structures for distribution. CPL modules are then fed to the CPL compiler to generate separate client and server stub code to access the RTS. The resultant C++ modules are compiled with an existing C++ compiler to generate the necessary executables for each active class and for the main module. Batch processing hides details from programmer. These files are then loaded onto the target nodes. After starting up the RTS on each node, the main program is loaded and started from the interactive shell which creates class servers and objects. Sample CPL class declarations, object creation, timed loops and statements with time constraints are shown below:

```
active class Class_B inherits Class_A {
uses Class_C;          //include the interface
priority 5;            //object scheduling priority
static:                //context specific data part
  int           mem_size, num_elem;
  Boolean_Type  ready;
dynamic 1024:          //amount of dynamic memory
  Link_List     element_list;
methods:               //class methods
  GetNumOfElem(out: int n);          //two-way call
  Compute(in: int X; out: int Y);    //two-way call
  Calculate(inout: int Num);         //two-way call
  Insert(in: int Num);               //one-way call
periodic 1000:         //time-trigger in millisecond
  Do_Processing();
publish:               //published data
  NewData(int);        //parameter type is used
subscribe:             //own method to another class
  Calculate to Class_C.New_Data;  //active class
  Insert to Serial_Comm.TheDevice.Read_Data; //device
private:
  void Square();       //visible to only this class
};

passive class P1 {
static:                //passive class data
  int       index;
  int       data[100];
methods:
  Insert(in: int Value);
  Get(in: int Key; out: int Value);
};

device class Serial_Comm {
read int;              //data type to read from device
buffer 10;             //number of elements in buffer
speed 19600;           //baud rate (bps)
methods:               //callable method
  GetValue(out: int val);
publish:
  Send_Data(int);  //published when data is read
};

Class_A     obj1;      //New creation
Class_A     obj3(initial_val) on "NODE_4";
Class_A*    obj4 = new Class_A on"NODE_4";
obj1.Bind("obj1");     //Binding to an existing object
obj1.GetA(val,TIMEOUT);   //millisecond, timed call
obj1.GetA(val) timeout 1000 { HandleTimeout(); }
obj1.SetA(val) on 15:30:00.0;
obj1.Calculate(a, b) within 50;

do {
  Sensor.Check_Status(status) timeout 100;
} every 1000;    //millisecond

do {
  a.Read();
  b.Write();
  sleep(1);
} until 20:45:00.0;
```

In addition to the keywords, some basic functions for CPL classes and RTS utility routines are also provided. The programming process will be less problematic if certain functionalities can be achieved through the use of keywords, rather than calls to library functions. Also, learning the rules of a language is easier than learning a given library. Since CPL is based on C++ language, any previously written C++ code is accepted by the CPL compiler.

6. PERFORMANCE ANALYSIS

During the system development, various tests are performed in order to figure out the system

bottlenecks and time consuming parts. Table 1 shows some performance figures in microseconds obtained by averaging the time consumed by one object calling another object's method. The first test environment consists of Sun Sparc4 (100 MHz) workstations with SunOS 4.1.3 on 10 Mbs ethernet. The second one is a stand-alone Sparc notebook (70 MHz) with Solaris 2.5 and the third one consists of Sun Ultra60 (300 MHz) workstations with Solaris 2.5 on 155 Mbs ATM network with LAN emulation.

The performance tests have shown that inter-object communication can be reduced dramatically if passive objects are used. However, active object communication latency increases as the number of active objects requiring parallel execution increases.

Table 1. Performance figures

Test	Sparc4	Sp.Book	Ultra60
One-way method call, same node	850	1300	550
Two-way method-call, same node	2600	3500	1550
Two-way method-call, different nodes	6700	N/A	2250
Reading passive object with Lock/Unlock	180	220	50
Reading passive object without Lock/Unlock	0.18	0.25	0.15

7. COMMAND AND CONTROL SYSTEMS

Computerized control systems provide data collection from various sensors or input devices, evaluate them and control some actuators. Command and control (C^2) systems in military platforms help a command team to understand tactical situations and allow them to control sensors, weapons and other subsystems. Recent C^2 systems include communication as well. Such systems have some common characteristics when technical and functional aspects are considered.

These systems are difficult to develop because, their use in defense applications makes correctness and reliability critical. Their requirements are difficult to determine and standardize as they are influenced by organizations, policies or doctrines. Their design require special techniques to guarantee real-time constraints are met. As with any large system, realizing such systems require high costs because of the amount of mission critical software to be developed. Modern C^2 systems have distributed processing, real-time constraints, multiple and predefined hardware interfaces and operational requirements. A C^2 system for naval platforms has several external interfaces to the user and to the platform sensors, weapon systems, navigation system and data links as shown in Figure 4.

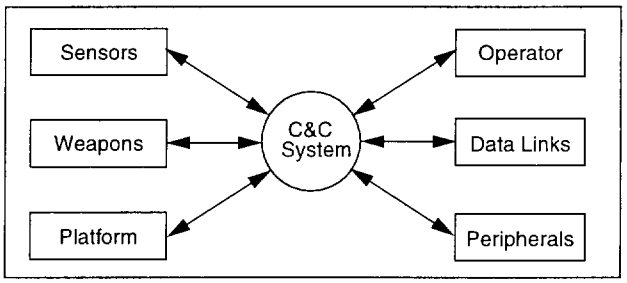

Figure 4. Context diagram of a C&C system

The primary object for a C^2 system used for surveillance is a *track*, which is defined as the representation of an external object in the system with several characteristics like type, position, kinematics and identity. The system maintains a common track database which is updated continuously by the sensors. This database is managed by a special software component, the Track Management, which provides correlation of multi-sensor track data to form a single track for the user. Tracks are identified uniquely by assigning numbers considering their types, such as point tracks, bearing tracks, reference positions, operator maintained tracks and network tracks.

8. PROPOSED SOLUTION TO C^2 APPLICATIONS

Large scale C^2 system software requires efficient infrastructure that is capable of handling large amount of high frequency data preserving real-time aspects. The CORD System can meet requirements for a soft real-time, distributed application well enough providing necessary decoupling of hardware, operating system and application software with a modular approach. CPL brings extra advantages by providing a straightforward solution with programming language abstraction to the complexity of design and implementation.

A common naval C^2 system on board a combat ship receives asynchronous data from radars and other sensors, processes them considering priorities and sends control commands to actuators, such as trackers, weapons or other peripherals.

8.1 Architecture

There are many different architectural solutions to naval C^2 applications. These can be addressed in two separate topics as hardware and software.

Hardware Architecture

Recent combat systems utilize loosely coupled hardware structure. Therefore a local area network is

used. Computation elements are usually placed over the network according to the selected model. One of these is the *centralized* model where a central computing element serves to all clients. Another solution is the fully *distributed* approach in which processing is distributed over the computing elements interconnected via a local area network. Since the distributed model provides a better fault tolerance for the proposed C^2 system, only this architecture will be emphasized.

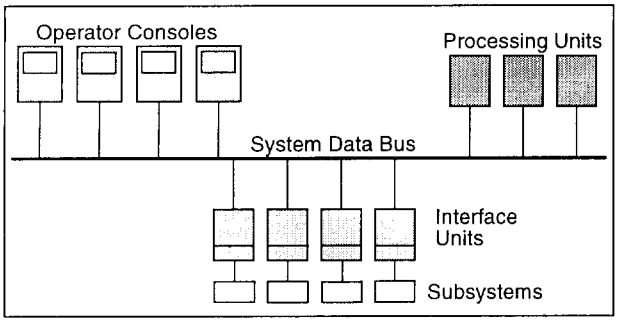

Figure 5. Distributed system architecture

The system, as shown in Figure 5, has different units for subsystem integration, processing and operator interaction. The operator consoles provides user interaction and graphical display of tactical situation. Displaying radar video, TV video and digitized map are also basic functionalities presented by the console infrastructure. The main processing units provides computation power for heavy processor loads. Integration units are used to connect a subsystem to the main system for data transfer.

Software Architecture

The CPL software architecture as shown in Figure 3 is applicable here. The application for such a system can be implemented as a CPL program on top of the RTS. It is also possible to use some special software components to make the system fault tolerant. In order to keep the system as highly available, the number of computing elements can be increased letting them have copies of active class servers to be used when a new object creation is necessary. In case a node failure, a mechanism which detects the fault can easily reallocate the active objects from the class servers on another node.

8.2 Implementation

A distributed C^2 system as described here can be implemented using the CORD System. The RTS handles inter-object communication and the CPL provides a high level interface to the RTS to help programmers at the language level. Entire C^2 system can be considered as one single CPL program in which all classes and their instances are unique. This program can also be treated as a *domain* which may exist in a naval C^2 system. A domain can be defined as a collection of subsystems and services. A C^2 system may contain several domains that are independent from each other and interconnected via special gateway software. Three typical domains can be identified on board a ship. Ship command level domain owns all the physical system resources. All weapons are controlled at this level. Tactical command level domain is managed by the group commander, having special tactical data links and command services controlled via operator consoles. A simulation domain can be configured with the existing consoles with simulated subsystems. Any combination of these domains can coexist in the same physical system. The CORD system provides a feasible solution for implementing these domains by using separate CPL programs.

CPL device objects can be used to receive data from external devices and distribute them to the interested active objects for processing. The active objects located on the main computing elements process the data according to some predefined rules, the command team directions and other necessary information previously distributed and stored in passive objects. The processed data are then either fed into an actuator via device objects, or distributed to the entire system to be stored and used on-demand basis. In order to keep nodal passive data storage always up-to-date, each node should have a manager object to subscribe such data and write into the passive objects. Thus, the generation frequency of data does not effect the consuming clients. Whenever a client wants to use data it simply reads it from the local storage, without any context switch.

The core C^2 system is identified as a collection of some major components such as Platform Data Handling, Navigation, Track Management, Warfare, Subsystem Management and Training. Following sections describe how some of these components can be implemented.

Platform Data Handling

This component provides distribution of platform specific data like reference time, compass, log, roll, pitch, wind, global positioning system data to all nodes in the system with appropriate frequencies.

Time synchronization among the nodes has substantial importance as it is necessary for accurate position calculations for weapon control. Hardware, software based solutions or a combination of them for network time synchronization has to be used.

The publish-subscribe mechanism of the CORD-RTS provides an easy solution to the distribution of

the platform data. An active object, Local Database Manager which runs on each node subscribes to the related methods of the Platform Data Generator running on the integration unit, and stores the data on the local passive object Platform Database. Any active object located on the same node is then able to access the platform data with less latency. In the proposed system, it is sufficient to store the accurate platform data only on the main processing units. The local databases provide manipulated platform data such as geographical position, cartesian position, drift, absolute course and speed. Figure 6 and Figure 7 shows the design and implementation respectively.

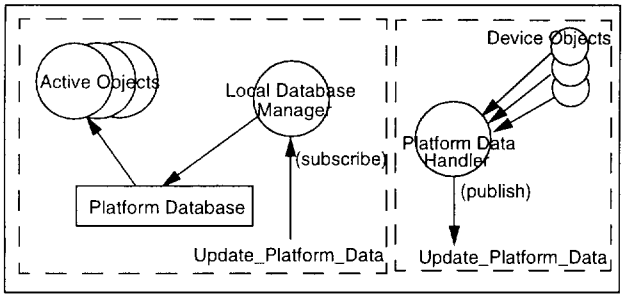

Figure 6. Platform data handling design

Track Management

A C^2 system that has to perform surveillance task must maintain a track database as a correct mirror of external world. There may be two different design approach for track management. The *centralized* model and the *distributed* model which are shown in Figure 8. In both models, real-time tracks that have special importance can be assigned priorities in order to represent urgency. Tracks are assigned priorities according to their importance to the platform. For instance, an engaged hostile track has the highest precedence, where a suspicious track has a higher priority than that of a friendly track. The objects manipulating these tracks use the priority values during method calls and the CORD-RTS takes these values into consideration.

1) Centralized Model

The centralized model provides central fusion of track data originated from different sources. This approach utilizes two basic active objects, System Track Manager and Tactical Track Manager, both running on the main processing units (Figure 8-a). The System Track Manager accepts primitive sensor tracks in relative position. When a track source calls this method with a new track, grid conversion is performed and correlation check with the other tracks is done. If correlation is successful, then a the primitive track data is combined to the system track. If it is not successful, then a new system track is constructed. Every sensor track update causes a decorrelation check inside the System Track Manager which calls the update method of the Tactical Track Manager. The Tactical Track Manager processes the incoming system tracks either from the System Track Manager or from Data Link Manager, performs correlation or decorrelation checks, maintains the Tactical Track Database with unique track identification.

```
active class Platform_Data_Handler {
priority 5;
static:
  Position_Type          position;
  Stabilization_Data     stab_data;
  Angle_Type             course;
  Speed_Type             speed;
periodic 100:
  Publish_Position();
periodic 50:
  Publish_Stabilization();
periodic 2000:
  Publish_Course_Speed();
publish:
  Update_Position(Position_Data);
  Update_Stabilization(Stab_Data);
  Update_Course_Speed(Angle_Type, Speed_Type);
subscribe:
  Update_Position to Serial_Comm.GPS.Update_Position;
  Update_Stabilization to
        Serial_Comm.Gyroscope.Update_Stabilization;
  Update_Course_Speed to
        Serial_Comm.Compass.Update_Course_Speed;
};
class body Platform_Data_Handler {
  Publish_Position() {
     Update_Position(position);
  }
  Publish_Stabilization() {
     Update_Stabilization(stab_data);
  }
  Publish_Course_Speed() {
     Update_Course_Speed(course, speed);
  }
}
```

```
passive class Platform_Database {
static:
  Position_Type       position;
  Time_Type           time_of_update;
  Stabilization_Data  stab_data;
  Angle_Type          course;
  Speed_Type          speed;
methods:
  Put_Position(in: Position_Type Pos);
  Get_Position(out: Position_Type Pos);
  Put_Stab_Data(in: Stabilization_Data Stab);
  Get_Stab_Data(out: Stablization_Data Stab);
  Put_Course_Speed(in: Angle_Type Crs,
                   in: Speed_Type Spd);
  Get_Course_Speed(out: Angle_Type Crs,
                   out: Speed_Type Spd);
};
class body Platform_Database {
  Put_Position(in: Position_Type Pos) {
     LOCK;   //explicit control
     position = Pos;
     time_of_update = CORD_RTS.Get_Current_Time();
     UNLOCK;
  }
  Get_Position(out: Position_Data Pos) {
     LOCK;
     Pos = position;
     UNLOCK;
  }
  Put_Stab_Data(in: Stabilization_Data Stab) {
     stab_data = Stab;
  }
  // other methods
}
```

Figure 7. Platform data handling implementation

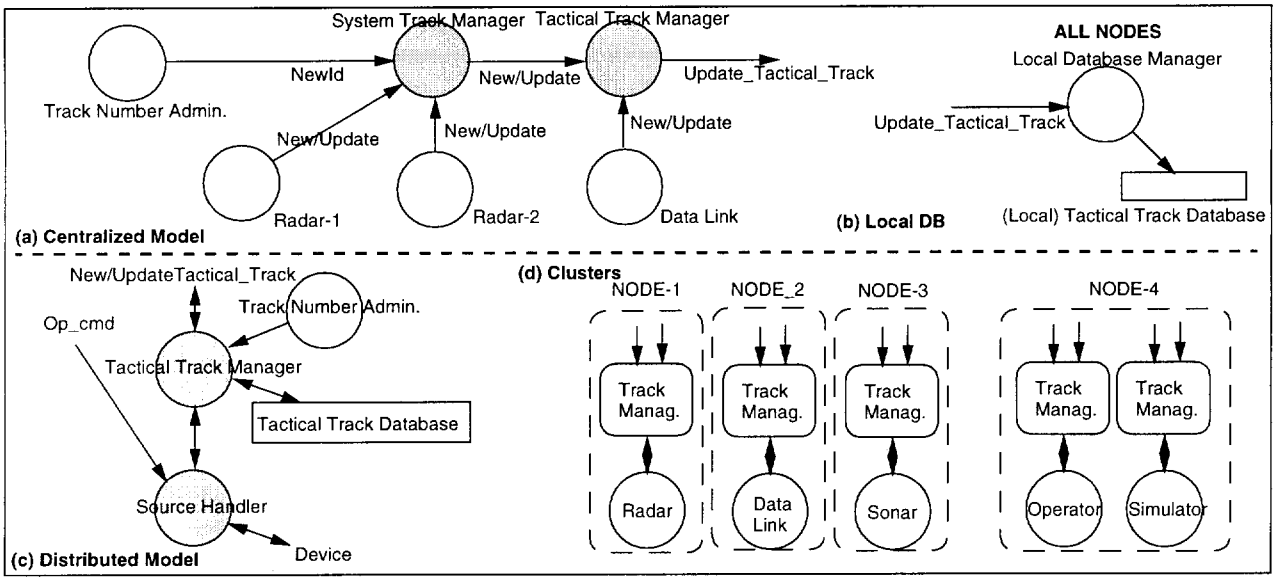

Figure 8. Track management design

An active object, Track Number Administration, provides unique track numbers whenever asked. The tactical tracks are updated system-wide by the publish mechanism, and stored locally as shown in Figure 8-b. In order to modify an existing track or delete a track, the user calls the related method of the Tactical Track Manager, which calls the appropriate method of track originator according to its source.

This model provides a central control over the track database, on the other hand, it may cause a bottleneck at the System Track Manager due to high update rate of track sources. Since correlation/ decorrelation check is done by one active object, the required processing has to be handled by the node on which the object resides. Possible solutions are to arrange the update rate proportional with the track priority and to use computationaly powerful nodes.

2) Distributed Model

The distributed model has also two components, Tactical Track Manager and Source Handler, with their associated track databases. The active object Tactical Track Manager and the passive object Tactical Track Database are located on every node in the system. This component maintains a local tactical track database. Tactical Track Manager object together with the other active object, Source Handler, form a *cluster* (Figure 8-c). A track cluster is responsible from accepting raw, primitive track data from the device and converting to a tactical track to be sent out of the node. Source Handler object has to be implemented for each type of track input device.

Source Handler receives a primitive track from the track source in relative position, performs the grid conversion with respect to own platform position, and sends it to the Tactical Track Manager. If this is a new primitive track generated by the source, it is checked against all the tactical tracks in the Tactical Track Database according to the join criteria. If the criteria is met, then the tracks are said to be *joined* and a responsibility check is performed in order to determine the reporting responsible source based on sensor accuracy. If the track is an update, then the tactical track related to that is updated with the new data. When a new tactical track is received from another cluster, it is inserted into the Tactical Track Database and updated thereafter. If the local source is more accurate, then it becomes reporting responsible and the Tactical Track Manager publishes the tactical track with information provided by the local source. If the remote source is more accurate, then the local primitive track is marked as a secondary source to the current tactical track held in the Tactical Track Database. Automatic take over can happen if the remote source ceases reporting. A central active object is used to provide the unique track numbers. Figure 8-c shows the design of this approach.

The necessary processing for join/disjoin or correlation/decorrelation checks is distributed over the source nodes on the network. If the number of tactical tracks in the system is too high, then creating a new track causes a join check to be performed for each track in the database. In the worst case this is equal to the number of existing tracks. Since this check can be performed separately and concurrently on each node, several track tests can be performed at the same time, saving computation time. Moreover, disjoin check for every primitive update uses the

processing power of the node on which the cluster resides. There may be as many track clusters as the number of track sources in a system as shown in Figure 8-d. Part of the source code of Track Management is listed in Figure 9.

Local Databases

A C^2 system requires objects residing on each node to be able to access all data fast enough to meet the time requirements. For reducing the overhead due to active object method call over the network, the CORD-RTS provides publish-subscribe mechanism which is used for data distribution. However, some objects may not need to be triggered by each new instance; instead, another active object subscribes to this kind of methods, accepts data and stores them in appropriate databases which are implemented as passive objects. It is for sure that calling a passive object method is much faster then calling a method of an active object. For instance, a tactical display must exhibit all tracks with sufficient refresh rate. Therefore each display should have a local track database rather than calling a central database manager.

Some examples to the data storages other than tracks

```
active class Track_Management {
uses Track_Number_Handler, Track_Database;
priority 3;
static:
  int           num_of_tracks;
methods:
  New_Sensor_Track(in: Sensor_Track ST);
  Sensor_Track_Update(in: Sensor_Track ST);
  Wipe_Tactical_Track(in: Track_Id_Type Id);
periodic 2000:
  Send_Tracks();  //non-real-time update rate
publish:
  New_Tactical_Track(Tactical_Track);
  Tactical_Track_Update(Tactical_Track);
  Delete_Tactical_Track(Track_Id_Type);
private:
  Boolean_Type  Join_Track(Sensor_Track&,
                           Track_Id_Type&);
  Boolean_Type  Disjoin_Check(Sensor_Track&);
};

class body Track_Management {
  New_Sensor_Track(in: Sensor_Track& ST) {
     Track_Id_Type    id;
     Tactical_Track   trk;
     if (Join_Track(ST, id) == TRUE) {
        Tactical_Track_DB.Update_Kinetics(id,
                                ST.Get_Kinetics());
        Tactical_Track_DB.Get(id, trk);
        Priority_Type  prio = ConvertPrio(trk);
        Tactical_Track_Update(trk,prio);  //publish
     } else {
        trk = Make_Tactical(ST);
        trk.Set_Track_Number(
           Track_Number_Admin.Get_New_Number());
        Tactical_Track_DB.Insert(trk);
        Priority_Type  prio = ConvertPrio(trk);
        New_Tactical_Track(trk, prio);  //publish
     }
  }
  Sensor_Track_Update(in: Sensor_Track ST) {
     Tactical_Track   trk;
     Track_Id_Type    id;
     if (Disjoin_Check(ST) == TRUE) {
        if (Join_Track(ST, id) == TRUE) {
           Tactical_Track_DB.Update_Kinetics(id,
                                ST.Get_Kinetics());
           Tactical_Track_DB.Get(id, trk)
           Tactical_Track_Update(trk);  //publish
        } else {
           trk = Make_Tactical(ST);
           trk.Set_Track_Number(
              Track_Number_Admin.Get_New_Number());
           Tactical_Track_DB.Insert(trk);
           Priority_Type  prio = ConvertPrio(trk);
           New_Tactical_Track(trk,prio);  //publish
        }
     } else {
        Tactical_Track_DB.Update_Kinetics(
                        id, ST.Get_Kinetics());
        Tactical_Track_DB.Get(id, trk);
        Priority_Type  prio = ConvertPrio(trk);
        Tactical_Track_Update(trk,prio);  //publish
     }
  }
  Wipe_Tactical_Track(in: Track_Id_Type Id) {
     Tactical_Track_DB.Remove(Id);
     Delete_Tactical_Track(Id);
  }
  Boolean_Type  Join_Track(Sensor_Track& ST,
                           Track_Id_Type& Id)
  { /* Fusion algorithm */ }
  Boolean_Type  Disjoin_Check(Sensor_Track& ST)
  { /* Disjoin algorithm */ }
}

active class Source_Handler {
uses Track_Management;
priority 4;
methods:
  Sensor_Track(in: Track_Type T);
  Operator_Update(in: Op_Cmd);
subscribe:
  Sensor_Track to
        Serial_Comm.nav_radar.Track_Data; //device
static:
  Track_Management     local_ttm;
};

clas body Source_Handler {
  Sensor_Track(in: Track_Type T) {
     //convert raw data to sensor track
     Sensor_Track     trk(T);
     if (trk.Get_Life_Cycle() == NEW_TRACK)
        local_ttm.New_Sensor_Track(trk);
     else
        local_ttm.Update_Sensor_Track(trk);
  }
  Operator_Update(in: Op_Cmd) {
     //apply operator changes on tracks
  }
main:
  //Get node name and make a name: NodeName
  local_ttm.Bind(NodeName + "local_ttm");
}

passive class Track_Database {
static:
  Tactical_Track          tracks[MAX_TRACKS];
methods:
  Insert(in: Tactical_Track T);
  Get(in: Track_Id_Type Tid, out: Tactical_Track T);
  Remove(in: Track_Id_Type T);
  Update(in: Tactical_Track T);
  Update_Kinetics(in: Track_Id_Type T,
                  in: Kinetics_Type K);
}
class body Track_Database {
  //method bodies
}

device class Serial_Comm {
read Track_Type;  //type to read from device
buffer 10;        //number of elements in buffer
speed 9600;
methods:
  Read_Data(out: Track_Type);
publish:
  Track_Data(Track_Type);
};
```

Figure 9. Track management implementation

are platform position data, weapons, sensors, engagements, tactical figures, tactical commands, operators and some state information.

Since CPL uses logical names to identify objects, instances of the active class Local Database Manager is created on each node using the node name as an extension for identification. It can be used to create node specific objects and subscribes to all relevant class methods and write them into the appropriate passive objects. Part of the source code is listed in Figure 10.

Services

A service is a graphical user interface (GUI) program that accepts user inputs or display system outputs. These services can also be implemented as active CPL objects, provided that the GUI platform works seamlessly with the CORD-RTS.

9. CONCLUSION

It is generally accepted that using linguistic mechanisms for abstracting real-time constraints and distribution simplifies program design and implementation. Such a capability even reduces the need for system level programming skill, enabling the programmer to concentrate on functional behavior rather than complex low level communication. For that reason, the ability to express distribution issues and real-time constraints through language constructs is focused.

It is intended to use CPL to develop distributed systems where soft real-time requirements exist. Some C^2 systems as presented or distributed knowledge-based systems are suitable areas for implementation in CPL. Application code written in CPL can easily be ported to new platforms after adapting the CORD infrastructure.

This work is still under development at the Turkish Navy Software Development Center (TNSDC). Research, implementation and test is being proceeded adapting new system requirements.

```
active class Local_Database_Manager {
uses Platform_Database, Track_Database,
     Platform_Data_Handler;
priority 3;
static:
  Name                  Node_Name;
  Platform_Database     Platform_Database_1;
  Track_Database        Tactical_Track_DB_1;
methods:
  Local_Database_Manager(in: Name Node);
  Set_Position(in: Position_Data);
  Set_Stab_Data(in: Stabilization_Data);
  Set_Course_Speed(in: Angle_Type Crs,
                   in: Speed_Type Spd);
  Add_Track(in: Tactical_Track T);
  //other methods related to tracks
subscribe:
  Set_Stab_Data to
        Platform_Data_Handler.Update_Position;
  Set_Stabilization to
        Platform_Data_Handler.Update_Stab_Data;
  Set_Course_Speed to
        Platform_Data_Handler.Update_Course_Speed;
  Add_Track to
        Track_Management.New_Tactical_Track;
  Update_Track to
        Track_Management.Update_Tactical_Track;
  //other methods related to tracks
};
class body Local_Database_Manager {
  Local_Database_Manager(in: Name Node) {
     Node_Name = Node;
  }
  Set_Position(in: Position_Data Pos) {
     Platform_Database_1.Put_Position(Pos);
  }
  Set_Stab_Data(in: Stabilization_Data Stab) {
     Platform_Database_1.Put_Stab_Data(Stab);
  }
  Set_Course_Speed(in: Angle_Type Crs,
                   in: Speed_Type Spd) {
     Platform_Database_1.Put_Course_Speed(Crs, Spd);
  Add_Track(in: Tactical_Track T) {
     Tactical_Track_DB_1.Insert(T);
  }
  //other method bodies related to tracks
main:
  Platform_Database_1.Bind(NodeName + "platform");
  Tactical_Track_DB_1.Bind(NodeName + "trackdb");
}
```

Figure 10. Local database management implementation

10. ACKNOWLEDGEMENT

I would like to thank to Mrs.Nadia Erdogan, instructor at the Istanbul Technical University and to Mr.Kubilay Tok, the director of TNSDC for their support and contribution to this study.

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NOVEL CONCEPTS FOR IDENTITY FUSION IN AN AIR COMBAT ENVIRONMENT

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1. SUMMARY

A concept is proposed for an identity fusion system to augment the current positional data fusion algorithm.

Data from the aircraft's sensors are fused by an Extended Kalman Filter to develop tracks in an air combat environment. The formed tracks can be considered to be a direct isomorphic mapping of the real space entity onto a software object. By programming the software object with its own self beliefs, the ability to vary its behaviour in response to varying situations, a set of goals and the knowledge of how to achieve its goals, an identity declaration can be asserted. This combines the extendibility and reusability of a modular architecture with the flexibility and adjustability of artificial intelligence.

2. INTRODUCTION

The Data Fusion Project at DERA Farnborough aims to research algorithms for combining sensor data for targets in a way that gives the greatest operational advantage to the pilot in an air combat situation. A complete system must be able to give increased situational awareness of contextually relevant targets and threats, whether air or ground based.

At the sensor processing level the system must be able to interpret sensor data in such a way as to track other aircraft and arrive at a discrete hypothesis regarding the aircraft's identity. The system should also be able to refine its hypothesis, in real time, upon the injection of new information. It must also be capable of augmenting the identity declaration with information about the environment and the context of the situation.

Psychologically, an operator would use his eyes to perceive the course and identity of a target aircraft. He would fuse the sensory input and use pattern recognition to conclude that the object belongs to a certain group of objects, e.g., the operator would have narrowed the search field down to F4, F15, F22. The operator would then apply reasoning to each alternative and select the optimal solution.

To reduce the workload of the pilot, the computer would be required to duplicate this process by combining sensor data, *a priori* knowledge and information regarding the context of the situation, to identify target aircraft. Inference and reasoning techniques are generally necessary to fuse and utilise more abstract data (i.e. knowledge composed of facts and heuristics rather than numeric data). It is not possible to implement these desired techniques using conventional statistical approaches and pure mathematics.

Herein lies the motivation for applying artificial intelligence techniques to the problem domain.

This paper summarises the work completed so far on the data fusion project at DERA Farnborough, which consists of a positional fusion algorithm capable of fusing data from multiple sensors and triangulating the targets position, using kinematic weaving, if in a bearings only environment. Then an outline is presented of the potential augmentation to the tracker by incorporating the ability to identify the tracks. The concepts that can be applied in order to meet the new requirements are then presented, together with a conceptual system architecture that will be coded.

Paper presented at the RTO SCI Symposium on "Sensor Data Fusion and Integration of the Human Element", held in Ottawa, Canada, 14-17 September 1998, and published in RTO MP-12.

3. POSITIONAL FUSION AND THE PROJECT SO FAR

The Sensor Tracking Applications Rig (STAR) [1] comprises a suite of software which run on a networked array of three workstations and interfaces with the operator through a set of flight and sensor Hands On Throttle And Stick (HOTAS) controls. The aggregate system allows man-in-the-loop assessment of data fusion and tracking algorithms.

3.1 Environment

The STAR contains a range of data files containing specifications for aircraft models, scenarios, sensors and other systems. These are read at run time and define the system behaviour during a real-time run. Scenarios may be defined as being "canned", that is with all the players' movements defined in a scenario file. Alternatively, the motion of one or more aircraft may be controlled by the operators flight controls.

3.2 Program

Sensor measurements are supplied to data fusion and tracking algorithms and the resulting estimated tracks are displayed on a generic B-scope and Tactical Evaluation Display. Measurements may either be generated in real-time by the software, or be read from file. In the latter case the file may have been generated by previous real-time activity or recorded in-flight (real world) data may be used. An interactive 'gods-eye' view of the scenario displays the 'true' behaviour, if available in the case of real data, of all platforms.

The tracker uses sequential estimation for multisensor positional data fusion. An Extended Kalman Filter (EKF) (as in Figure 1) implements kinematic ranging to passively triangulate the target aircraft's position. There is an option of implementing either centralised or autonomous fusion. The autonomous fusion algorithm will become more useful as sensors become more intelligent with an increased capability of developing local tracks prior to fusion.

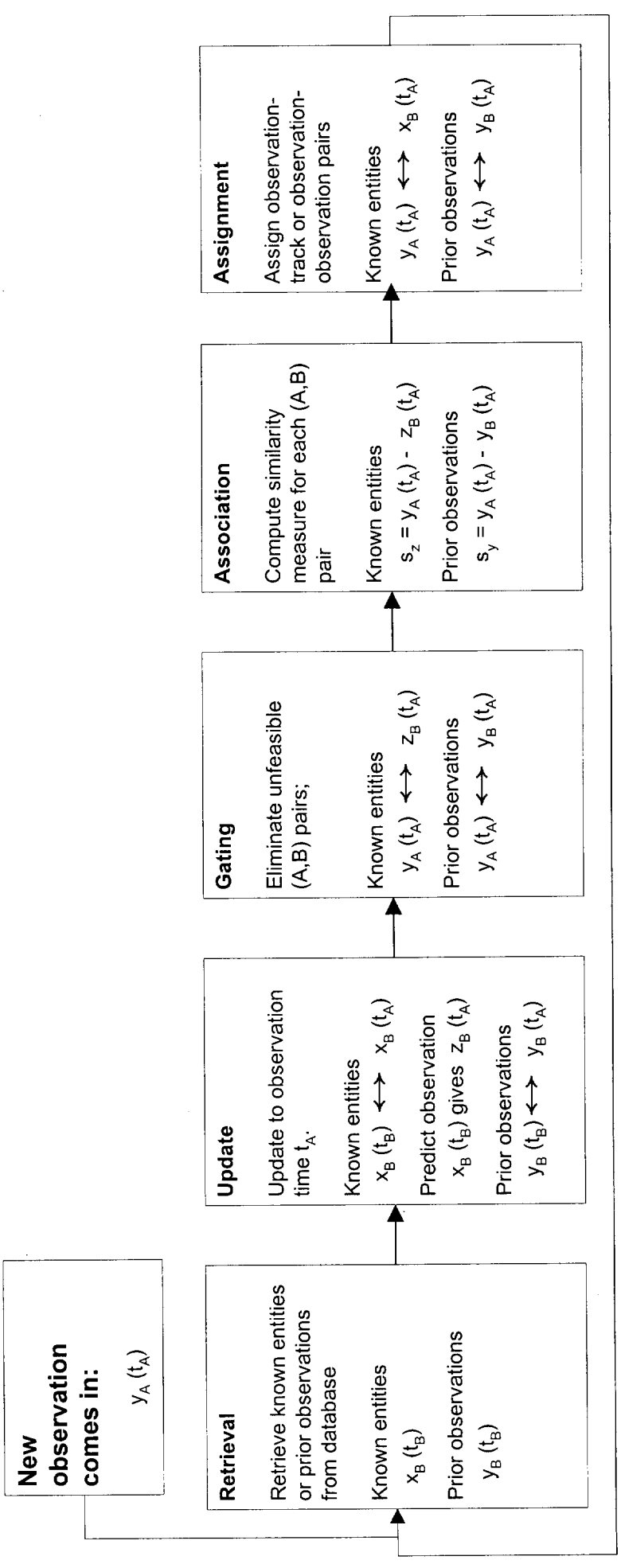

Figure 1 – RECURSIVE LOOP OF THE EXTENDED KALMAN FILTER (EKF)

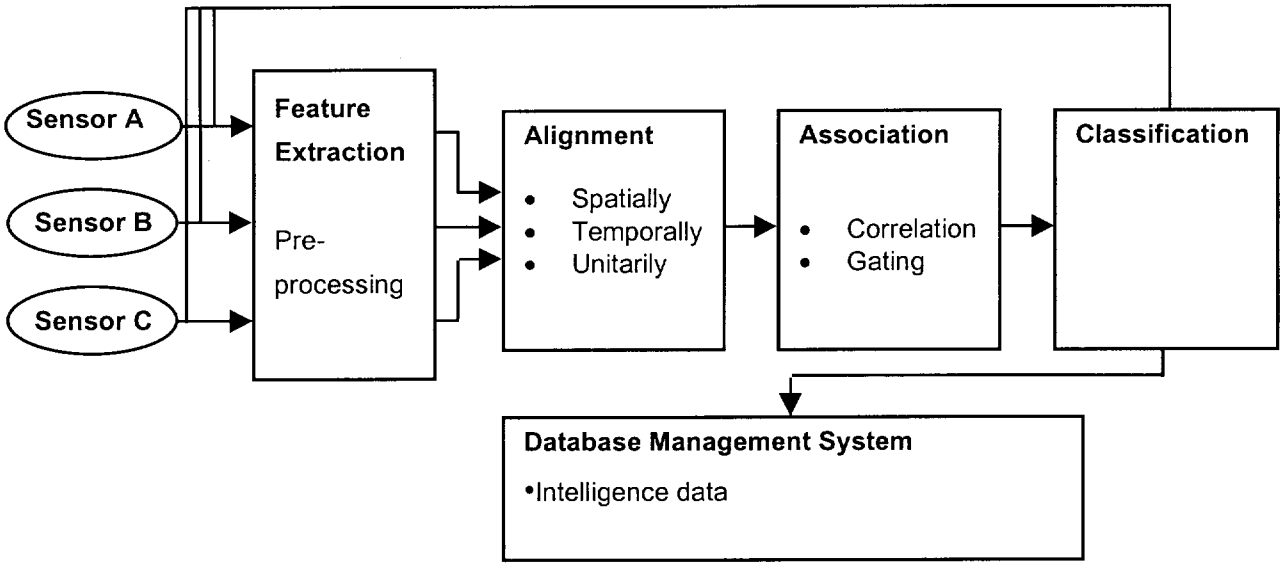

Figure 2 – ARCHITECTURE FOR FEATURE LEVEL MULTISENSOR IDENTITY FUSION

4. IDENTITY FUSION

Determination of track identity or identity fusion is concerned with attempting to convert multiple sensor observations and uncertainty of a target's attributes (parametric sensor data) into a consensual declaration of identity. The model for feature level fusion is illustrated in Figure 2. From a software engineering standpoint, there exists formal frameworks into which specific techniques can be inserted and any system can be represented, checked and verified.[2]

Referring to Figure 2, each sensor provides observational data from which feature vectors can be extracted. The feature vectors are then *aligned* in space and time. The aligned vectors are then *associated* with other measurements and pre-existing tracks. These feature vectors are then fused together into a single feature vector, which in turn is input to an *identity declaration* technique such as a neural network or clustering algorithms. The output is then a consensual declaration of identity based on the combined feature vectors from all of the sensors.[3]

5. POTENTIAL AUGMENTATION OF THE TRACKER BY IDENTIFYING THE TRACKS

Next is a discussion of what further requirements exist to enable the fused tracks formed by the Extended Kalman filter tracking algorithm, to be identified. The requirements extend beyond basic reasoning techniques and toward intelligent techniques capable of inference, adaptation and machine learning.

The project is ongoing with potential for expansion. Duplicating pre-written code is unnecessary and should be avoided. It would be useful if the code were *reusable*. Positional fusion and identity fusion are low level components of a much wider field. The system must be able to integrate and combine easily integration in whole or in part with existing legacy systems. It needs to be *extendible* and *compatible*.

The system needs to be *understandable* so that future generations can take on the development, *maintain* the software and build on what has been achieved. There is great potential for the problem domain to get unnecessarily complicated, so *decomposing* the problem into several modules will simplify the system. Further benefits of decomposing the problem into modules are that errors or abnormal conditions are less likely to effect the system its entirety, thus making it more *robust*.

In order to meet these criteria, the principles of object-orientation together with selected artificial intelligence

techniques, can be applied to the problem domain.

6. CONCEPTS THAT CAN BE APPLIED IN ORDER TO MEET THE REQUIREMENTS

There exists an entity of interest in real space. The sensor returns are such that the integrated tracking algorithm has formed a track and has a range and bearing estimate on the entity. The entity in real space therefore has a direct isomorphic mapping onto the data fusion system. The associated object within the data fusion system can be created to be pro-active and autonomous, with it's own beliefs, desires and intentions. It can be capable of intrinsic reasoning, [4] have the ability to query segregate knowledge sources [5] and have a goal or existential purpose to identify itself.

6.1 Objects

The real-space entity representing an air platform can be considered to have a software counterpart called an *object*. An object is an intuitive mapping of the problem space to a computational model.[6] Objects can contain data, knowledge bases (properties) and procedures (events), objects inherit properties from parent objects based on an explicitly represented object hierarchy and objects can communicate with, as well as control other objects.

6.2 Agents

An *agent* may be thought of as a meta-object, they too have the properties of objects. Unlike objects however, agents have goals and pro-actively work to achieve them. [7] An agent is described as a self-contained, interactive and concurrently executing object.[8] An objects methods are simply procedures coded by a programmer to deal with different messages (e.g. A dog can bark when pinched). An agent, on the other hand, can synthesise plans to deal with contingencies not foreseen by the programmer, and can learn from experience (e.g. A dog agent can discover that insistent barking gets him fed a lot quicker). [10]

If programmed as such, agents can embody cognitive notions. These are generally designated the terms 'Beliefs, Desires and Intentions' (BDI) and determine how rational agents will act. Agents can be defined as entities whose state is viewed as consisting of mental components such as beliefs, capabilities, choices and commitments ... What makes any hardware or software component an agent is precisely the fact that one has chosen to analyse and control it in these mental terms. [9] This leads to the study, modelling and specification of mental attitudes. An accomplishment that stand-alone statistical analysis is not capable of.

The agents within the architecture will be composed of interacting task-based components. The components can be primitive reasoning components using a knowledge base, but may also be subsystems which are capable of performing tasks using methods as diverse as neural networks, bayesian inferencing and genetic algorithms. [10]

The value of an intelligent agent will typically be as an augmentation upon the value of the application that it enhances. The resulting system will consist of highly modular, pluggable components for inferencing, authoring and communication, embodied in a fine-grained object-oriented class library. [4] The resultant agent will therefore be capable of reasoning about its own tasks, processes and plans, its knowledge of other agents, its communication with other agents, its knowledge of the world and its interaction with the world. [11]

7. LOWER LEVEL DESCRIPTION

Agents possess knowledge of the various information sources and how to access them, and an acquaintance model specifying the abilities of other information agents. The intelligent agent would consist of three sections, the Self model, the World model and the Acquaintance model.

The *self model* is a database of characteristics and properties, together with confidences. It would also contain the agent's goals and intentions. An example is shown in Figure 3. The *world model* represents the real world. This would be the intelligence database or knowledge base. However, a full, shared situational model would be too complex. Therefore and agent specific world model can be defined whereby the part of the real world relevant to that agent constitutes the agents world model. The *acquaintance model* is a list of the outputs given and inputs needed by other agents and the inputs and outputs that they take. This enables communication between modules within the architecture. For example, the operational agent might want to communicate with other information agents in order to prevent unnecessary duplication.

Self model - requirements, internal state of the agent				Acquaintance model - who the agent can communicate with and how	
Characteristic	**Value**	**Hypothesis 1**	**Confidence 1**	**Acquaintances**	
Size	30	Small	16%	1	Names/locations of other agents
IFF	friend	Objects 1-7	75%	2	What other agents require as input
JEM	3240	Emitter 3	61%	3	What other agents output
PRI	280	Emitter 2	82%	4	How to reformat for cross comprehension
World Model - representation of the system according to the agent				**Ability model - what the agent can do with its information**	
Object	**Confidence**	**World**		**Abilities**	
Air target	90%	Fuel flow graphs		1	Query intelligence database
Fixed wing	86%	Environmental effects		2	Self terminate
Harrier	58%	Altitude effects		3	Maintain and store track
Tornado	40%	Air target capabilities		4	Update reasoning
				5	Hierarchical search

Figure 3 - INFORMATION AGENT STRUCTURE. NUMERICAL VALUES ARE ARBITRARY EXAMPLES AND NOT REAL DATA.

As the model becomes more sophisticated and the individual agent integrates into the society that forms the complete system, the emergent properties that ought to become evident are as follows; [12]

- Autonomy – Agents exercise control over their internal state and their behaviour.
- Pro-activity – The ability to execute autonomously without being evoked externally.
- Reactivity – The ability of the agent to perceive and react to changes in the environment.
- Communication – The ability to exchange information with other entities such as other agents, objects, humans and the environment.
- Reasoning – The ability to infer and extrapolate based on current knowledge, information and experiences.
- Planning – An agent can synthesise and choose between different courses of action with an aim to achieving its goals.
- Learning – An agent may be able to accumulate knowledge to assemble a history and so adapt its behaviour to respond to new situations.

The main problems with building agent systems is that they have all the problems associated with traditional distributed, concurrent systems, and have the additional difficulties which arise from having flexible and sophisticated interactions between autonomous problem solving components.

There are also social and psychological impediments to the implementation of agent systems. The operator must be comfortable delegating tasks to the computer. The stability and consistency of decision is also important, if the system frequently changes its mind then the operator will lose confidence in it and not use it. It must demonstrate reliability and consistency.

8. CONCEPTUAL SYSTEM ARCHITECTURE

If a software project has been a long time in development then it often reaches a level of complexity such that rewriting the project is unfeasible and impractical. That is one reason why many industrial agent applications are additions to well developed existing systems (legacy systems). A reasonable way to connect the legacy system to the new system is to encapsulate it as an agent. [13]

Building an 'agent wrapper' around the multisensor data fusion tracking algorithm will allow for the interconnection and interoperation of the tracker with the identity fusion architecture. The benefits of this application integration are that legacy systems can still remain useful and be exploited by other pieces of software.

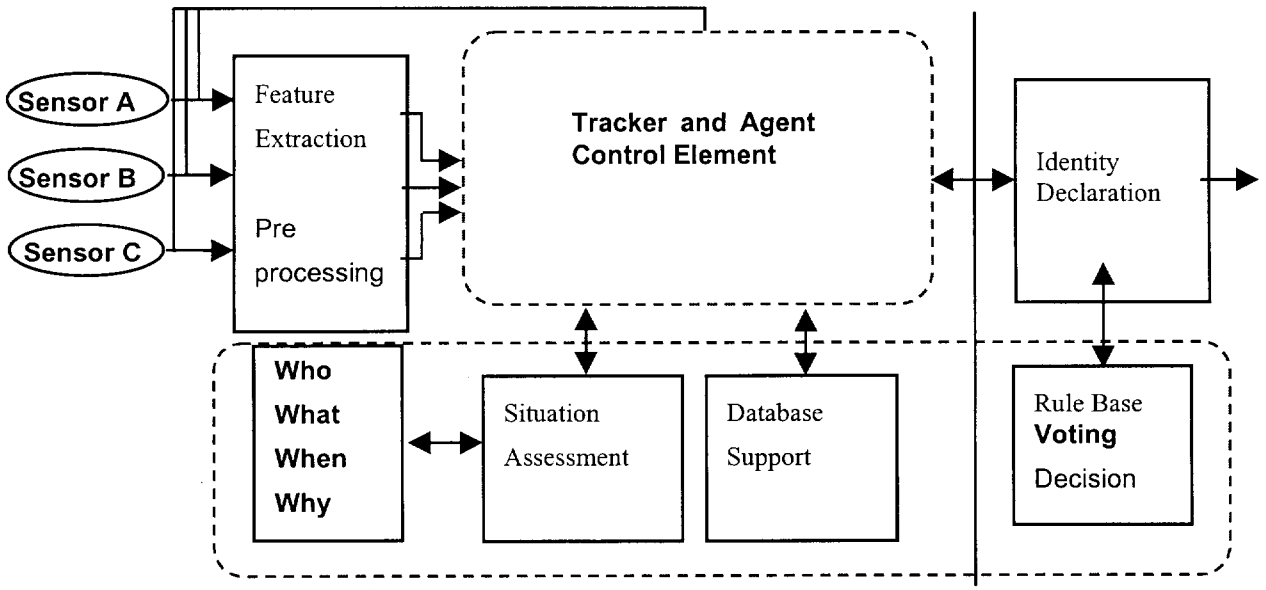

Figure 4 – OPTIMISED SYSTEM ARCHITECTURE

9. CONCLUSIONS

A complete multisensor data fusion system must be able to give increased situational awareness of contextually relevant targets and threats.

At a low level the system must be able to process, fuse and explicate all incoming information, whether this is from the sensor suite, the *a priori* information database or any intelligent support. The low level data fusion system should be able to utilise this information to efficiently and accurately track and identify other aircraft. The stability of decision is also important, the decision must be consistent and not fluctuate.

Currently, the project consists of an Extended Kalman Filter tracker which implements kinematic ranging to passively triangulate the target aircraft's position. The tracker has been validated against authentic flight data and has demonstrated robustness, accuracy and proficiently meets specified performance criteria. It is capable of multisensor data fusion in either a centralised or autonomous mode.

Present research is concerned with determining the identity of the formed tracks.

Arguably, the best method for identifying targets and reasoning about the situation in a combat environment, is the cognitive ability of the pilots. The demands on the pilot are increasing with the sophistication of the aircraft. The workload of the pilot needs to be reduced as much as possible, so by incorporating cognitive notions and artificial intelligence into the system itself, more tasks can be carried out by the aircraft's system. There is also potential for the automated system to detract from the fallibility of the pilot and increase the speed of response.

By building an intelligent agent wrapper around the tracking algorithm an incorporating classification techniques the present assemblage can be integrated into a data fusion environment, that can provide a comprehensive decision support to the pilot, by giving him an enhanced awareness of the situation, in an air combat situation.

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MIDS Triangulation and De-ghosting of Intersection Points

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Summary

MIDS-Triangulation denotes a triangulation procedure to determine the range of ownship spokes by means of spokes and/or kinematically ranged tracks of other platforms. It is a method, which is especially suitable to determine the position of jammers.

This paper develops a method to determine in three steps the range of a target/spoke to the own aircraft. The first step consists in the calculation of the geometric intersection points. In the next step, the geometric intersection points will be investigated whether they behave as real existing targets by means of physical parameters. To this purpose an evaluation function will be introduced, indicating the measure of believe for an existing and therefore known target, which behaves like a calculated geometric intersection point.

The set of believable intersection points will then be tested on association of ownship spokes with MIDS spokes. The association test (or de-ghosting test) decides whether an ownship spoke can be determined unambiguously or not. Crucial for the hit rate of successful triangulation is the geometric constellation of the MIDS platforms to the ownship.

Simulation results prove the correctness and efficiency of the developed method.

Keywords

Triangulation, Deghosting, Association, Fuzzy sets, Fuzzy Logic, Spokes

List of Symbols

ϕ	Geographic Latitude
λ	Geographic Longitude
R_e	Main axis of the earth ellipsoid
$\in$	Excentricity of the earth ellipsoid
h	Height above the earth ellipsoid
φ	Spoke azimuth angle
ε	Spoke elevation angle
R'	Distance of Spoke Intersection point to the MIDS platform
R	Distance of Spoke Intersection point to the Ownship
$\vec{x}_j$	3-dimensional distance vector from MIDS platform to the ownship
$\vec{O}_j$	3-dimensional vector of the ownship spoke
$\vec{S}_i$	3-dimensional vector of the MIDS platform spoke
$\vec{P}(\phi_j,\lambda_j,h_j)$	3-dimensional position vector of the ownship, expressing the *relationship* between the geographic co-ordinates (ϕ_j,λ_j), height h_j above ground and the elliptical co-ordinates of the ownship position above the earth ellipsoid.
$\vec{P}(\phi_i',\lambda_i',h_i')$	3-dimensional position vector of the MIDS platform expressing the *relationship* between the geographic co-ordinates (ϕ_i',λ_i'),height h_i' above ground and the elliptical co-ordinates of the MIDS platform position above the earth ellipsoid
$\vec{v}_j$	Ownship velocity in (N,E,D) system of the ownship platform
$\vec{w}_j$	Ownship velocity in (N,E,D)system of the MIDS platform
$\underline{D}(\phi,\lambda)$	Transformation-matrix, to transform a point $\vec{P}(\phi,\lambda,h)$ given in elliptical coordinates to (N,E,D) Local Horizontal Coordinates

1 Introduction

MIDS stands for **M**ulti-functional **I**nformation **D**istribution **S**ystem and is a time division multiple access data link, permitting data exchange among airborne, land and sea forces, and any combination of these armed forces. The data link is currently introduced by NATO nations.

Paper presented at the RTO SCI Symposium on "Sensor Data Fusion and Integration of the Human Element", held in Ottawa, Canada, 14-17 September 1998, and published in RTO MP-12.

This treatise suggests a triangulation and de-ghosting method for supposed air-to-air targets reported as spokes (direction information only: azimuth, elevation) by the ownship platform and other MIDS platforms. The aim of this paper is to develop a concept, which can be easily implemented in any airborne computer, in order to

- support jammed onboard sensors by providing them with calculated ranges and range rates, in order to locate jammers
- provide this data for the displays in the cockpit to improve the situation awareness
- provide this data to a possibly available kinematic Sensor Fusion process in a fighter/bomber aircraft.

At the beginning, all necessary terms and data are defined and/or explained, which are frequently used in the succeeding chapters.
Chapter 5 starts with the preprocessing of the spoke data, e.g. time alignment of the spoke data to a common point in time and transformation of all spoke data in a common reference frame prior to start with the calculation of the slant range and slant range rate. The slant range and slant range rate for the ownship spokes are calculated relative to the ownship platform and it can be shown that the slant range relative to the MIDS platform can also be calculated, however in this case the range is dependent from the unknown height of the MIDS platform.
Chapter 6 introduces the motivation for the development of the credibility tests and defines a set of credibility measures expressing the degree of strongness that a target belongs to the fuzzy set, which is defined as the set of realistic target behavior.

Chapter 7 presents two alternatives for the assignment of MIDS spokes to an ownship spoke.

Chapter 8 with the simulation results complete the paper. The simulation results are very encouraging. The authors believe that with more improved computer hardware in terms of processing power, an improved MIDS data link, and approximations minimizing the calculation effort for the slant range and slant range rate calculation, this triangulation method can be very successful in real applications.

2 Definitions

2.1 Used Coordinate Systems

2.1.1 Earth fixed Coordinate System

The coordinates (x,y,z;O) are noted as earth fixed coordinates with the origin O in the mass center in the earth. The x-Axis is in the equator plane and parallel to the Meridian through Greenwich 0°, the z-Axis is orthogonal to the x-Axis and directed to the North pole, and the y-Axis orthogonal to the (x,z)-plane, but directed to the east. The angle λ is called the Longitude and is measured from Greenwich Meridian 0° to the east. The latitude is the angle measured from the equator plane to the Radius vector of a point P on the earth ellipsoid. The angle is positive when the radius vector points to a point on the north hemisphere on the ellipsoid. The latitude and the longitude of this coordinate system are called ***geocentric*** coordinates.
Note: The geocentric latitude is not identical with the geographic latitude.

2.1.2 Geographic Coordinates

The ***geographic latitude*** ϕ is the angle between the Normal of the earth ellipsoid and the equatorial plane of the earth ellipsoid.
The ***geographic longitude*** λ is the angle between the Greenwich Meridian and the Meridian of a point P on the earth ellipsoid, measured in east direction.

2.1.3 (N,E,D) Coordinate System

The (NED) coordinate system is defined to be an earth fixed frame with the origin in the aircraft. Down, D, is defined to be the normal to the reference ellipsoid which is an approximation of the geoid. The north axis, N, is in the direction of the projection of the earth's inertial angular velocity vector into the local horizontal plane (the plane which is perpendicular to down direction). The east direction, E, is orthogonal to N and D. The frame is right-handed.

2.2 Definition of the Polar Coordinates of a point in the Local Horizontal System(NED)

For the formulation of the intersection point equations of a spoke - line, it is required to define the direction angles of a supposed target relative to the ownship position.

φ: Azimuth angle clockwise positive between the North axis and the projection of the spoke line on to the (N,E)- plane

ε: Elevation angle is the angle between the spoke-line and the projection of the spoke-line onto the (N,E)-plane. The angle is positive, when the spoke-line directing to the target is above the (N,E) - plane.

r Distance between the origin of the NED frame of a system and the target

The relation between the polar coordinates $(\varphi, \varepsilon, r)$ and the cartesian coordinates (N,E,D) of a point $\vec{P}$ in space is given by the following equation:

Equation 2.2-1

$$\vec{P} = r \begin{pmatrix} \cos\varepsilon \cdot \cos\varphi \\ \cos\varepsilon \cdot \sin\varphi \\ -\sin\varepsilon \end{pmatrix}$$

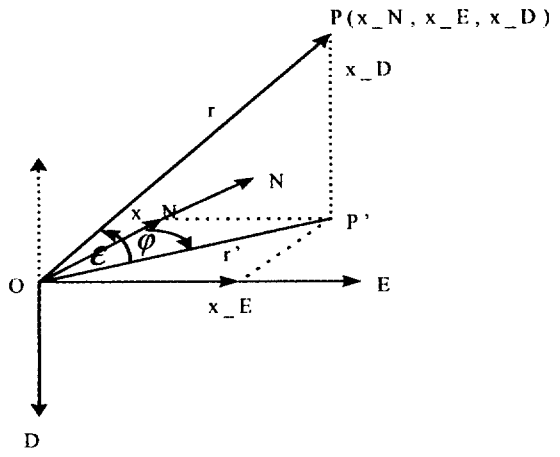

Figure 2.2-1 Definition of Spoke Coordinates in the NED frame

2.3 Definition of a 'Spoke'

If one knows only the direction of a point $\vec{P}$, i.e. the angles φ and ε, but not the relative distance r between the origin in the ownship (N,E,D) coordinate system and the supposed target, then one notes this geometric relation as a ***'Spoke'***.

3 MIDS Spoke Data

MIDS spokes are broadcasted every six seconds in the C² network by means of a dedicated message of the Stanag 5516 and can be received by all network participants. The spoke data are refreshed with a frequency of 1/6 Hz. However, there is no indication in the message, which permits to identify a specific spoke in two consecutive transmissions.

For the development of the triangulation method it will be assumed that for the triangulation the data sets of N spokes $S_1,\ldots,S_N$ are available. The parameters of the MIDS spokes shall be noted as follows:

* MIDS Platform Longitude: λ_i'
* MIDS Platform Latitude: ϕ_i'
* MIDS Platform Speed: v_i'
* MIDS Platform Course: τ_i'
* Spoke Azimuth: φ_i'
* Spoke Azimuth Rate: ω_i'
* Spoke Range Estimate: r_i'
* Spoke Range Accuracy: $\Delta r_i'$
* Time Tag: t_i'

Consequently a spoke is characterised by the tupel

$$S_i = (\lambda_i', \phi_i', v_i', \tau_i', \varphi_i', \omega_i', r_i', \Delta r_i', t_i')$$

Note: All MIDS spoke variables are going to be noted as dashed variables (').

Although the Stanag message doesn't contain height information of the MIDS platform and of the spoke (e.g. in form of an elevation angle), these parameters shall be amended:

* MIDS Spoke Elevation: ε_i'
* MIDS Spoke Elevation Rate: ρ_i'
* MIDS Altitude: h_i'
* MIDS Vertical Velocity: $v_{D,i}'$

None of these four parameters are contained in the MIDS message, but it will be shown that the elevation and the elevation rate can be reconstructed, provided one can make some assumptions about the MIDS altitude, e.g. $h_i' = 10{,}000m$. It will be seen that the knowledge of the MIDS Vertical Velocity is in fact not required.

4 Ownship Spoke Data

It will be assumed that for the Triangulation the data of M ownship spokes $O_1,\ldots,O_M$ are available. The parameters of the ownship spokes will be noted as follows:

* Ownship Platform Longitude: λ_j
* Ownship Platform Latitude: ϕ_j
* Ownship Platform Altitude: h_j
* Ownship Velocity: $\vec{v}_j$
* Ownship Spoke Azimuth: φ_j
* Ownship Spoke Azimuth Rate: ω_j
* Ownship Spoke Elevation: ε_j
* Ownship Spoke Elevation Rate: ρ_j
* Ownship Time Tag: t_j

An ownship spoke is therefore characterized by the tupel $O_j = (\lambda_j, \phi_j, h_j, \vec{v}_j, \varphi_j, \omega_j, \varepsilon_j, \rho_j, t_j)$

whereby

$\vec{v}_j = (v_{N,j}, v_{E,j}, v_{D,j})^T$ is a column vector.

5 The Triangulation Mathematics

For the triangulation calculations it will be assumed that all the information about a spoke is available from the MIDS spoke message. In order to be able to determine the three-dimensional position and velocity of a supposed target, only the slant range and the slant range rate in relation to the ownship position is required. The ownship spoke is then completely described as state vector in the polar coordinate system by means of the azimuth angle, the azimuth angle velocity, the elevation angle and the elevation angle velocity.

5.1 Extrapolation of the Ownship Data

The position of the ownship spokes and of the ownship are going to be extrapolated to the point in

time of the validity of the MIDS spokes. This proceeding is highly recommended since there is more information available from the ownship spokes(Elevation and 3-dimensional velocity).

Equations 5.1-1

$$\tilde{\lambda}_j = \lambda_j + (t_i' - t_j) \cdot \frac{v_{E,j}}{R_e \cdot \cos\phi_j}$$

$$\tilde{\phi}_j = \phi_j + (t_i' - t_j) \cdot \frac{v_{N,j}}{R_e}$$

$$\tilde{h}_j = h_j - (t_i' - t_j) \cdot v_{D,j}$$

$$\tilde{\varphi}_j = \varphi_j + (t_i' - t_j) \cdot \omega_j$$

$$\tilde{\varepsilon}_j = \varepsilon_j + (t_i' - t_j) \cdot \rho_j$$

Unless otherwise stated, it will be assumed that in the following chapters the above parameters are already extrapolated according to Equations 5.1-1 and therefore the tilde indices will not be used. This eases the reading of the paper.

Angular rates from azimuth and elevation, as well as the ownship velocities will not be extrapolated.

5.2 Derivation of the Intersection Equations

5.2.1 Determination of the Basis-vector from the MIDS Platform to the Ownship

Figure 5.2-1 sketches the triangulation method. In the following it will be assumed that the positions of the ownship and the MIDS platforms are available in (N,E,D) coordinates and that the kinematic data of the ownship platform are already extrapolated according to Equations 5.1-1. The extrapolated ownship data are going to be transformed into the local horizontal coordinate system of the MIDS platform with origin(0,0,0).

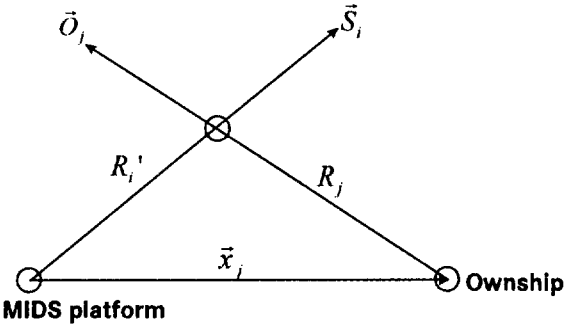

Figure 5.2-1 Geometric Basis for Triangulation

The distance vector $\vec{x}_j$ (see Figure 5.2-1) between the MIDS platform and the ownship platform has in the (N,E,D) system of the MIDS platform the following form:

Equation 5.2-1

$$\vec{x}_j = \underline{D}(\phi_i', \lambda_i') \cdot (\vec{P}(\phi_j, \lambda_j, h_j) - \vec{P}(\phi_i', \lambda_i', h_i'))$$

whereby

$$\underline{D}(\phi_i', \lambda_i') = \begin{pmatrix} -\sin\phi_i' \cdot \cos\lambda_i' & -\sin\phi_i' \cdot \sin\lambda_i' & \cos\phi_i' \\ -\sin\lambda_i' & \cos\lambda_i' & 0 \\ -\cos\phi_i' \cdot \cos\lambda_i' & -\cos\phi_i' \cdot \sin\lambda_i' & -\sin\phi_i' \end{pmatrix}$$

$$\vec{P}(\phi_j, \lambda_j, h_j) =$$

$$\begin{pmatrix} (\frac{R_e}{\sqrt{1-\epsilon^2 \cdot \sin^2\phi_j}} + h_j) \cdot \cos\phi_j \cos\lambda_j \\ (\frac{R_e}{\sqrt{1-\epsilon^2 \cdot \sin^2\phi_j}} + h_j) \cdot \cos\phi_j \sin\lambda_j \\ (\frac{R_e(1-\epsilon^2)}{\sqrt{1-\epsilon^2 \cdot \sin^2\phi_j}} + h_j) \cdot \sin\phi_j \end{pmatrix}$$

$$\vec{P}(\phi_i', \lambda_i', h_i') =$$

$$\begin{pmatrix} (\frac{R_e}{\sqrt{1-\epsilon^2 \cdot \sin^2\phi_i'}} + h_i') \cdot \cos\phi_i' \cos\lambda_i' \\ (\frac{R_e}{\sqrt{1-\epsilon^2 \cdot \sin^2\phi_i'}} + h_i') \cdot \cos\phi_i' \sin\lambda_i' \\ (\frac{R_e(1-\epsilon^2)}{\sqrt{1-\epsilon^2 \cdot \sin^2\phi_i'}} + h_i') \cdot \sin\phi_i' \end{pmatrix}$$

The computation of Equation 5.2-1 yields

Equation 5.2-2

$$x_{Nj} = (N_j + h_j)(\cos\phi_i' \sin\phi_j - \sin\phi_i' \cos\phi_j \cdot \cos(\lambda_i' - \lambda_j)) - \epsilon^2 \cdot \cos\phi_i' \cdot \Delta K;$$

$$x_{Ej} = (N_j + h_j)(\cos\phi_j \sin(\lambda_i' - \lambda_j));$$

$$x_{Dj} = (N_j + h_j)(\cos\phi_i' \cos\phi_j \cos(\lambda_i' - \lambda_j) + \sin\phi_i' \sin\phi_j) - \epsilon^2 \cdot \sin\phi_i' \cdot \Delta K - N_i' - h_i'$$

with

$$N_i' = \frac{R_e}{\sqrt{1-\epsilon^2 \cdot \sin^2\phi_i'}}$$

$$N_j = \frac{R_e}{\sqrt{1-\epsilon^2 \cdot \sin^2\phi_j}}$$

$$\Delta K = N_j \cdot \sin\phi_j - N_i' \cdot \sin\phi_i'$$

5.2.2 Transformation of the Ownship Velocity into the MIDS Platform NED-Coordinate System:

The relative velocity of the ownship as measured from the MIDS platform yields

Equation 5.2-3

$$\vec{w}_j = \begin{pmatrix} w_{N,j} \\ w_{E,j} \\ w_{D,j} \end{pmatrix} = \underline{D}(\phi_i', \lambda_i') \cdot \underline{D}^{-1}(\phi_j, \lambda_j) \cdot \vec{v}_j$$

Define

$$\underline{D}^*(\phi_i', \lambda_i', \phi_j, \lambda_j) = \underline{D}(\phi_i', \lambda_i') \cdot \underline{D}^{-1}(\phi_j, \lambda_j),$$

Then Equation 5.2-3 can be written as

Equation 5.2-4

$$\vec{w}_j = \underline{D}^*(\phi_i', \lambda_i', \phi_j, \lambda_j) \cdot \vec{v}_j$$

5.2.3 Intersection Point of the Ownship Spoke with the MIDS Spoke

The direction vector $\vec{O}_j$ of the ownship RADAR spoke O_j in the MIDS platform is given by the transformation equation

Equation 5.2-5

$$\vec{O}_j' = \begin{pmatrix} O'_{N,j} \\ O'_{E,j} \\ O'_{D,j} \end{pmatrix} = \underline{D}^*(\phi_i', \lambda_i', \phi_j, \lambda_j) \cdot \vec{O}_j$$

with $\vec{O}_j = \begin{pmatrix} cos\varepsilon_j \cdot cos\varphi_j \\ cos\varepsilon_j \cdot sin\varphi_j \\ -sin\varepsilon_j \end{pmatrix}$ being the direction of the spoke in the ownship (NED) coordinate frame. The direction vector $\vec{S}_i$ of a MIDS spoke S_i is defined as

Equation 5.2-6

$$\vec{S}_i = \begin{pmatrix} S_{N,i} \\ S_{E,i} \\ S_{D,i} \end{pmatrix} = \begin{pmatrix} cos\varepsilon_i' \cdot cos\varphi_i' \\ cos\varepsilon_i' \cdot sin\varphi_i' \\ -sin\varepsilon_i' \end{pmatrix}$$

With the above given definitions and designations, we can now establish the **intersection equations** for the linear equations of the MIDS and ownship spokes:

Equation 5.2-7

$$R' \cdot \vec{S}_i = \vec{x}_j + R \cdot \vec{O}'_j$$

5.2.4 Spoke Velocities in the MIDS Platform (NED) Coordinate System

By differentiation - with respect to time - of the spoke vectors $\vec{O}'_j$ and $\vec{S}$ given in Equation 5.2-5 and Equation 5.2-6 above, one yields the spoke velocities:

Equation 5.2-8

$$\dot{\vec{O}}'_j = \underline{\dot{D}}^* \cdot \left[\cos\varepsilon_j \cdot \omega_j \cdot \begin{pmatrix} -\sin\varphi_j \\ \cos\varphi_j \\ 0 \end{pmatrix} - \rho_j \cdot \begin{pmatrix} \sin\varepsilon_j \cdot \cos\varphi_j \\ \sin\varepsilon_j \cdot \sin\varphi_j \\ \cos\varepsilon_j \end{pmatrix} \right]$$

Equation 5.2-9

$$\dot{\vec{S}} = \cos\varepsilon_i' \cdot \omega_i' \cdot \begin{pmatrix} -\sin\varphi_i' \\ \cos\varphi_i' \\ 0 \end{pmatrix} - \rho_i' \cdot \begin{pmatrix} \sin\varepsilon_i' \cdot \cos\varphi_i' \\ \sin\varepsilon_i' \cdot \sin\varphi_i' \\ \cos\varepsilon_i' \end{pmatrix}$$

The intersection equation of the spoke velocity vectors is derived by differentiation of the linear intersection equation of the two spokes given in Equation 5.2-6:

Equation 5.2-10

$$\dot{R}' \cdot \vec{S}_i + R' \cdot \dot{\vec{S}}_i = \vec{w}_j + \dot{R} \cdot \vec{O}'_j + R \cdot \dot{\vec{O}}'_j - \vec{v}_i$$

whereby

$\dot{R}'$ = Range Rate of the MIDS spoke measured in the coordinate system of the MIDS platform

$\dot{R}$ = Range Rate of the ownship spoke measured in the coordinate system of the MIDS platform

$\vec{v}_i$ = velocity of the MIDS platform

The velocity $\vec{v}_i$ of the MIDS platform expressed in coordinate form is described by the absolute value v_i' and the course angle τ_i' in the (N,E)-plane, the vertical velocity component $v_{D,i}'$ is unknown:

$$\vec{v}_i = \begin{pmatrix} v_{N,i} \\ v_{E,i} \\ v_{D,i} \end{pmatrix} = \begin{pmatrix} v_i' \cdot \cos\tau_i' \\ v_i' \cdot \sin\tau_i' \\ v_{D,i} \end{pmatrix}$$

Further it must be observed that both the elevation ε_i' and the elevation velocity ρ_i' of the MIDS spoke are unknown.

With the above derivations, the intersection point is now formally defined by the two vector equations Equation 5.2-7 and Equation 5.2-10:

$$R' \cdot \vec{S}_i = \vec{x}_j + R \cdot \vec{O}'_j$$

$$\dot{R}'\cdot\vec{S}_i + R'\cdot\dot{\vec{S}}_i = \vec{w}_j + \dot{R}\cdot\vec{O}'_j + R\cdot\dot{\vec{O}}'_j - \vec{v}_i$$

5.2.5 Determination of the Slant Ranges R and R'

In order to gain the slant ranges R and R', the first Equation 5.2-7 will be separated in two equations, one which expresses a two-dimensional vector equation and a one-dimensional equation for the third component:

Equation 5.2-11

$$R'\cdot\cos\varepsilon_i'\cdot\begin{pmatrix}\cos\varphi_i'\\ \sin\varphi_i'\end{pmatrix} = \begin{pmatrix}x_{N,j}\\ x_{E,j}\end{pmatrix} + R\cdot\begin{pmatrix}O'_{N,j}\\ O'_{E,j}\end{pmatrix}$$

Equation 5.2-12

$$-R'\cdot\sin\varepsilon_i' = x_{D,j} + R\cdot O'_{D,j}$$

The scalar Equation 5.2-12 can be resolved in the following form

$$R'\cdot\cos\varepsilon_i' = \sqrt{R'^2 - (x_{D,j} + R\cdot O'_{D,j})^2}\,.$$

By using this result in Equation 5.2-11, this equation can be written as

Equation 5.2-13

$$\sqrt{R^2 - (x_{D,j} + R\cdot O'_{D,j})^2}\cdot\begin{pmatrix}\cos\varphi_i'\\ \sin\varphi_i'\end{pmatrix} = \begin{pmatrix}x_{N,j}\\ x_{E,j}\end{pmatrix} + R\cdot\begin{pmatrix}O'_{N,j}\\ O'_{E,j}\end{pmatrix}$$

This equation is now mapped onto the vector $(\cos\varphi_i', \sin\varphi_i')$:

Equation 5.2-14

$$\sqrt{R'^2 - (x_{D,j} + R\cdot O'_{D,j})^2} = a + b\cdot R$$

whereby

$$a = (\cos\varphi', \sin\varphi')\begin{pmatrix}x_{N,j}\\ x_{E,j}\end{pmatrix}$$

$$b = (\cos\varphi', \sin\varphi')\begin{pmatrix}O'_{N,j}\\ O'_{E,j}\end{pmatrix}$$

If one projects on the other hand Equation 5.2-13 on to the vector $(O'_{N,j}, O'_{E,j})$, then this projection becomes the following form

Equation 5.2-15

$$\sqrt{R'^2 - (x_{D,j} + R\cdot O'_{D,j})^2} = \frac{c}{b} + \frac{R}{b}\cdot(O'^2_{N,j} + O'^2_{E,j})$$

whereby

$$c = (O'_{N,j}, O'_{E,j})\cdot\begin{pmatrix}x_{N,j}\\ x_{E,j}\end{pmatrix}.$$

By means of the Equation 5.2-14 and Equation 5.2-15 the square-root can now be eliminated:

Equation 5.2-16

$$a + b\cdot R = \frac{c}{b} + \frac{R}{b}\cdot(O'^2_{N,j} + O'^2_{E,j})$$

or

Equation 5.2-17

$$R = \frac{a\cdot b - c}{O'^2_{N,j} + O'^2_{E,j} - b^2}$$

Remark:
R is not a function of the unknown height information $x_{D,i}'$ of the MIDS platform and therefore the height is not required for the calculation of the slant range of the intersection point.

By using Equation 5.2-17, R will be substituted in Equation 5.2-14 and one yields the slant range R' from the MIDS platform to the intersection point:

Equation 5.2-18

$$R' = \pm\sqrt{(a + b\cdot F)^2 + (x_{D,j} + O'_{D,j}\cdot F)^2}$$

whereby

$$F = \frac{a\cdot b - c}{O'^2_{N,j} + O'^2_{E,j} - b^2}$$

Remark:
In this equation the slant range R' is a function of the height of the MIDS platform!

The question to be asked now is "How strong is the influence of the unknown height $x_{D,j}$ on to the slant range R'?"

If one assumes that $\sigma^2_{x_{D,j}} \approx \sigma^2_h$, and

$$\frac{\sigma'_R}{R'} \approx \frac{\sigma'_{h,i}}{R'^2}\cdot\left|x_{D,j} + O'_{D,j}\cdot\frac{ab - c}{O'^2_{N,j} + O'^2_{N,j} - b^2}\right|,$$

then this relation should be far less than 1(e.g. <0.04).

5.2.6 Determination of the Range Rate $\dot{R}$

The method to determine the range rate is similar to the method to determine the range.
From Equation 5.2-10 one obtains

Equation 5.2-19

$$\dot{R}'\cdot\cos\varepsilon_i'\begin{pmatrix}\cos\varphi_i'\\ \sin\varphi_i'\end{pmatrix}+R'\cdot\cos\varepsilon_i'\cdot\omega_i'\cdot\begin{pmatrix}-\sin\varphi_i'\\ \cos\varphi_i'\end{pmatrix}$$
$$-R'\cdot\sin\varepsilon_i'\cdot\rho_i'\cdot\begin{pmatrix}\cos\varphi_i'\\ \sin\varphi_i'\end{pmatrix}$$
$$=\begin{pmatrix}w_{N,j}-v_{N,j}\\ w_{E,j}-v_{E,j}\end{pmatrix}+\dot{R}\cdot\begin{pmatrix}O'_{N,j}\\ O'_{E,j}\end{pmatrix}+R\cdot\begin{pmatrix}\dot{O}'_{N,j}\\ \dot{O}'_{E,j}\end{pmatrix}$$

With the identities

$$R'\cdot\cos\varepsilon_i' = a+b\cdot R$$
$$-R'\cdot\sin\varepsilon_i' = x_{D,j}+R\cdot O'_{D,j}$$

applied in Equation 5.2-18 and succeeding projection onto the vector $(-\sin\varphi_i', \cos\varphi_i')$ delivers

Equation 5.2-20

$$\dot{R}=\frac{(a+b\cdot R)\omega_i'-R\cdot f-d}{e}$$

whereby

$$d=(-\sin\varphi_i',\cos\varphi_i')\cdot\begin{pmatrix}w_{N,j}-v'_{N,i}\\ w_{E,j}-v'_{E,i}\end{pmatrix}$$

$$e=(-\sin\varphi_i',\cos\varphi_i')\cdot\begin{pmatrix}O'_{N,j}\\ O'_{E,j}\end{pmatrix}$$

$$f=(-\sin\varphi_i',\cos\varphi_i')\cdot\begin{pmatrix}\dot{O}'_{N,j}\\ \dot{O}'_{E,j}\end{pmatrix}$$

Again, it shall be mentioned here that the result is not dependent from $v_{,i}'$ and $x_{,i}'$.

In summary it can be said that it is really possible to determine the slant range R and slant range rate $\dot{R}$ from a supposed target relative to the ownship position. Further it could be shown that a slant range R' for the supposed target can be calculated relative to the MIDS platform, which however is dependent from the unknown parameter $x_{,i}'$.

5.3 Alignment

The result yielded in section 5.2 for the intersection points of the spokes must be time-aligned to the point in time of the occurrence of the ownship spoke. Assuming the Radar providing the spokes has extrapolated all its spokes to a common reference point of time prior to delivery to a mission computer performing these triangulation calculations, then all t_j are identically equal. However the intersection points are calculated to the points in time t_i'. The alignment of the intersection points to the point in time t_j will be achieved by means of the extrapolation of the range R_{ij} by means of the slant range rate $\dot{R}_{ij}$:

Equation 5.3-1

$$\tilde{R}_{ij}=R_{ij}+(t_j-t_i')\cdot\dot{R}_{ij}.$$

And, as agreed in section 5.1, the tilde for the extrapolation will be left out. The slant range R' of the MIDS platform is not going to be extrapolated.

6 Analysis of the Credibility

Preliminary Remark:

In the following R will be replaced by R_{ij}, R' will be replaced by R_{ij}', and $\dot{R}$ will be replaced by $\dot{R}_{ij}$, in order to indicate the dependency of these quantities upon the selection of the spokes S_i and O_j.

The calculated range and range rate in section 5.2 represent a complete three-dimensional data record of the intersection point with regard to location in space and velocity. This data record of an intersection point shall now be investigated towards properties of a real target.

To this purpose a credibility concept will be developed, which uses concepts of the Fuzzy Set Theory. In this application, the Fuzzy Set shall be defined as the set of realistic target behavior. The credibility parameter evaluates how strong this supposed target belongs to the Fuzzy set.
From one or many parameters, which describe the adhered to intersection point, characteristic quantities are calculated, such as for velocity, altitude and altitude rate. Then, these quantities are investigated towards adherence to a realistic target. If this is the case, then a credibility measure of 1 will be assigned to this parameter.

If one can exclude with a high probability that a real target behaves like the intersection point for one parameter, then the credibility measure 0 will be assigned to this parameter. In limit areas between realistic and unrealistic behavior of the intersection point a continuous function with values between 0 and 1 is going to be applied.

By testing as many as possible parameters on their credibility, and by forming the product of the credibilities of the individual parameters, it is possible to separate between intersection points with a credible, realistic physical behavior from those with a less credible realistic behavior, or even from those with a total unreliable behavior. This leads to a pre-selection of MIDS spokes, which may belong to a dedicated ownship spoke and which at all describe a realistic target.

6.1 The Credibility of the MIDS Range

MIDS spokes may contain a range estimation, which was gained by Kinematic Ranging. Assuming there is no range estimation available, then every range must be assigned the credibility 1.

Suppose now, there is a range estimation r'_i available and suppose that $G_{ij}{}^R$ is the measure of credibility for the calculated range R_{ij}':

$$
\begin{aligned}
&If\ R_{ij}' < 0\ then\ G_{ij}{}^R = 0 \\
&\quad else\ if\ \left| r_i' - R_{ij}' \right| < \Delta r_i'\ then \\
&\qquad G_{ij}{}^R = 1 \\
&\quad else\ if\ \left| r_i' - R_{ij}' \right| < 2\Delta r_i'\ then \\
&\qquad G_{ij}{}^R = 2 - \frac{\left| r_i' - R_{ij}' \right|}{\Delta r_i'} \\
&\quad else\ G_{ij}{}^R = 0 \\
&end\ if
\end{aligned}
$$

6.2 Credibility of the Visibility

For this credibility test, it will be assumed that the range $R_{ij} > 0$ is acceptable and the origin of the coordinate frame is in the center of the earth.

Under these assumptions, the ownship position P_0 is $P_0(0,0,h_j + R_e)$. Further the intersection point of the spokes shall be in the direction

$$\vec{S}_T = (\cos\varepsilon_j, 0, -\sin\varepsilon_j)^T$$

Under these conditions one can form the linear equation from the ownship to the spoke:

Equation 6.2-1

$$\vec{y}_T(m) = \vec{P}_0 + m \cdot \vec{S}_T$$

For $m = R_{ij}$ one gets the position of the intersection point. The question now to be put, is: When cuts this straight line the surface of the earth globe?

This happens exactly then and only then, when the following condition is fulfilled:

Equation 6.2-2

$$|R_e| = |\vec{y}_T(m)|$$

Calculation provides

Equation 6.2-3

$$m_1 = -\sin\varepsilon_j (h_j + R_e) + \sqrt{R_e{}^2 - (R_e + h_j)^2 \cos^2\varepsilon_j}$$

$$m_2 = -\sin\varepsilon_j (h_j + R_e) - \sqrt{R_e{}^2 - (R_e + h_j)^2 \cos^2\varepsilon_j}$$

In case the discriminant is less zero, then one can conclude that no real solutions of the equations exist. The visibility is given then and only then, when the discriminant of the square-root is less zero, i.e. when the following condition is fulfilled:

Equation 6.2-4

$$h_j > \frac{R_e(1 - \cos\varepsilon_j)}{\cos\varepsilon_j}$$

The demanding of an intersection point, when m is positive, is also excluded, in case the elevation angle is not negative.

Therefore the visibility is not given or at least doubtful, in case ε_j is negative and

Equation 6.2-5

$$h_j \le \frac{R_e(1 - \cos\varepsilon_j)}{\cos\varepsilon_j}$$

Since $m_2 \le m_1$, one concludes that $\vec{S}_T(m_2)$ is the first intersection point of the straight line with the earth globe. Visibility is given then and only then, when $R_{ij} < m_2$.

The considerations up to now are based on pure geometric approaches. But one has to assume that the elevation will have a statistical error and therefore the question of visibility can only be answered statistically.

The straight line from the ownship to the intersection point touches the surface of the earth exactly for one angle ε_B, if the following condition is satisfied

Equation 6.2-6

$$\varepsilon_B = -\arccos\left(\frac{R_e}{R_e + h_j}\right)$$

In case the elevation angle ε_j is less ε_B, then the intersection point is geometrically not visible. But still there exists a certain probability that the true elevation angle to the intersection point is in fact larger than ε_B.

On the other side if $\varepsilon_j > \varepsilon_B$, then the intersection point is geometrically visible, but yet it exists a certain probability that the true elevation angle to the intersection point is in fact smaller than ε_B and consequently the intersection point remains invisible.

It is therefore legible to demand - assuming normally distributed errors of the elevation angle directed to the intersection point - that the intersection point is at least in 95% of all cases not visible, in order to be in the position to assert that the intersection point is geometrically invisible. This means - assuming a variance σ_j^2 for the elevation angle ε_j - that first the straight line to the smaller elevation angle $-(\varepsilon_j + 2\sigma_j)$ is not visible.

From these considerations a test can be developed for the intersection point credibility G_{ij}^S:

If $R_{ij} < 0$ *then* $G_{ij}^S = 0$

end if

If $\varepsilon_j \geq \varepsilon_B - 2\sigma_j$ *then* $G_{ij}^S = 1$

else

$$m_2 = -\sin\varepsilon_j (R_e + h_j) - \sqrt{R_e^2 - \cos^2\varepsilon_j (R_e + h_j)^2}$$

If $R_{ij} < 1.1 \cdot m_2$ *then* $G_{ij}^S = 1$

else if $R_{ij} < 1.2 \cdot m_2$ *then* $G_{ij}^S = 1 - \dfrac{R_{ij} - 1.1 \cdot m_2}{0.1 \cdot m_2}$

else $G_{ij}^S = 0$

end if

end if

6.3 The Height Creditibility

It will be assumed that the slant range R_{ij} and the elevation ε_j of the intersection point are given at the time t_j. Further it will be assumed that the earth is a sphere.

The altitude of the target above ground, calculated by means of the ownship position relative to the target, is

Equation 6.3-1

$$h_T = h_j + R_{ij} \cdot \sin\varepsilon_j + \frac{R_{ij}^2 \cdot \cos^2\varepsilon_j}{2R_e}$$

The credibility test for the supposed altitude of the target can then be formulated as follows:

If $0 \leq h_T \leq 60{,}000\ ft$ *then* $G_{ij}^H = 1$

else if $60{,}000\ ft < h_T < 80{,}000\ ft$ *then*

$$G_{ij}^H = \frac{80{,}000\ ft - h_T}{20{,}000\ ft}$$

else if $-5{,}000\ ft < h_T < 0\ ft$ *then*

$$G_{ij}^H = \frac{5{,}000\ ft + h_T}{5{,}000\ ft}$$

else

$$G_{ij}^H = 0$$

end if.

6.4 Credibility of the Vertical Velocity

It will be assumed that the slant range R_j, the slant range rate $\dot{R}_{ij}$, the elevation ε_j and the elevation rate ρ_j of the intersection point are given at the time t_j, as well as the ownship platform vertical velocity v_{h_j}. Further it will be assumed that the earth is a sphere. Under these assumptions the vertical velocity of the intersection point can be calculated:

Equation 6.4-1

$$\dot{h}_T = v_{h_j} + \dot{R}_{ij}\left(\sin\varepsilon_j + \frac{R_{ij}}{R_e} \cdot \cos^2\varepsilon_j\right) + \rho_j \cdot \cos\varepsilon_j \cdot R_{ij}\left(1 - \frac{R_{ij}}{R_e} \cdot \sin\varepsilon_j\right)$$

The vertical velocity of the intersection point shall be evaluated in three velocity domains:

If $-300\ \frac{m}{s} \leq \dot{h}_T \leq 150\ \frac{m}{s}$ *then* $G_{ij}^H = 1$

else if $-600\ \frac{m}{s} < \dot{h}_T < -300\ \frac{m}{s}$ *then*

$$G_{ij}^H = \frac{\left(600\ \frac{m}{s} + \dot{h}_T\right)}{300\ \frac{m}{s}}$$

else if $150\ \frac{m}{s} < \dot{h}_T < 250\ \frac{m}{s}$ *then*

$$G_{ij}^H = \frac{\left(250\ \frac{m}{s} - \dot{h}_T\right)}{100\ \frac{m}{s}}$$

else

$$G_{ij}^H = 0$$

end if.

6.5 Maneuver Test

Altitude and altitude velocity determine authoritatively the maneuverability of a flying object. Among the altitude and altitude velocity exists a correlation,

according to this a low flying target can never possess a large, negative height rate and a high flying target should not have a large, positive height rate.

The credibility of the maneuver of a flying target should recognize this inherent correlation. The test for this credibility should make transparent the compatibility of the height and height velocity:

$$
\begin{aligned}
&If\ 3{,}300\ m \le h_T \le 16{,}500\ m\ then\ G_{ij}^{\ M} = 1\\
&else\ if\ h_T < 3{,}300\ m\ then\\
&\quad if\ \dot{h}_T > T_1(h_T)\ then\ G_{ij}^{\ M} = 1\\
&\quad else\ if\ \dot{h}_T < T_2(h_T)\ then\ G_{ij}^{\ M} = 0\\
&\quad\quad else\\
&\quad\quad\quad G_{ij}^{\ M} = \frac{T_2(h_T) - \dot{h}_T}{T_2(h_T) - T_1(h_T)}\\
&\quad\quad end\ if\\
&else\ if\ h_T > 16{,}500\ m\ then\\
&\quad if\ \dot{h}_T < T_1^{*}(h_T)\ then\ G_{ij}^{\ M} = 1\\
&\quad else\ if\ \dot{h}_T > T_2^{*}(h_T)\ then\ G_{ij}^{\ M} = 0\\
&\quad else\\
&\quad\quad G_{ij}^{\ M} = \frac{T^{*}{}_2(h_T) - \dot{h}_T}{T^{*}{}_2(h_T) - T^{*}{}_1(h_T)}\\
&\quad end\ if\\
&else\ G_{ij}^{\ M} = 0\\
&end\ if.
\end{aligned}
$$

The quantities $T_1(h_T), T_2(h_T), T^{*}{}_1(h_T)$ and $T^{*}{}_2(h_T)$ represent functions of the threshold values, which for a given height h_T provide upper and lower thresholds for the credibility of the altitude and altitude rate. These functions are defined as follows:

$$T_1(h_T) = -300\ m/s \cdot \frac{h_T + 2{,}000\ m}{5{,}000\ m},$$

whereby $0 \le h_T < 3{,}300m$;

$$T_2(h_T) = -600\ m/s \cdot \frac{h_T + 2{,}000\ m}{5{,}000\ m}$$

whereby $0 \le h_T < 3{,}300m$;

$$T^{*}{}_1(h_T) = 150\ m/s \cdot \frac{25{,}000\ m - h_T}{8{,}000\ m}$$

whereby $h_T > 16{,}500m$;

$$T^{*}{}_2(h_T) = 300\ m/s \cdot \frac{25{,}000\ m - h_T}{8{,}000\ m}$$

whereby $h_T > 16{,}500m$;

6.6 Credibility of the Velocity

In the following it will be assumed that at time t_j a valid slant range R_{ij}, slant range rate $\dot{R}_{ij}$, the ownship spoke parameters elevation ε_j, the elevation rate ρ_j, the azimuth angular velocity ω_j and the ownship platform velocity $\vec{v}_j$ are given. Further it will be assumed that the earth is a sphere. Under these assumptions the absolute velocity of the intersection point can be calculated:

Equation 6.6-1

$$
\begin{aligned}
\vec{v}_T = {} & \dot{R}_{ij} \cdot \vec{O}_j + R_{ij} \cdot \cos\varepsilon_j \cdot \omega_j \cdot \begin{pmatrix} -\sin\varepsilon_j \\ \cos\varphi_j \\ 0 \end{pmatrix}\\
& - R_{ij} \cdot \rho_j \cdot \begin{pmatrix} \sin\varepsilon_j \cdot \cos\varphi_j \\ \sin\varepsilon_j \cdot \sin\varphi_j \\ \cos\varepsilon_j \end{pmatrix} + \vec{v}_j
\end{aligned}
$$

Further it shall be $v_T = |\vec{v}_T|$.

The test for the credibility of the velocity v_T of the target can be formulated as suggested:

$$
\begin{aligned}
&If\ 200\ m/s \le v_T \le 700\ m/s\ then\ G_{ij}^{\ v} = 1\\
&else\ if\ 100\ m/s < v_T < 200\ m/s\ then\\
&\quad G_{ij}^{\ v} = \frac{v_T - 100\ m/s}{100\ m/s}\\
&else\ if\ 700\ m/s < v_T < 900\ m/s\ then\\
&\quad G_{ij}^{\ v} = \frac{900\ m/s - v_T}{200\ m/s}\\
&else\ G_{ij}^{\ v} = 0\\
&end\ if
\end{aligned}
$$

6.7 Credibility of the Intersection Point

The credibility of an intersection point can now be calculated by formulating the product from the credibilities of the individual parameters:

Equation 6.7-1

$$G_{ij} = G_{ij}^{\ R} \cdot G_{ij}^{\ S} \cdot G_{ij}^{\ H} \cdot G_{ij}^{\ \dot{H}} \cdot G_{ij}^{\ M} \cdot G_{ij}^{\ v}$$

The elements G_{ij} can be looked at as elements of a matrix $\underline{G}$. The matrix $\underline{G}$ will be noted as credibility matrix in the forthcoming chapters.

If one defines now a constant threshold value G_{Mm} for the minimum credibility for the acceptance of an

intersection point as a supposed target, then one can define an acceptance matrix $\underline{A}$, whose elements will receive the values 0 or 1. I.e., does an element A_j receives the value 1, then this intersection point under investigation will be regarded as a potential target:

$$If\ G_{ij} \geq G_{Min}\ then\ A_{ij} = 1$$
$$else\ A_{ij} = 0$$
$$end\ if.$$

The matrix $\underline{A}$ defines now all intersection points, which are regarded as potential targets. In the second phase of the analysis the remaining targets and supposed targets must be filtered.

7 Association

7.1 Alternative1

Association is the identification of one or many MIDS spokes, which define, together with one ownship spoke, one real target. The aim is that from the analysis of the density of the intersection points - by means of the slant range and slant range rate -, to achieve the association of the MIDS spokes with one of the ownship platform sensors spokes. The analysis shall take place in three individual steps:

1. Separation of good and/or believable data from not accurate and/or unbelievable data.
2. Selection of possible slant range candidates for each ownship spoke
3. Minimization of the assignment conflicts

7.1.1 Separation of the Data

The following NxM-matrices are used:

$\underline{A}$ the acceptance matrix

$\underline{R}_Q$ the range matrix with 'good' quality

$\underline{\dot{R}}_Q$ the range rate matrix with 'good' quality

$\underline{R}$ the slant range matrix

$\underline{\dot{R}}$ the slant range rate matrix

The separation of good and/or believable data takes place by setting a threshold Q_{ij} with respect to the required *minimum quality*. The minimum quality can thus be defined individually for each ownship sensor, if one knows significant quality differences of the utilized onboard sensors. To that purpose the following conventions shall be applied:
The acceptance matrix defines, which of the inputs to the other matrices are valid. One can eliminate this matrix: For all not accepted intersection points with $A_{ij} = 0$ set $R_{ij} = \infty$ and $R_{Q_{ij}} = 0$. After this transformation there will remain for the further analysis only the matrices $\underline{R}$, $\underline{\dot{R}}$, $\underline{R}$ and $\underline{\dot{R}}_Q$. With the above explanations and agreements one can formulate the following separation algorithm - from now on called ***'Q-Cut'*** - which eliminates the low quality intersection points from the Slant Range Matrix $\underline{R}$ and the Slant Range Rate Matrix $\underline{\dot{R}}$, which do not exceed a certain quality minimum:

Q - Cut:

for j in 1..M loop
  for i in 1..N loop
    if $G_{ij} < Q_{ij}$ *then*
      $R_{Q_{ij}} = \infty, \dot{R}_{Q_{ij}} = \infty$
    else
      $R_{Q_{ij}} = R_{ij}, \dot{R}_{Q_{ij}} = \dot{R}_{ij}$
    end if
  end loop
end loop

It must be pointed out that the Q-cut cannot be interpreted in that way that the intersection points are wrong or non-physical. One can only say that these points are to a great extent casual, i.e. one could interpret them as "background noise" of intersection points on the ownship spoke.

After the execution of the Q-Cut, the decision has been taken, which elements in the $\underline{R}$ and $\underline{\dot{R}}$ matrices will be trusted and those, which are regarded as casual. For the further proceeding only the matrices $\underline{R}$ and $\underline{\dot{R}}_Q$ are still required.

7.1.2 Slant Range Candidates

One analyses now all slant ranges and slant range rates of the matrices $\underline{R}$ and $\underline{\dot{R}}_Q$ of the intersection points of the MIDS spokes S_i with each ownship spoke O_j with regard to the density in the histogram. To that purpose a reasonably defined range domain will be defined over which a slant range window will be moved and the number of intersection points in the window will be counted.

Let be

$$I_n = [n \cdot d - d, n \cdot d + d); \quad 1 \leq n \leq 24$$
$$J_m = [m \cdot \dot{d} - \dot{d}, m \cdot \dot{d} + \dot{d}); \quad 1 \leq m \leq 24$$
$$I_{25} = [24 \cdot d - d, \infty); J_{25} = [24 \cdot \dot{d}, \infty);$$
$$J_{-m} = (-m \cdot \dot{d} - \dot{d}, -m \cdot \dot{d} + \dot{d}] \quad 1 \leq m \leq 24$$
$$J_{-25} = (-\infty, -24 \cdot \dot{d}]$$

whereby d and $\dot{d}$ represents the half width of the movable window and may have for example the value $d = 20km$ and $\dot{d} = 50m/s$.

With these definitions one is now in the position to form the product sets

$$I_n \times J_m = \{(x,y) \mid x \in I_n \wedge y \in J_m\},$$

whereby the pairs (x,y) are ordered in the mathematical sense. These rectangles form a partition of the set of permissible slant ranges and slant range rates. Further it is

$$\bigcup_{n=1}^{25} I_n = [0,\infty) =: I, \quad \bigcup_{\substack{m=-25 \\ m\neq 0}}^{25} J_m = (-\infty,\infty) =: J$$

$$I \times J = [0,\infty) \times (-\infty,\infty)$$

For each $n \in \{1,...,25\}$ and $m \in \{-25,...,25\} - \{0\}$ a set M_{nm} will be defined:

$$M_{nm} = \{S_i : 1 \le i \le N, 1 \le j \le M; R_{Q_{ij}} \in I_n, \dot{R}_{Q_{ij}} \in J_m\}$$

M_{nm} contains the set of all MIDS spokes S_i, which do possess an intersection point with ownship spoke O_j with regard to the slant range $R_{ij} \in I_n$ and slant range rate $\dot{R}_{ij} \in J_m$.

For each ownship spoke O_j one looks for up to three rectangles

$$K_j^{\,1} = I_{n_1}^{\,j} \times J_{m_1}^{\,j}$$

$$K_j^{\,2} = I_{n_2}^{\,j} \times J_{m_2}^{\,j}$$

$$K_j^{\,3} = I_{n_3}^{\,j} \times J_{m_3}^{\,j}$$

so that each of these rectangles contains at least one intersection point and none of the other rectangles $I_n \times J_m$ should contain more intersection points.

The pairs $(R_{ij}, \dot{R}_{ij})$ with j fix, $i = 1,...,p, p \le N$ are the potential values of the slant range and slant range rate of the supposed target. The corresponding sets of MIDS spokes causing the existence of the pairs $(R_{ij}, \dot{R}_{ij})$ in the windows K_j^{μ} shall be denoted as

L_j^1 = set of MIDS spokes with intersection points in K_j^1

L_j^2 = set of MIDS spokes with intersection points in K_j^2

L_j^3 = set of MIDS spokes with intersection points in K_j^3

with $L_j^{\mu} \subseteq M_{nm}$.

7.1.3 Minimization of the Assignment Conflicts

An assignment conflict occurs, when a particular MIDS spoke S has more than one intersection point, i.e., with at least two Radar spokes O_j and $O_k, (k \neq j)$. These intersection points are contained in different sets K_j^{μ} and K_k^{μ}, $\mu = 1,2,3$, $k \neq j$ The aim is to minimize the assignment conflicts, i.e. exactly one rectangle K_j^{μ} shall be assigned to each ownship spoke O_j. The conflict exists then and only then, when

Equation 7.1-1

$$\bigcap_{j=1}^{M} L_j^{\mu_j} \neq \varnothing, \mu_j \in \{1,...,3\}.$$

whereby $\mu_j = \mu$, which is the value of the index μ of the adhered to window K_j^{μ}.

As *measure for the size of the assignment conflict* one can use the *cardinality* of the set of the multiple assigned MIDS spokes:

$$C = \left| \bigcap_{j=1}^{M} L_j^{\mu_j} \right| \qquad \mu_j \in \{1,...,3\}$$

whereby $|U|$ denotes the cardinality of a set U.

On the other hand an assignment is desirable, when a maximum D of intersection points can be used, which calculates according to the formula

$$D = \sum_{j=1}^{M} \left| L_j^{\mu_j} \right| \qquad \mu_j \in \{1,...,3\}$$

The optimal assignment for the hypothesis

$H^o : (n_1^o,...,n_M^o, m_1^o,...,m_M^o)$

with the meaning

a) range R_{ij} of spoke O_j is contained in the interval $[n_j^o \cdot d - d, n_j^o \cdot d + d]$ and

b) range rate $\dot{R}_{ij}$ of spoke O_j is contained in the interval $[m_j^o \cdot \dot{d} - \dot{d}, m_j^o \cdot \dot{d} + \dot{d}]$

can then be defined by demanding that

$$D - C = \max!$$

In this case a maximum of used intersection points leads to a minimum of assignment conflicts.

7.1.4 Assessment of the method

The presented method requires intense calculations: Firstly histograms have to be plotted for each ownship platform spoke and the adhered to intersection points, and secondly, an optimization process has to be defined, evaluating the many hypotheses from which the correct assignment can be suggested with as few as possible assignment conflicts.

7.2 Alternative II

The aim of this method for solving the assignment problem is to investigate the usefulness of the MIDS spokes. This method requires the following steps:

1. Separation of the (almost) unambiguous spokes from ambiguous spokes
2. Allocation of MIDS spokes to ownship spokes.

7.2.1 Selection of the MIDS spokes

The separation of the (almost) unambiguous MIDS spokes from the ambiguous MIDS spokes will be achieved by setting two thresholds. With the definitions from 7.1.1 and the threshold Λ to limit the maximum number of valid intersection points of a MIDS spoke with all the ownship platform sensors spokes, one can now formulate a combined limiting process called 'Λ - Q-Cut'.

Λ - Q- Cut

for j in 1..M loop
  $k := 0$
  for i in 1..N loop
    if $G_{ij} < Q_{ij}$ *or* $k > \Lambda$ *then*
      $R_{Q_{ij}} = \infty, \dot{R}_{Q_{ij}} = \infty$
    else
      $k := k + 1$
      $R_{Q_{ij}} = R_{ij}, \dot{R}_{Q_{ij}} = \dot{R}_{ij}$
    end if
  end loop
end loop

The Λ - Cut guarantees that for one MIDS spoke S_i not more than Λ intersection points - with at least the minimum quality Q - are allowed with the ownship spokes $O_j, j = 1,...,M.$

A further effect of the Λ - Cut can be described as follows: If there are too many intersection points of one MIDS spoke with many ownship Radar spokes, then one can argue that the quality of the information content of these intersection points must be small and can therefore be ignored in the assignment considerations.

7.2.2 Assignment

Having performed the Λ - Q - Cut in section 7.2.1, it may be the situation that already many (or most) of the intersection points are rejected. I.e. for the further proceeding, only those MIDS spokes have survived, which do possess a sufficient quality and do not have too many intersection points with too many ownship spokes. The question to be allowed here is, whether an ownship spoke at all has still intersection points with the remaining MIDS spokes. If this is not the case, the ownship spoke cannot be "deghosted".

Assuming now that some MIDS spokes passed successfully the Λ - Q - Cut, which do have sufficient quality and do not have too many common intersection points with many ownship spokes. Then in the final step one tries by means of permutation logic to achieve a final mapping of the MIDS spokes to the ownship spoke.

Chapter 8 shows simulation results of this method.

8 Simulations

Simulations for the Triangulation algorithms have been performed in order

- to test the formulas for the intersection points especially the coordinate transformations
- to fine-tune the credibility tests and the included fuzzy logic decisions
- to unambiguously filter realistic targets out of a dense random scenario
- to measure the processing time

The programming tool used was MapleV due to the excellent graphical possibilities. The algorithms are written in a special programming language of MapleV. For the generation of the scenario an internal random generator was used which generates all the above mentioned Spoke data.

The results have been displayed in a two dimensional polar coordinate system (range [km], azimuth) with the ownship at the origin and in a three dimensional coordinate system (x_N [km], x_E [km], altitude [m]) with the ownship position at $(0,0,h_{own})$. All intermediate results (kinematic data of each intersection point, each single credibility test, the whole credibility matrix and the final association results) have been monitored through the whole process, so that the behavior of the algorithm was traceable and possible unreasonable values could be recognized immediately.

8.1 Generation of a Random scenario

First simulations have shown that triangulation is most accurate when the Spokes are arranged in angle close to 90°. Taking this into account, we can set up our scenario in the following manner:

- Static ownship kinematic data (speed, course, altitude, Latitude, Longitude)
- Generate ownship Spokes (eventually with range estimate) within a certain azimuth and elevation range (assume a typical Radar scan volume of ±60°) around the ownship course; azimuth rate, and elevation rate, generated also by random but with reasonable values for a certain range
- Generate random MIDS positions (Latitude/Longitude) and kinematics (speed + course); the course of the MIDS platform shall be close to 90° of the ownship course!

- Generate random MIDS Spokes (azimuth within ±60° around the MIDS course, azimuth rate with a reasonable value)
- Fix configurable fine tuning constants for each run
- Take all these input data and run through the algorithms

To generate the scenario we have different possibilities to vary the environment:

- Number of Radar Spokes r
- Number of MIDS Spokes m
- Maximum and minimum range of MIDS platforms
- Maximum and minimum velocities for the random generator (used for MIDS platform kinematics)
- Displayed range

To fine-tune the algorithms we can also configure some constants used in the credibility tests and in the association:

- Fuzzy logic limits for the velocity test (4 values)
- Fuzzy logic limits for the maneuver test (5 altitude and 4 altitude rate limits)
- Range accuracy for both range credibility tests
- Cut-off possibility for the credibility
- Association thresholds for range and range rate
- Assumption for MIDS platform altitude

For all shown simulations following symbols are used:

+ = incredible intersection points (IPs)
+ = credible intersection points
+ = Ownship position (with altitude)
– – = MIDS platform positions 3D (without altitude)
◊ = MIDS platform positions in the polar display
— = Ownship course (length ∝ velocity)
— = MIDS platform courses (length ∝ velocity)
— = Radar Spokes (in the polar display ——)
··· = MIDS-Spokes (without elevation info)
□ = unambiguous IP (= real target)

For the tests with the realistic targets the following further symbols are used:

o— = Target position + course

All simulations have been performed with various input data. For a better comparability of the different tests, same input data (ownship kinematic,..) are used for the figures in this paper:

Ownship velocity: 300 m/s
Ownship course: 0° (north direction)
Ownship altitude: 5000 m
Ownship Latitude: 48°
Ownship Longitude: 11°
Random MIDS velocities: 150 m/s.. 500 m/s
Random vertical velocity: -100 m/s.. 100 m/s
Maximum distance between ownship and MIDS platforms: 100 km

Before we start with the test results some words to the language used in the following text:
An *incredible point* is an intersection point, which has already been filtered out by the credibility tests.
A *credible point* is an intersection point, which has passed successfully the credibility tests.
An *unambiguous point* is a credible point which has passed successfully the association decision and is therefore determined as a real target by the algorithm!

The first test which was set up was a complete random scenario with 6 Radar Spokes combined with 10 MIDS Spokes with no range estimate available at all. As expected, there are some credible and even two unambiguous intersection points beneath a huge amount of incredible points (see Figure 8.1-1 and Figure 8.1-2).

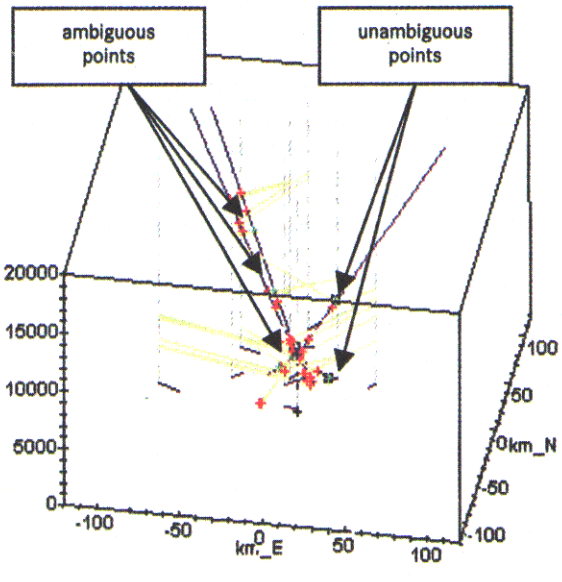

Figure 8.1-1: 6 Radar +10 MIDS Spokes without any range estimates available.

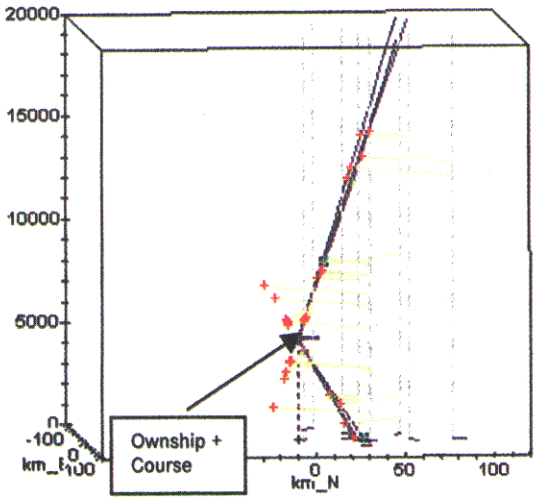

Figure 8.1-2: 6 Radar +10 MIDS Spokes without any range estimates available seen from east.

In the second step, we examine, how the algorithm behaves, if we only use Radar Spokes with range estimates (possibly kinematically ranged Radar tracks!). In Figure 8.1-3 and Figure 8.1-4 you can see again a generated random scenario but with an available Radar range estimate. In this case, there are only incredible points, which are filtered out by the very strong range credibility test!

In this case a real target which would be placed in the scenario and which is seen from 2 different origins (Ownship + one MIDS platform) can be filtered out unambiguously even if no range estimates of these two Spokes are available!

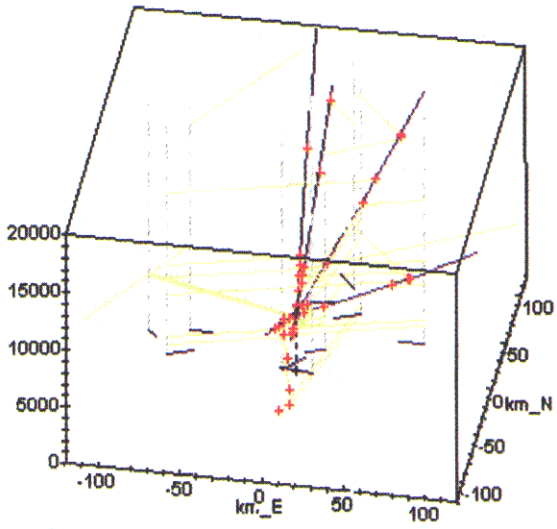

Figure 8.1-3: 6 Radar + 10 MIDS Spokes with range estimate for the Radar Spokes

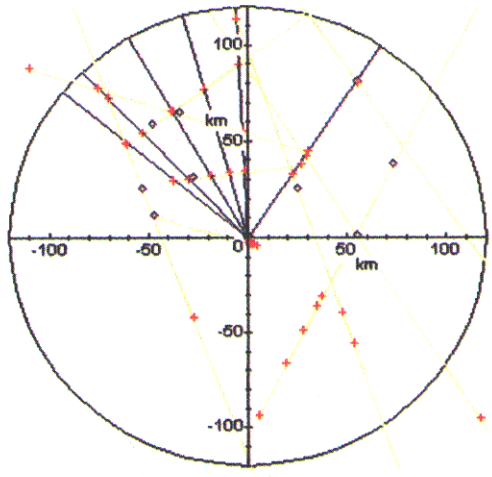

Figure 8.1-4: 6 Radar + 10 MIDS Spokes with range estimate for the Radar Spokes in polar coordinates

The same result is achieved, if we use MIDS Spokes with and Radar Spokes without range estimates (see Figure 8.1-5).

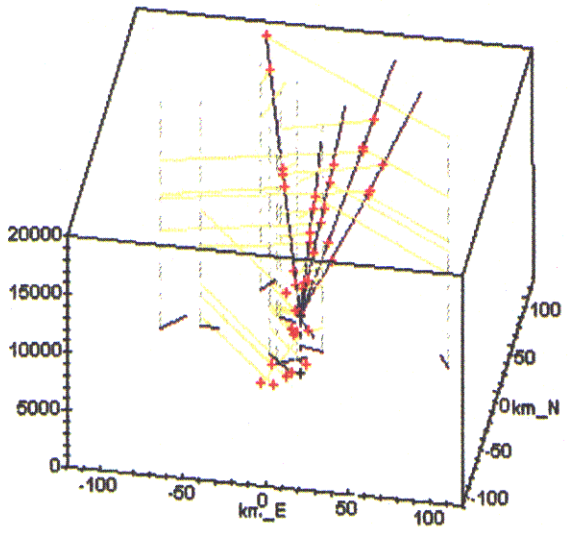

Figure 8.1-5: 6 Radar + 10 MIDS Spokes with range estimates of the MIDS Spokes

In the last step where we only use random Spokes we examine the behavior of our algorithms in a very dense (20 Radar + 30 MIDS Spokes!) scenario, but we assume a range estimate which is available for the Radar Spokes. Even in this case you can't find unambiguous points anymore, only few credible ones. But most of the intersection points are incredible (see Figure 8.1-6).

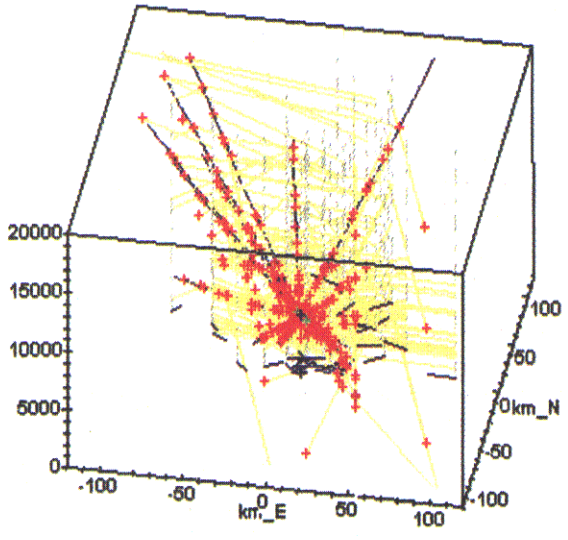

Figure 8.1-6: 20 Radar + 30 MIDS Spokes with range estimate of the Radar Spokes available

Results:

- Ambiguities in the case of no range estimate
- Almost all intersection points are filtered out in the case of existing range estimates (Δr=5000m)

8.2 Recognition of a realistic target

The first step is again the generation of a realistic random scenario as explained above.

In the second step one realistic target (*i.e. it behaves like a real aircraft*) is placed somewhere (input: range, azimuth, altitude, course, velocity and vertical velocity) in the scenario and then Spoke data for this target are generated "by hand" as follows:

- Calculate the ownship Spoke data
- Place one MIDS platform in the scenario
- Calculate the MIDS Spoke from this platform to the target
- Simulate with and without range estimates of the Spokes
- Place a second (or even further MIDS platforms) in the scenario and generate again the Spokes to the real target

The ownship data are constant and are the same from above. Additionally the kinematic data of the realistic target is variable, but for comparison reasons in this presentation fixed as follows:

Target Range: 60 km
Target Azimuth : $\pi/5$
Target velocity: 400 m/s
Target vertical velocity: 0 m/s
Target course: $-\pi/2$ (west direction)
Target altitude: 10000 m

The position of the MIDS platform which "sees" the target is also variable, but for the demonstration here defined as follows:

MIDS platform Range: 50km
MIDS platform Azimuth: $\pi/2$ (east from ownship)
MIDS platform velocity: 400m/s
MIDS platform course: $-\pi/4$ (north-west direction)

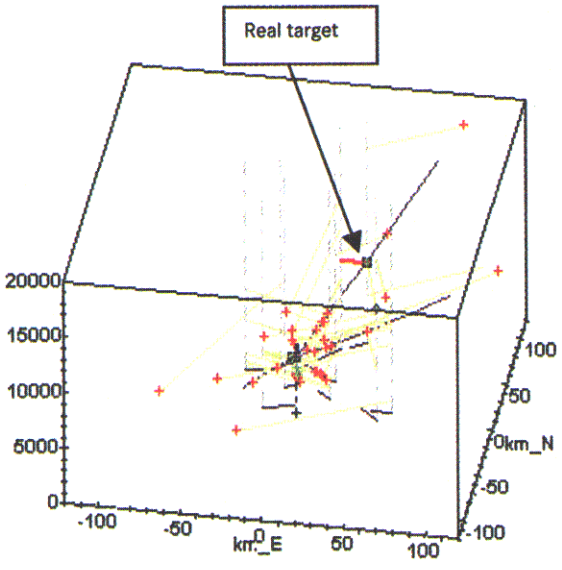

Figure 8.2-1: 6 Radar and 10 MIDS Spokes with a real target placed in the random scenario

Figure 8.2-1 shows, that in the case of existing range estimates (even if there is only one range estimate available!) the real target is filtered out unambiguously. The range accuracy for the range credibility tests was set to Δr=5000m.

As you can see in Figure 8.2-2 the result gets even more better, if you assume a real target which is seen from the Ownship and from two different MIDS platforms with range estimates available! In this case the snapshot on the scenario delivers a brilliant determination of the real target even if you have a rather dense scenario with 10 Radar and 20 MIDS Spokes!

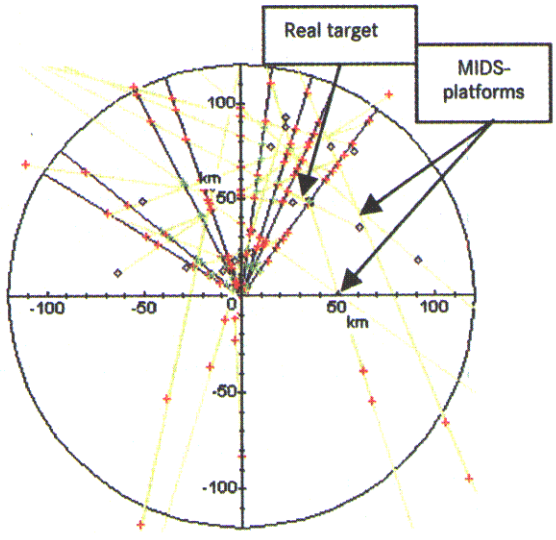

Figure 8.2-2: Real target seen from 2 different MIDS platforms.

8.3 Processing time measurements

The simulations give us also the possibility to measure the total processing time and the processing times of the different main parts of the triangulation process (calculation, credibility tests and association).

The simulations have been performed on a PC with a Pentium II MMX processor (233MHz).

The processing times have been averaged over 10 runs.

In the first test the number of MIDS Spokes is fixed to 10 and the number of Radar Spokes is variable from 1 to 10; Figure 8.3-1 shows a linear increase in the processing time.

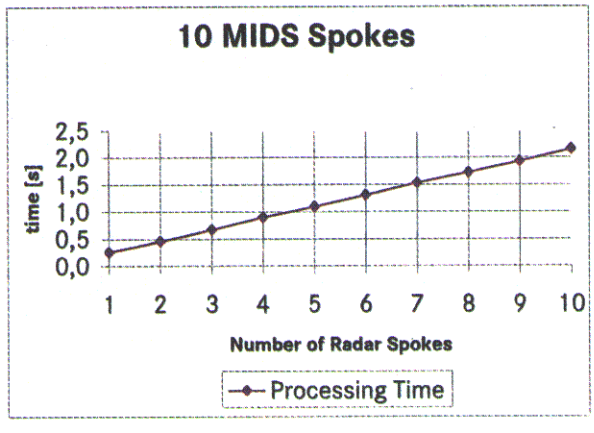

Figure 8.3-1: total processing times with 10 MIDS Spokes and variable number of Radar Spokes

In a second test the number of Radar Spokes is constant (6) and the number of MIDS Spokes is variable. The result is shown in Figure 8.3-2.You can

also see a linear increase in the processing time with growing MIDS Spoke number.

In a third test, where r·m is kept constant the processing time stays also nearly constant.

The linear time behavior should change in that moment, when we introduce a more complicated association algorithm, e.g. the munkres algorithm with the credibility matrix as basis.

The processing time measurements show also that in the current design it is partitioned on the 3 main processes as follows (for a medium number of Spokes 6Radar x 10MIDS):

- Calculate intersection points: 88%
- Credibility tests: 10%
- Association: 2%

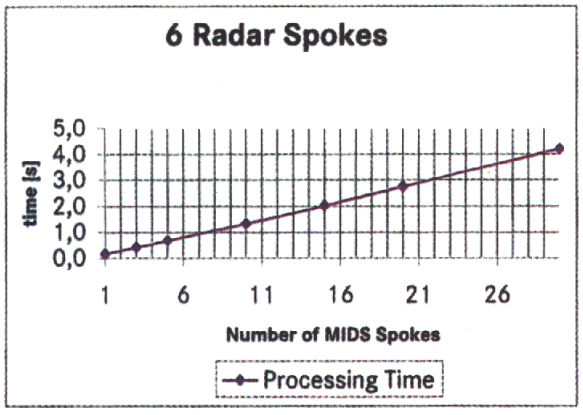

Figure 8.3-2: Processing time over MIDS Spoke number by maintaining the number of Radar Spokes constant.

8.4 Results of the fine tuning constants

All the above mentioned simulations are performed for one main reason, to make the algorithms as accurate as possible by 'turning the buttons' of the fine tuning constants.

The achieved best results of these parameters are:

- Threshold for range credibility test: 5000m
- Cut off possibility for the credibility matrix: 95%
- Association thresholds for range: 5000m
- Range rate: 50m/s

SUBJECTIVE INFORMATION GIVEN BY USER IN BEARINGS-ONLY TARGET MOTION ANALYSIS

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SUMMARY

The Bearings-only Target Motion Analysis (BTMA) problem with two observers on ground consists of estimating the position and velocity of maneuvering targets from bearings-only measurements corrupted by noise. In the entire process, there are two parts : first association of the measurements on each observer then fusion of tracks made by each observer in order to find the trajectory of the targets. Fusion performances are highly dependant of the trajectory estimation algorithm. In some cases, conditions of interception are very bad : few measurements, targets hidden by hill, etc... One way to improve performances is to introduce subjective information coming from user's expertise or external processes. We present here the application of a trajectory estimation algorithm based on the Hidden Markov Models (HMM) which is a global stochastic method where subjective information can easily be introduced.

1. INTRODUCTION

The Bearings-only Target Motion Analysis (BTMA) problem with two observers on ground consists of estimating the position and velocity of maneuvering targets from bearings-only measurements corrupted by noise.

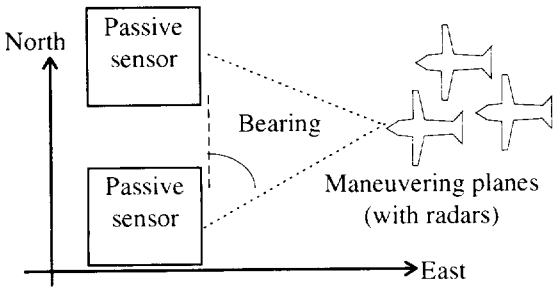

Figure 1.a. : Bearings-only Target Motion Analysis (BTMA) with two observers

We have an observation system composed of two observers on ground which measure bearings coming from maneuvering targets. The goal is first to **associate** (on each observer) the bearings in order to make tracks, each track being supposed relative to a single target, and then to **fusion** tracks made by each observer, in order to find the trajectory of targets. The track fusion uses trajectory estimation algorithms, so if the estimation has a good quality, the fusion is kept, if not, the fusion is rejected. We see that algorithms used for estimating a trajectory have an important role in the fusion process.

In BTMA, the estimation problem is non-linear and *sometimes* assumptions made in algorithms as Extended Kalman Filtering can be too rough. In some cases, it's often usual to have very bad conditions of interception : few measurements available, or none during a few periods in the case of ground stations used at a low altitude in mountainous areas. In these cases, one way to improve the trajectory estimation problem is to

Paper presented at the RTO SCI Symposium on "Sensor Data Fusion and Integration of the Human Element", held in Ottawa, Canada, 14-17 September 1998, and published in RTO MP-12.

use subjective information given by the user or by an external system.

Many ways are possible to introduce subjective information in algorithms. The Hidden Markov Models (HMM), which is a global stochastic method adapted to the non-linear problems and where subjective information can easily been given, is used in this paper.

Let's see the problem of estimating the trajectory in the BTMA with two observers, which is a non-linear problem of estimation. If we note $X_N = \{x_1,...x_N\}$ the state vector sequence to estimate, which are position and speed in BTMA, and $Z_N = \{z_1,...z_N\}$ the observation sequence at time $\{t_1,...t_N\}$, which are bearings in BTMA, then the goal of estimation is to determine the conditional probability density function (pdf), $p(X_N/Z_N)$, which contains all the information on X_N.
In many cases, the assumption of a Gaussian pdf is done which needs only two parameters (mean and variance) to be completely determined.
The Kalman filtering is applied in the case of linear systems with Gaussian initialisation. The Gaussian property is preserved along the linear transformations and the Bayesian corrections. The Kalman filtering gives an estimation of the mean and the variance of the state given the observations, which completely determined the Gaussian pdf. A classical approach to extend the Kalman filtering to the non-linear case is to expand the equations in Taylor series about the nominal values. This lead to the Extended Kalman Filter (EKF). This extension is an approximation and the performances can be poor in the case of high non-linearity or non-Gaussian problems.
An other point that is important to see is that the problem of estimating a pdf is compatible with the evolution of many sensors for example in the BTMA. Indeed more than more parameters are measured (bearings, time difference of arrival, Doppler,...) and this measured are translated in pdf on the digitalized state space, not necessarily in a Gaussian way because the behaviour of the sensors is more than more well-known and this knowledge as to be taken in account in order to enhance the tracking. On the other hand, the estimation of a pdf is multimodal (i.e. multitargets) when the Kalman filtering is monomodal.
For the tracking, we need to follow the evolution of the pdf. In this paper we use the Hidden Markov Model (HMM). In a general point of view for this kind of algorithm, we know the transition law $p(x_K/x_{K-1})$ and the observation law $p(z_K/x_K)$. Our aim is to estimate $p(x_K/z_K)$ recursively in time. At time k-1, we suppose to know $p(x_{K-1}/z_{K-1})$. Due to the Markov assumption for x, we can compute the prediction :

$$p(x_K / z_{K-1}) = \int p(x_K / x_{K-1}).p(x_{K-1} / z_{K-1}) .$$

Then the measurement z_K is used to do a correction in order to obtain $p(x_K/z_K)$ with Baye's formula :

$$p(x_K / z_K) = \frac{p(z_K / x_K).p(x_K / z_{K-1})}{p(z_K / z_{K-1})}$$

Correction — Prédiction

The knowledge of $p(x_K/z_K)$ gives the possibility to give an estimate $\hat{x}_K = I(x_K)$ of the state. For example :

$$I(x_K) = \int_{x_K} x_K p(x_K / z_K) \text{ or}$$

$$I(x_K) = \max_{x_K}(p(x_K/z_K)).$$

The aim of the methods is to propagate the pdf and estimate $I(x_K)$.

The term $p(x_K/x_{K-1})$, which is a probability of transition allows the user to give easily subjective information on the state vector and so to improve the performances of estimation and then the performances of the fusion. This information is given by the user with an easy-to-use interface.

2. THE INTERACTING MULTIPLE MODELS

The Interacting Multiple Models (IMM) in the case of two passive-only sensors has been developed in [1]. This algorithm is based on M Extended Kalman Filter (EKF) in parallels, each of them corresponding to a particular maneuvering hypothesis. Knowledge is introduced by modelling the change of hypothesis with a Markov chain.

3. THE HIDDEN MARKOV MODELS

Elements on Hidden Markov Models (HMM) can be found in [2]. Applications of the HMM to the problem of tracking are developed in [3], [4] and [5].
In the HMM with the Viterbi algorithm, the pdf is estimated on a fixed grid of the state vector x and the recursion is built following the equation $\delta(x_K) = p(z_K/x_K).\max_{x_{K-1}}(p(x_K/x_{K-1}).\delta(x_{K-1}))$.

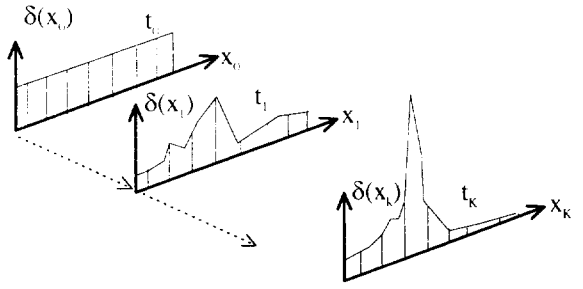

Figure 3.a. : HMM and Viterbi algorithm

One particularity of the HMM is the fact that it doesn't introduce a formal model of evolution of the target as in the IMM. A simple hypothesis of a maximal acceleration for example is sufficient. *On the other hand, if the user wants it, it's also possible and easy to introduce complex prior information on the motion of the target.*

We give here the mains equations :
Notations :
N the number of states in the model,
O_t : Observation at time t,
B : observation probability distribution in the state j
$B = \{b_j(O_t)\}$, $b_j(O_t) = pr[O_t/\text{state j at t}]$, $1 \le j \le N$
A : state transition probability distribution
$A = \{a_{ij}\}$, $a_{ij} = pr[\text{state j at t+1/state i at t}]$, $1 \le i,j \le N$
π : initial state distribution
$\pi = \{\pi_i\}$, $\pi_i = pr[\text{state i}]$, $1 \le j \le N$
T : number of observations.
Viterbi Algorithm:
Initialization

$$\delta_1(i) = \pi_i b_i(O_1), \qquad 1 \le i \le N$$

Récursion

$$\delta_t(j) = \max_{1 \le i \le N}[\delta_{t-1}(i)a_{ij}]b_j(O_t)$$

$$\Psi_t(j) = \arg\max_{1 \le i \le N}[\delta_{t-1}(i)a_{ij}]$$

$$2 \le t \le T,\ 1 \le j \le N$$

Termination

$$q_T = \arg\max_{1 \le i \le N}[\delta_T(i)]$$

We get the state from the *backtracking* :

$$q_t = \Psi_{t+1}(q_{t-1}),\ t = T-1, T-2, \ldots 1$$

B is given by the model of sensor and can be on analytic form (uniform, Gaussian,...) or can be given in a numeric form, more or less complex, in the state space. In the example of section 5, we have taken a Gaussian distribution.
A can be fixed with many criterion. In our case, we suppose that at time t the target can have a maximal acceleration (for example ±3g). This give the states possible at time t+1, each of them having the same probability. As we see, this hypothesis is very simple and could be easily improved in order to enhance the performances.
In our case, the state space is in 4 dimensions and the targets are highly maneuvering. The hypothesis chosen for A are very simple and the number of states possible can be very high. In order to reduce the computation, we have chosen a *sub-optimal* version of the HMM which consists on keeping the N_{max} states the more probable at time t.

If we know nothing about the target, except some large bounds on position and speed, π can be an uniform distribution on the state space. On the other hand, it's easy to introduce prior information to reduce computation.

4. SUBJECTIVE INFORMATION GIVEN BY USER

In a real situation, one could imagine that a system made of two ground stations is installed in an area where enemy planes are likely to fly or even to attack.

The user has a terminal where he can see a map of the area concerned and the position of observers (Figure 4.a).

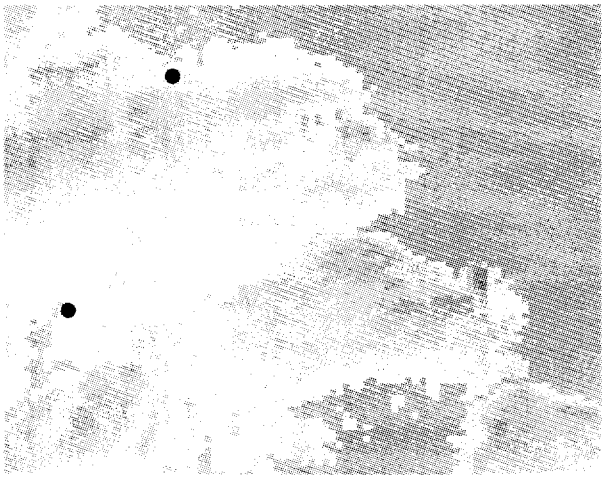

Figure 4.a. : Area concerned and observers's position

The user has certainly an expertise of this kind of situation and he might also have a few tools and external information such as maps, geodesic information, kind of targets, and so on. In our example, the user is able to define air corridors where he thinks a plane can be. So the user draws a few points on the map, describing corridors. Then, giving a grid size, it will finally give a grid 2D of possible positions (Figure 4.b).

At this point, the user can also give more information on parts of the corridors which are more likely than others, or decide that the distribution on the grid is uniform.

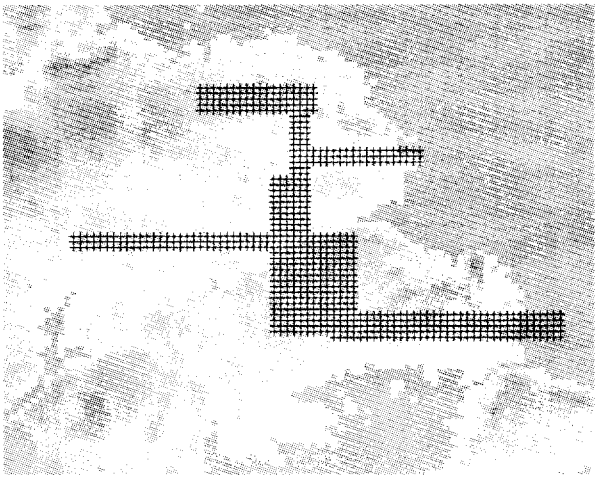

Figure 4.b. : Grid 2D of possible positions

5. SIMULATION

We take the same subjective information as in part 4.
The scenario is shown on Figure 5.a. A plane is coming first in a straight line, then it turns right, a straight line again and finally it turns left going in the direction of one of the observers.

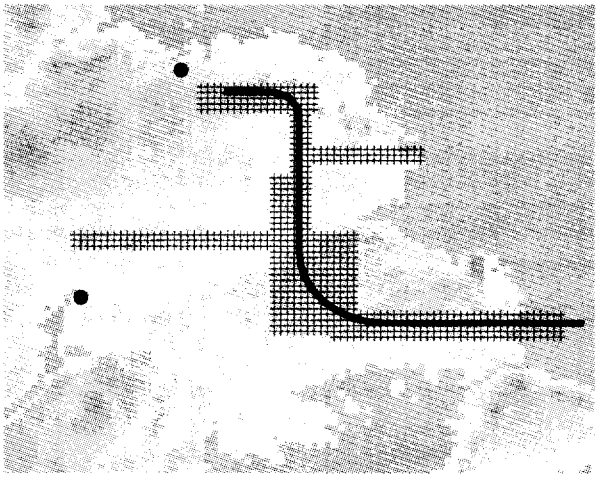

Figure 5.a. : Scenario

Each observer has a measurement period of 10 seconds, and a probability of detection of 0,5. The standard deviation is 3 degrees. One of the observer has no measurement due to an hill which hides the plane during 80 seconds.

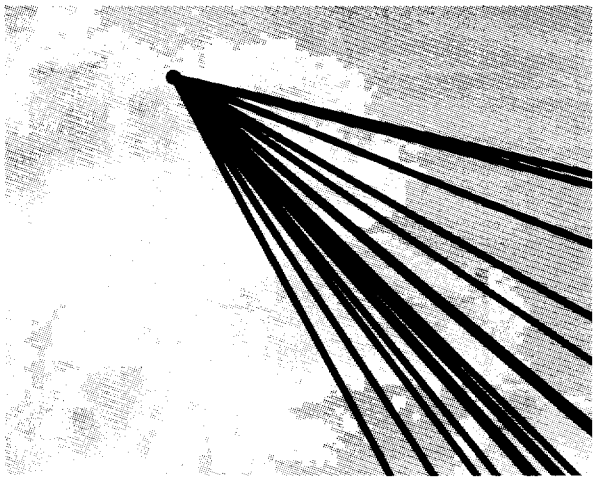

Figure 5.b. : bearings measured by one observer

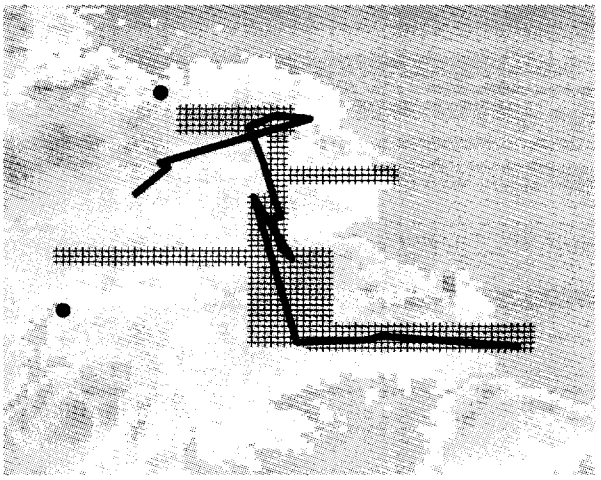

Figure 5.c. : Position estimated by IMM with no subjective information

We see that the conditions of interception are not very good : few measurements, plane hidden by hill.
In order to compare two opposite situations, we have applied first the extended Kalman filter IMM with no subjective information and then the HMM with the grid given on Figure 4.b. Both algorithms have been initialized with a batch Least Mean Square algorithm with straight line hypothesis on the first part of the trajectory.
The position estimated by the algorithms are shown in figures 5.c and 5.d. The IMM has some erratic behaviours, particularly on the end of the trajectory, while in the same time, the result of the HMM is quite good.
One can also see the distance error curve on Figure 5.e. The HMM curve is the solid line and the IMM's one is the dashline. After the initialization which is identical for both algorithm, the result given by the HMM with subjective information is very good compared to the IMM one.
Note that the good quality of the result is completely dependant of the subjective information quality. As it is well-known in the theory of estimation : when the subjective information is good the performance of algorithms increases greatly, but when this information is erroneous, the performance decreases dramatically.

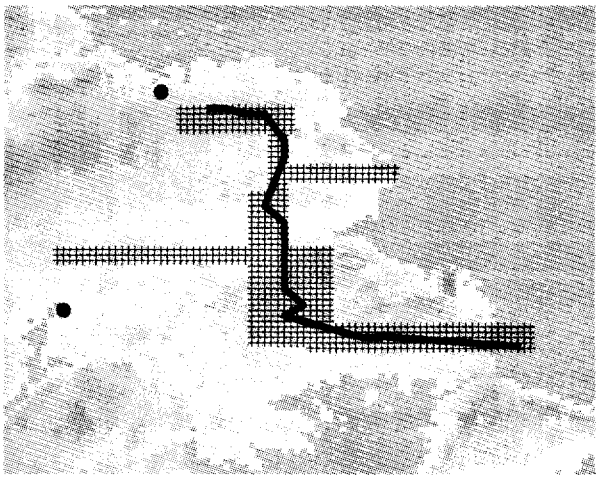

Figure 5.d. : Position estimated by HMM with subjective information

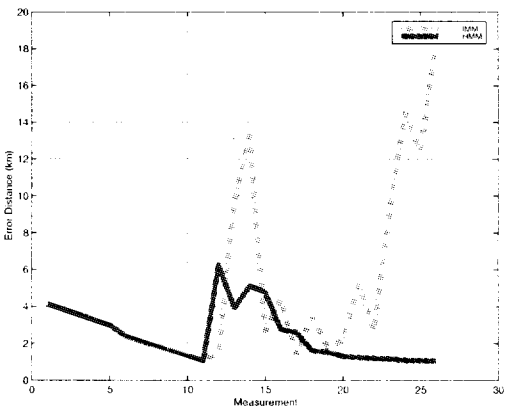

Figure 5.e. : Distance error for IMM and HMM

6. CONCLUSION

After a brief review of the Bearings-only Target Motion Analysis, we have seen one way to introduce subjective information by using the Hidden Markov Models. If the subjective information has a good quality, the result of the trajectory estimation becomes very good compared to a classical extended Kalman filtering without prior information. This can provide a solution to compensate bad conditions of interceptions as seen in the part 5 of this paper.
The next step is to develop an automatic learning process which uses external information and human knowledge in order to propose a set of subjective information to the user.

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1. INTEGRATION OF THE HUMAN OPERATOR INTO COMPLEX AIR SYSTEMS USING ALTERNATIVE CONTROL TECHNOLOGIES

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1.1 INTRODUCTION

In general, a combat aircraft can be described as manoeuverable airborne weapons platforms which contain a series of electronic and other systems with which the aircraft is controlled, navigated, weapons selected etc., and a series of systems which provide protection for the aircrew throughout the performance envelope of the aircraft and when emergency escape is unavoidable. Most aircraft platforms have an operational life of over 20 years - some a lot longer - and, in this timescale, although the basic platform does not significantly alter - mainly for cost reasons - the avionics and crew support systems fits can continue to advance a number of generations - which can allow the airframe to retain its operational competitiveness against newer designs

The speed and capacity of future avionic systems, themselves increasing in complexity, will result in the amount of information output heavily increased. This is often all fed to a single pilot who is flying the aircraft close to the ground at around 450 knots or more, perhaps in bad weather at night, and the flying process alone needs continuous monitoring. In addition s/he needs to keep safe control of the aircraft, find the target, select and arm weapons, be aware of, and react to, enemy countermeasures, perform complex operations with smart weapons, etc., all in a degraded environment with high noise levels, high vibration and heat, high 'g' levels, high agility, disorientation, etc. Out of this scenario, one of the primary problems is the amount of data - not necessarily in the right information format for easy digestion - that it is necessary for the pilot to process and the interaction with the displays which s/he will need to ensure that the correct inputs are entered at the right time, and quickly enough, to get the operationally relevant information out.

Aircraft avionic, weapons, navigation and other systems are unlikely to become less complex and this increasing complexity is often needed to counter the increasing subtlety of enemy countermeasures, there is a tendency to need more inputs to a greater number of systems by the pilot and the additional time to carry out these extra operations is not generally available.

The current, and traditional, methods of data input or selection of systems normally require the use of the hands to either switch a system to a particular state or enter data through a key-board. Most current aircraft, both civil and military, make large use of keyboards to enter a wide range of data both on the ground and whilst airborne. Errors do occur in data entry, even under benign conditions, and sometimes can result in serious consequences. In military aircraft, data entry is often an operational requirement in flight and experiments have shown that errors of around 2.2% to 2.9% can occur in high-speed low-level flight [1-1] and, even in the office environment, typing errors in the region of 1.5% occur, and this is with a full sized keyboard under unstressed conditions and without the need for NBC gloves and the smaller keyboards and key sizes often found in aircraft. Next generation systems may need a larger number of data inputs and to increase the manual input capability of the pilot either requires an increase in 'typing' speed, a larger number of hands or an alternative control technique.

In civil systems errors occur traditionally during high workload periods [1.2] - often during a runway change required by Air Traffic during approach and, for the military, similar errors could be expected to occur in aircraft which use a combination of military and civil systems in the cockpit (C-130J, E3D, C-17, etc), particularly, perhaps, in the more demanding battlefield support role.

More demanding operations in the current generations of fixed and rotary wing aircraft, particularly at night and in poor weather, have increased the need for more 'eyes-out' operations, which decreases the time for 'head down' or 'head in' viewing time, both for switching operations and for assimilation of information from head down displays. Similarly the speed of operations has led to less time being available for these two operations. Progress has been made towards the assimilation of visual display data through the move towards Helmet Mounted Displays and the time reductions in switching have been achieved through ensuring that the pilot has no need to move his hands from the primary aircraft controls during high workload periods by the use of the **H**ands **O**n **T**hrottle **A**nd **S**tick (**HOTAS**) concept. Using Fitts Law, namely that the time to move the hand to a target (in this case a switch or button) depends only upon the relative precision required, indicates that the movement time - a summed combination of perceptual processing, cognitive processing and motor processing - is in the region of 250 ms (an aircraft moving at 500 knots travels in the region of 80 metres in this time). Thus a time saving of around 250msec is achievable by minimising the hand movements. This generally involves the provision of all of the necessary manual switches on either the throttle top or the control column (stick) top, (HOTAS) or **H**ands **O**n **C**ollective **A**nd **C**yclic (**HOCAC**) - for helicopters - during all critical flight operations. An example of HOTAS controls is shown in Fig. 1 for the AFTI F-16 aircraft [1-3.]

As the capabilities of aircraft will continue to increase through the use of more sophisticated, and a wider range of, sensors, and control through software increases, the ability to control the aircraft systems will inevitably require an even greater number of controls - many of these being necessary, at least in principle, on the HOTAS controls, as many are time critical and need to be operated eyes-out. The rise in the number of avionic systems and the consequent number of manual switching operations necessary during critical phases of operations (eg beyond FEBA and set-up & attack phase of a ground target) has resulted in a gradual increase in the numbers of switches/controls per crew member in the cockpit and this is illustrated in Figure 1-2.

Paper presented at the RTO SCI Symposium on "Sensor Data Fusion and Integration of the Human Element", held in Ottawa, Canada, 14-17 September 1998, and published in RTO MP-12.

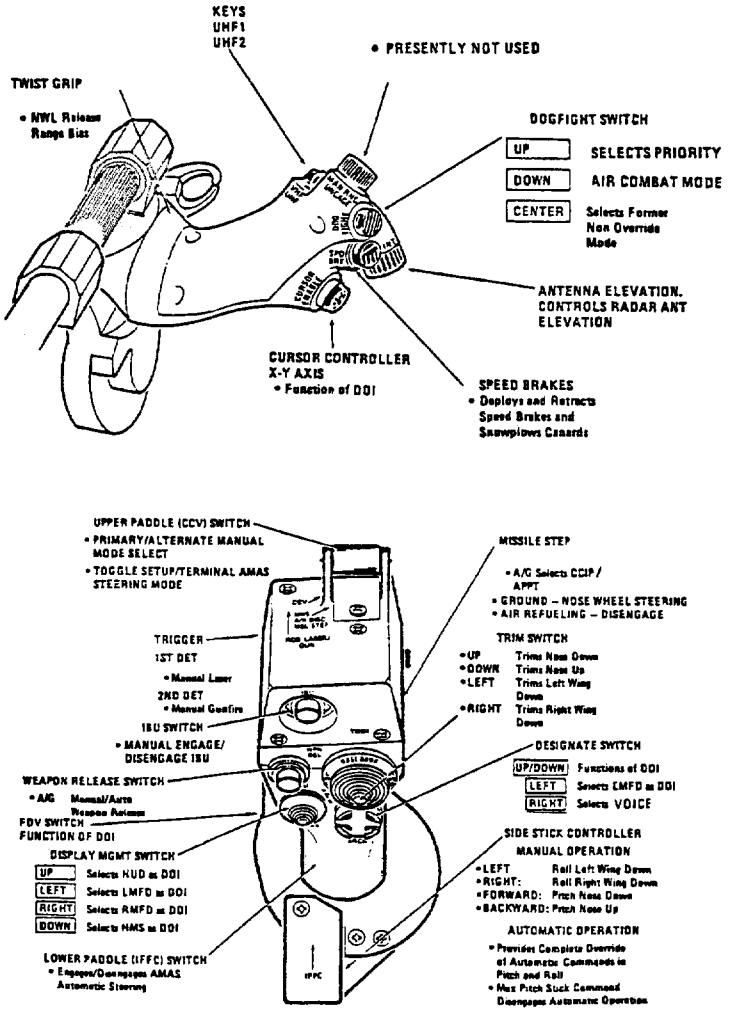


Figure 1-1 HOTAS Controls for AFTI/F-16 Aircraft

The increased numbers of switches and controls results both in longer selection and switching times and with the necessity to look head down into the cockpit to operate the correct switch or series of switches. This has led to the HOTAS concept and, on HOTAS, aircraft of the 1970's design era were using around 16 stick and throttle top functions, and, whilst some aircraft designs in the late 80's still used less than 20 functions, some fixed wing aircraft were up to 33 functions and helicopters up to 40. Figure 1-3 illustrates this trend and Table 1 shows the functions allocated to HOTAS for a number of aircraft [1-3].

There are some indications from aircrew that the numbers of functions are becoming both difficult to remember - needing more training - and sometimes difficult to operate with either standard aircrew gloves or NBC gloves. More complex aircraft systems will almost inevitably require more control mechanisms, and the most obvious approach is to increase the number of HOTAS keys - at least for the time critical operations. If the physical space is no longer available on the throttle or stick, the temptation will be to use 'chording' - the simultaneous use of two, or more, (existing) keys to select or operate systems - with an inevitable increase in mental complexity.

Where the numbers have reached a level where some aircrew are finding some difficulties in remembering the functions of all of the switches, and since it is impracticable to label the

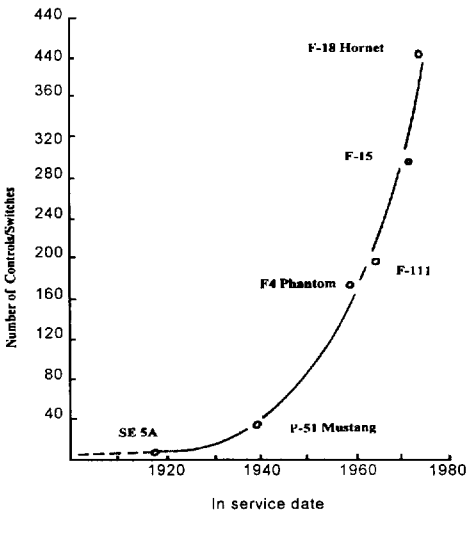


Figure 1-1 Number of controls/switches per crew member

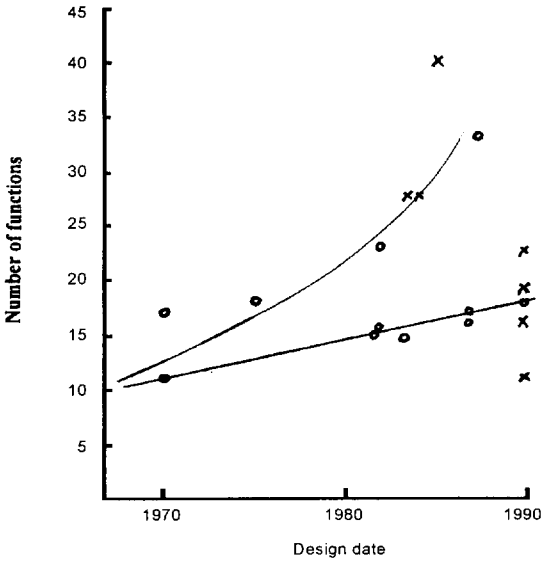


Figure 1-2 Trend of HOTAS Switching

switches - it would, in any case, be almost impossible to either clearly read the labels in their position in the aircraft or have the time to read the labels during critical parts of the sortie, - there is no possibility of identifying the correct switch or button if the memory fails or falters for any reason. Since a large percentage of the buttons/switches are for critical aircraft functions, and thus will be time critical, any delay or error can jeopardise the aircraft mission. Further, even if the error is known, the procedures to recover from such errors - if any - inevitably take time. It may not always be clear to a pilot that he has made an error, or that he has pressed the wrong switch or button. If a button is pressed and the expected consequences do not occur, a number of options appear in his mind:

- The switch or button may not have worked:
  - Solution ?? - press again or harder
- The feedback system - if any - may have failed
- The display or function may have failed
- The system may have failed - is there any feedback?
- It may be the wrong button - which one now?

All of these take time, which generally is in critically short supply in these phases of flight. A well implemented **alternative** control input method would provide alleviation of this type of operationally critical problem.

A potential further problem, particularly with the necessary physical positioning of a larger number of switches or buttons is the difference in anthropometric span of the hand & fingers. Not only are there differences in the populations of an individual country, but there are statistical and practical differences between countries - sometimes significant. Currently, a number of countries are accepting female aircrew for combat aircraft, and the differences in HOTAS systems designed for male aircrew may elicit problems for female crew with differing effective digit length and hand-reach anthropometry.

Table 1-II shows an example of the differences in hand length of a number of countries and of a number of trials. The average hand length for males is 191.65 mm with an average spread of 48

Table 1.1-I A sample of functions allocated to HOTAS controls

Aircraft	Design Date	Throttle Functions	Stick Functions	Hand Controller	Total
F15C Eagle	1970	11	6	0	17
F15E-front	1982	9	6	0	15
F15E- rear	1982	0	0	6	6
Tornado IDS - front	1970	4	7	4	15
Tornado IDS - rear	1970	0	0	5	5
F-18 A toD - front	1975	10	8	0	18
F-18 E/F - front	1990	10	8	0	18+
F-18 E/F	1990	0	0	6	6
AV8B+	1989	9	8	0	16
Harrier GR7	1989	17(8)	17(8)	0	16+
Mirage 2000-5	1987	14	9	0	23
Rafale	1988	21	11	0	33
EF2000	1991				
AMX	1982	6	9	0	15
F-16 C/D Falcon	1983	6	8	0	14
AFTI F-16		8	10	0	18
MIG-29		7	12		19
Tiger -rear	1985	14	12		26
- front		14	12		26
AH 64 Longbow-rear	1990	6	13	0	19
-front		0	0	11	11
EH101	1984	19 (14)	21 (12)	0	40
RAH66 Comanche	1990	14	8	0	22
MV22 Osprey	1988	9	7	0	16
A330 Airbus	1990	0	3	0	

mm. Standard deviations are in the region of 9 mm, which, as an estimate, would allow a HOTAS mounted set of switches and buttons to be designed to be used by perhaps some 70% (>1 sd) of the pilot population without undue difficulty. The remaining 30% may need to make some sliding movements around the stick or throttle to accommodate the full range. The female average hand length, however, is an average of 176.3 mm with a spread of 42.5 mm and an sd of 8.6 mm. The difference in mean length is some 16 mm, which could provide some difficulty in design of HOTAS controls which must be operated by both genders.

Table 1-III supports this hypothesis with figures comparing, in considerably more detail, differences between UK male and female hand dimensions [1-4]. As an indication of the potential problems, the distance from the 'hand crease' - representing, in this case, the apex of the HOTAS grip - to the finger tips displays an average difference of 1.2 cm. If a wider range of male and female crews need to be accommodated, then this difference may be increased to over 3 to 4 cm. Similarly for span between the thumb and the individual digits, which gives an indication of the ability to operate a thumb switch and another with one of the other digits average differences of around 1.3 cm are apparent. Similarly the true digit lengths - the length of each finger -is shorter for females by around 5 mm and the curved hand length is shorter in females by some 1.65 cm. Many of these differences

Table 1.3-I Hand Length Data

	Date	Sample	mm	sd	Range	Spread
Male						
UK Military	1982	300	191.30	9.71	169-224	55
Canadian Military	1974	565	191.90	8.78	170-212	42
German Air Force	1966	1006	189.10	8.70	168-210	40
British Army	1970-75	2000	193.00	10.30	159-219	60
US Army	1970	1482	192.00	8.70	172-214	42
US Army	1966	6682	190.30	9.60	169-214	45
US Air Force	1970	148	197.20	9.30	173-228	55
French Army	1973	793	189.00	9.00	174-205	5th-95th% range
UK Civilian	1981	300	191.00	8.30	165-219	54
mean values			(191.65)	8.27	(159-228)	48
Female						
UK Military	1982	187	176.10	8.07	159-197	38
US Army	1977	1331	174.40	9.00	155-196	
US Air Force	1970	211	179.30	8.60	157-205	43
UK Civilian	1980	92	177.50	10.10	161-194	5th-95th% range
UK Civilian	1981	200	174.20	7.20	152-195	43
mean values			(176.30)	(8.6)		42.5

may be able to be accommodated by good design, but there must be a high probability that, in current designs, and in future designs where the increasing number of controls surfaces will perhaps result in physically smaller switches and buttons, the potential competition between switch numbers and available surface area, as numbers of switches or tactile controls compete with surface area, will play a more significant limitation.

1.2 ALTERNATIVE CONTROL TECHNOLOGIES

Many of these problems can be solved, or at least ameliorated in operational terms, by the use of Alternative Control Technologies. There are five fundamental technologies that will allow use of alternative control strategies. These are:

* **Head-Based Control**
* **Speech-Based Control**
* **Eye-Based Control**
* **Gesture-Based Control**
* **Biopotential-Based Control**

Of these five alternative control systems, head tracking and speech control are considered the most mature, with head tracking control already being in operational use. Eye tracking, whilst technologically advanced and useable in simulators etc., still requires some development for use in the environment of the airborne cockpit. Gesture based and biopotential based systems are regarded as longer term solutions for the airborne cockpit, although, of course, many simple EMG systems are regularly in use as aids for persons with disabilities.

There is a gradual transition to use of some of the alternative controls and this is apparent in the next generation operational aircraft of the Eurofighter, F-22 and Rafale type. Experimental flying in the UK, France and USA are using Helmet Mounted

Table 1.1-II Details of Hand Dimensions

		Male			Female		
		Mean	Sd	Range	Mean	Sd	Range
Finger number to hand crease							
Digit 2	Left	12.26	0.81	10.2-14.4	11.16	0.70	9.4-13.4
	Right	12.21	0.79	10.2-14.9	11.17	0.69	9.3-13.1
Digit 3	Left	13.51	0.92	11.1-16.0	12.12	0.79	10.3-14.4
	Right	13.40	0.87	11.3-16.5	12.09	0.78	10.3-14.6
Digit 4	Left	12.44	0.95	9.8-15.0	11.00	0.86	9.0-13.5
	Right	12.31	0.90	10.0-14.9	10.97	0.85	9.2-13.6
Thumb	Left	6.02	0.50	4.7-7.6	5.50	0.44	4.3-6.9
	Right	6.11	0.48	4.9-7.8	5.62	0.43	4.2-7.0
Digit 5	Left	9.13	0.98	7.0-12.3	8.28	0.80	6.2-10.9
	Right	9.49	0.90	7.1-11.8	8.31	0.89	6.3-11.1

Sights & Displays which are fully dependent upon head tracking to provide the helmet pointing capability. Some production systems are in service use in a number of countries (Russia, Romania, South Africa, Israel...) and are generally simple sights, but, even at this stage of development, allow significant increases in operational performance, when correctly integrated with a suitable weapon system. Similarly Voice Control systems are flying experimentally and being used during simulation to demonstrate significant operational benefits. Eurofighter will use voice control as an integrated part of avionics control and Rafale will have the use as an option. Eye tracking would appear to have strong potential in military systems, particularly when used in conjunction with head tracking. Whilst head tracking gives a good indication of the position in which the head is pointing - and is fully adequate for a number of applications - it does not, of course, necessarily show what the pilot is actually looking at (ie where the gaze is fixed). A number of techniques exist to measure eye position, some more robust than others in an operational environment, and many are used in the simulation environment, where many practical environmental limitations are minimised. The electrophysiological measures, and measures of gesture, are currently limited in their application in the operational cockpit, although there is considerable potential for these type of systems in the 2010 to 2015 timescales. The Adaptive Interface between the pilot and aircraft systems, in which the aircraft will infer the state of the pilot and the pilot and aircraft will have a knowledge of the state of each others systems, will need the capabilities of these technologies.

A further important practical issue that must be addressed arises from the implications that the alternative control technologies involved with head pointing, eye tracking and voice control all require some sort of head mounted system. In the cockpit environment these systems are generally head mounted on the flying helmet or an existing helmet mounted display. However, care must be taken to minimise both the total head mounted mass and the centre-of-gravity offsets caused by the additional head mounted equipment, as there are flight safety issues involving injury to aircrew from such systems, which can have serious implications in operational use.

1.3 HEAD POINTING

Of the potential alternative control technologies, Head Movement Tracking is undoubtably the most used and is, and has been, in operational use in a number of forms, for a number of years, with a number of airforces. Such tracking technology is of primary importance as it is fundamental to all future systems that will wish to use Head or Helmet Mounted Displays - in any conceivable form - or any type of visually coupled system.

Currently, the majority of aircraft carrying out a missile attack on a ground or airborne target must point the nose of the aircraft towards the target in order to suitably align the enemy aircraft on the weapon aiming displays on the HUD to lock-on the weapon prior to firing. This is not only a time consuming approach, but may require the aircraft to perform tortuous manoeuvres in pursuit of the also manoeuvering target aircraft. Figure 1.2-4 illustrates the sustained and instantaneous manoeuvre capability that is currently required from an air-to-air combat fighter, in this case the F16.

Unfortunately the human body, being developed over a few million years for a less stressful environment, does not respond well to these violent manoeuvres and technologically complex and ingenious methods of protecting the body must be employed. Currently airframe soft limits in the region of 9 'g' are in use in current production and future aircraft and the protection of the crew to these levels is complex and cumbersome.

The emergence of the technology, over the last 15 years, to allow flight worthy Helmet Mounted Displays (HMD) [1-5, 1-6, 1-7] and the development of accurate flight worthy Head Pointing Tracker Systems (HPS) has allowed methods other than manually boresighting the aircraft, to be used to enhance weapon delivery techniques.

Future-current and next generation weapon systems, particularly air-to-air close combat engagements, will be able use an alternative form of control system that will integrate the HMD, the HPS and the missile seeker head, Figure 1.2-5.

This enables the missile seeker to be driven by the head pointing system to look in the direction that the pilot's head is pointing, and, as the pilot sights the target aircraft in his helmet mounted sight, for the missile to lock-on and be fired at high off-boresight angles, without the necessity for violent manoeuvering of the aircraft.

There are a number of technologies available to provide head tracking; mechanical, inertial, acoustical, optical, but currently (1998) the most mature is the a.c. magnetic tracker. This system, in its well developed form, provides the bulk of the systems in use in the world. It provides good accuracy when mapped into individual cockpits, and, as importantly, it provides a large headbox in the cockpit allowing the pilot to obtain head position data from essentially the whole effective cockpit volume. Accuracy is variable across the cockpit volume, particularly towards the extremities of the headbox, but accuracies in the region of 4 mR, with no worse than 8mR are achievable (1998), and degredation of the sensor signals are generally regarded as 'graceful'. In the first instance, this is fully acceptable for use in close combat in 'one v one' or 'one v more' engagements with short range missiles. The missile seeker head is slaved to the pilots head movement and the Field of Regard of the seeker head is large enough to negate the need for very high accuracy (< 3mR). Significant savings in target engagement times are achievable with this simple system. For air-to-ground targeting, this simple system also has some advantages. With a targeting FLIR, the FOV is generally small, typically 10 degrees, and searching for a ground target with a hand controller and head down display is difficult and time consuming. Designation of the ground target through the helmet sight, with the FLIR slaved to the head movement, will again allow significant time savings to be made in target designation, particularly for targets of opportunity. As part of this targeting system, it would be feasible to use the voice command as a control medium, - an alternative to using a manual action - to mark and lock onto the ground target. Where 'eyes out' operations are at a premium and the manual processes require glances inside the cockpit, voice command would provide an alternative control strategy.

In a similar way, the use of visually coupled systems, to allow a pilot to fly operationally in night and poor weather conditions by the use of sensor derived images, place an essential need upon the measurement of head position. In helicopters of the US Apache type, the Pilot Night Vision System (PNVS) couples the nose mounted Infra-Red sensor directly to the pilots' eye-piece on the helmet display, and slews the sensor to the pilots head position, lining up the sensor point of regard with the pilots' eye, using the optical head tracking system. Similar systems exist on a number of other helicopters, either experimentally or close to operational deployment. In current operational deployment, the pilot retains a view of the outside world to help retain some external situational awareness, but eventually it may be necessary to operate without a direct external view, if the ultimate protection against optical blinding weapons (e.g. lasers etc.) and other considerations become necessary. This situation then, essentially, becomes the beginning of the Virtual Cockpit and some of the limitations of the systems needed to enable implementation of this 'virtual cockpit' philosophy become apparent. One of the major limitations is in the temporal delays (also called transport delays or latencies) that are induced by the system processing needed between the sensor inputs from the outside world and the sensor output to the crews eye. For instance, the delays between the pilot moving his head to look at a particular point in space and the sensor fixing on that same point should be minimised, and, whilst not yet well defined by flight experimentation, figures of 20 to 50 ms are often quoted - the shorter the better. The delays depend upon the level of processing needed in both the head movement and the image transfer system, and the more complex the system, generally the longer are the delays. For next generation helmet mounted displays, where, for instance, flat panel displays may be the image source on the helmet, the considerable levels of processing needed to carry out, for instance, distortion correction in off-axis optical systems, needs good and careful system design to minimise transport delays.

The operational advantages of the use of this head tracking technology has been shown in flight trials both in the USA, where live missiles have been fired at drones (BOXOFFICE) and in the UK, where air-to-air close combats have been carried out in 1 v 1 trials (JOBTAC) significant reductions in target acquisition and engagement times are apparent.

The use of a helmet mounted display and head tracking system in an F16, combined with a missile capable of acquiring targets of over 60 degrees off-boresight, has allowed, in live firings against a QF 106 target drone at 0.7M, successful intercepts at 57 degrees off-boresight whilst the target was manoeuvering at 5g. Similarly, in one-on-one or two-on-two air-to-air combat between a MIG-29's fitted with a simple Russian helmet mounted sight and using a AA-11 (Archer) missile, and F16's with no helmet sight, the MIG-29 was able to attain the major number of first shot missile releases by use of the Helmet sight system. To pass the head position information to the missile

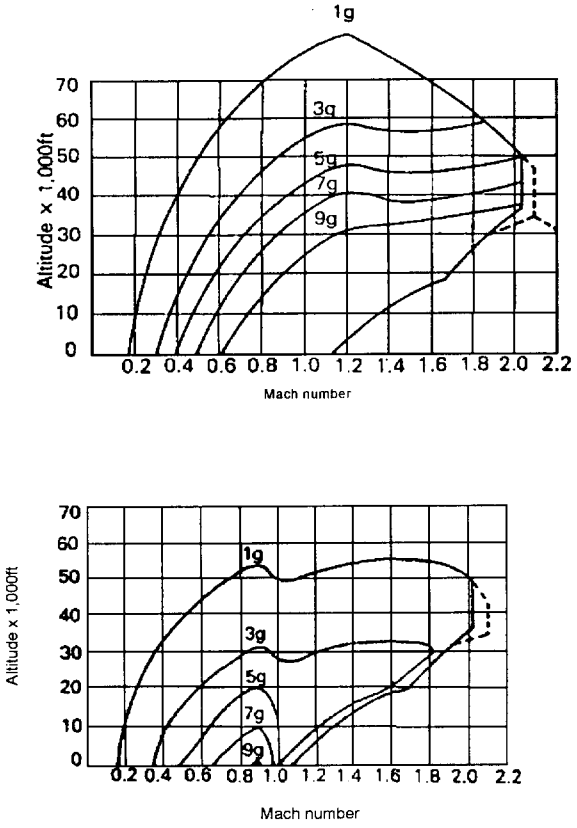


Figure 1-3 Instantaneous (upper) and sustained (lower) manoeuvre capability of the F-16/79

seeker, the MIG-29 used an electro-optical head tracking system. [1-8].

Similarly, at Farnborough in the UK, trials have been flown of one-on-one combat in a Jaguar, using a captive AIM9L and a standard Mk4 UK flying helmet fitted with a simple DERA/GEC sight providing weapon systems information through an LED display and an AC electro-magnetic head tracker. Target acquisition and engagement times were significantly reduced, with off-boresight acquisitions up to 60 degrees being achieved.

Head Tracking can also be used to designate ground targets from the air, or to point narrow FOV sensor systems at targets - and these generally replace manual control systems that are displayed on a HDD. Hunting for a target, in a moving aeroplane, with a narrow FOV sensor (likened to looking for a target through a straw) can be difficult in the best of conditions and may take longer than is acceptable. By the use of either a Helmet Sight with Head Tracking, or with the addition of Eye Tracking, this type of operationally essential process can be considerably shortened and higher accuracies attained. UK trials have linked together such a system enabling the FLIR sensor in TIALD (Thermal Imager and Laser Designator) to be located directly on a target of opportunity using a helmet sighted system in conjunction with the head tracker.

As with most systems, however, whilst there may be significant operational shorter term advantages, there are also some longer term restrictions in the systems use of Helmet Mounted Head Pointing Systems. One of those comes from the inability of a correctly strapped-in pilot to move his head much more than 90

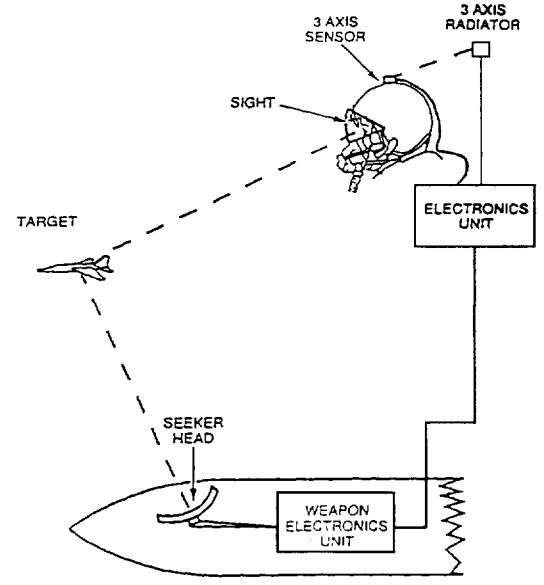


Figure 1-4 Use of head pointing in an off-bore-sight capability weapon system

degrees to the left or right. Figure 1-6 shows the head pointing envelope of a pilot, in full flying clothing, in a fast-jet strike aircraft cockpit, and, whilst the envelope is acceptable, it is limited by the available head movement of the human body. If, however, a further alternative control method, in the form of eye-tracking is utilised, then the useable envelope is significantly increased. This will allow, on average, tracking to around ± 140 degrees in the horizontal plane, compared to ± 90 degrees for head tracking and up to 90^0 in the vertical planes, compared to 55^0 with head tracking (in an aircraft with the restricted rearward and upward movement of the head from an Ejection Seat Headbox).

Thus, it should be technologically possible to targets in the rear hemisphere - or, at least be able to input information into the weapon systems as to the position of target aircraft outside of the conventional radar systems field-of-regard or missile seekers FOR [unless missile design changes] - but not, perhaps, outside of next generation thermal sensors FOR. The Russian Vympel Design Bureau is reported as having tested a rear engagement capability in 1993 on a Sukhoi Su-27. The control authority of thrust vectoring allowing a rearward shot without the missile losing control as it initially flies backwards, [1-8].

One of the assumptions with head tracking, and noted peviously, is that the head position reflects, in hopefully an accurate way, where the eyes are looking. Whilst this may be broadly true, there are, of course, many times when this will not be the case. Measurement of eye position and gaze point, along with head position, will nullify the errors in these assumptions.

1.4 EYE TRACKING

There are a number of distinct advantages to using eye position sensing as an operational tool. A primary advantage is the increased surface area that can be swept by the eye in comparison with the head movement range in the cockpit environment.

Figure 1.6 shows this clearly, with the average horizontal range increasing in the order of 50 degrees and the vertical range by 35 degrees. This increase in the swept spherical surface area should provide the ability to locate and designate a wider range of targets particularly in air combat, and this may be of a particular advantage during high 'g' manouevres, where head movement may be restricted, but eye movement not, and an adequate field for targeting available, from eye movement alone, with the head being necessarily held in a fixed position during the high 'g' manoeuvering part of flight.

Experimental trials at Farnborough (1998) in the centrifuge have shown that, at least up to 8 'g_z', eye fixation and change of eye fixation on a range of targets could be accomplished with subjectively acceptable results. The equivalent trials using head pointing was problematical at the higher 'g' levels. Objective results are in the process of analysis.

A further application, in air-to-ground attack, could be improvements in the accuracy of designation, by the eye, of ground targets for smart weapons, the accuracy being improved by the capability of the eye to be naturally physiologically stabilised in the presence of turbulence or the low frequency buffet normally present in the ground attack phase [1-9]. The accuracy of head pointing under these conditions of turbulence is unlikely to be of adequate quality for precision designation.

Eye Tracking has also some similar potential outside of the current conventional fast jet or helicopter cockpit or cabin, particularly in aircraft using any form of large picture displays. These displays are currently more used in surveillance or Command & Control type aircraft, although there is liable to be an increasing use of big picture displays in rotary and/or fixed wing strike aircraft as well. The problem lies in the use of a cursor in a large, and often cluttered, display, where the position of the cursor on the screen is not always immediately clear. For small FOV displays (say 20 deg x 20 deg) the cursor position can be determined more easily as it lies generally within the foveal cone of the eye and conventional manually controlled mice or joy-sticks are adequate. In a larger display, however, it can need considerably more scanning to find the cursor prior to repositioning it - with the obvious time delays. With conventional cursor control, it is necessary to find the existing position of the cursor in order to know which way to move the manual control to reposition the cursor at its new point. By the use of eye tracking, however, it will be possible to reposition the cursor by the combination of fixing the eye on the required point and commanding the reposition with either a manual control or by the use of a voice command. This could also be used to reposition target boxes or similar designators in large screen displays, and combinations of eye tracking for coarse control and manual for fine control are feasible options. This combination of eye designation, manual fine control and target box labelling by voice command - a multi-modal dialogue - has the potential to provide not only greater flexibility in the control of complex display systems, but, potentially, significant reductions in aircrew workload.

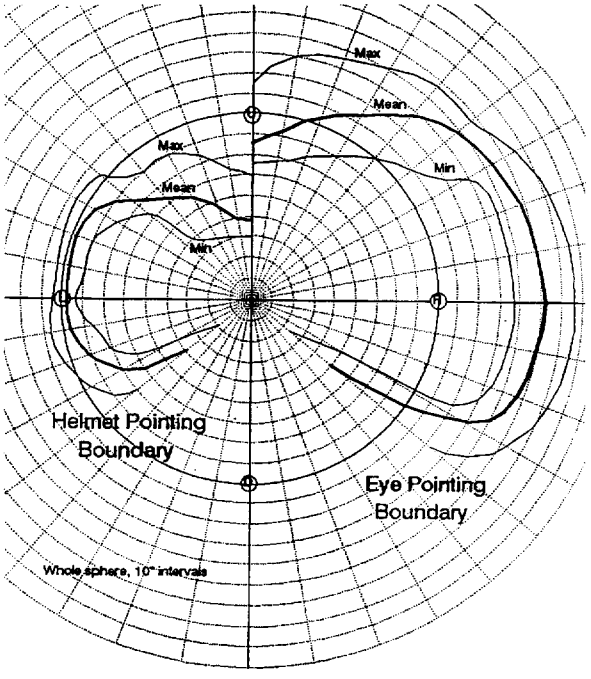
One useful spin-off application of viewing the eye in an eye tracking system is the potential capability of monitoring the eye state (pupil size, blink rate.... etc) as part of an Aircraft Adaptive Interface that may be feasible in providing adaptive controls, displays and aircraft systems that respond, in some way, to the changing levels of aircrew state.

1.5 VOICE CONTROL

Although not quite as mature as Head Tracking, there have been significant increases in capability in the last few years and this Direct Voice Input (DVI) technology now has the potential to enter service with operational aircraft in short timescales. The technology is, at least in speaker dependent systems, at a level that will allow it to compete successfully against manual switching for a number of operational tasks. A number of experimental flight trials have been carried out, in a number of countries, and the results, in terms of technical capability, are essentially identical across countries in the normal cockpit environment. However, the extremes of the operational envelope ie under high 'g', reduce the recognition rates of DVI systems. The ability to fly 'eyes-out' whilst switching systems that normally require a visual operation within the cockpit, can provide a significant advantage in the heat of operations and enable reductions in crew workload. Experimental flying has shown DVI clearly as an enabling technology, particularly in the areas of complex or time consuming switching. As an example, radio channel selection or in the areas of switching the modes of map displays or other displays, DVI has an important role to play and it is often the additional time-consuming detail of systems operation, which causes interference with sequential operational tasks, that causes high workload for aircrew. The use of DVI where the feedback of the successful recognition is clearly visible or audible is clearly more appropriate for aircraft use at this stage of potential operational use. However, even where the feedback loop is not directly perceived, DVI can be used successfully and trials in ground simulators during helicopter tactical operations have shown that digit strings, for instance waypoint entries into navigation computers, can be easily accomplished with audible feedback of the recognised digits being fed to the ear in real time. This is particularly so in the cases of aircrew who regularly listen and communicate across a number of radio nets. Thus feedback of the digit, word or phrase that the system has recognised can be either overt in terms of audio or visual feedback or covert in terms of the pilot recognising that the voice command has actually changed the display or system (e.g. a map display changing scales from 50,000 to 250,000)

One major advantage over manual hard or soft key control is in being able to enter a, sometimes complex, hierachical control structure at any point. In most current systems (navigation, attack, TV-TABS, etc.) it is necessary to page through the levels of a hierarchical menu to reach the level required. In the RAE (now DERA) Tornado flight trials, DVI was used on the navigators TV-TABS and it was possible to access different levels of the navigation hierarchy directly with potential time savings. Whilst later systems have a less time consuming approach to the ability to access deeper parts of the system hierarchy, by buttons or switching, there remain structural problems with this approach, and whilst considerable ingenuity has been expended on reducing the number of button presses to access the required information, only manual keyboarding or voice control will allow direct access to the functions

The acceptance by aircrew of such voice command systems has been generally high in all countries where experimental flying has taken place. In 1993 RAE trials in the UK in a Tornado aircraft, 65 % of aircrew thought that the system was acceptable, with small improvements needed, 25% rated the system as neutral (ie neither good nor bad) and the remaining 10% thought it unacceptable and needing major improvements. None, however, thought it totally unacceptable. Since those trials there



Comparison between helmet pointing and eye pointing envelopes

9 subjects
Mk10 ejection seat, flight harness
Tornado cockpit
Mk4 helmet, summer AEA and LSJ
(from RAE Tech Memo FS(F)-680 1987 by T K Manning)

Figure 1-5 Head and Eye tracking Envelopes

have been improvements in the technology of recognition systems and acceptability ratings should have improved.

Similarly in the EF 2000 programme the use of DVI in the active cockpit simulator has shown the operational effectiveness of using such systems, and the systems are fully supported by pilot opinion

The extremes of the cockpit environment, that is extremes that affect either the speech signal to noise ratios (eg noise) or the effect of the environment on speech production (eg high noise, pressure breathing, high 'g' etc.) still cause some problems with speech recognisers and this is obviously more evident in the high-performance fixed wing aircraft than rotary wing aircraft, which, at this stage, makes DVI systems more suitable for immediate operational use in helicopters and transport aircraft. For fixed wing applications experimental research has shown that under increasing levels of g_z, relative speech levels increase by up to 13 to 14 dB at $8g_z$, with a large spread, and this, combined with speech spectrum changes, results in a declining recognition performance from around 94 to 96% accuracy at the standard $1g_z$ to around 90% at $5g_z$. The necessity to use pressure breathing at the higher 'g' levels, also results in reductions in recognition accuracy, with both 'g' and pressure breathing, are down to around 65% at 6g, and 78% at 5g. Thus comparing pressure-breathing and non pressure-breathing conditions at 5g, a loss of some 12% can be attributed to pressure-breathing effects alone.

However, in spite of these performance losses at the performance extremes, DVI systems work well in the high percentage of mission time that the operational aircraft spends below 5 to 6 g - and in a well loaded ground-attack aircraft of the Tornado or Harrier type - this is essentially the majority of the time.

The further development of speaker independent systems will reduce the need for training speech recognition systems and further techniques to improve recognition rates when operated under high environmental and battle stress, will, in the near future, make voice recognition a highly flexible alternative control technology.

Voice control also has potential for the supplementary aspect of Alternative Control Techniques. In the HOTAS case, for instance, the problems may lie in the inability to remember either the position of the switch or the name of the function to be operated - more probably the former than the latter. With the use of voice command to switch the system, the problem of memorising the switch or button positions is effectively nullified, and only the lesser problem of remembering the functions is left - in practice this should significantly reduce errors. Again, in practice, as with most **alternative** control technologies, it would be wise to retain redundancy in the system and allow operation by either manual and/or voice operated controls - pilot preference being allowed depending upon sortie patterns and phases. By using both systems, the number of manual operations on the HOTAS controls could be significantly reduced and HOTAS used for the time critical functions only, rather than its current potential for over-use - as there are no alternative control techniques to replace manual switching.

1.6 Biopotential and Gesture based

Gesture based and biopotential based control are probably more longer term, certainly in the context of the conventional cockpit. There are essentially two types of biopotentials that can be used in control. One is the electromyographic (EMG) signal which is associated with the contraction of the skeletal muscle and the other is the electroencephalographic (EEG) signal associated with the brain activity, because these signals can be modified voluntarily to indicate the intention of the operator. As a control modality, the principal objective is to measure the biopotential activity from the operator so that it can be designated desired control options or augment other control modalities to reduce selection ambiguities. As an example of the augmentation of other control modalities, recent work [1-10] has shown that the phonetically-relevant orofacial motions can be estimated from the underlying EMG activity. It is reasonable to assume that information from the EMG of facial muscles could improve the performance of current speech recognition systems, particularly under the adverse environmental conditions found in cockpits during operational flight.

In the area of state monitoring of the operator, processed EMG and EEG signals can also be used to assess operator alertness, muscle fatigue and workload.

However, as the cockpit evolves from the conventional to the virtual cockpit, a wider range of opportunites arise. The trend towards the use of UAVs gives rise to the potential of both airborne based and ground based 'cockpits' where full or partial control of the UAVs are based on 'man-in-the-loop' principles. As 'cockpits' move away from the harsh environment of existing military aircraft operations, to the potentially more benign conditions of the ground based, or the control-aircraft (Civil/Transport type) based cockpit, the conditions for use of most alternative control technologies become more attractive, and this is particularly so for gesture and biopotential controls. Environments in aircraft of the C^3I type, AWACS. Rivet Joint etc, have control areas that will be similar to some airborne based

cockpits and perhaps are potentially the first type of aircraft that will be able to make use of these advanced alternative controls.

1.5 UNMANNED AIR VEHICLES (UAVS)

Over the next decade there is likely to be an increasing transition from air based cockpits to ground based cockpits for use with man-in-the-loop Unmanned Air Vehicles (UAVs). In the manned aircraft, the trend is likely to be, at least in a large number of air-to-ground operations, to isolate the human crew, as much as possible from the risks associated with combat areas. The natural trend, which is already visible from recent conflicts, is to produce stand-off weapons, either autonomous or with a man-in-the-loop control capability. Currently this is done from an airborne platform situated far enough from the target to minimise the risk of loss of, or damage to, the aircraft. As data links improve, by increased distance, immunity to jamming and increased bandwidths, the controlling site will be able to move to larger aircraft platforms and finally to ground borne stations. In each of these ground stations (ground or air based), control can be of either UAVs which are intended to fly returnable missions - or UAVs which are not intended to return to base.

Movement of the control station to the technically, and environmentally, more friendly ground station has a number of obvious advantages. Noise, vibration, heat..... and those discomforts and partial disablers associated with aircraft manoeuvres - high 'g' for example - are not present and the encumbrancies necessary for aircrew protection -laser protection, flying helmet, oxygen mask, 'g' suit, NBC personal equipment etc., - are eliminated. Other factors, such as displays equipment, do not require the airborne equipments limitations on mass & volume to be implemented, nor do associated issues such as display brightness and display power. This should allow Commercial Off the Shelf (COTS) avionics equipment to be more utilised which will significantly support the affordability of these type of military operations.

Consequently, the use of Alternative Control Technologies to supplement the natural human performance, often in terms of speed and accuracy, rather than compensate for the inadequacies and compromises that are essential in the cockpit environment, are more viable.

For instance, head-tracking systems are not exposed to unwanted motion from ground induced turbulence during ground attack sorties, voice system recognition rates improve in a low noise and vibration free environment, eye tracking devices will not require the complex integration into the airborne flying helmet and devices that are sensitive to environmental infra-red emissions (eg sunlight) can be more readily used - if appropriate.

The benefits of using alternative control technologies are not only apparent in the severe military air environment. The ability to operate more naturally with avionic and military systems, even in the more benign environments of the surveillance aircraft or the ground-borne UMA/UAV cockpit, should provide significant benefits to military operations.

1.6 CONCLUSIONS

Future manned cockpits will inevitably have more complex avionic fits to cope with more demanding operational scenarios and aircraft roles, and there will need to be an advance in the way that aircrew interface with the aircraft systems in order to enable efficient control between man and the rising complexity of aircraft systems. The number of manual control systems, including buttons, keyboards, and switches, is reaching a point where training aircrew to remember the phases and modes of switching could become both a significant proportion of operational training cost and also have flight safety implications. Similarly the increasing number of switches on HOTAS controls has the potential to heighten confusion rather than provide solutions. What is required are **alternative** methods of inputting data to aircraft avionic systems, particularly if they provide a more natural, and quicker, interface. A simple example of this is in the use of voice input as an alternative to remembering and dialling up radio frequencies. A single command phrase - Farnborough Tower - for instance, replaces, essentially, a three segment approach - remember frequency, dial frequency and call controller on that frequency. Of the more mature alternative control technologies, voice recognition and head tracking are both in operational flight and experimental flight - depending upon the level of sophistication of the technology - and are both technically mature enough for full operational use, with research on the next generation, higher capability, systems in progress.

Eye based control is laboratory mature, and used for assessing eye movement in simulators, and, with development, has the potential to integrate effectively in the operational environment with head and voice based control. Gesture and biopotential are probably the least mature, but provide potential for the longer term aircraft systems (2020) and may be particularly of use in ground based cockpits of man-in-the-loop UAVs.

All systems in a civil and military aircraft must provide some tangible operational benefit - particularly in retrofit cases - and both head and voice based control are expected to provide that benefit in the third generation aircraft (Eurofighter and Rafale). This would be supplemented, in due course, with eye based control, particularly in the air-to-air engagement role, but, also, to a lesser extent, in the air-to-ground role.

The benefits of alternative control techniques lie in a more natural interface with the aircraft, improved speed of operation and reduction in training overheads.

Released from the constraint of only one communication channel with the aircraft systems - manual - the use of alternative control technology invites aircrew, aircraft and systems designers, and others, to be more imaginative in their interaction with the aircraft and systems, using these alternative controls as appropriate to the operational benefits and needs. Such alternatives are not intended primarily to replace manual controls but to supplement manual systems and to provide alternatives, to be used as the occasion requires. Aircraft systems, however, need to be practical, to retain as simple an interface as the technological complexity of the systems allows and be operated by aircrew with a wide range of capabilities. This should ensure that the use of these alternative controls is balanced by the aircraft designers natural, and often historically justified, inherent scepticism of the useability of new technologies.

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This research has been supported by the MOD Corporate Research Programme under TG5 funding

Fusion and Display of Data According to the Design Philosophy of Intuitive Use

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1. SUMMARY

Microelectronics have forced their way into military aircraft- and airliner-cockpits more than a decade ago. On the military side it was physical contest, on the civil side, economic competition was the drive leading the evolution from the analogue to the digital cockpit.

Regarding today's state-of-the-art military and civil transportation aircraft, one can hardly find any information on pilots' wish-list, that can not be picked up by a sensor already installed. Despite of this technical ability to seize the aircraft in its full complexity, there is obviously still something wrong according to the aviation accident statistics. 'Human-factors' often is the ultimately found result in the search for crash reasons. But this conclusion's correctness depends on the definition of 'human-factors'.

It is a well-known fact, that even highly trained professional pilots' abilities can easily be reduced to amateur status under excessive mental stress. In these situations the human mind only accepts intuitively perceived information as basis for behaviour. Therefore it is vital, that new avionics with their inert tendency to become complex, are carefully developed along the principles of intuitive use.

This paper describes several parts of a project comprising the development of a new cockpit for General Aviation aircraft. It focuses on aspects of the target group, design-philosophy and low-cost realisation.

2. INTRODUCTION

Both military and civil commercial aviation development is driven by competition. Where it is a rather physical one on the military side, it is economic contest on the civil side:

The world wide inclining need for transportation results into a continuous increase of the aviation branch. Especially the last two decades saw civil aviation traffic grow by the factor of five [1].

With the positive development of this economical branch, an increasing number of airlines were founded, competing on safe and fast arrival on defined destinations. But the growing number of participants in air traffic and the increasing air-speeds raised the risk of mid-air collisions. To keep up flight-safety an air traffic control system was erected. For the operation of the system, precise locating and navigation was necessary, as well as reliable communication between air- and ground-stations.

Forced by the competition the airlines wished to run their aircraft in the most economic way. Beside safety-relevant information, an ever increasing number of additional system-data became important for aircraft-operation.

From this point of view, the man-machine-interface 'cockpit' can be divided into five functional groups: in-flight conditions/configuration, engine, subsystems, locating/navigation and communication.

Regarding communication, locating/navigation, engine and subsystems, one can describe several technological developments used to increase safety and economical quality of aircraft. Most of them were invented for military applications, but were quickly transferred into Commercial Aviation due to their usefulness.

In the field of communication, several procedures operating on radio-waves were developed after 1930. In the beginning one used Morse-code, later language, nowadays Information can be exchanged digitally (e.g.: ADS-B).

In the beginning of navigation, landmarks were used for orientation, followed by astro-navigation and dead reckoning. With the increasing quality of micro-mechanics, gyros were used for inertial navigation and finally radio beacons (e.g.: VOR, DME) were set up. With two stations in range, the position of the aircraft could be plotted, using an on-board receiver. At last satellite navigation systems were deployed in the 80's. The US-American GPS provides users with three-dimensional position data. The almost world wide service is independent from time and weather-conditions and is precise within 100 m for civil users. Using several correction techniques, precision within sub-meter-range can be realised [2].

Regarding engine and subsystem surveillance the cockpit instrumentation was confined on 'engine revolutions per minute' and 'fuel quantity' up to WW II. Only the use of ever more sophisticated piston engines and turbines on the one hand and the deployment of electric and hydraulic subsystems on the other hand required the increased recording of relevant data.

The usual integration procedure of new cockpit devices was an addition. Substitution of systems was carried out sparsely and thus, the complete system 'aircraft' became more and more complex. The cockpit evolution resulted into the extension of training and the increase of number of the cockpit-staff.

Starting with one pilot and peaking five members in the early sixties, the cockpit crew was reduced to pilot, first officer and flight-engineer until the late seventies due to the automation of several subsystems (figure 1). Extensive developments in microelectronics allowed a further reduction down to two cockpit crew members in the mid-eighties (figure 2).

Paper presented at the RTO SCI Symposium on "Sensor Data Fusion and Integration of the Human Element", held in Ottawa, Canada, 14-17 September 1998, and published in RTO MP-12.

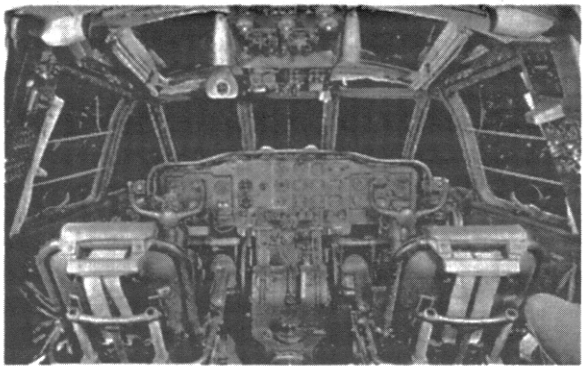

Figure 1: Sud-Aviation Caravelle cockpit (1957). Source: Aerokurier

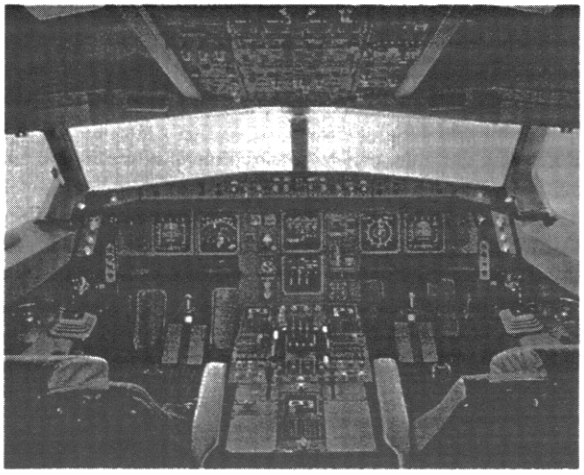

Figure 2: Airbus A340 cockpit (1997). Source: Airbus Ind.

The use of computers and electronic displays opened another complete step in automation. Sophisticated electronic systems (e.g. EFIS, EICAS, FMS) carry out complex procedures of planing and surveillance. The man-machine communication, necessary therefore, is performed by using the multi-functional input- and display-devices.
The connection between technological progress and cockpit design is obvious. Especially developments in microelectronics caused the last distinct change-in-trends.

3. GENERAL AVIATION COCKPIT DESIGN

The term 'General Aviation' entitles a special branch of aviation. Its existence is obvious, but its description is difficult, because neither the pilots, nor the aircraft included, share a common characteristic.
As a consequence, there is no specific definition for this term. According to [3] it may usefully be described through an exclusion: General Aviation (GA) includes those areas in aviation, being not military- or airline-/charter-aviation.

The term 'General Aviation' was created in the sixties, when there was a significant increase in numbers of aircraft. Nowadays, GA has a great significance compared to other branches in aviation. About 90% of world wide registered civil aircraft are reckoned among GA. With those aircraft 75% of in-flight hours are produced, 50% of the passengers are transported, but only 7% of fuel is consumed world wide. Most of the flights in GA are carried out under visual flight rules (VFR). In this specific sort of flight, the attitude of the aircraft and traffic co-ordination is controlled through vision.
More than 80% of GA aircraft are powered by a single piston engine, include up to four seats, and have a maximum take-off weight up to 5.7 t. More than 60% of the world wide GA aircraft are registered in the USA, the average age of all GA aircraft is about 20 years [1].
The world wide number of GA pilots is estimated about 1.4 Million [1]. The statistics regarding age, total in-flight hours and in-flight hours per year show a high standard deviation. Therefore the forming of a mean value, allowing a statement relating to physical capability, experience and training condition is pointless. This fact rather outlines the picture of the extreme heterogeneity among GA pilots. Designing for this target group means to take into consideration both, the professional's claim as well as the amateur's abilities.
Comparing Commercial and General Aviation cockpits, only the first periods of the evolution, described above is detectable in the field of GA. As shown in figures 3 and 4, there are no fundamental differences obvious between the instruments featured in both cockpits. The number of input- and display-devices has doubled in the last 40 years. Automation and deployment of computers or electronic displays does virtually not occur.

Figure 3: Beech Bonanza cockpit (1957). Source: Aerokurier

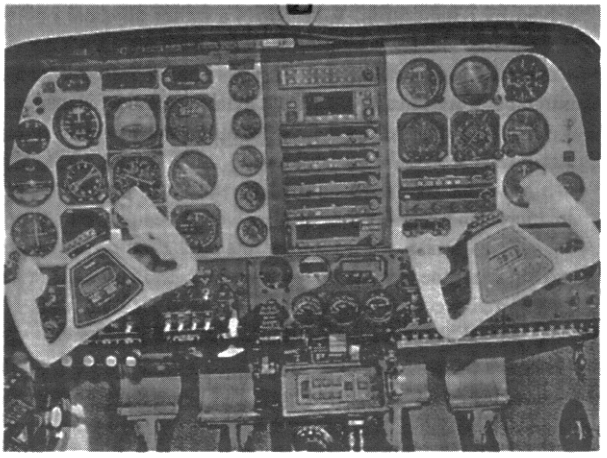

Figure 4: Beech Bonanza cockpit (1997). Source: Aerokurier

Nevertheless do GA pilots likewise wish to take the advantages of the new technologies. As a result, aircraft were equipped with degraded Commercial Aviation (CA) products (e.g. NAV-radio, GPS-receiver). These devices have their own specific operation-strategies and thus, are often not suitable for the use in GA. Furthermore, the implemented variety of functions as well as the means of communication between device and user is often inadequate for non-professional pilots. Especially under high-workload conditions or in critical phases of flight the pilot may be overstrained.

In addition, one can detect that the great number of input- and display-devices results into installation problems. Only a few displays are located within the pilot's central field of vision and several input-devices can only be reached under extensive movements of the pilot.
The great number of displays, their eccentric position and therefore poor readability force the pilot into long 'head-down flying' periods. Especially on VFR flights this state must be regarded as extremely safety-critical.

The reason for the non-appearance of the last step of evolution in GA cockpit design is the cost-factor. An empirical coefficient is, that up to ten percent of a GA-aircraft's worth may be spend for avionics. The facts are, that one has to spend as much for a CRT (cathode-ray tube) used for a display in the Airbus A340 and the necessary periphery as about for a used Cessna 172 (a typical GA-aircraft). In view of these two figures it becomes clear, that beside the fact that those CRTs are too large and heavy to be installed, it would economically make no sense to base the development of a new cockpit on this technology.

As the total costs result out of development, certification and production costs, especially the down-headed trend in production costs of micro-electronic devices suggest the introduction of new technologies into GA.

4. The COSIMA – PROGRAM

In view of this situation, a team-program featuring several mid-sized enterprises and the Institut für Flugführung at the Technische Universität Braunschweig was initiated in January 1996. The COSIMA-program (Cockpit and Simulator for General Aviation) is sponsored through the DLR (German Aerospace Centre) by the German Ministry of Economics as part of the aviation research.

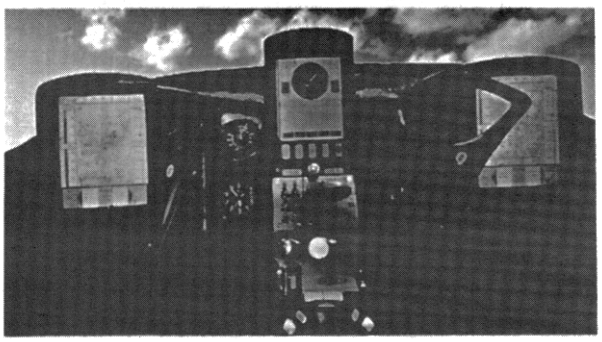

Figure 5: COSIMA-cockpit implemented in the C-172-simulator fuselage.

The schedule shows three different phases within the program. In the beginning, the basic cockpit-concept was designed. In the second step, the concept was realised in a research-simulator (based on an original Cessna C-172 fuselage) for testing purposes. For the now-running third step, the cockpit was implemented in a real C-172 and undergoes excessive in-flight testing necessary for certification [4].

Figure 6: COSIMA-cockpit implemented in the C-172-testbed.

4.1 Basic Structure

As described above, the cost-factor is of great importance for the program. As a consequence, the concept has a modular layout and can therefore be easily adapted to a variety of GA aircraft. Furthermore, system components may be separated out and can be implemented as subsystems into conventional cockpits. Last but not least in case of a failure or damage of one module, it can easily be replaced. First, the concept was designed for VFR-flying, an IFR upgrade is planned (IFR: Instrument Flight Rules).

The main purpose of the new cockpit-concept is the integration of new technologies, considering the specific premises in GA. Therefore the extent of implemented functions, the operational logic of subsystems, the graphic user-surfaces and the three-dimensional environment of the pilot have to be taken into account for the new design.
The basis for the design process is founded through operation analysis carried out in several GA cockpits.

The system features two PC-like computers, operating three LC-Colour-Displays (figure 7). The input is performed through a five button keyboard and a track-ball-like graphic input-device.

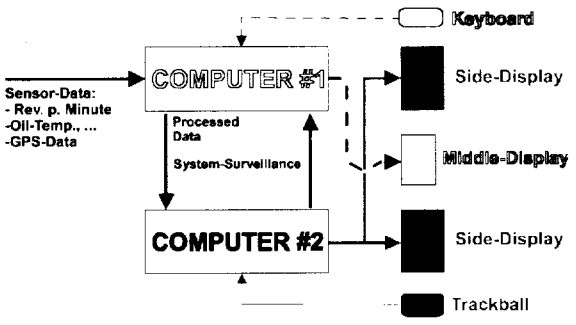

Figure 7: Schematic structure of the electrical system components.

The main task of the first computer is to record data of several different sensors (engine-sensors, GPS-sensor, etc.) and to generate the output on the centre-display (CD). The first computer's performance may be compared to a 100-MHz Pentium PC. The second computer processes the provided data and performs the output on the displays on the left and right side (SD). The second computer's performance must be higher for best graphic results.

The computers are supplied by redundant sources of electricity and perform a permanent surveillance of both their operational status. In case of a serious disturbance, the system switches to 'emergency-mode'. In this secured mode the pilot is provided only with relevant basic instrumentation.

4.2 Basic Physical Layout

A basic design principle is the definition of areas or space for input- and display devices. The pilot should be able to identify areas of different context easily. The aircraft should be controlled out of the left or right seat, as it might be used for training purposes. This premise leads to the concentration of single-appearing input- and display-devices on the longitudinal centre axis of the cockpit between the front seats.
Each side-display is placed in front of the seats, whether the third display is fixed in a middle-position (figure 8).

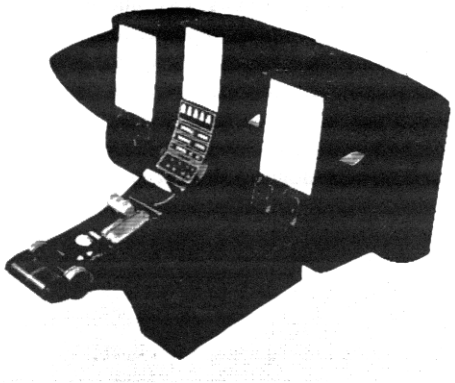

Figure 8: COSIMA cockpit concept: physical layout.

The cockpit consists of three main segments. The middle-segment practically contains all major input-devices (except for steering wheel/ control column and pedals). Its shape results out of the longitudinal ergo-cinematic curve that is virtually drawn by the fingertips of a human being, trying to reach all the input devices. The surface orientation is designed to give the pilot perfect view angles on any device installed (three-dimensional devices unequal 90°, flat input- or display-devices about 90°).

In the remotest, almost upright part of the middle-segment, the centre-display for joint use is fixed. In this place it has a perfect position for the fast switching of view between display and outside airspace. Furthermore, the increased distance from eye to display makes the eye's near-far-accomodation easier for the pilot. On this screen, the 'Aircraft Monitoring System' is displayed.

The side-segments mainly serve as housings for the side-displays (and possibly for the steering linkage). The side-displays are fixed in the upper part of the segment and remotely from the pilot's eye, corresponding to the centre-display mounting. On these screens, the in-flight conditions and the Flight Planing and Navigation System are displayed.
By giving the cockpit this specific shape, all hard-surface and glass objects are away from typical crash-related movements of the pilot's head and upper body, and thus the injury-risk is significantly decreased (figure 9).

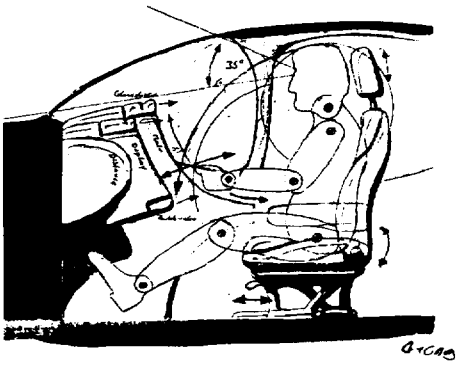

Figure 9: Sketch of the new cockpit concept, showing ergonomic details (side view).

4.3 The Aircraft Monitoring System (AMS)

The AMS contains the engine and electrical subsystem data. The following information is displayed: engine revolutions per minute (r.p.m.), oil pressure, oil temperature, exhaust gas temperature (EGT), cylinder head temperature (CHT), battery-voltage, generator-amperes and time.
Oil pressure and oil temperature, EGT and CHT, as well as battery-voltage and generator-amperes are automatically monitored and displayed in groups (figure 10).

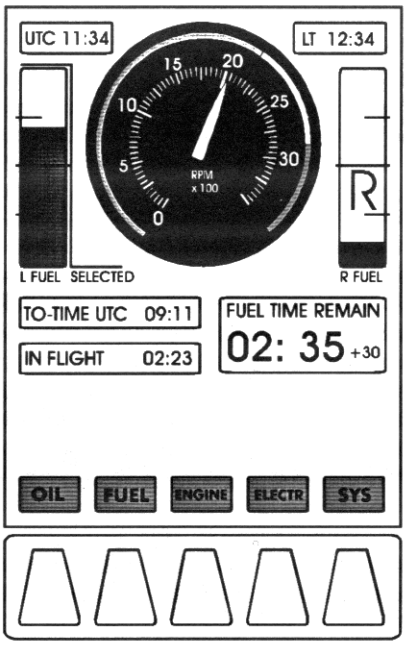

Figure 10: AMS-display in main level status with keyboard.

By using the keyboard, any individual information can be displayed explicitly and the pilot is not excluded by the automation from the 'information-loop'.
Engine revolutions are still displayed as a circular-instrument, dominating the AMS-screen. A further important component of the AMS is the fuel-management. The connection between fuel and time is expressed through the 'fuel-time-remain' display.

The AMS has a four-level lay-out. Each level can be selected by using the appropriate button on the keyboard (figure 11).

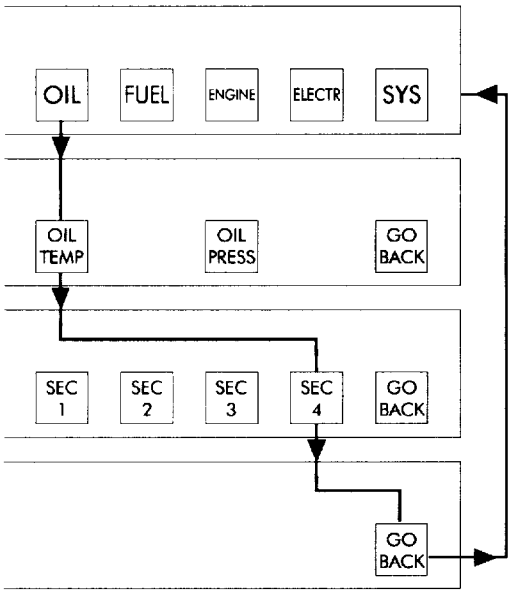

Figure 11: Typical operational process in the AMS system-hierarchy.

The surveillance-status of the system-groups is displayed in the main level. In the detail level the information within one specific group is graphically and digitally indicated. In the proceeding-level I and II the temporal development of one specific information is indicated. Proceeding-level I shows the time from the point of engine start-up, proceeding-level II focuses only on one fourth-section ('SEC') of that time.
The pilot switches levels by using the keyboard, installed under the screen. The shape and the position of the switches generate a clear connection to the symbols presented on the screen. The user may return from any sub-level to the main-level by choosing the always available 'go-back' function.
In case of a measured value turning to 'Amber', the display remains in the main-level. The icon, representing the group, containing the specific measured value turns amber likewise and a detailed trend-report is displayed along with an acoustic warning signal.
In case of a measured value turning to 'Red', the display automatically switches to the detail-level after an acoustic warning-signal and thus the specific measured value is explicitly displayed.

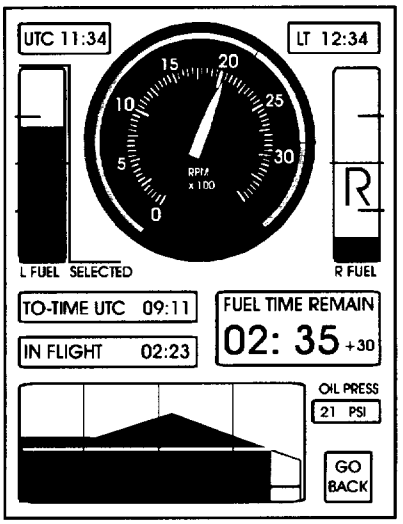

Figure 12: AMS-display in proceeding-level I status (oil pressure turned 'amber').

If more than one value turns Amber or Red a situation-adaptive hierarchy is generated within the system according to the priority of action. Following this hierarchy only the most urgent information is displayed at a time.
Thus the AMS enables the pilot to focus on the temporarily essential and relevant information. A complete system-check may be performed with a glance on the centre-display. The automated surveillance decreases the pilot's workload, but its permanent-accessible design doesn't lock him out of the information-loop. Furthermore, any user is able to realise trends in measured values, just by switching to the proceeding-levels. This function enables pilots to do a 'trouble-shooting' on any system of the aircraft and offers means for strategic planing of the further flight under failure-conditions. In the past only exceedingly experienced pilots were able to perform this task and only under low workload conditions.
The design of the AMS-symbols follows several criteria, like intuitive perception (fuel quantity indicators on left an right side, separated by the circularly-shaped r.p.m.-indicator), tradition (circular shape of r.p.m.-indicator) and regulation (colour-coding). This results into a permanently decreased perceptual effort and almost zero-hour training periods for ratings on the new cockpit.

4.4 Flight Planing and Navigation System (FPNS)

All in-flight conditions and navigational data are presented on the side-displays. In particular, the following information is indicated: indicated air speed (IAS), temporal change of IAS (speed-trend), ground speed, barometric altitude (ALT), temporal change of ALT (variometer), compass heading and ground track. Furthermore, a map and the planned flight-track is displayed (figure 13).
Whereas speeds and altitudes are directly indicated, a special way of presentation was designed for navigation-tasks, to enable the pilot to handle the amount of information.

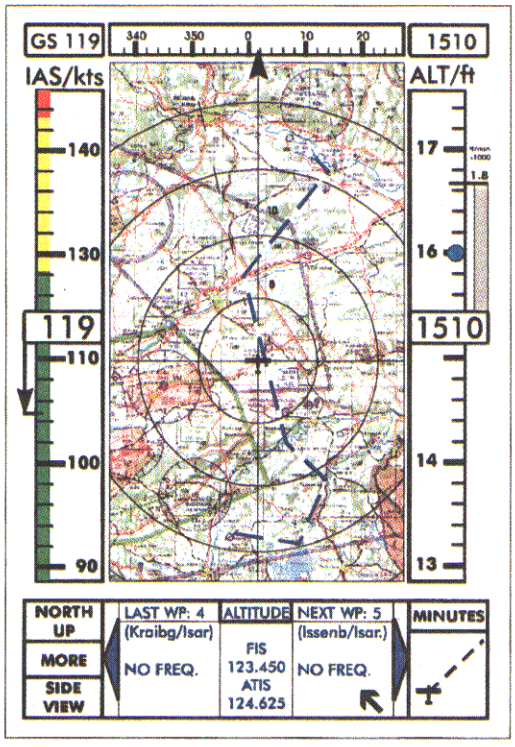

Figure 13: FPNS on side-displays (flight-mode status).

Normally, a flight preparation is supposed to be created with special software on a separate computer some time before the flight. Using an ordinary disc, the flight log is transferred to the board-computer of the aircraft. Exceptionally a flight preparation may as well be generated in the cockpit right before the flight.
The navigation system features a true moving map. The actual position of the aircraft, as well as the planned flight-track are permanently displayed on the map. The flight-track is defined through way-points. Each way-point and each way-section, enclosed by a pair of way-points may be connected manually or automatically (using prepared data-bases) with specific additional data (e.g. en-route frequencies, airfield information, planned cruising-altitude, etc.).

Operations on graphic-display units inevitably demand a graphic-input-device (GID) for optimal intuitive use. The device's function should be way-proportional and not speed-proportional. Therefore, a 'track-ball'-like device was specially designed for use in aircraft (figure 14).

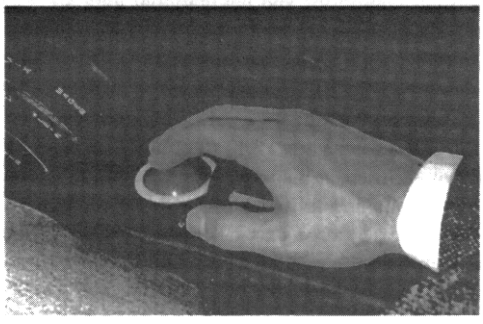

Figure 14: GID (graphic-input-device) for COSIMA.

Beside the graphic-positioning device, it features three main functional units. The primary-selection function is realised through a two-button solution. The buttons' linear push-axis are arranged out of main acceleration-axis of the aircraft and contrary to one-another. This makes accidental manual release or release by, e.g. a touch-down-shock almost impossible.
Furthermore there are two zoom-buttons, to be operated with thumbs (each one for left- or right-hand use) and one switch, to select Planing or Flight Mode.
The GID is used for all FPNS input operations (s.b.). It works with a defined fuzzy-area. That means, the system presumes the user to have tried to graphically mark a specific point (e.g. an airfield on the map) if he actually hit within the fuzzy-area of that point.
In this case, the FPNS offers the user a choice of the actually marked point and alternatively all specific points whose fuzzy-areas have been hit.
This special software design excessively increases the operational precision and efficiency of the graphic input device.

The FPNS may be operated in two different modes (figure 15).

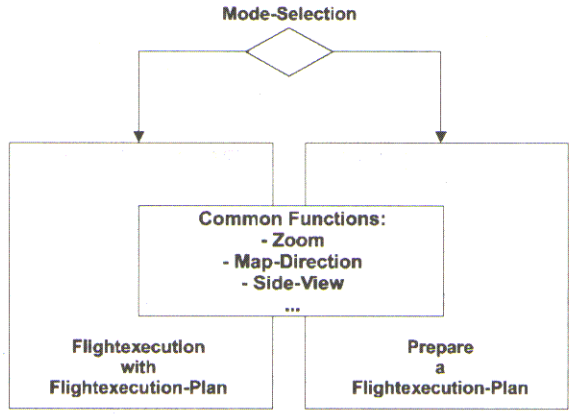

Figure 15: Basic logical structure of the FPNS.

The Flight-Mode (FM) screen shows all in-flight conditions, the map and the flight-log strip, containing way-points and -sections and also several display-optional functions (s.b). The FM works on a defined, invariable flight preparation. The only options within the flight log are to skip certain way-points or to re-activate them. Several operational options are implemented, to adjust the display to the preferences of the user (s.b.).
In the Planing Mode (PM), flight preparations may be created or already existing logs may be altered. After having created a new flight preparation, it may substitute the operational one at any time.

A 'zoom'-function, featured in both modes enables the pilot to get an overall view of the aircraft's geographical environment, as well as a detailed impression of its immediate surrounding. Furthermore, several different kinds of maps may be chosen with respect to the actual flight-task, if available for that area (ICAO-map, visual approach chart, etc.). Several further settings may be made in accordance to

the users preferences (e.g.: map display in heading-up or north-up mode).
To avoid any graphic interference with in-flight condition indicators, the movements of the graphic-input-symbol (GIS) on the screen are confined to the map-area and the rectangular flight-log area on the bottom of the screen. A potentially activated functional field on the display is graphically emphasised to clarify the consequences of the planned action.

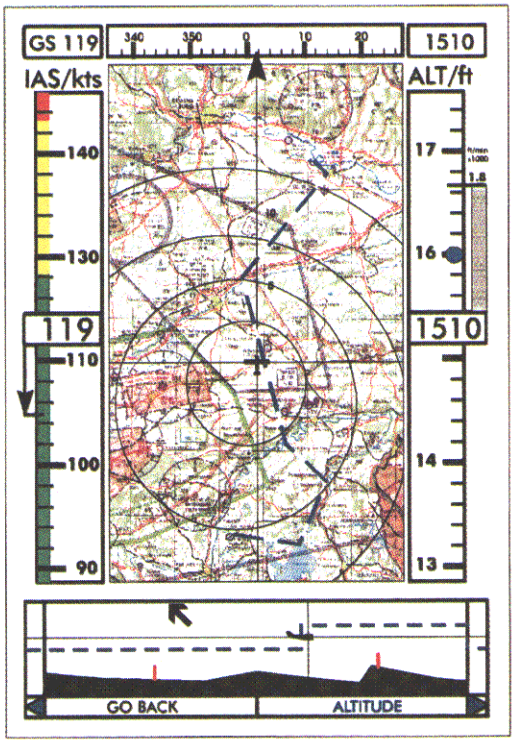

Figure 16: FPNS with active 'side-view' and circles of equal flight-time in the map area (flight-mode status).

Using the 'side-view' function, the third dimension of the planned flight-path is displayed in the flight-log area. The side view shows ground elevation, specific obstacles, the planned flying altitude and the aircraft's actual altitude and position along the planned track. By displaying the third dimension of the actual air space structure, the situation awareness of the pilot is substantially improved (figure 16).
With air- and ground-speeds, heading and ground track, the board computer can estimate the actual wind-vector in speed and direction. This information can be used to show points of equal flight-time on the map display (in general non-concentric circles) instead of points of equal distance (concentric circles).

If an airfield is chosen as a way-point, all available special maps are offered in the corresponding zoom-level, near that point. Due to the unforeseeable situation no planned flight-path is displayed with those maps. In this case, the side-view function is of great importance to gain a three-dimensional overall view of the situation.

The presented FPNS decreases the workload for keeping the aircraft on the path and for navigation tasks compared to conventional cockpits. Especially the three dimensional graphical display of actual position and heading in comparison to the planned track makes orientation easier and sets free mental capacity. The system has a low degree of complexity and is adapted to the specific requirements of VFR flights.

3.4 Integration of input devices into the cockpit

The centre-panel has the affiliated keyboard mounted directly under the centre-display. It can easily be reached with one arm stretched out. The keyboard's design allows the fingers to fix the position of the hand, in order to facilitate a safe operational process. The graphic input-device for the side-displays is installed on the level part of the centre-panel. For reliable operation, the armrest and bearing surface for the palm of the hand may be used.

The partially revised shape of input-devices (e.g.: semantic connection of the flap-lever) and their special arrangement (e.g.: orientation of operational processes on electrical switches) support processes of intuitive acting and motorial learning.

4. SUMMARY

The presented cockpit-concept makes the opportunities of several new technologies accessible for pilots, flying GA aircraft. Furthermore it increases the safety in aviation by optimising processes of perception and conduct within aircraft operation. The system layout is open to any future digital air-traffic-management-system and provides the necessary tool to participate even for non-professional pilots.

The permanent information flow is reduced by a balanced lay-out and an adjusted variety of functions, appropriately processed information and an adaptation of input- and display-devices on the characteristics of GA pilots. The specific software layout keeps the pilot in the information-loop and creates a useful transparency of the entire system 'aircraft'.
By taking into account the great individual differences between GA pilots' skills and giving the cockpit a modular lay-out, the concept is suitable for a great number of applications. This is besides the low-cost availability the basis for the successful introduction of new technologies into GA.

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Enhanced and Synthetic Vision System Concept for Application to Search and Rescue Missions

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Summary

The Flight Research Laboratory (FRL) of the National Research Council (NRC) in co-operation with the Department of National Defence and industrial collaborators Canadian Marconi Company (CMC) and CAE Electronics Ltd. (CAE) is working to integrate new cockpit technologies to improve mission effectiveness and system safety of Search and Rescue (SAR) missions conducted from helicopters.

Search and Rescue aircraft operate in a demanding environment, often in remote areas, at night, or in inclement weather. Cockpit systems that reduce pilot workload and improve pilot situational awareness can save lives when appropriately integrated into the aircraft.

NRC and partners are building, integrating and conducting research on an enhanced and synthetic vision system (ESVS) to help SAR helicopter pilots complete their missions in degraded visual environments. The ESVS will provide SAR pilots with a real-time display that mimics visual flight rules (VFR) conditions.

NRC plans to integrate and evaluate a prototype system by the year 2000. The prototype system will include a visually coupled helmet mounted display (HMD) system, a synthetic image generated from a terrain database, an advanced sensor and an image fusion system. A complementary research program is under way at NRC to investigate fundamental human-machine interface issues relevant to the proposed prototype system

Introduction

Search and Rescue missions are difficult to carry out at the best of times, and especially difficult over unknown terrain in the dark or during inclement weather. To identify particularly difficult aspects of these missions, CMC performed a human factors analysis of the SAR mission in very poor flight conditions with a 100-foot ceiling and one eighth of a nautical mile visibility (1). They identified several significant issues, two of which are particularly interesting: first, they identified mission task elements for which a high pilot workload is necessary for successful completion; and second, mission task elements that are impossible to perform without enhanced equipment.

To solve these problems, an enhanced and synthetic vision system was proposed to alleviate high workload situations and augment the pilot's situational awareness in degraded visual environments. DND commissioned a study (2) to outline the overall requirements, capabilities and conceptual design for the augmented ESVS system.

As a result of the study and further analysis, the ESVS system was targeted toward improving SAR mission performance during four key mission phases in degraded visual environments;

- first, to aid the pilot in descent below Minimum Descent Altitude in a search area, without prepared navigation systems (i.e. an instrument landing system (ILS) or other predefined instrument approach procedure);
- second, during the search for the crash site, survivors, and wreckage in unknown terrain;
- third, after the crash site has been identified and the helicopter is preparing to rescue the survivors, to aid the pilot in the transition to and

Paper presented at the RTO SCI Symposium on "Sensor Data Fusion and Integration of the Human Element", held in Ottawa, Canada, 14-17 September 1998, and published in RTO MP-12.

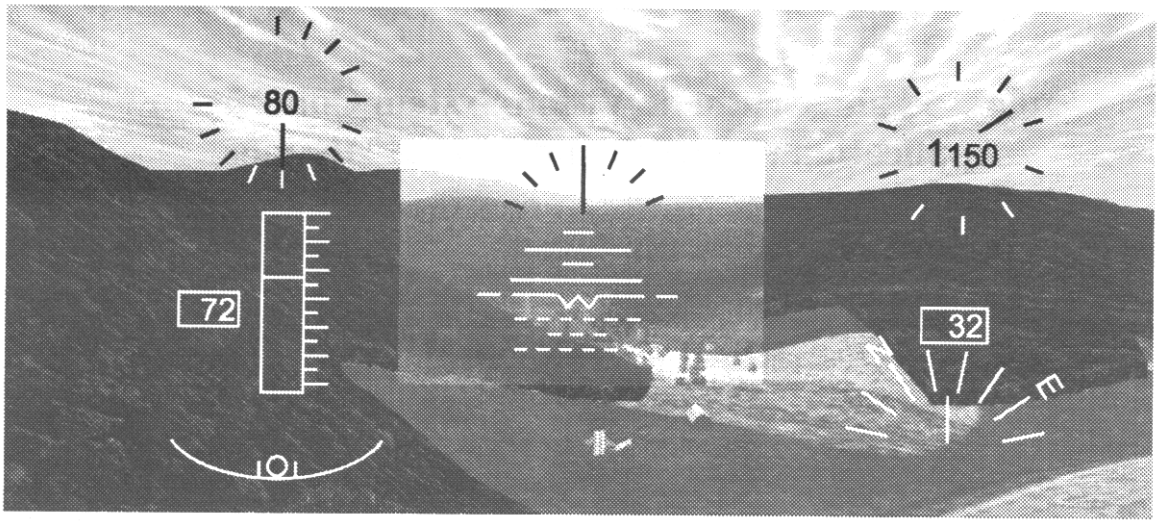

Figure 1 ESVS Display Concept

maintenance of hover during rescue operations; and,

- finally, to help the pilot depart safely from the rescue area.

To improve performance in these areas, the ESVS system displays an augmented visual scene to the pilot that includes three separate image sources: a synthetic computer-generated terrain image; an enhanced visual image from an electro optical sensor; and aircraft instrument symbology. Figure 1 shows the ESVS display concept. The system provides an immersive environment that simulates VFR conditions using a visually coupled system made up of a helmet-mounted display system, a head tracker and a slewable camera platform, all of which allows a wide variation in the pilot's point of regard.

The synthetic image provides the pilot with a wide field-of-view terrain display that can be used to maintain a global sense of position and orientation and to navigate en-route by recognising landmarks that would otherwise be hidden by poor visibility. The synthetic image is generated in real time from aircraft navigation system data and the pilot's view point based on head orientation.

The enhanced image is a high confidence image that can be used during manoeuvring close to the ground. As the pilot's head turns, the head tracker reads the pilot's head position and sends a signal to the sensor platform telling it to follow the pilot's head movement. The central region of the image comprises the enhanced vision system output fused with the synthetic image.

The flight symbology provides the primary flight references necessary for the pilot to fly the aircraft: airspeed, altitude, attitude, power, a turn co-ordinator, and a compass.

But why are both enhanced and synthetic images necessary? In short, the sum utility of the two images is greater than the utility of either one by itself because each image has its own advantages and limitations.

For instance, the synthetic image is always available to the pilot and is displayed over a wide field-of-view. However, it does not include all objects in the viewing region and the accuracy of the synthetic image depends on the accuracy of the database from which it is created, meaning that inaccuracies in the database will be reproduced in the synthetic image. This is a critical shortfall when manoeuvring close to the ground.

Similarly, the enhanced image has texture and culture detail lacking in the synthetic image giving the pilot higher confidence in the veracity of the enhanced image. On the downside, the enhanced vision sensor has a much narrower field-of-view than the synthetic image. By fusing both images, the pilot will be able to use the best aspects of each image overcoming the limitations of each.

ESVS System Architecture

Figure 2 shows the ESVS conceptual architecture. Large parts of the subsystems are constructed from

ESVS 2000

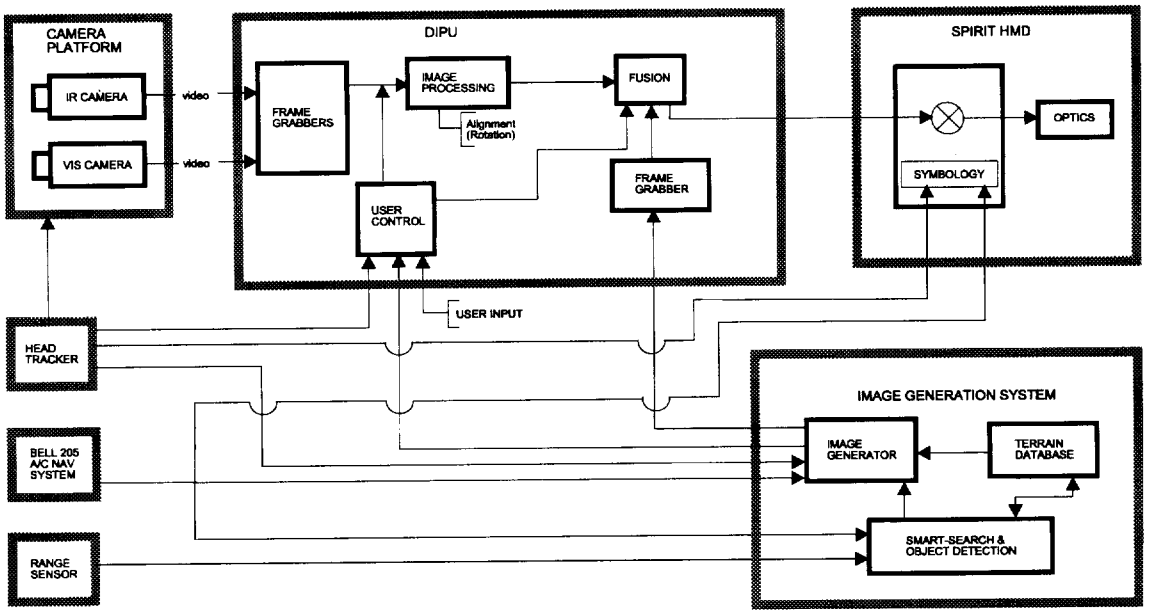

Figure 2 ESVS Architecture Block Diagram

commercial off the shelf items (COTS) with custom software. CAE is building the synthetic image generator (IG) which will combine a map database and head tracker data to produce a synthetic landform image based on the pilot's view point. The synthetic image and the enhanced sensor image will be fused in the digital image processing unit (DIPU), a prototype of which has been built by CMC. The image will then be displayed to the pilot using a helmet mounted display system built by CAE.

In the conceptual ESVS system, the image generation system will produce a synthetic terrain image using existing terrain map databases available from Canadian Government. The synthetic image will also include a representation of non database objects detected by an aircraft-mounted range-finding sensor. This sensor will sweep the area of interest to determine the actual position of features in the terrain database, providing the ability to register the synthetic image so that it overlays the real world. The range sensor will also be able to detect features not present in the terrain database, and provide this information to the image generator as well. The registration and detection functions provide greater image accuracy and flight safety and are among the most difficult to implement.

The ESVS sensor will be oriented to the pilot's point of regard. As with the synthetic image, the enhanced image will not be sufficient by itself to provide all the visual cues necessary to control the aircraft to the pilot. The enhanced image will contain textural and detail cues that will not be available in the synthetic image. The synthetic image and the enhanced sensor image will be fused in the digital image processing unit. Various image fusion techniques will be tested to determine the best way to present the combined enhanced and synthetic image to the pilot. It is expected that the pilot will have control over the fusion process and will be able to display the unprocessed sensor image if required.

The sensors being considered for the enhanced image include infrared, low light level TV and small wavelength radar. The optical elements for the infrared or simulated low light level TV will be chosen with an appropriate field-of-view that matches the pixel size of the area covered by the enhanced image within the synthetic image. This eases the processing load required to fuse the enhanced and synthetic images.

Head position will be provided by a head tracking system. The head tracker information will be used to drive the sensor platform and provide view point orientation for the image generation system and the symbology generator.

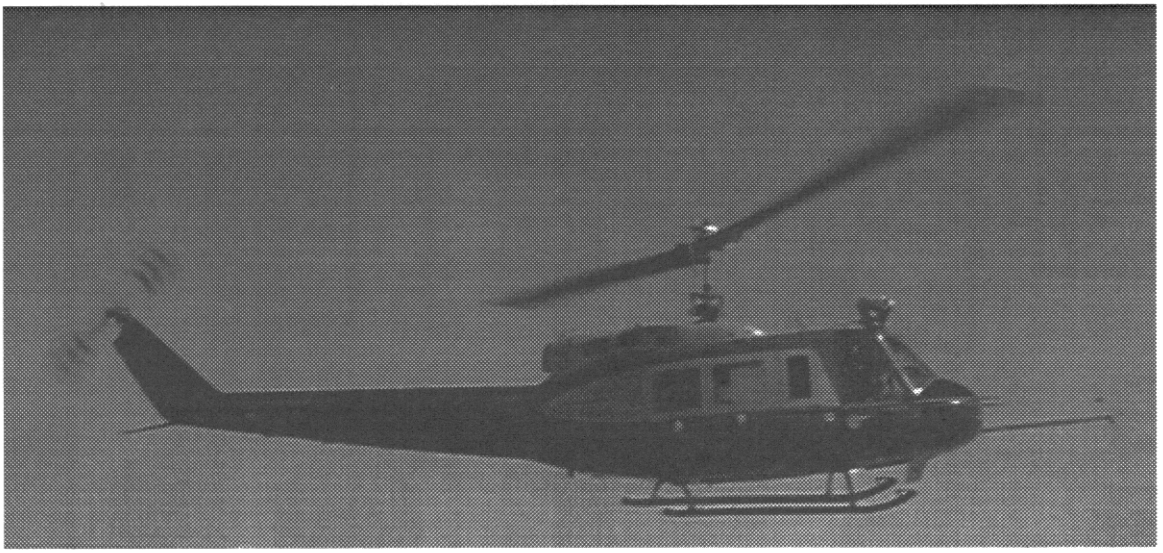

Figure 3 NRC Bell 205

Experimental System

NRC will be integrating and testing a prototype demonstration ESVS to be fielded in the year 2000. The functionality of the demonstration system is reduced from the conceptual ESVS because the range finding system has been deleted.

The demonstration system will be installed in the Flight Research Bell 205 Airborne Simulator shown in Figure 3. The ESVS image will be displayed on the SPIRIT II airworthy helmet mounted display system produced by CAE. A Polhemus 3Space magnetic head tracker will provide head position information.

The SPIRIT HMD is a binocular high resolution wide field-of-view display. The display is 55°x40° in each eye, with a 30° binocular overlay giving in a total field-of-view of 80°. The display consists of a transmissive ferro-electric liquid crystal display (FELCD) backlit by a laser light source, and has a resolution of 1280x1024 pixels.

The airborne simulator has a full authority fly-by-wire control system with specially designed dual-mode electro-hydraulic actuators to allow the system to be controlled either mechanically by the safety pilot or electrically by the evaluation pilot. The use of the fly-by-wire system allows the augmentation of the basic helicopter stability to offset the degraded visual cues provided by the ESVS system. The aircraft navigation instrumentation includes both inertial navigation information and differential GPS, used to compute aircraft position with a real-time accuracy of one meter.

During any test at NRC, two pilots operate the aircraft. The evaluation pilot assesses the ESVS while the safety pilot monitors flight safety. If the evaluation pilot encounters difficulty controlling the aircraft or interpreting the displayed visual scene, the safety pilot can take over control of the aircraft. The aircraft also contains a video and audio recording system that monitors the evaluation pilot, the sensor and symbology visuals and the intercom channels to allow analysis of any problems reported by the pilots.

ESVS Research Program

A comprehensive research program has been developed to understand the limitations of the demonstration ESVS hardware, to promote a fundamental understanding of human-machine cockpit interfaces, and to gain experience in the integration of sophisticated cockpit technology. The research is being conducted at four facilities: CAE's offices in Montreal, Quebec; the CMC Systems Integration Facility in Kanata, Ontario; the ground-based, moving base flight simulator at UTIAS in Toronto; and at NRC's Flight Research Laboratory in Ottawa, Ontario.

An effective ESVS will be based on a solid understanding of human performance and technological limitations. The ESVS team has

identified a list of high priority research topics, including;

- the determination of an effective field-of-view for the required tasks;
- an understanding of the effect of limited sensor platform roll motion on pilot behaviour;
- quantification of the effects of system latencies on pilot performance;
- the design of symbology sets to overcome ESVS system deficiencies;
- selection of an appropriate image fusion technique;
- analysis of the trade-off between binocular and biocular imagery; and
- evaluation of scene content issues.

NRC has already completed a number of investigations into these topics. Each research project is described below, along with the status of the study.

Experiments are ongoing into the effectiveness of HMD systems in helicopter operations using a Fibre Optic Helmet Mounted Display (FOHMD) which was installed in NRC's Bell 205 helicopter in 1996 (4). The FOHMD system has a larger FOV than the SPIRIT system (total FOV of 105° with a 25° binocular overlap region), but has a lower resolution image (754x485 pixels). Baseline performance of the FOHMD system, reported in (5), shows handling qualities as a solid Level 2 system in degraded visual environments when using a rated damped control system.

Field-of-View

A study was conducted to investigate the effect of field-of-view and amount of binocular overlap on pilot performance (3). The tests were carried out in NRC's Bell 205 and 206 helicopters using a set of goggles with cut-outs that were set up to restrict the pilot's vision. The experiments showed that a binocular overlap region is necessary for manoeuvring close to the ground, landing and other nap of the earth operations. While larger FOV is better, improvements in handling qualities are marginal beyond a 100° FOV and Level 1 handling qualities are maintained with at least an 80° FOV. The results of these tests indicate that the field-of-view and binocular overlap provided by the SPIRIT II HMD system are acceptable to perform the ESVS mission.

Roll Compensation

The present NRC sensor platform has yaw, pitch and roll motion capability, unlike most current sensor platforms that do not have full three degree of motion systems. Due to the complexity and cost, production systems are usually restricted to yaw and pitch motion. The current series of NRC tests is looking at the effects of restricting the amount of camera platform roll on aircraft handling. Preliminary results of the study indicate that some platform roll is necessary for proper aircraft operation when using the fully immersive FOHMD system.

System Delays

The ESVS will require a significant amount of graphics processing of the displayed image which can potentially introduce time delays into the visual display system. Pilot co-ordination in handling aircraft can be degraded by large delays in image presentation on the HMD. NRC is conducting an investigation to study the effect of time delay on aircraft handling qualities. This information will be used to determine the maximum allowable processing delay for the graphics system.

Symbology

The current NRC HMD symbology has evolved over the course of two years of testing at NRC and UTIAS. A systematic flight test program for HMD symbology is planned for the next year to look at the minimal set of instruments required for navigation and flight maintenance. Questions to be answered include the acceptable level of clutter, the required compatibility with other sources of information in the cockpit, the optimal format (including different configurations for different mission phases), and integration issues.

Image Fusion Techniques

As mentioned earlier, the enhanced image will be fused into the synthetic image and displayed to the pilot. There are a number of issues that need to be investigated regarding this image fusion such as how close the registration of the enhanced and synthetic image must be before the image causes problems with the pilot's ability to handle the aircraft, and under what conditions the pilot may want to control the fusion algorithm. The results of tests at the UTIAS simulator will be evaluated in-flight when the systems and results are available.

Binocular and Biocular Trade-offs

The use of two optical sensors on the camera platform adds to the complexity and weight of the fielded system. However, two sensors are necessary to produce a true binocular image. The CMC DIPU has the capability to use one camera image to

produce biocular images for display on the HMD. NRC plans to run an experiment to investigate the differences in handling qualities when using a biocular image versus a true binocular image.

Scene Content

Simulator studies have been carried out at the UTIAS simulator using the map database of the selected test site area to investigate the graphics image requirements for the synthetic image system. NRC will be looking at scene content issues based on the finding from the UTIAS studies. The issues to be investigated include image texture, level of cultural detail and problems with producing the graphics image from the terrain database. The problems include such anomalies as rivers which flow up hill and lakes with contours due to inaccuracies in the geographical database.

Conclusions

Search and Rescue operations are important in any country, but with the size and remoteness of large areas of Canada, the capability of carrying out SAR missions in day and night, all weather conditions is of paramount importance. The enhanced and synthetic vision system described in this paper will help alleviate many problems facing SAR pilots flying aircraft equipped with present day technology. The ESVS team is working toward preparing a demonstration system by the year 2000 and in parallel, are conducting a research program to understand the human factors issues associated with the ESVS system.

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Evaluation of the Cockpit Assistant Military Aircraft CAMA in Simulator Trials

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1 SUMMARY

Inappropriate automation is considered to be a major reason for deficiencies on interaction between pilot crew and aircraft systems. The lack of situation awareness is pointed out to be a crucial cause of pilot failure. Because of this, cockpit assistant systems are being developed in support of human-centered automation. CAMA assists military crews during transport missions.

This paper consists of three main parts, briefly describing the functional prototype of CAMA, the experimental means taken in order to evaluate the integrated system, and the comprehensive results of two flight simulator campaigns.

Firstly, a general survey is given on human factors related problems in this particular domain. Their influence on the principals of cockpit crew assistance will be shown and a brief circumscription of CAMA's main functionalties follows.

The description of the simulator facilities for experimentation includes the visual system, the available flight controls and the means for interaction between the pilot and CAMA. The experimental scenario and tasks are pointed out.

To get an estimation on the pilot's overall acceptance of the approach and the benefits of the CAMA-system, thorough evaluations were conducted.

2 INTRODUCTION

Military transport pilots are confronted with both, flying under IFR conditions in high density airspace as well as performing tactical multi-threat missions. Due to the variety of tasks that have to be handled, crews suffer from a high workload.

Situations inevitably arise where the crew members are overtaxed regarding their limited mental information-processing resources, and thereby act erroneously. Because of this, situations may develop which jeopardise the mission success. The high crew workload is caused by the variety of different tasks, an insufficiently adapted crew interface, and the poor availability of information relevant to the situation and task in the cockpit. Closely related to this is the problem of situation awareness. Situation awareness has been achieved when the pilot has all relevant information which is required to resolve the most urgent task at his disposal [7]. This includes the objectively correct awareness, which is actually the most urgent task. Situation awareness is therefore the result of a continuous process of situation assessment [18].

Human-centred automation [1] appears to be a promising approach to the design of future cockpit avionics functions. The starting point is the analysis of the crew's tasks. These tasks comprise information gathering, situation interpretation and analysis including the ownship situation as well as tasks relating to in-flight mission planning and tactical low-level flight trajectory computation, and finally flight guidance and navigation tasks.

A technical system which is meant to be an effective crew assistant system for the transport mission management should cover at least the above-mentioned chain of functions. Given this basis of crew assistance it ought to be taken into consideration that the assistant system should not replace the crew for certain tasks in terms of automation. The machine should be able to perform the tasks in parallel with the human operator and in co-operative function allocation [7]. Like the human operator, the machine part of such a man-machine system also needs to have the information relevant to the situation (task) at its disposal.

Incorporating these guidelines, the *Crew Assistant Military Aircraft* (CAMA) was developed. The subsequent sections deal with evaluation in simulator trials. Details will be given on the experimental setup, the investigated scenarios and the found results.

3 CREW ASSISTANT MILITARY AIRCRAFT

The Crew Assistant Military Aircraft (CAMA) is a knowledge-based cognitive assistant system under development in close cooperation between the partners ESG, the University of the German Armed Forces, the German Aerospace Research Establishment (DLR), and DASA since 1995. CAMA and its philosophy have been described in various other papers such as [14][16][17], so that there is no need to go into detail too much, here. However, the following paragraphs will give a bief insight into the functional modues of CAMA. Figure 1 shows the functional structure of CAMA.

The interface between CAMA and the crew is controlled by the module *Dialogue Manager (DM)*. Speech output is suitable to focus the pilot's attention on important aspects. More complex information is transmitted using graphical displays [13]. Information input is realised utilising speech recognition to a large extent [3][4].

Various modules provide crucial information on health status of aircraft systems (SI), environmental aspects (EI), and the flight progress.

The *Tactical Situation Interpreter (TSI)* calculates the local threat distribution along the mission plan. Thereby, CAMA is able to perform the conflict detection with respect to local changes in the tactical situation [10].

In order to ensure situation awareness for the machine-system, all information produced by the modules is assembled in a *Central Situation Representation (CSR)* and this way provides a complete dynamic database of the current situation. This can be seen analoguously to the pilot's own mental representation of

Paper presented at the RTO SCI Symposium on "Sensor Data Fusion and Integration of the Human Element", held in Ottawa, Canada, 14-17 September 1998, and published in RTO MP-12.

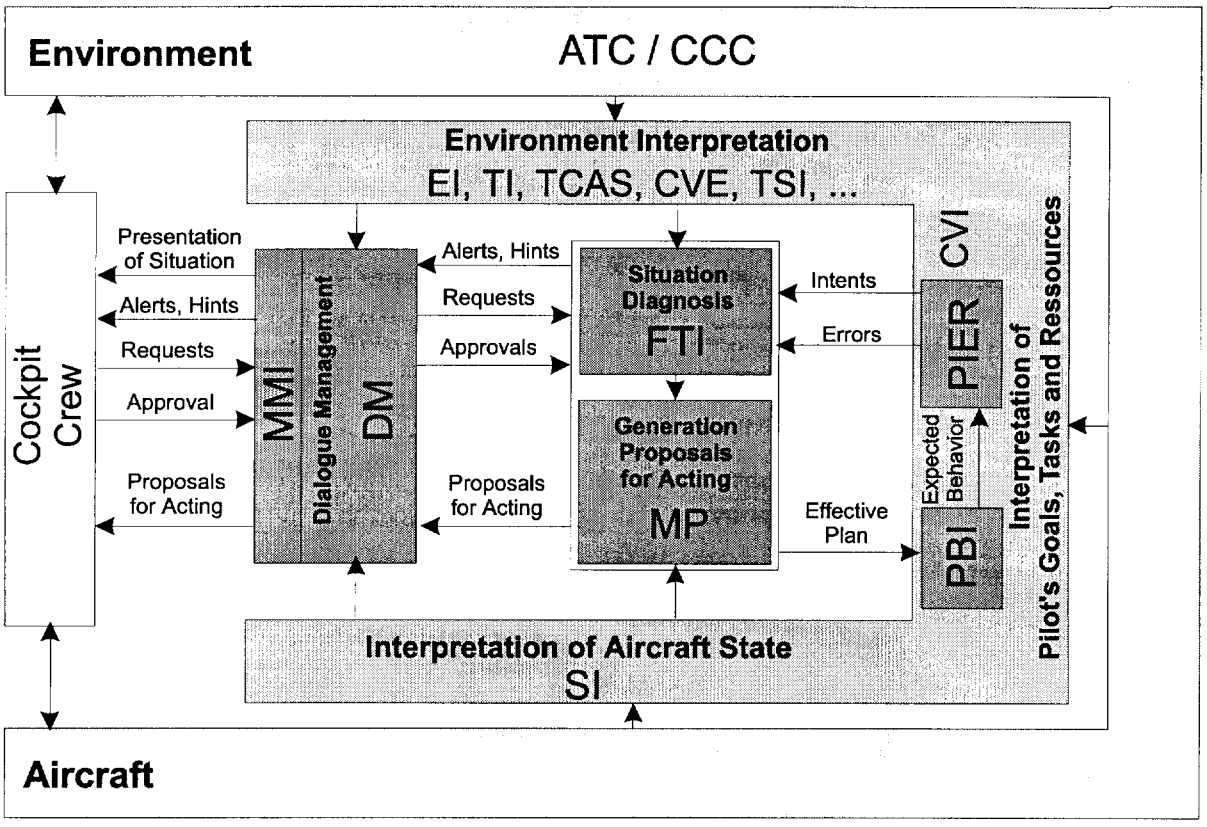


Figure 1: Functional Structure of the Crew Assistant Military Aircraft.

the actual situation. It ensures that the system is working on the same assumptions as the crew, thus making it different from existing cockpit functions which make use of only a restricted amount of relevant knowledge.

On the basis of situation knowledge, possible conflicts ahead can be identified (e.g threats, weather) by the *Flight Situation and Threat Interpreter (FTI)*. Here the impact on the current flight is assessed, conflicts are detected, and resolution activities are initiated.

The *Misson Planner (MP)* generates a complete 3D/4D mission plan [8] either on demand by the crew or autonomously, in case the crew not having the resources to interact. It is important to mention that the planning process again takes all aspects of the situation (provided by the *Central Situation Representation*) into consideration [16].

If the penetration of hostile area is inevitable necessary, the *Low Altitude Planner (LAP)* is activated to achieve a threat minimising low-level routing taking the output of the aforementioned modules into consideration. It allows the incorporation of corridors and tactical delivery procedures, such as a payload drop procedure. Both, low-level as well as IFR-routing are combined to on homogenious flight plan.

The modules *Pilot Behaviour Interpreter (PBI)* as well as *Pilot Intent and Error Recognition (PIER)* serve mainly for monitoring of pilot behaviour, which shall be described in more detail in [14] and [15].

Dynamic external data like air traffic control and C&C instructions as well as environmental information are gathered via an external communication interface.

Static databases comprise information like navigational, terrain and feature data.

4 SIMULATOR TRIALS

After going through a module intergration phase of several months, a scientific approach was chosen in order to evaluate CAMA. The following sections will describe the experimental design.

4.1 Apparatus

CAMA has been integrated and tested in the research flight simulator located at the University of the German Armed Forces at Munich (see Figure 2 for a schematic view).

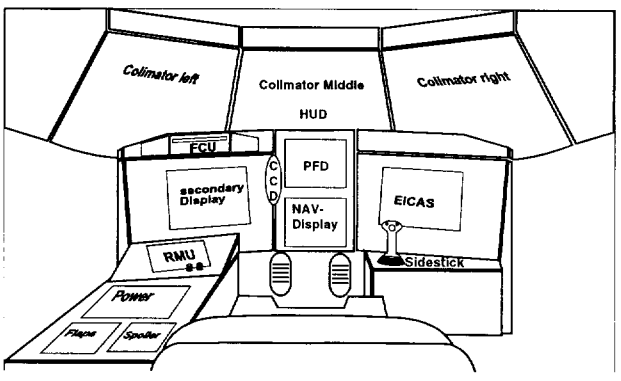


Figure 2: Experimental Simulator Configuration

Flight simulation and visual simulation run on Silicon Graphics workstations. The dynamic model is derived from the ATTAS experimental aircraft of the DLR. A wide field-of-view visual simulation system provides visual cues to perform low-level flight missions. The database was derived from DMA DTED and DFAD [19] data, giving information on terrain elevation as

well as on topolgrahical features (airports, populated areas, forrests, rivers, powerlines, etc.) in order to enable visual navigation.

The pilot's station is a generic glass cockpit equipped with monitors presenting the CAMA-Displays:

- *Primary Flight Display*: It incorporates two basic display types. A standard ADI display in order to support the IFR portions of the mission and a three-dimensional perspective format (Figure 3) enhancing low-level flight guidance in particular under restricted visual conditions. The latter not only provides information to the surrounding terrain and feature data, but also basic aircraft parameters. It further depicts the planned trajectory, generated by CAMA´s low-level planning module [6] and the evasive maneuvres, generated by CAMA´s terrain interpreter. Both are displayed as a three-dimensional flight guidance tunnel. Additionally, the expected behaviour parameters generated by the pilot model are displayed and respective deviations in the actual behaviour of the pilot are indicated.

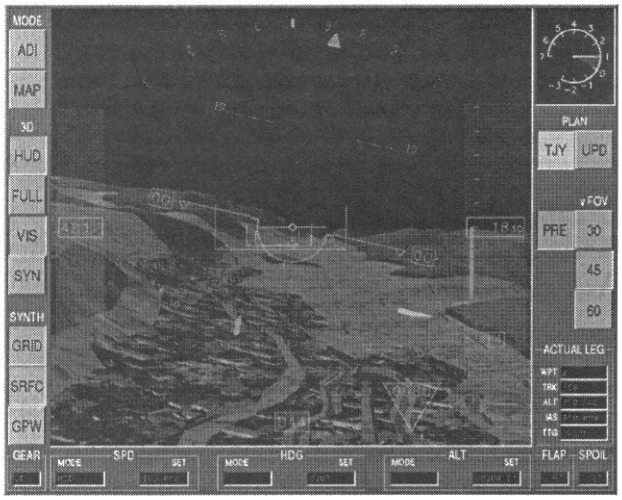


Figure 3: Three-Dimensional Flight Guidance Display

- *Interactive navigation display*: This multimodal display [3] provides a variety of functions. Most important, it supports the pilot during lateral navigation, showing his position in reference to several situational elements. Depending on the actual task during flight, navaids, airports, weather, converging traffic (TCAS-symbology), flight plan, SAM locations and ACO information are culled and displayed. Terrain information and the calculated threat map [11] are underlayed. Resulting from CAMA´s internal situation assessment, certain symbols are highlighted or blinking in order to attract the pilot's attention (e.g. new SAMs, blocked corridors, etc.). In parallel the relevant speech output is displayed on the upper edge (see Figure 4). By touching the symbols on the map, the pilot can enquire more information concerning these elements and/or subject them to further processing. For example, navaids can be picked directly via touch input, new corridors can be selected for a replanning, etc.
- The *Secondary Dislplay* supplements the *Navigation Display* by presenting a flight log, ATIS information, and approach charts on the pilot´s request.

Primary flight control is performed by a sidestick, an Airbus-type Flight Control Unit, throttle, etc.

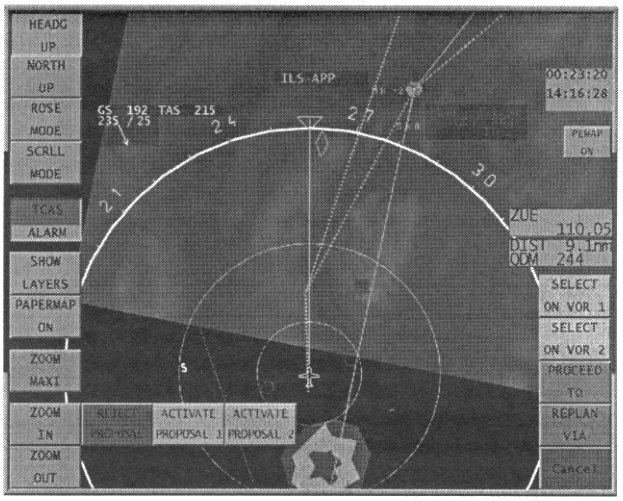


Figure 4: Interactive Navigation Display

Another important media for information exchange between the pilot and is speech recognition / synthesis [4]. Using a SUN workstation based speech recognition system the pilot is able to communicate the system on a "natural speaking" level. In order to enhance recognition probability, situation adapted syntaxes are generated and used. The following list shows the main functionalities that can be requested by the pilot via speech input.

Command	Function
"request flight plan to ... (arpt id)" *"request flight plan via ... (wptt id)"* *"activate flightplan ... (proposal number)"*	automatic re-planning
"climb/Descent ... feet/flightlevel" *"increase/reduce ... knots"* *"turn left/right ... (hdg)"* *"proceed to ... (wpt)"*	autopilot settings
"display heading up/ north up/ rose mode/ ..." *"zoom ... miles/ mini/maxi"*	display configuration
"select ... (nav id) on vor1/vor2/adf" *"select course"* *"select ils"*	navaid configuration
"request alternates" *"request ATIS of ... (arpt id)"* *"request distance to ... (arpt id/ navaid id/ ...)"* *request approach/departure briefing/chart"*	supplementary information

Table 1: Speech Syntax

In addition to the information given on the displays, CAMA issues important messages by voice output to the pilot. Regarding the importance of the message different voice levels are chosen.

The simulator includes a operator console, allowing interference during mission progress. Researchers can

- control situational elements (weather, other aircraft, etc.),
- dispatch ATC / C&C commands via datalink,
- control data acquisition and eye movement measurement.

4.2 Subjects

The subjects were ten German Air Force transport pilots (Airlifter Wing 61, Landsberg) between the age of 29 and 43 (mean age 38.4 years). The subjects were well experienced (combat ready) and had between 800 and 5300 total flying hours on the C-160 Transall (mean flying hours 2550). Figure 5 shows a pilot interacting with the CAMA system during the experimental flight.

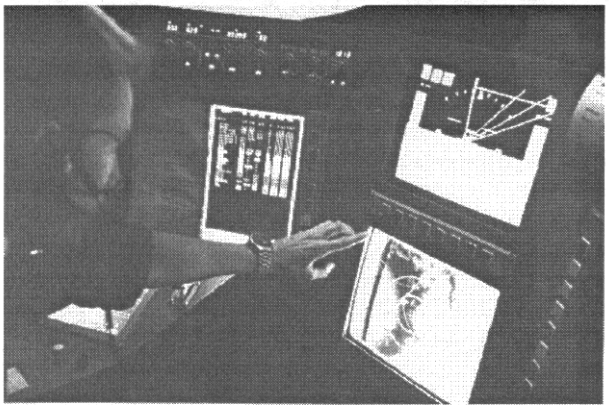


Figure 5: Pilot in Experimantal Cockpit

4.3 Scenario and Tasks

Prior to the evaluation phase, time was given for familiarisation and training on the system. Emphasis was put on

- basic aircraft handling,
- aircraft guidance in low-level flight using the three-dimensional flight guidance display,
- use of the autopilot,
- use of the interactive navigation / information displays,
- use of speech recognition, and
- interpretation of speech output.

The tasks to be performed during the evaluation phase were described by a full scale air transport mission, consisting of segments under IFR conditions followed by tactical low-level flight.

The IFR scenario incorporated

- adverse weather conditions,
- high density airspace,
- varying availability of landing sites, and
- extensive ATC communication.

The tactical scenario was characterised as a dynamic multi-threat theatre due to the presence of

- surface-to-air missile sites,

and tactical constraints such as

- air tasking order (ATO), and
- airspace coordination orders (ACO).

Before take-off, the subjects received a standard mission briefing using conventional maps, but also already CAMA's displays.

Take-off was performed at a controlled airport. During the IFR transit flight into the tactical operation area the subjects had to perform several planning and re-planning tasks. These were induced by thunderstorm areas and ATC requests.

After passing the entrance corridor to the hostile area the mission continued in low-level flight, avoiding known threats where possible, minimising the exposure to unknown threats and keeping clear of the terrain. Next, a tactical drop procedure had to be performed while being loaded by additional planning tasks concerning the low-level route ahead.

Having left the exit corridor the pilot resumed the IFR flight. Converging traffic in terminal areas and closed airports forced the pilot to make various short-term and medium-term decisions.

4.4 Experimental Plan

Each subject had to perform the mission 3 times, once on each of the three experimental days. The simulator trials took place in autumn 1997 and spring 1998. Table 2 gives the experimental time schedule for the first evaluation period. In the second experimental period the schedule was repeated, but only the second flight evaluated.

Experiment	Duration
Introduction to simulator	30 min
Simulator familiarisation flight	45 min
CAMA familiarisation flight	45 min
1st experimental CAMA mission	60 min
Debriefing and questionnaires	120 min
Pilot behaviour model tuning flights	180 min
2nd experimental CAMA mission	60 min
Debriefing and questionnaires	120 min

Table 2: Experimental Time Schedule

5 RESULTS

In this chapter the results of an extensive experimental evaluation of the CAMA functional prototype are summarised. The main focus is on the subjective ratings given by the experimental pilots. A few statements concerning objective evaluation criteria are added afterwards.

5.1 Subjective ratings

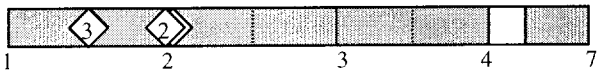
In order to assess the pilot's overall acceptance of the approach and the benefits offered by the cockpit assistant system, a debriefing session concluded the experiments as described above. The evaluation results presented here give an overview over the subjective ratings given by the experimental pilots concerning the tactical cockpit assistant functions, as well as concerning the IFR-operations related cockpit assistance provided by CAMA.

All ratings were given within a range from 1 through 7, where 1 represents the best evaluation and 7 marks the negative end of the scale. The diamonds mark the median value of the ratings given after the first (1) and second (2) experiment of the first campaign. (3) stands for the flight performed during the second campaign.

First of all, it was necessary to ensure that the simulation environment was adequate for performing the required tasks. Therefore, several aspects of the simulation which are relevant to the performance of tactical flight missions were evaluated.

Figure 6 displays some summarised results of the evaluation with respect to the flight simulation environment.

(a) Flight Simulation System Handling



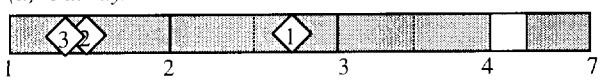
(b) Visual Simulation appropriate for Low-level Flight

Figure 6: Evaluation of flight simulation

Here the evaluation of the flight simulation handling (a) comprises several parameters such as manual sidestick control, FCU, and RMU operations during IFR and tactical flight. It can be stated that the acceptance of the experimental platform slightly improved over the course of three flights, and is certainly satisfatory as prerequisite for the CAMA evaluation.

In order to gain an overall impression of CAMA's performance, the following statements were evaluated. Figure 7 shows the rating results, again measured on a scale from 1 (strong agreement) to 7 (strong disagreement).

(a) 'I always understood CAMA's Actions.'



(b) 'I was (made) aware of my own faults.'

Figure 7: Evaluation of CAMA philosophy

The ratings show that the pilots were able to understand the intents and actions of CAMA (a) only after the short familiarisation of one flight. A significant training effect was observed from the first flight with CAMA to the second campaign, as the ratings are improving noticably. It is significant that it does not only seem to be an effect of familiarity with the simulation facility and displays, but an apparent increase in understanding the aims followed by CAMA (see Figure 7 (a)).

The methodological approach to the subjective evaluation of CAMA followed a certain scheme of questions, which has been derived from the considerations mntioned below. [9] proposes the following aspects for the evaluation of man-machine-systems:

Compatibility: Is the system adapted to the operators capabilities and limitations?

Intelligibility: Does the organisation and the contents of the man-machine-dialogue provide a meaningful communication?

Effectiveness: To what extent does the system enhance task-performace?

According to [5], meeting these three criteria is a prerequisite to reach a high degree of acceptance for the man-machine-system. Another important aspect for the evaluation of a crew assitant system is the term of situation awareness. [2] defines situation awareness as follows:

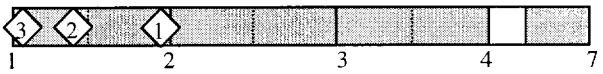
> "Situation awareness is the perception of the elements in the environment ... , the comprehension of their meaning, and the projection of their status in the near future."

Therefore, the questionnaires were structured according to the following aspects:

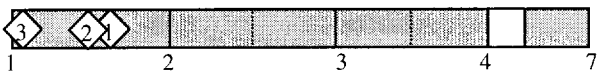
- In order to evaluate the situational awareness aspects, the considered situation space was classified and structured into classes and sub-classes of relevant situational elements. Again, with regard to these classes the pilots had to indicate whether they had all the situational element-related information at their disposal whenever needed.
- The effectiveness and the benefit provided by the functions were evaluated by listing all relevant tasks and sub-tasks throughout the mission. The subjects had to comment on the quality of assistance provided by CAMA with respect to these tasks.
- To evaluate the degree of acceptance, the pilots had to refer to a list of statements characterising the system behaviour and handling features.

Figure 8 depicts the situational awareness ratings with respect to a collection of situation elements. The diamonds on the bars show the median values of the pilots ratings evaluating their subjective sensation of situational awareness. It should be kept in mind that the Figure only depicts the positive half of the ranking scale. Again, (1) and (2) indicate the results of the first experimental campaign and (3) stands for the second campaign with CAMA.

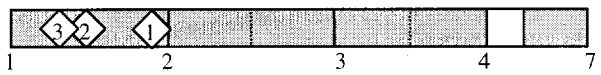
(a) Aircraft Attitude



(b) Aircraft Position



(c) Terrain Relief



(d) Threat along Low-level Flight Trajectory

(e) Re-planning needs

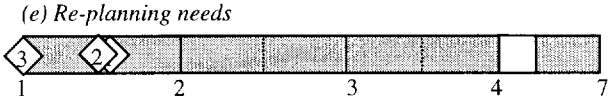


Figure 8: Evaluation of situation awareness

Figure 8 makes clear that the situation awareness ratings concerning the tactical situation elements remained unchanged over the two-day experimentation at a very high level. On the other hand, the pilots situation awareness on primary flight parameters such as speed or altitude is certainly more crucial and has therefore been evaluated more critically.

The following collection of ratings shown in Figure 9 depicts the pilot's rating on the quality of assistance provided by the CAMA functions.

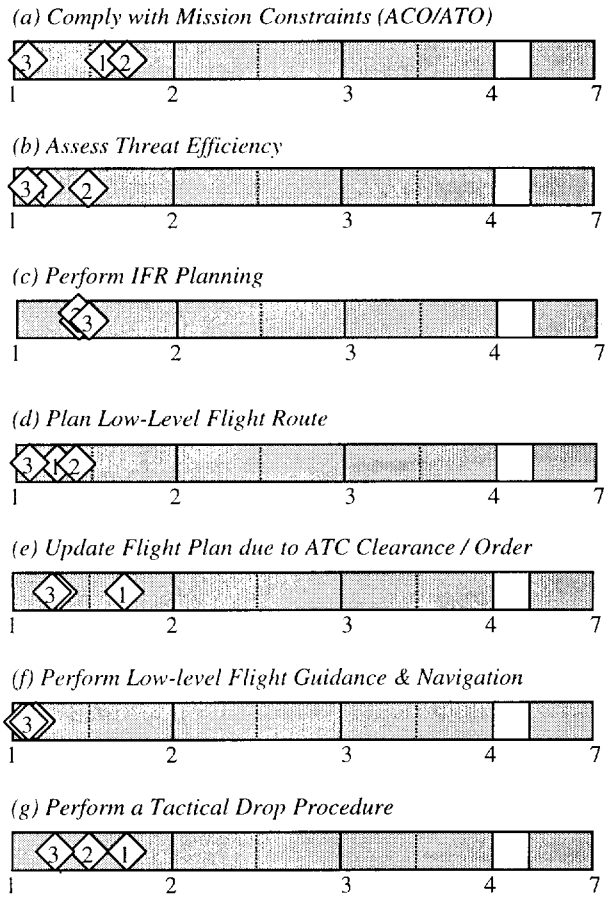


Figure 9: Evaluation of assistance quality

Figure 9 (c) and (d) clearly prove that the automatic flight planning functions (for IFR and low-level) are well established in the context of the CAMA functions. Their performance is well appreciated by the pilots. The low-level flight guidance and navigation assistance (f) provided mainly by the various features of the three-dimensional flight guidance display and the navigation display is regarded as very powerful. The effectiveness of the tactical assistant functions gained constant high ratings. For all other tasks the quality of machine assistance improved over the succession of the experiments.

The following Figure 10 puts the focus upon the evaluation of CAMA's advice and warning philosophy. Advices and warnings are issued whenever the flight-deck crew acts erroneously with respect to a CAMA-internal model of what the pilot is supposed to do. Most effort in modelling pilot's behaviour was made in the field of primary and secondary flight control adjustments. Therefore, the evaluation of the advice and warning philosophy gives a good indication of the performance of the pilot's behaviour models and the intent and error recognition.

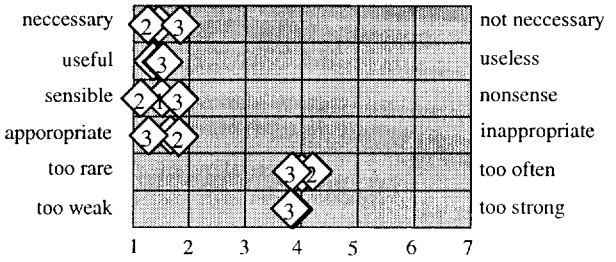


Figure 10: Evaluation of advice and warning philosophy

In Figure 10 it becomes evident that CAMA's concept of giving advice and warning is very well accepted by the pilots. Furthermore, the philosophy appears to be well balanced in terms of warning frequency/sensitiveness and intensity.

The next selection of experimental evaluations is concerning the subjective measurement of the degree of acceptance. The acceptance was determined by evaluating the behaviour of the assistant system, as well as its handling qualities, as indicated in Figure 11 and Figure 12.

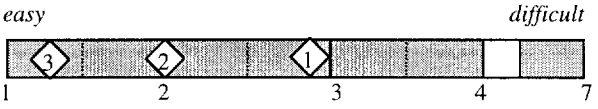


Figure 11: Handling qualities of CAMA

Like Figure 7 (a), Figure 11 indicating the subjective easyness of the CAMA operations shows a strong training effect. The handling of CAMA became much easier during the course of the experiments.

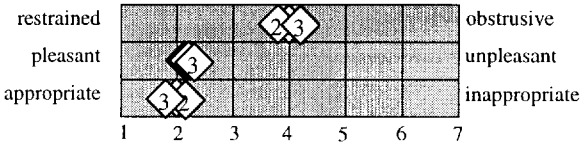


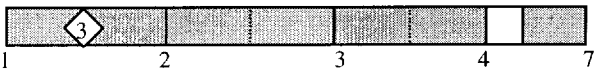
Figure 12: Acceptance of CAMA behaviour

The overall somewhat hesitant acceptance shown in the results of the evaluation (Figure 12) may indicate a certain amount of disapproval of new technologies on behalf of the pilots. Of course, a cockpit system which points out faulty crew actions might be found sometimes obstrusive or somewhat unpleasant. It might also be the outcome of immaturity of the implementation of certain functions or procedure models. On the other hand the actions of CAMA were not only understood, but regarded as being appropriate.

The second experimental campaign was concluded by a more general subjective evaluation. The pilots were asked to give their opinion on CAMA in the context of some general terms. Figure 13 shows the results. 1 indicates a strong agreement to the statement, 7 means the strongest possible experession of disagreement.

(a) CAMA increases Flight Safety

(b) CAMA increases Mission Efficiency



(c) CAMA increases Survival Probability

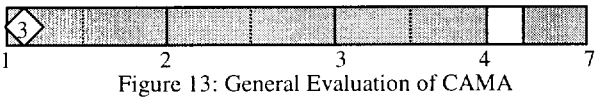


Figure 13: General Evaluation of CAMA

The results in Figure 13 show that the potential users strongly beleive in the benefit and an increase of overall mission performance and success created by cockpit assistant system for military aircraft as proposed with CAMA.

Generally, the results of the evaluation of the questionnaires and also of informal statements from the pilots can be regarded as very good. One experimental subject stated that CAMA gives him the opportunity to fly even more perfectly than he does anyway!

5.2 Objective evaluation statements

In this study objective evaluations were done only on the level of the functional modules (e.g. concerning the Pilot Behaviour Model and the Pilot Intent and Error Recognition). A detailed description of respective results would be beyond the scope of this paper. (See [14] and [15] for details.)

However, the following Table 3 gives an idea of a comparison of typical reaction times (RT) between CAMA and an unassisted crew (estimated).

Situation	Appropriate Reaction	RT [s]	
		unassisted	with CAMA
new threat pops up	check current flight plan	12	2
threat affects current plan	check re-planning required	5	< 1
destination changed	IFR re-planning	> 30	2
tactcal transit corridor chng.	optimal trajectory re-planning	N.A.	2 - 5

Table 3: Comparison between reaction times

It is obvious that CAMA takes a lot of mental workload from the cockpit crew by applying its highly automated functions or simply enables the crew to take advantage out of its complex computations in the context of situation interpretation and conflict resolution tasks.

Furthermore, continuous observations of the experimental task performance led to some optimisation steps between the two evaluation periods:

- The presentation of flightplan proposal on the navigation display was found to be irritating for the pilot in certain situations. Therefore the depiction was moved to the secondary display.
- A pure visualisation of terrain elevation on the primary flight display was found to be insufficent for terrain relief perception and low level flight guidance. As a result three-dimensional, triangulated feature data and textures were added.

6 CONCLUSIONS

The results of the experimental evaluations of the Crew Assistant Military Aircraft yield a wide variety of approaches and solutions in the field of crew assistance for tactical flight missions. The next two subsections conclude the paper by giving an overview and evaluation of the present work reported in this paper, and pointing out some future prospects for forthcoming developments.

6.1 Present work

In the present work the functions required in order to construct an assistant system for military aircraft operations were derived from the tasks relating to tactical mission management. The result of this analysis shows that functions for situation interpretation / assessment, conflict detection / resolution and a man-machine interaction management make up the core of such an assistant system. Taking the requirements of human-centered automation into consideration, the cognitive assistant system CAMA provides well founded solutions. The integration of tactical mission management functions into CAMA completes the system, so that an autonomous recognition of crew intent and errors as well as the detection of flight plan conflicts can trigger dedicated mechanisms of conflict resolution.

CAMA and its various assistant functions were throroughly evaluated during two experimental campaigns utilising a flight simulator. A total of ten professional military pilots performed complex missions in the simulator, assisted by the Crew Assistant Military Aircraft. In the de-briefing sessions the pilots gave extremely positive ratings on the system, its contribution to situation awareness, the quality of the assistant functions, and the degree of acceptance of such an electronic crew member. The effect of the minimum amount of training on the system, in particular on the easyness of handling, is remarkable.

6.2 Future prospects

After the successful experimental simulator evaluation, a flight trial campaign with CAMA is under contract and scheduled for early 2000. Further developments will focus upon the integration of imaging sensor information into the three-dimensional flight guidance display in order to achieve an enhanced vision system.

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Fusion and display of tactical information within battlefield helicopters

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1. INTRODUCTION

Battlefield helicopters will form an important element of the Digitized Battlespace. Helicopter aircrew will be presented with large amounts of data from both on-board sensors and other units. The way in which this information is presented to the crew will have a critical impact on operational effectiveness. This paper describes the a trial carried out by the Defence Evaluation and Research Agency (DERA) for UK MoD, to assess the impact of providing Tactical Situation Displays (TSD) of varying degrees of data fusion and complexity.

Previous trials [1, 2] assessed the impact on operational effectiveness of the provision of tactical information in the helicopters. These concluded that the provision of tactical information improved operational effectiveness, survivability and situational awareness. Instances of fratricide reduced dramatically. These parameters improved still further when on-board sensor data was fused with the tactical display.

The two previous trials were undertaken prior to the selection of the WAH-64 as the UK Army's Attack Helicopter. It was considered important to re-assess the conclusions of the earlier trials in the light of the capabilities of the WAH-64. This trial was designed to assess the effect on operational effectiveness of providing on-board tactical information displays of varying degrees of integration to the Commander of the WAH-64. A fourth trial, due to take place in 1998, will examine the impact of different levels and accuracies of tactical information.

2. HELICOPTER SIMULATOR TRIAL

2.1 Hovers

The trial was conducted using the HOVERS real-time man-in-the-loop helicopter mission simulator. This is a fixed base workstation based facility. HOVERS models helicopter systems (sensors, weapons, flight dynamics), a synthetic battlespace environment, and semi-automated Computer Generated Forces (CGF).

Cockpits, with stations for the Pilot and the Commander, are located in separate rooms. Each simulated helicopter is flown using conventional cyclic stick, collective lever and yaw pedals. The Pilot's view is provided by computer-generated terrain images displayed on three large monitors. This view is also visible to the Commander. Both Pilot and Commander also have head-down displays showing basic flight and mission related information. Controls include touchscreen buttons, switches and joysticks. The Pilot and Commander can communicate with each other, with other helicopter crews and with the tactical controller.

2.2 Cockpit configuration

The models developed for this trial were generic representations of the systems which will be fitted to the WAH-64 at its In Service Date (ISD), together with enhancements and additional systems likely to fitted by 2010. The 2010 timeframe was selected as the earliest date at which a highly integrated TSD could be fitted to the WAH-64.

It was assumed that tactical information from the digitized battlespace would be displayed on the TSD, overlaid on a digitized map, together with information from on-board sensors. The TSD configurations are described in Section 2.3.

The three sensor systems modelled were a Fire Control Radar (FCR) (used for target classification and prioritisation), a Radio Frequency Interferometer, and a Target Acquisition Designation System (TADS). The TADS model consisted of an Infra-Red (IR) sensor, Laser Range Finder and Image Autotracker.

The helicopter was provided with three weapons systems. Generic models of Radio Frequency (RF) missiles, Cannon and IR Fire and Forget Air to Air Missiles were implemented.

A Combat Identification model was integrated with the TADS and FCR to prevent RF or IR missiles from being targeted at friendly vehicles.

A generic integrated DAS suite was modelled, consisting of a Radar Warning Receiver, Laser Warning Receiver, Omni-directional RF Jammer, Missile Warning System, Directional IR jammer and Flares.

2.3 Tactical Situation Display Configurations

The trial used three different configurations of the Commander's TSD, while the Pilot's display remained unchanged. The level of fusion of on-board sensor data and imported tactical information on a digitized map differed in each configuration. Some additional display functionality was also added. The three configurations were:

- Baseline: On-board sensor data as available at ISD overlaid on a digitized map displaying tactical information from the digitized battlespace;
- Improved: Some integration of on-board sensor data with the tactical information from the digitized battlespace;
- Fused: Complete fusion of on-board sensor data and imported tactical information to provide a simpler, more accurate TSD.

Paper presented at the RTO SCI Symposium on "Sensor Data Fusion and Integration of the Human Element", held in Ottawa, Canada, 14-17 September 1998, and published in RTO MP-12.

2.3.1 Baseline display

The baseline display comprised the following:

- Digitized map: With tactical symbology overlays;
- Sensor data: Similar to that expected on the TSD on the WAH-64. Targets, allegiance, ownship position, DAS warnings, and FCR display;
- Tactical information updates: Accurate, up to date information on Blue Forces. Incomplete information on Red Forces, subject to errors in position, vehicle type and staleness. Stalenness portrayed by fading vehicle symbols;
- Controls: Similar to those expected on the WAH-64 at ISD. The map could be manipulated to alter scale, intensity under the tactical symbology overlay, and centre position (on ownship symbol or grid reference).

2.3.2 Improved display

The improved display provided the Commander with all of the information and options that were available in the baseline, together with the following additional features:

- Limited integration of on-board sensor data with tactical data;
- Intervisibility calculations;
- Additional map manipulation functionality.

Limited integration provided between the on-board sensor data and the tactical data provided the following improvements in tactical symbology:

- Listing of the last position measured with the laser range finder;
- Lines on the map to indicate the range and bearing of the laser range finder;
- Display of Laser Warner Receiver warnings on the border of the map together with other DAS warnings, rather than on the map itself;
- Lines from the ownship symbol to DAS symbols on the edge of the TSD;
- Colour coded DAS warnings to indicate type;
- TADS and FCR sensor footprints, including intervisibility.

Intervisibility information was calculated in real time using terrain heights and cultural features. The following could be displayed on the map:

- Line of sight areas to a fixed maximum range;
- Sensor foot prints showing angular coverage of the sensor and the area of ground to which the sensor had line of sight;
- Virtual helicopter positions: By selecting a point on the map and a height, the Commander could display the area of ground that would be visible to the helicopter if it moved to that position;
- Virtual ground force positions: By selecting a point on the ground, the Commander could display the area over which a ground platform would have line of sight to helicopters at various heights.

Additional map manipulation functionality was provided as follows:

- Map scrolling;
- Additional scale options;
- Additional orientation options: Aircraft referenced, North up, FCR up and TADS up.

2.3.3 Fused display

The fused display had the following key features:

- Complete fusion of tactical data from the digitized battlespace with on-board sensor information. This simplified the picture. The accuracy of the information was also improved, as the single most accurate and up to date source of vehicle position information was used to update the display;
- DAS warnings associated with specific platforms rather than bearings;
- Intervisibility calculations and map functionality as for the improved display.

2.3.4 Pilot's display

The Pilot's display, which remained unchanged, comprised the following:

- North up single scale digitized map;
- Baseline TSD;
- Tactical information updates as provided for the Commanders.

2.4 Scenarios and threat environment

Army Air Corps (AAC) personnel designed eight different scenarios. The scenarios were designed to provide a high intensity threat environment. In each scenario a pair of manned (Blue) HOVERS helicopters was tasked with seeking and destroying enemy (Red) CGF. One helicopter assumed the role of patrol commander. In the event of one of the helicopters being killed, the second was to proceed with the mission alone.

Missions were conducted with sensor and weapon systems appropriate to the 2010 timeframe. The ground force threat was formed into groups comprising main battle tanks, air defence units (ADUs) and armoured personnel carriers carrying man portable air defence systems. Generic CGF attack helicopters provided an air threat.

2.5 Trial procedure

AAC personnel flew 72 missions over a 3 week period. The HOVERS military co-ordinator acted as the tactical controller. An initial period of structured training was provided for the trials aircrew to ensure familiarity with the aircraft systems. Crews were issued with orders prior to each mission, and allocated time to plan the mission.

Data were logged during each mission for later analysis. The key measures of effectiveness for these attack missions were the survivability of Blue helicopters and the number of enemy vehicles destroyed. Crews also completed debriefing questionnaires to provide a subjective analysis of workload [3] and situational awareness [4].

3. RESULTS

3.1 Survival probability

Figure 3.1 shows that survival probability of the Blue helicopters increased slightly for both the improved and fused configurations.

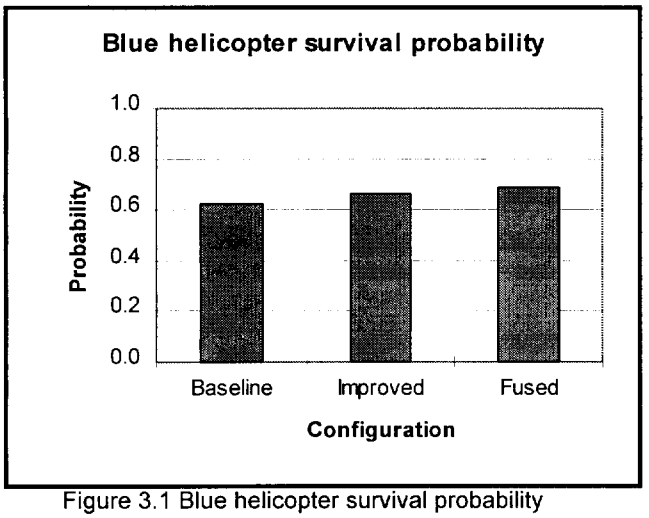

Figure 3.1 Blue helicopter survival probability

As shown in Figures 3.2 and 3.3, a significant reduction in the number of kills by ADUs was balanced by an increase in the number of kills by Red helicopters.

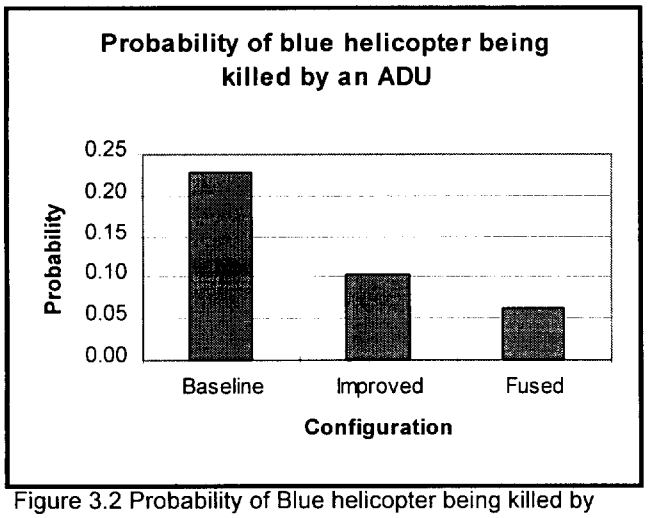

Figure 3.2 Probability of Blue helicopter being killed by ADUs

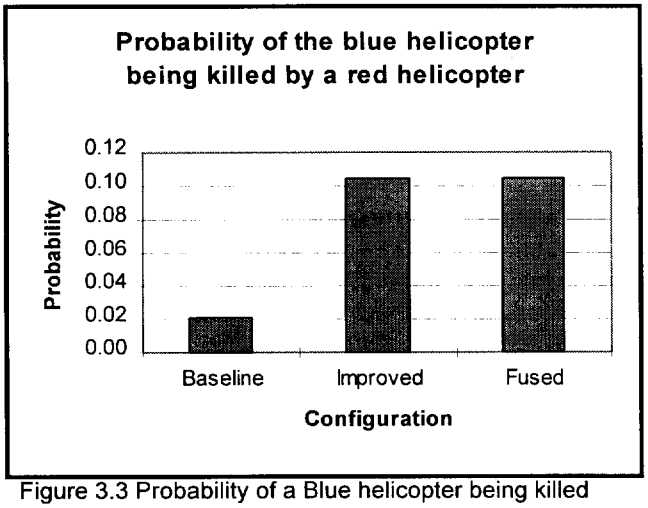

Figure 3.3 Probability of a Blue helicopter being killed by a Red helicopter

3.1.1 *Reduction in kills by ADUs*

The improvements in survival probability against ADUs were analysed further. Figure 3.4 shows that there was a reduction in the number of sightings of Blue helicopters by Red ADUs, leading to a drop in the number of missiles fired at Blue helicopters. Intervisibility information and increased confidence in the accuracy of the more integrated displays allowed Commanders to plan more covert routes to firing positions.

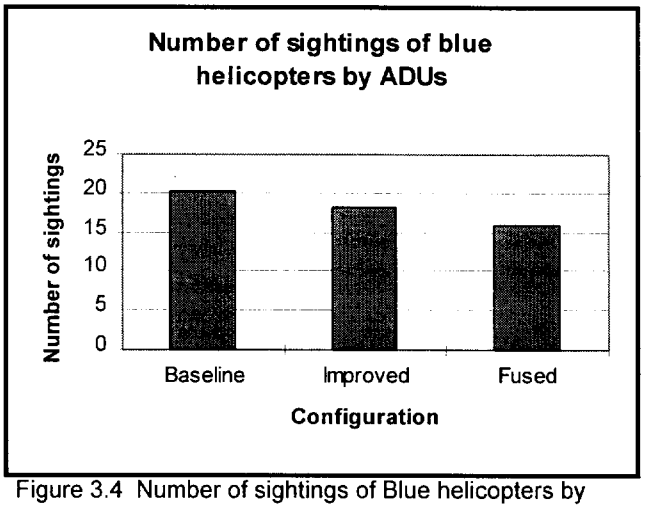

Figure 3.4 Number of sightings of Blue helicopters by ADUs

Figure 3.5 shows that the effectiveness of ADU missiles fell with the more integrated displays. Crews used the intervisibility options to improve their use of terrain, selecting firing positions from which it would be easier to break missile lock. Increasing integration of the displays improved the accuracy of the intervisibility options. The increasing integration of DAS warnings with the map further increased crew awareness of the threat.

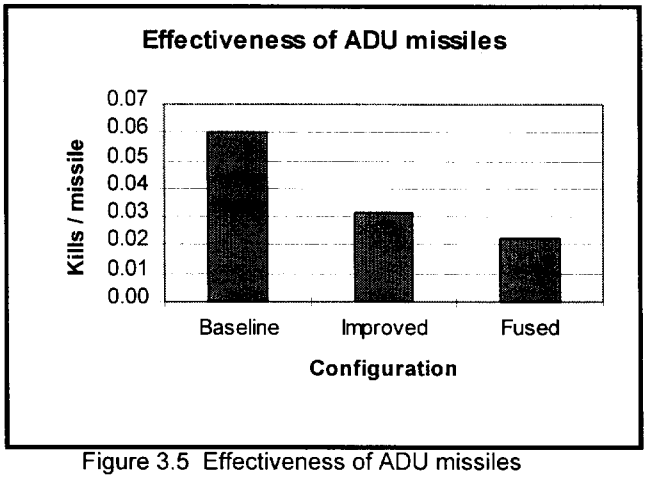

Figure 3.5 Effectiveness of ADU missiles

3.1.2 *Increase in kills by Red helicopters*

The increase in the number of kills by Red helicopters was demonstrated by a fourfold increase in the probability that a missile fired at the Blue helicopter by the enemy helicopters would successfully destroy it. This is shown in figure 3.6.

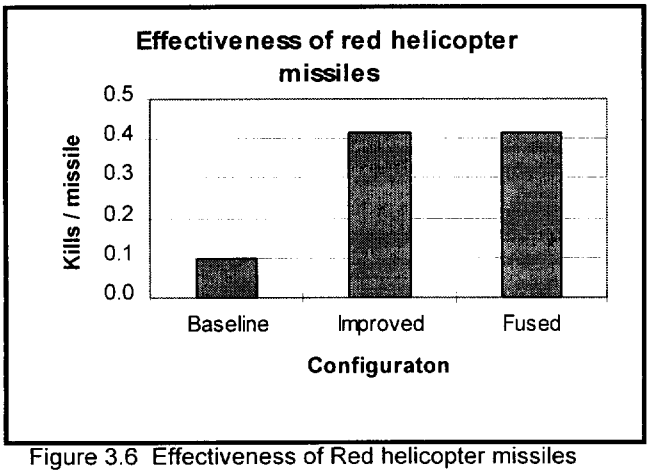

Figure 3.6 Effectiveness of Red helicopter missiles

Observation of the crews and subsequent analysis of the video tapes recorded during the trial showed that this was due to a combination of factors:

- Commanders tended to focus their attention on the map display, which did not show the position of fast moving enemy helicopters with great accuracy. Commanders focused on the ground threats at the expense of searching for air threats;
- Commanders tended to rely on the intervisibility calculations to determine when it was worth scanning for ground vehicles with the FCR. Less frequent use of the FCR with the improved and fused configurations reduced long range warning of an enemy helicopter approach;
- Commanders selected their observation points using the virtual helicopter and virtual enemy position functions. Crews were then confident that they had selected a suitable and covert position from which to observe enemy ground vehicles. With increased confidence in the safety of the observation point, they appeared to be less vigilant in detecting air threats, despite the availability of DAS warnings.

3.2 Destruction of enemy vehicles

Despite the increase in covertness, no significant change was observed in the total number of enemy vehicles killed. This indicated that improvements in survivability were achieved without impacting operational effectiveness. Moreover, the proportion of ADUs (priority targets) destroyed rose sharply with increasing integration, as did the ability of Blue helicopters to fire first.

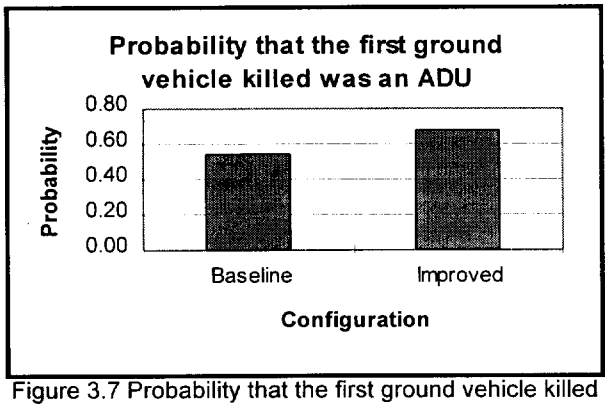

Figure 3.7 Probability that the first ground vehicle killed was an ADU

There were two primary reasons for the lack of variation in the total number of vehicles destroyed.

- Once the Blue helicopter reached the point of firing, the FCR was used to prioritise the targets. The number of vehicles destroyed was largely determined by the performance of the FCR and the missiles rather than by use of the TSD.
- The Blue helicopters did not have significantly longer to destroy the enemy vehicles as the survival probability and average mission duration were only slightly increased in the improved and fused configurations.

3.3 Other factors

The length of time after take off before crew fired their first shot was significantly increased for the fused configuration over the baseline and improved configurations. This appeared to be due to an increase in planning time in the field as tactical information was updated by more accurate information from on-board sensors.

However, the time required for mission planning prior to the mission increased for both the improved and fused configurations.

Commanders experienced considerable frustration when false alarms and errors appeared in the improved and fused displays. It appeared that their expectations of the accuracy of the system were too high. A guide to the likely magnitude of the error in position would have been useful.

Pilots did not feel able to contribute fully to the mission. Effective teamworking within the cockpit was hampered due to the disparity in the information displayed to the two crew members.

4. CONCLUSIONS

4.1 The following conclusions were drawn:

- Increasing the level of fusion of on-board sensor data and imported tactical information to provide a simpler tactical situation display improved crew planning and survivability;
- Comprehensive training in the operational use of advanced fused tactical situation displays will be essential if their full benefit is to be realised;
- Similar information, tailored to roles, should be provided to both crew members so that Pilot and Commander can communicate effectively and take on an appropriate share of the workload;
- On-board planning tools and additional display functionality, particularly intervisibility options, can augment the benefits of the fused display.

5. NOMENCLATURE

AAC	UK Army Air Corps
ADU	Air Defence Unit
CGF	Computer Generated Forces
DAS	Defensive Aids Suite
FCR	Fire control radar
ISD	In-Service Date
TADS	Target Acquisition Designation System

TSD Tactical Situation Display

WAH-64 Westlands Apache Attack Helicopter

6. ACKNOWLEDGEMENTS

The authors would like to express their thanks all those who participated in Trial CONTACTS3, and to the Customer for this work, DDOR4(Air).

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THE MULTI-SENSOR INTEGRATION SYSTEM FOR NATO E-3A MID-TERM MODERNISATION

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ABSTRACT

In the NATO E-3A Mid-Term Modernisation Programme, the Airborne Systems Division (ASD) of Daimler-Benz Aerospace was selected in a competitive process to contribute three work packages. These packages comprise the Multi-Sensor Integration, Tracking and Identification Software as well as the AWACS Mission Computer and the Multi-Sensor Integration Computer Hardware. When the selection process for the individual work packages was completed, the Statement of Work (SOW) for DASA ASD was extended in order to deliver a single integrated subsystem comprising both, hardware and software.

The requirements in the NATO E-3A Mid-Term Modernisation Programme call for real-time integration of all available information pertaining to one real world object, in particular geometric, kinematics and signature data. The new system shall improve tracking quality and additionally give automatic identification/classification of targets in order to significantly reduce operator workload.

The Multi-Sensor Integration function as it will be realized for AWACS will use data of the primary surveillance radar, secondary surveillance radar (IFF), data of passive electronic support measures and crosstold data of several links including Link-16. All these data are input to a data fusion process in order to generate a clear and true picture of the real-world situation.

This paper will present an overview of the technical concepts and the selected solutions for the multi-sensor integration task. It will show how the multi-sensor integration is performed and what the critical issues are in the course of data fusion. Furthermore it will briefly outline the test concepts which will be used for the final acceptance of the system.

LIST OF ABBREVIATIONS

AMC	AWACS Mission Computer
AMCP	AWACS Mission Computer Program
ASD	Airborne Systems Division (a division of Daimler-Benz Aerospace)
CORBA	Common Object Request Broker Architecture
COTS	Commercial-of-the-shelf
CSCI	Computer Software Configuration Item
DASA	Daimler-Benz Aerospace
DSI	Distributed Software Infrastructure
EMD	Engineering and Manufacturing Development
ESC	Electronic Systems Center
ESM	Electronic Support Measures
GPS	Global Positioning System
IDBO	Identification by Origin
IPT	Integrated Product Team
LAN	Local Area Network
MSI	Multi-Sensor Integration
MSIC	Multi-Sensor Integration Computer
MSICP	Multi-Sensor Integration Computer Program
NIC	Network Interface Card
RMA	Removable Memory Assembly
SCSI	Small Computer System Interface
STRP	Supplier Technical Requirements Package
TADS	Test and Development Software

Paper presented at the RTO SCI Symposium on "Sensor Data Fusion and Integration of the Human Element", held in Ottawa, Canada, 14-17 September 1998, and published in RTO MP-12.

1 HISTORICAL BACKGROUND

The definition of the NATO E-3A Mid-Term Modernisation Programme began in the first years of the nineties when the military community was confronted with a radically changed political situation. This new situation resulted in changed tasks for all forces of the NATO countries. Especially, the former relatively stable situation with well known border lines between the eastern and western block was not in place any more. Consequently, the surveillance task has become much more demanding and challenging. Airborne surveillance systems now have to cope with a much higher number of inputs stemming from ground, maritime or airborne targets which are moving in the area of many different smaller countries. This situation imposes special high challenges to the identification task because during peace keeping missions for example the situation may vary often and quickly.

Therefore, the planning for the Mid-Term Programme asks for much higher flexibility and adaptability to the actual situation in comparison to today's systems. In parallel, the operator workload shall be reduced from today's levels, even in much denser and much more complex scenarios.

2 PROGRAMME OVERVIEW AND USER EXPECTATIONS

The Mid-Term Modernisation Programme will enhance the capabilities of NATO E-3A aircraft in a number of major system-related areas. New equipment will be installed for:

- Digital communication including satellite communication systems with automatic record and replay of all data
- Broad spectrum VHF radios
- GPS-based navigation to provide accurate passive own-ship positioning
- Enhanced identification capabilities to cope with new international air traffic regulations
- Real-time integration of all available sensor data to provide timely and accurate situation displays
- Operator workstations containing state-of-the-art flat panel situation displays
- New computers based on COTS products employing an open systems architecture, also to provide a basis for future systems upgrades.

These enhancements will significantly contribute to enable AWACS handling the complex scenarios in the future and to further reduce operator workload.

The users demand a system which can be adapted to specific requirements driven by actual tasks and scenarios. This requirement lead to the concept of a generic software package which can be „programmed" by a set of mission preparation data to be loaded into the system prior to operation. Also, the system can handle several identification schemes in parallel.

3 THE MULTIS-SENSOR INTEGRATION SYSTEM

3.1 MSI System Overview

At the end, the ultimate goal of all multi-sensor integration measures is to generate a precise picture of the according real world scenario. The system has to merge all available inputs that pertain to one target to only one object in the picture on the display. This picture must contain only real and no false targets, all correctly identified at the correct locations. This goal can only be achieved by a careful harmonization of the sensor integration software with the high performance of the contributing sensors. The term Multi-Sensor Integration comprises essentially two distinct functions, which are Multi-Sensor Tracking including the correlation function and the Multi-Sensor Identification.

The CSCI MSICP will provide multi sensor tracking and identification functionality within the NATO Mid-Term Modernisation Programme of the NATO E-3A aircraft. The MSICP will consist of the following parts:

- MSI Tracking
- MSI Identification
- MSI Manager

The MSI Tracking and Identification functions provide the basic operational functionality of the MSICP. The MSI Manager includes functionality mainly in the area of control and monitoring, communication, redundancy support and test and maintenance provisions for the MSICP.

The MSICP software will be coded in ADA95 and C/C++. It will be implemented according to POSIX standards and executable on a SUN/SPARC compatible computer running a Solaris 2.x operating system.

The improved MSI function will be hosted on a redundant state-of-the-art hardware computer architecture, the MSIC. It will be integrated into the overall system by a direct interface to the AMCP, which is not part of the work share of DASA Airborne Systems. This AMCP will again be hosted on a redundant computer system of a similar architecture, the AMC.

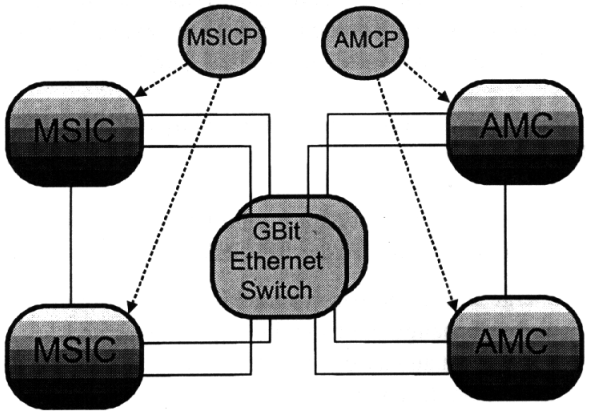

Figure 2-1

3.2 The Computer System

In the initial STRP a proposal for the MSI computer and an adjunct computer to the existing CC-2A computer was requested. During the following concept refinement, it was decided to remove the current CC-2A computer completely and replace it by an all new AWACS mission computer in order to unify systems architecture and to minimize life-cycle cost.

Both, the AWACS Mission Computer and the Multi-Sensor Integration Computer are fully redundant computer systems with cross monitoring between the active and passive computer. In case of a failure in the active computer, the passive computer will be able to take over immediately, because of permanent input of sensor data and checkpointing of results into the passive computer. This approach gives extremely high system availability, i.e. under normal operational conditions the air/surface/ground picture never will be lost.

The AMC and MSIC are computers based on COTS elements. The new computer systems use Ultra-Sparc 2 processor chips from SUN computers of the latest generation and they are build as industry standard VME-Bus cards and are software compatible with commercial SUN workstations. The industry standard VME-Bus architecture allows quick and cost effective integration of external interfaces such as Mil-Bus I/F and special build interfaces. All computers contain a system surveillance board with temperature sensors and voltage monitoring.

For the purpose of data exchange, the computers will be linked via a Gigabit Ethernet designed to be fully redundant. Again standard COTS communication protocols will be used for all communication via this network.

The AMC is a single processor computer equipped with 256 Mbytes of Memory. The AMC computers have access via two SCSI busses to the RMA hard disks and CD-ROM changers. In case of failure, the active computer is disconnected from the SCSI busses and the passive one takes over the disks (see figure 3.2-1 AMC). The MSIC is a dual processor computer with again 256 Mbytes of memory. It has no access to external devices (see figure 3.2-2 MSIC).

Both computer systems (AMC and MSIC) have access to a private local area network (LAN) to perform communications related to health monitoring. This LAN is used exclusively for that purpose.

All computer hardware is housed in industry standard 19-inch racks. Each computer is housed in its own rack; all hard disks and CD-ROM changers are housed in one rack. Hence, the total number is five racks.

The application software development takes place on regular workstations with the standard UNIX based operating system Solaris and a state-of-the-art software engineering environment.

The CSCI AMC/MSIC System Software delivered by ASD will provide all operating system functionality needed to operate the AMC and MSIC on a Sun/Solaris 2.x operating system basis. This CSCI will consist of COTS software products configured for use within the DASA delivered computer hardware components.

On top of this operating system level software a Lockheed-Martin provided Distributed Software Infrastructure (DSI) middleware will be responsible for communication issues within this system. The DSI will be CORBA 2.0 compliant.

3.3 The Multi-Sensor Tracking System

The Multi-Sensor Tracking is capable to use sensor inputs from a wide variety of different sensors which are the primary AWACS radar, the SSR/IFF sensor, the ESM system and crosstold sensor inputs via the various tactical data links. It is based upon Multi-Model technology which guarantees in the various maneuver conditions optimal track stability and continuity. New tracks will be initiated automatically either based on data inputs from active radars or from passive sensors only. The tracking process is capable to perform self-triangulation based on passive strobes from onboard sensors. Additionally, ESM reports from tactical data links are used together with reports from onboard sensors to perform multi-sensor cooperative passive tracking. Deghosting is done automatically.

The functions of the Tracking system are grouped in the following categories (see Figure 3.3-1):

- Data preprocessing
- Correlation/Association
- Track Update
- Track List Management

- Post processing

The preprocessing comprises functions like ordering of measurement data in a timeline related sequence, performing coordinate system transformation, etc.. In this processing bias compensation is performed for all input sensors.

In the correlation function, either the classical nearest neighbor algorithm or the advanced Multi-hypothesis concepts are applied. Which concept will be applied is dependent on the actual complexity of the scenario in the vicinity of the current measurement/track position. Adaptive selection of the most suitable correlation algorithm will significantly reduce processor load. In doing so, maximum track continuity will be provided under all target conditions, and hence, track identification will be preserved through complicated target track crossing situations. Furthermore, ESM-based signature data and cross correlation between ESM- and kinematic data will also be used for the final report/track pairing. The operator can at any time either prohibit a selected correlation or enforce a correlation.

The track update function is executed for each track which has been associated to a target report. Depending on the type of the target report either a kinematic and/or a attribute update is performed for every model which is currently applicable to the track. Kinematic updating is done by means of a Kalman component filter, whose peculiar feature is that updating of the state vector is performed for each measurement component separately. A major advantage of this Kalman component filter is that even under jammed or distorted conditions all available useful measurement information will be utilized. Attribute updating is performed by keeping record of attribute data of target reports incorporated into the track (see Figure 3.3-2).

The Track List Management contains functions like track initiation, track deletion, track prediction and bias error estimation. Track initiation is performed on target reports for which no correlation was found. They will be initiated as tracks and labeled as potential track. Initiation of tracks will not only be performed on sensor data from active sensors but also on data from passive sensors. Track deletion will be applied to tracks, whose quality figure recedes below a certain threshold. These deletion thresholds automatically adapt to environment parameters and to the different track states. Track prediction is performed for the time when the next sensor update is expected. The predicted position is input to the correlation function the next time. The bias error estimation function analyzes measurement residuals of each sensor with respect to the system track. In order to maximize overall track quality and accuracy, possible offsets between all sensors (onboard and offboard) are monitored and estimated continuously in background. If necessary, observed offsets are compensated automatically by an adaptive logic.

In the post processing, coordinate system transformations are performed to adapt the tracker to the external system. Finally, data is converted to external data formats.

In summary, the functions performed by the MSI-Tracking are:

- processing of input data from different types of sensors - Primary Radar, IFF, ESM, Links
- merge active and passive tracking (both cooperative and self triangulation) including sophisticated correlation and association logic. This makes use of geometric data and attributes. The correlation and association logic uses rules about identity indications from ID sources
- update each measurement component (Range, AZ, EL, Range Rate) separately, using a special form of Kalman Filter algorithm
- automatically associate of signature and attribute parameters (IFF, ESM, ECM, Link data) to tracks
- update attributes (IFF codes, ESM attributes, ECM attributes)
- compensate ownship motion
- automatic track initiation and track drop
- automatic maneuver detection
- measurement dropout coasting
- automatic detection & compensation of bias (registration) errors
- processing of operator initiated track commands
- determination of target environment (air, ground, surface) based on kinematics data

Upon reception of system control commands issued automatically by the MSI monitoring & control as part of MSI management SW, the tracking adapts its functions automatically to graceful degradation measures in order to prevent uncontrolled program behavior in case of special conditions (e.g. overload). Additionally, the MSI-Tracking function monitors sensor input data for plausibility in order to generate inputs for error logging.

3.4 The Multi-Sensor Identification System

The MSI Identification function is capable to identify air, surface, and ground tracks. It will operate fully automatic and uses all available data of the available sensors as well as derived information and background information dependent on the confidence which can be given to the information sources. The system can handle different identification schemes in parallel. The identification schema is loaded as data during system initialization.

High flexibility in the ID process is achieved by providing the operator with several means to adapt the identification

function to mission specific needs. Some of these means are:

- modification of the set of information to be used for identification,
- modification of mission data
- overriding of identification results.

These functions of the multi-sensor identification are based upon artificial intelligence concepts, which use a rule based artificial intelligence system. This rule-based system was developed by DASA ASD with the focus to be used in operational systems and give responses with minimum delay.

The MSI Identification function does provide the capability to assign track identities based on integrated sensor, communications and operator provided data. ID related information as for example conformance of tracks to flight plans, or platform identification by origin (IDBO), which on its own may not provide conclusive ID are combined in order to extract maximal benefit from the available sources of data. Conflict resolution is performed in case of contradictory data. Therefore, the MSI-Identification function will make maximum use of the available information to provide its results.

The MSI Identification function uses the information from different sources to determine the identity of MSI tracks. These sources are:

- 2D-position, altitude, speed and heading, their error values, environment category (air, surface, ground) and time of track update of the targets from MSI Track File
- ID related data from local AWACS-sensors which are attributes of MSI Tracks
- ID related data from data links
- Mission data

All available information for the MSI Identification process is used in a most effective way to derive a unique target identification and classification for the environment categories air, surface, and ground. The identification is done automatically or by operator input. The manual ID assignment has priority over automatically determined ID. In case of manual ID assignment automatic ID determination will continue and MSI ID will report detected differences between automatic identification based on available information and the manually assigned ID.

The automatic identification process will evaluate all available identification information for every MSI track using „identification indicators". These identification indicators will be combined into a track identity by an artificial intelligence (AI) supported combination process. Conflicts in the available identification information will be detected. The automatic system will provide conflict resolution functionality. In cases where conflict resolution is not possible operator alerts will be generated automatically. Possible ID conflicts with ID data from the data links are indicated to the operator. In case of detected severe ID-changes (e.g. from FRIEND to HOSTILE or vice versa) a manual ID assignment will be requested.

The MSI Identification function will provide rationale for its results to the operator. The complete MSI Identification process will be controlled in a flexible way by operator changeable "Adaptation Data".

The incoming (live) sensor and communication data may be mixed with simulated data in order to train operators during real mission flights.

Upon reception of system control commands the MSI Identification adapts its functionality automatically to graceful degradation measures to prevent uncontrolled program behavior in case of special conditions (e.g. overload).

3.5 MSI Manager

The MSI Manager function will integrate the MSI Tracking and Identification functions. It will provide all necessary communication mechanisms for MSI Tracking and MSI Identification based on the DSI middleware.

The MSICP application software will implement the tracking and identification functions as required by the MSICP STRP. It will make use of the DSI and AMC/MSIC System Software layers and provide CORBA 2.0 compliant interfaces for external communication and communication between major internal software components.

An overall MSICP system control will be provided by the MSI Manager including system startup and shutdown mechanisms as well as the overall control of operational modes of the MSICP. The MSI Manager will also provide an overall system monitoring function. This function will provide all required MSICP system status data in regular manner to the MSICP external interfaces.

The MSICP will be responsible for redundancy support of MSI Tracking and MSI Identification using the Boeing provided checkpointing service.

The MSI Manager will be responsible for the overall computer load management within the MSICP. It will measure computer load, detect overload situations and activate the load adaptation functionality of the MSI Tracking and Identification function to prevent unpredictable behavior.

Within the MSI Manager and within MSI Tracking and Identification provisions for test functionality will be included, which can be activated by the MSI Software

Test Bed. These provisions will be used during system testing and integration and may be used for maintenance activities in the software life cycle. These provisions will support:

- recording of external and internal MSICP interfaces
- logging of MSICP internal data for test and maintenance purposes.

The MSI Software Test Bed will include the functionality to make use of these provisions including the external interfaces.

4 SYSTEM TEST

During Test and Development the MSI Software Test Bed provided by DASA Airborne Systems will include all functionality needed to operate the MSICP in a test environment, without having the Boeing provided AMCP available. It will additionally provide simulations of AMCP functionality as needed to run the MSICP in a test bed. The MSI Software Test Bed will simulate interfaces to the MSICP compatible to the AMCP real time interfaces. Parts of this MSI Software testbed may also be used for maintenance purposes during the operational usage of the MSICP. Functionality and performance of the MSICP will be verified by a two stage approach. First, testing is performed via computer models. The Test and Development Support software contains a variety of representative scenarios and generates the inputs of all relevant sources. It also considers the sensor behavior that affects detection performance and accuracy of the measurements. The Test and Development Support Software (TADS) will include all features needed to generate the necessary data, and do the analysis of results. Second, the MSICP is tested by using recorded life data. The evaluation of the results is also performed by the TADS.

In the final qualification test run, the configuration data of the multi-sensor tracking and identification function will be optimized during real flight tests. This will finally verify the functions and the performance of the MSICP.

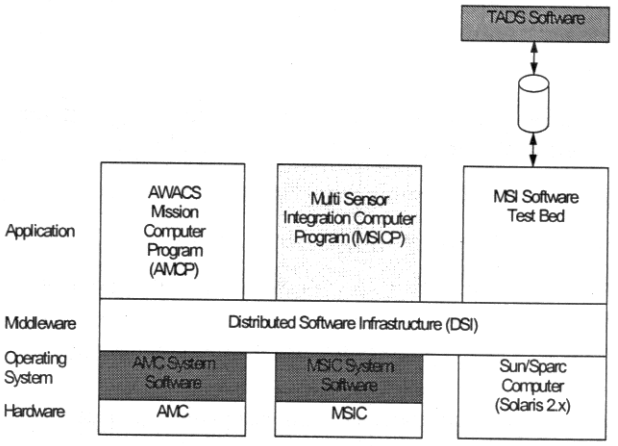

Figure 2-2 Software Layers (Test Configuration)

5 PROGRAMME STATUS

After subcontractor selection in October 97 a transition phase was initiated. This phase prior to start of Engineering and Manufacturing Development (EMD) was used for requirements clarification, to further reduce program risk and improve program affordability. To that end, representatives of NAPMA, the user community, MITRE, US Air Force/Electronic Systems Center (ESC), Boeing and ASD worked together in Integrated Product Teams (IPT).

Engineering and Manufacturing Development started in November 97 with contract award.

The first version of the MSICP will be supplied to Boeing in November 98 in order to support integration testing. Further software versions with added capabilities will be supplied in a time frame of roughly 6 months until the final version is due in May 2000.

6 SUMMARY

In this paper, a brief overview of the NATO AWACS Multi-Sensor Integration System was given. It explains the requirements for the new system and its performance drivers as well as the concepts which were applied in the system design in order to match the requirements. Especially in the identification function a new dimension of flexibility is implemented to enable operators to cope with the changing real world situation.

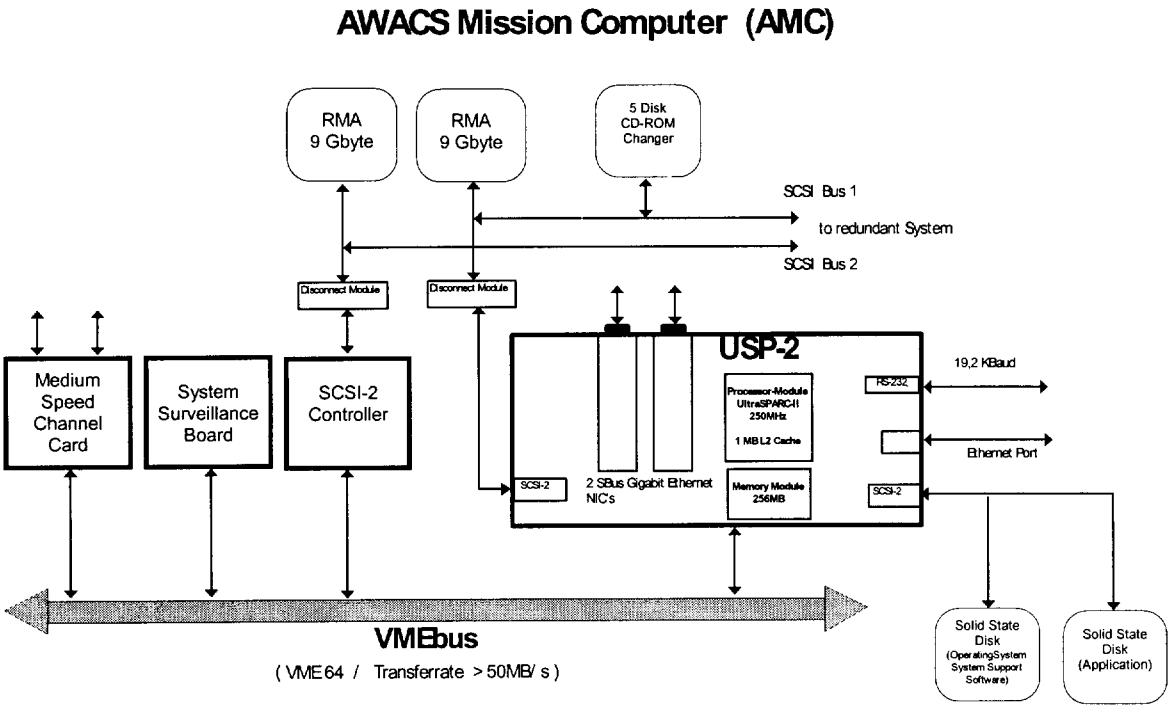

Figure 3.2-1 AMC

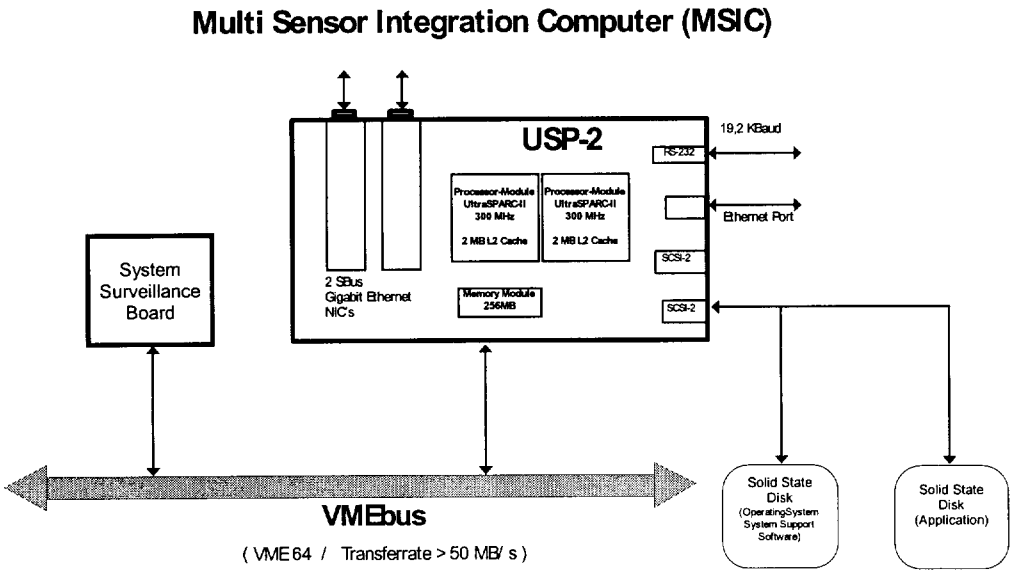

Figure 3.2-2 MSIC

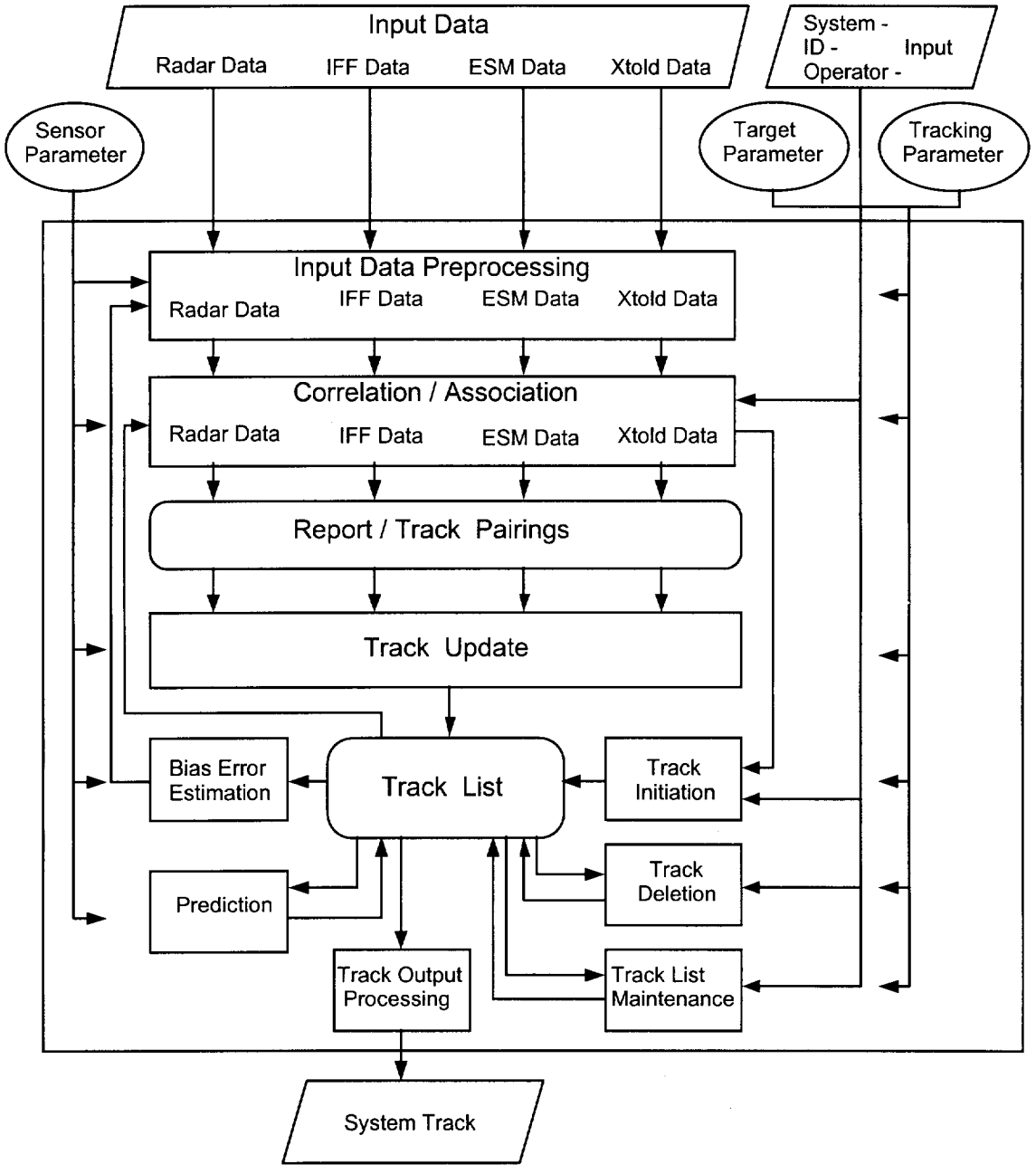

Figure 3.3-1 MSI Tracker

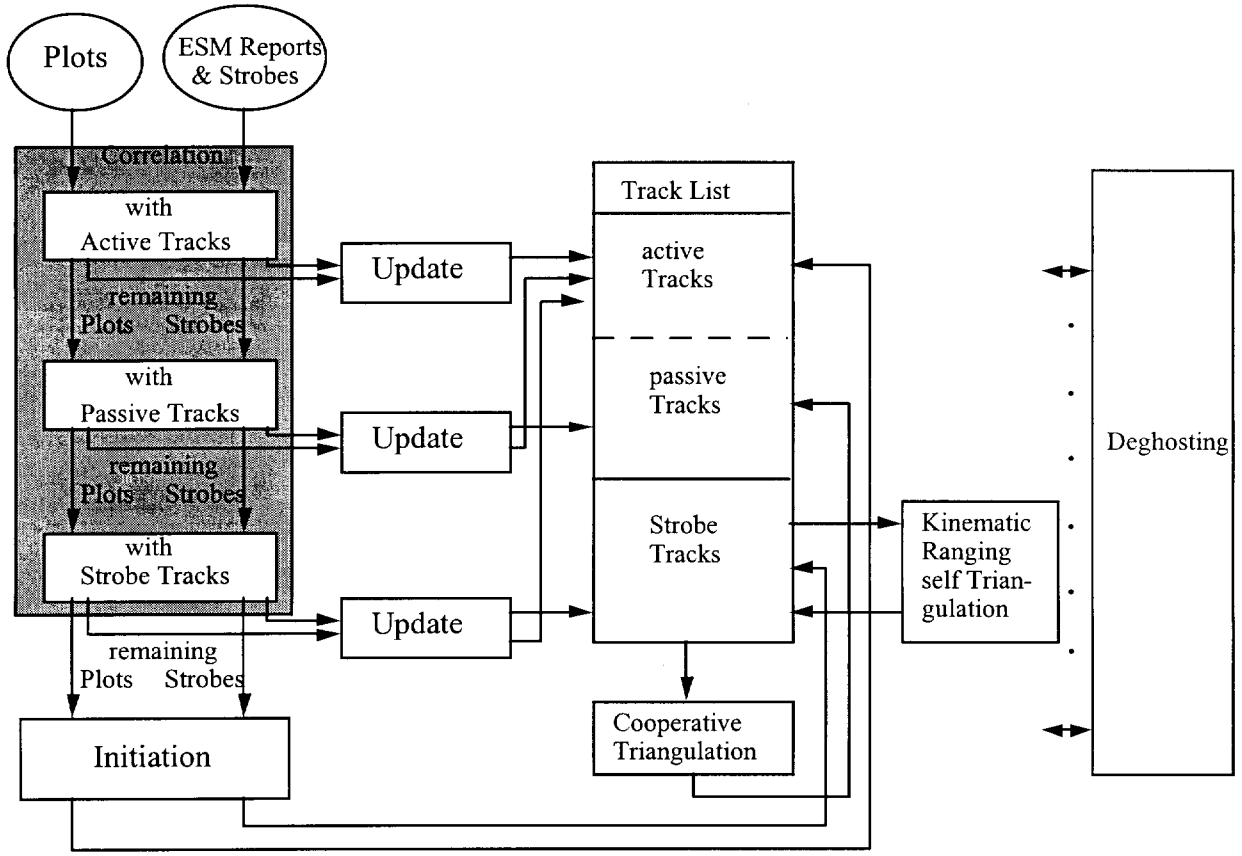

Figure 3.3-2 Active / Passive Correlation and Initiation

ENVIRONMENT PERCEPTION PROCESS IN MARITIME COMMAND AND CONTROL

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1. SUMMARY

Various operational trends in naval warfare, such as technological advances in threat technology and an ongoing shift to littoral warfare, put the shipboard decision making process under pressure. Data must be processed under time-critical conditions and, as a consequence, the risk of saturation in building the tactical picture and of making the wrong decision increases. One must also realise that the human plays an essential role in the naval command and control cycle. *Situation awareness* is essential for commanders and their staff to conduct decision-making activities. *Data Fusion* is seen as an essential process to enable operators to achieve situation awareness. This paper discusses the *environment perception process* (EPP) as an important aspect of the problem of *dynamic decision making* in the context of naval command and control. The EPP is aimed at achieving the first level of situation awareness that forms the basis for the subsequent more abstract levels. The quality of the results of the EPP is of utmost importance for the situational awareness that can be achieved at the higher levels. This paper is a step towards the definition of an integrated architecture for data fusion giving emphasis to situation awareness in the context of dynamic human decision making. Such an integrated architecture facilitates the proper conceptualisation and design of decision support systems taking into account the human role in the command and control cycle.

2. INTRODUCTION

At the heart of a shipboard combat system is a command and control system (CCS)[1] by which the commanding officer can plan, direct, control and monitor any operation for which he is responsible, to defend the ship and fulfil his mission. The increasing tempo and diversity of open-ocean and littoral scenarios, the technological advances in threat technology and the volume and imperfect nature of the data to be processed under time-critical conditions pose significant challenges for future shipboard CCS.

This emphasises the need for warships to be fitted with an efficient combat system featuring a real-time, joint human-machine decision support system (DSS) integrated into the ship's CCS. This DSS consists in the combination of a multi-source data fusion (MSDF) capability, a situation and threat assessment (STA) capability, and a resource management (RM) capability (including the management of weapons, sensors, navigation and communication). These capabilities intimately match the four levels of the JDL (Joint Directors of Laboratories) data fusion model. The main role of such a real-time DSS is to aid the ship's operators to achieve the appropriate *situation awareness (SA)* state for their tactical decision-making activities, and to support the execution of the resulting actions.

The Decision Support Technologies Section at the Defence Research Establishment Valcartier (DREV, Canada) and the Maritime Command and Control group of the Physics and Electronics Laboratory of the Netherlands Organisation of Applied Scientific Research (TNO-FEL, The Netherlands) are both conducting research and development (R&D) activities in the field of decision support for Maritime Command and Control at the shipboard level. Investigations have been undertaken to study the concepts and design of a real-time DSS for their respective frigates in order to improve their performance against current and future threats.

This paper presents a brief overview of one particular collaborative effort focusing at deriving a functional decomposition of the data fusion process giving emphasis to situation awareness concepts [Ref. 1]. This is important for the integration of the human element into the design of an efficient decision support system aiding the operators to achieve the appropriate *situation awareness (SA)*. SA is essential for commanders and their staff to conduct decision-making activities. *Data Fusion* (DF) is seen as an essential process to enable operators to achieve situation awareness.

[1] Also known as the Combat Direction System (CDS)

Paper presented at the RTO SCI Symposium on "Sensor Data Fusion and Integration of the Human Element", held in Ottawa, Canada, 14-17 September 1998, and published in RTO MP-12.

The paper is thus a step towards the definition of an integrated data fusion architecture adapted to human's needs for situation awareness and dynamic decision making in maritime command and control. The *environment perception process (EPP)* is part of this architecture and is aimed at achieving the first level of situation awareness. This first level forms the basis for the other, more abstract levels. Thus, the quality of the results of this level is of utmost importance for the situational awareness that can be achieved at the higher levels. The EPP is analysed in this paper, and the inputs/outputs of its sub-processes are identified. With a better knowledge of the environment perception process, one can proceed with the study of the processes required to achieve the higher levels of SA.

This paper is organised as follows. Section 3 provides background information on the command and control (C2) process and the role of a decision support system in this process. Data fusion and the role of situation awareness in dynamic human decision-making are also presented in this section. Making a link between multiple models, section 4 then discusses data fusion from a situation awareness perspective. A functional decomposition of the environment perception process is presented and described in section 5. Section 6 briefly discusses potential pitfalls in designing an integrated architecture for data fusion. Section 7 provides conclusions and recommendations, and discusses future work.

3. BACKGROUND

3.1 Command and Control Process

Command and control (C2) is the process by which commanders can plan, direct, control and monitor any operation for which they are responsible [Ref. 2]. In a naval context, most tactical decisions taken within the ship's operations room are made after completing a number of perceptual procedural and cognitive activities linked to the C2 process. The C2 process is indeed a suite of periodic activities which mainly involves the perception of the domain (environment), an assessment of the tactical situation, decision making about a course of action and the implementation of the chosen plan

The C2 activities are performed by either humans, machines (i.e., hardware and software computer systems), or a combination of both. Characteristics of this suite of activities are described in Ref. 3 and were captured through the Boyd's Observe-Orient-Decide-Act (OODA) loop illustrated in Figure 1. Although this loop might give the impression that C2 processes are executed in a sequential way, in reality, the processes are concurrent and hierarchically structured.

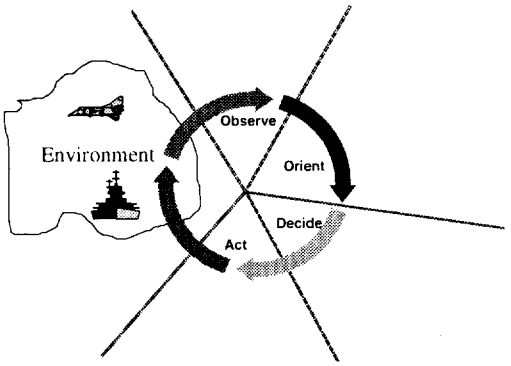

Figure 1 - Boyd's OODA loop.

The military community typically states that the dominant requirement to counter the threat and ensure the survivability of the ship is the ability to perform the C2 activities (i.e., the OODA loop) quicker and better than the adversary. Therefore, the speed of execution of the OODA loop and the degree of efficiency of its execution are the keys of success for shipboard tactical operations. Decision support systems can contribute significantly to the execution of this loop.

3.2 Decision Support System

The complexity of the shipboard environment in which operators conduct C2 activities emphasises the need for warships to be fitted with a real-time decision support system (DSS). The main role of this DSS is to aid the operators in achieving the appropriate situation awareness in order to support them in their tactical decision making and action execution activities.

Operators need to be aided by a DSS that continuously fuses data from the ship's sensors and other sources (MSDF capability), helps the operators maintain a picture of the tactical situation (STA capability), and supports their response to actual or anticipated threats (RM capability).

Figure 2 presents the mapping of the MSDF/STA/RM system onto the OODA loop. The data fusion process, described in the next section, is seen as an important element of a DSS to provide the appropriate situation awareness to operators in support of their C2 activities.

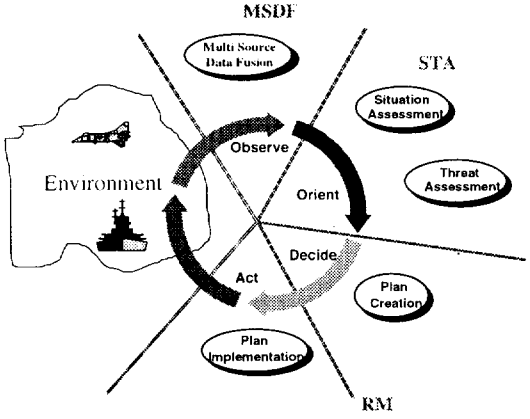

Figure 2 – Mapping of the MSDF/STA/RM system onto the OODA loop.

3.3 Data Fusion

According to the JDL model (see Refs. 4-15), DF is fundamentally a process designed to manage, organise, combine and interpret data and information obtained from a variety of sources, that may be required at any time by operators and commanders for decision making. It's an adaptive information process that continuously transforms the available data and information into richer information. Refined (and potentially optimal) kinematics and identity estimates of individual objects, and complete and timely assessments of current and potential future situations and threats (i.e., contextual reasoning) are achieved through continuous refinement of hypotheses or inferences about real-world events. The DF process is also characterised by the evaluation of the need for additional data and information sources, or the modification of the process itself, to achieve improved results.

Given these considerations, a complete DF system can typically be decomposed into five levels:

- Level 0 – Signal Data Refinement (source pre-processing);
- Level 1 – Object Refinement (Multi-Source Data Fusion (MSDF));
- Level 2 - Situation Assessment (SA);
- Level 3 - Threat Assessment (TA); and,
- Level 4 - Process Refinement through Resource Management (RM).

Each succeeding level of DF processing deals with a higher level of abstraction. Level 1 DF uses mostly numerical, statistical analysis methods, while levels 2, 3, and 4 of DF use mostly symbolic or Artificial Intelligence (AI) methods. Note that resource management in the context of level 4 fusion is mainly concerned with the refinement of the information gathering process (e.g., sensor management). However, the overall domain of resource management also encompasses the management of weapon systems and other resources (including the management of navigation and communication systems).

The JDL model provides a good description of the data fusion process. This process is an important element within the C2 cycle. One must also realise that the human plays an essential role in the C2 cycle. He is the one responsible for taking decisions [Refs. 16-17]. Because of the importance of humans, one needs a mechanism to reason about their role in the C2 cycle in order to facilitate the proper conceptualisation and design of DSS. Endsley [Ref. 18] showed that situation awareness is an essential precondition in this decision making process.

3.4 Situation Awareness

Endsley has derived a theoretical model of situation awareness based on its role in dynamic human decision making. Endsley [Ref. 18] defines situation awareness as the perception of the elements in the environment within a volume of time and space, the comprehension of their meaning, and the projection of their status in the near future. Figure 3 depicts the three levels of situation awareness as identified by Endsley.

SA can be interpreted as the operator's mental model of all pertinent aspects of the environment (process, state, and relationships). This mental model of the environment is also known in Rasmussen's work as the hierarchical knowledge representation (HKR) in decision-making [Refs. 19-21]. Although this paper focus at the process building this HKR, R&D works is ongoing to define in details this HKR in the context of naval C2.

Finally, bearing in mind the scope of this paper, one should note that SA could be achieved without the transformation and the fusion of data. For instance, training techniques typically enhance the operator's performance, resulting in a better SA. Similarly, advanced techniques in human computer interaction (HCI) allow a representation of the information in a meaningful way for the human.

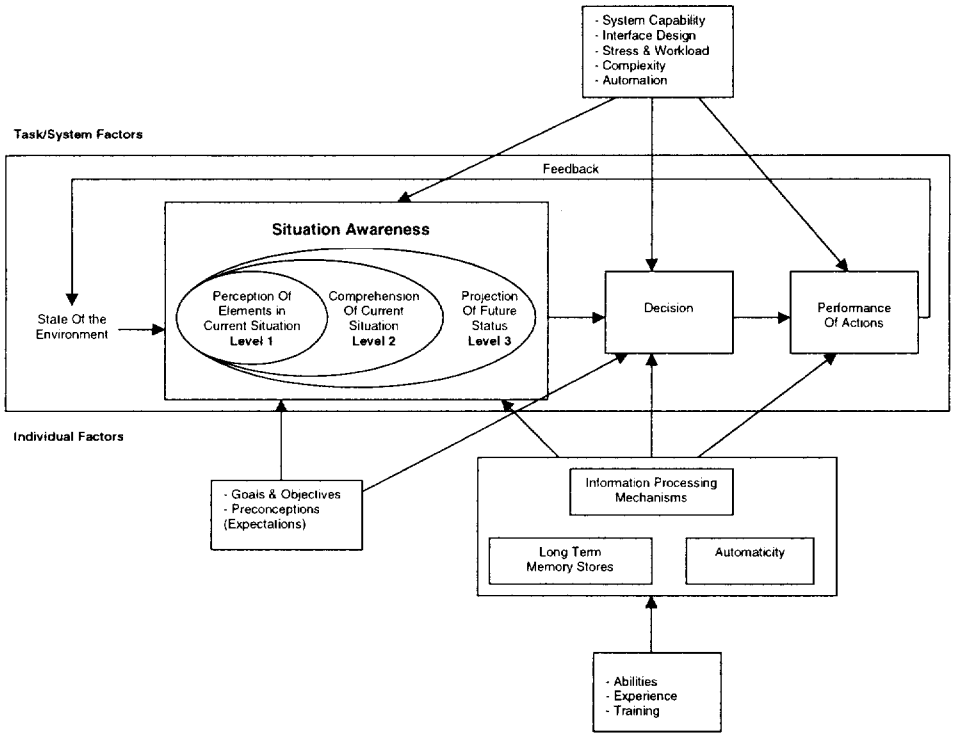

Figure 3 – SA model in dynamic human decision making

4. SA PERSPECTIVE FOR DATA FUSION

If one compares the OODA loop with the SA model of Endsley, one sees a close resemblance. In both models one finds a *decision-making* part and an *action* part. In Endsley's model, SA is one of the main inputs for decision-making. In the OODA loop, the processes Observe and Orient provide inputs for the decision making process. One should recall, however, that situation awareness in Endsley's model is a *state of knowledge* and not a process. The processes Observe (MSDF)[2] and Orient (STA) of the OODA loop can thus be seen as processes acquiring, achieving, and maintaining situation awareness. In turn, this means that we can link the observation and orientation processes to the situation awareness model of Endsley.

The MSDF process (or level 0-1 fusion) can be viewed as the process providing the first level of SA. It is responsible for the *perception* of the status, attributes, and dynamics of relevant elements in the environment. If we look at our problem domain, maritime command and control, the basic element relevant for the command team is any object in the environment (e.g., air, surface or subsurface target).

The STA process is responsible in providing the next two levels of SA. The second step in achieving situation awareness is called *comprehension*. Endsley describes the comprehension process as follows: "Comprehension of the situation is based on a synthesis of disjointed level 1 elements". Level 2 of situation awareness goes beyond simply being aware of the elements that are present to include an understanding of the significance of those elements in light of pertinent operator goals. Based on knowledge of Level 1 elements, particularly when some elements are put together to form patterns with other elements, the decision-maker forms a holistic picture of the environment, comprehending the significance of objects and events.

The third and last step in achieving situation awareness is the *projection* of the future actions of the elements in the environment. This is achieved through knowledge of the status and dynamics of the perceived and comprehended situation elements.

In order to bootstrap the functional decomposition of an integrated data fusion architecture taking into account Endsley's SA theory, the processes leading to the first level of SA are analysed and discussed in the next section.

[2] Here level 0 is included in MSDF

5. ENVIRONMENT PERCEPTION PROCESS

As mentioned above, the perception process leading to the first level of SA corresponds to levels 0-1 of the data fusion model. An important characteristic of this data fusion model is that it is an adaptive and iterative multi-level process that continuously transforms the available data into richer information. One should also note that these levels of fusion are linked together and cannot be considered independently without missing functionalities and/or reducing the quality of their results. The functional decomposition of the perception process and the quality of its results (the estimated perception of the environment) are thus different whether the process is implemented as an opened or a closed loop.

The closed loop implementation inherently uses the notion of process refinement (explained later in this section). This means that the perception process will be refined and enhanced leveraging from the results of higher levels of data fusion. As a result, the perception process then benefits indirectly of contextual information. This is a major difference from the opened loop implementation where the results of the perception process are context-free.

In view of the discussion above, the environment perception process (EPP) is referred to as the process achieving the first level of situation awareness according to Endsley's theory, through a closed loop implementation.

The main requirement for a closed loop implementation and for the use of the process refinement notion is the integration of all levels of data fusion. Unfortunately, most of the R&D efforts in data fusion have been in the domain of opened loop levels 0-1 fusion. Accordingly, this domain is more mature and years of R&D have lead to the definition of a generic MSDF system [Ref. 11] shown in Fig. 4.

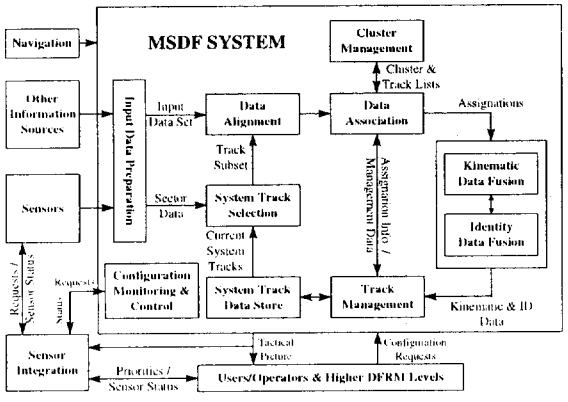

Figure 4 – Generic MSDF System

An MSDF system processes the information data reported by multiple dissimilar sources in order to correctly and quickly derive the best estimates of the current and future kinematics properties for each hypothesised (or perceived) entity in the operational environment, and to develop inferences as to the identity and key attributes of these entities.

The MSDF system attempts to acquire and maintain unambiguous, stable tracks corresponding to the perceived population of real objects within the operational volume of interest (i.e., establish a number of clean tracks that corresponds exactly to the number of objects in the physical environment).

The functional decomposition of the EPP is derived leveraging from this definition of a generic MSDF system that was itself derived without explicitly considering the results of higher levels of fusion processing. The following section describes the extended notion of process refinement including the use of the results from higher levels of processing.

5.1 Process Refinement in Data Fusion

One can distinguish three different types of process refinement in a multi-level data fusion process. First, providing information with less uncertainty at its input can refine a process. In this case, *refined inputs* leads to enhanced results of the process. This type of refinement can be achieved by enhancing the results of a prior stovepipe process, the results of a lower level process or, the environment sensing process.

Another way to refine a process, without changing the set of inputs, is to modify the algorithm used for the process by either tuning its parameters or selecting a totally different algorithm. This type of refinement is referred to as *process control.*

Additional or complementary processing based on the results of higher levels of fusion processing corresponds to the third type of process refinement. This type of refinement has not been considered in the previous derivation of the generic MSDF system.

5.2 Examples

By illustrating the refinement mechanisms shortly described in the previous subsection with two examples, we show that these mechanisms are beneficial.

The first example, illustrate in Figure 5, is about the provision of extra information regarding the possible existence of a target currently not detected. Suppose that a number of air targets have been observed, proceeding close to each other, with the same course and speed. If the inferred identity of the targets and the structure of the formation are combined with our knowledge of doctrines, we can infer that it is likely a formation of a specific type. According to our knowledge of doctrines however, a formation of the inferred type usually consists of four targets, while only three targets have been observed.

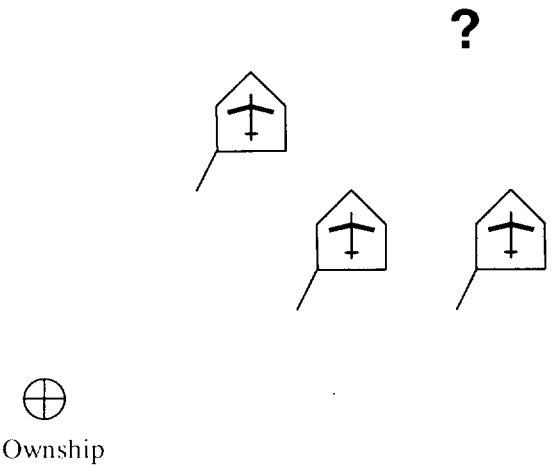

Figure 5 – Example 1: formation fighters

Knowing all this, the results of the EPP can be enhanced by providing the process with this extra information. For instance, creating a new track hypothesis could do this. In turn, the existence of this extra hypothesis may have impact on several sub-processes of the EPP (data association, cluster management, etc.). Furthermore, it may even have impact at the sensor level. A radar system might be cued, for example, to perform some extra volume search dwells to verify the new track hypothesis.

As a variant of this example, one could also imagine that the fourth target has already been detected, but not identified. In this case, the EPP could be provided with evidence for the type of the target.

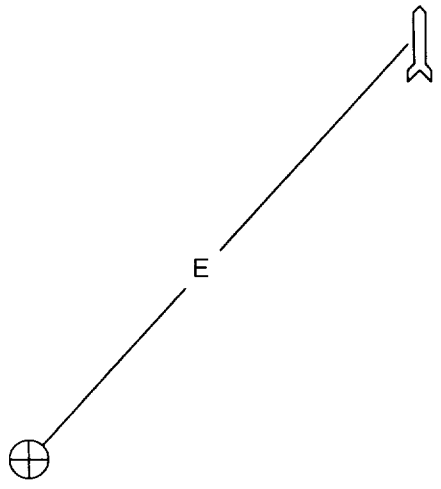

Figure 6 – Example 2: bearing-only track

The second example (Figure 6) is about a request for extra information about the kinematics of a track. Suppose there is a bearing-only track based on ESM measurements of the seeker-head of an incoming missile. For effective engagement of the missile with hard-kill and soft-kill measures, information about the distance of the target to our own ship is of relevance. Some distance information can often be derived from the mode of the seeker-head of the missile (searching, lock-on). However, more precise distance information can be of help.

In the situation described above, an information request can be issued. It is unlikely that this request will have an important impact on the EPP itself. If distance information would have already been available somehow, it should have been associated with the bearing track. It is more likely for such an information request to have an impact on sensors. Like for the previous example, a radar might be cued to perform a search dwell to find out whether a radar track can be initiated that can be associated with the existing bearing-only track.

5.3 Environment Perception Process Framework

Figure 7 is an attempt to illustrate the environment perception process. The EPP framework is composed of the levels 0-1 functional decomposition as if they were in an opened loop. As explained earlier, the EPP is the perception process within a closed-loop using the notion of process refinement. This can be visualised in Figure 7 by the presence of the level 4 fusion, the additional processes for levels 0 and 1, and the outputs of higher levels of fusion redirected toward levels 0-1.

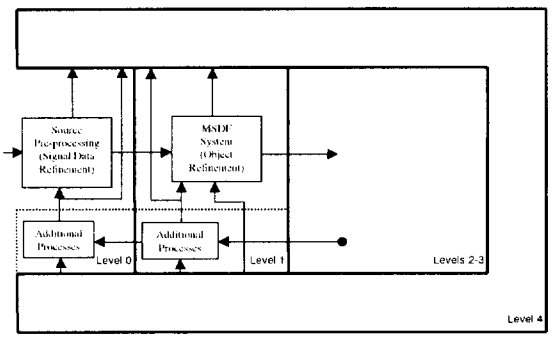

Figure 7 – EPP Framework

5.4 Tactical Information Abstraction Framework

In her theory of situation awareness, Endsley clearly presumes *patterns* and *higher level elements* to be present according to which the situation can be structured and expressed. In Section 3.4 we already made a link between Endsley's situation awareness model and the work of Rasmussen. In the context of our problem domain, maritime command and control, we would call such a structuring language *Tactical Information Abstraction Framework* (TIAF).

If we are able to use a TIAF in the data fusion process according to which situation awareness can be structured, we can make a smooth match of this process with the situation awareness framework. Thus we will be able to

integrate the human element into the design of a decision support system aiding the operators to achieve the appropriate situation awareness.

6. UNCERTAINTY AND POTENTIAL PITFALLS

In the context of naval command and control, the imperfect nature of the result of any data fusion process is caused by several reasons. First of all, the sources of information provide incomplete, noisy, and inconsistent data because of the physical and/or environmental constraints. Furthermore, due to restrictions imposed by the mission, use of active sensors (such as radar systems) is not always allowed. Uncertainty can be connected to the existence of a track. This type of uncertainty is often expressed in terms like *pending*, *tentative* and *confirmed*. Uncertainty can also be connected with the kinematics attributes of a track. In our second example we saw a target of which only the bearing was known. But even if the position and the speed of a track are known, there is likely to be uncertainty associated with their measurements or estimates. Uncertainty can also be connected with the identity of a track. What type or class of target the track represents can be represented with identity propositions.

The above-mentioned uncertainty types are related to tracks. There is also uncertainty of a different kind. It might be the case that a particular sensor has not covered a certain geographical or spatial area. There are several realistic reasons for this. The mission of our platform might imply restrictive use of active sensors. A spatial area may be obscured by a big object or land mass. A more obvious reason would be a restriction of the sensor range due to physical factors (such as radar horizon).

For an effective use of the information request and provision mechanism, it is important that all these types of uncertainty are explicitly represented. Only if this is the case, extra information can be provided and/or requested to the point. A serious complication is that all these different kinds of uncertainty will not likely be expressed in a similar uncertainty paradigm. Because of the multi-type uncertainty problem, many uncertainty conversions may be necessary [Refs. 22-25].

Another potential problem is as follows. If new information is derived from the information received from the lower data fusion levels and if this new information is later provided to the lower levels as an extra information source, we must be aware of a serious risk of data corruption (e.g., data looping) [Ref. 26]. The information provided to the lower levels will somehow be worked into the product we receive from these lower levels. We somehow must make provisions in order to prevent such data looping. We will illustrate this risk with the first process refinement example we gave. Based on the observation of three fighters of a certain type, we posed a hypothesis of a specific formation. From this hypothesis, we derived evidence for a fourth fighter at a specific position in the formation. If we provide this extra information to the EPP we will receive this hypothesis from EPP, as a track hypothesis. As long as the track hypothesis has not been confirmed by real observations, or by other means, we must be aware of the fact that we cannot use this track hypothesis as extra evidence for the formation hypothesis.

7. CONCLUSION

This paper presented the first step toward an integrated architecture for data fusion process giving emphasis to situation awareness concepts. The main objective is the integration of the human element into the conceptualisation and the design of efficient computer-based tools adapted to human's needs for situation awareness and dynamic decision making in maritime command and control.

The paper has highlighted the need to study, in a closed loop and integrated environment, the perception process according to SA concepts. The resulting model coupled with a Tactical Information Abstraction Framework will allow to structure and express the knowledge or information in a meaningful way to the human responsible to take a decision.

Future work is planned to broaden the scope of this study for the integration of all data fusion levels and also to assess the use of blackboard systems as an integration framework for the data fusion process. Finally, efforts are also planned to derive, using Rasmussen's methodology, the tactical information abstraction framework needed to structure and express the information to the decision-maker.

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TACTICAL MISSIONS OF TRANSPORT AIRCRAFT: A PROVEN LOW LEVEL GUIDANCE CONCEPT TO REDUCE CREW WORKLOAD

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Abstract

A concept for a new flight guidance system that focuses on the problem of low level flight and reduction of crew workload for a military transport aircraft is presented. A digital terrain database is used to eliminate the need for an active, forward-looking radar, thus permitting silent terrain following and terrain avoidance. Coupled to the database are a highly reliable, precision navigation, 4D flight guidance and display functions. The demonstration of key technologies associated with this system has been carried out in several R&D programmes to prove the high maturity of available technologies and to reduce the development risks. The target aircraft for these studies is the future European tactical transport aircraft, known as Future Large Aircraft (FLA) or Future Transport Aircraft (FTA). The present low level flight (LLF) technical solution has been prototyped and tested by German Air Force in Airbus Experimental Cockpit Simulator and two flying testbeds (C160 Transall and ATTAS). The experimental verification process is still currently in progress.

Introduction

The development of a modern flight guidance system for military transport aircraft must meet the requirements of future mission scenarios. The mission success of many of these scenarios is greatly increased through the use of low-level and terrain following flight, where the terrain can be effectively used to mask the aircraft from enemy threats. Typical tactical mission profiles can include long distance low-level segments of up to 500 NM or more. Additionally, operations must be conducted from any main base in adverse weather conditions and, at times, from forward operating strips in increasingly sophisticated and hostile environment.

Low altitude, terrain following flight for large transport aircraft is a challenge that bears some similarities, but many differences, from the ground-hugging flight of an attack aircraft. Military transports obviously have more structural constraints, but the biggest difference is a low thrust-to-weight ratio, especially when heavily loaded. Lacking a tactical aircraft's ability to pop up quickly to follow the terrain, a transport's pull-ups over rising terrain must be planned much further ahead, which requires a detailed knowledge of the terrain ahead.

During terrain following, both the crew and the aircraft are pushed to the limits. Thus a system, that supports and aids the crew in this difficult task, is required. For low level flight to be effective, the system must be silent and not use any high-powered, detectable sensors, such as forward looking radar. The use of digital terrain data can effectively fulfil this requirement and provide maximum safety.

Therefore military transport aircraft must be capable of flying autonomously and automatically at the lowest possible altitude, where the crew is supported by a four dimensional low-level flight guidance system. Therefore, the system must be able to perform combined vertical and horizontal terrain avoidance/terrain following manoeuvres, which assists the aircrew by reducing their workload during a low-level flight phase within a dynamic threat environment, or at the presence of a system failure. The system can also increase the effectiveness of logistic missions, where flying in poor weather forces the pilot to fly under the cloud level and close to the ground to drop payloads under line-of-sight conditions.

Paper presented at the RTO SCI Symposium on "Sensor Data Fusion and Integration of the Human Element", held in Ottawa, Canada, 14-17 September 1998, and published in RTO MP-12.

In this paper, a new system concept developed by DaimlerChrysler Aerospace (Dasa) will be presented. The main components of the system include a digital terrain database, an integrated, precision navigation system, and 4-dimensional flight guidance and display functions. The heart of the system is a digital terrain model used for autonomous, jam-resistant, terrain-referenced navigation and the generation of 4-dimensional flight trajectories (Figure 1). Relevant information is presented to the crew on a combination of Head Up, Head Down and Navigation Displays for improved situation awareness. The system has been prototyped and individual key technologies developed and demonstrated in three key research and development programmes. The demonstration of system components within each technology programme has been accomplished with German Air Force transport pilots in two flying testbeds and in the FLA Experimental Cockpit Simulator at Deutsche Airbus in Hamburg, Germany.

Experience

Dasa (formerly Messerschmidt-Bölkow-Blohm and Vereinigte Flugtechnische Werke) has nearly two decades of Terrain Following (TF) experience, starting with the System Design Responsibility (SDR) for the Tornado's TF system and culminating in 1993 with the Tornado flight demonstration of LATAN (Low Altitude Terrain Avoidance and Navigation). LATAN, a terrain databased navigation and terrain following system, completed more than 40 successful sorties and the entire Tornado low-level flight envelope under LATAN control was tested. Due to the system's maturity, LATAN was granted the experimental flight clearance by the German Federal Office for Military Technology and Procurement (BWB-ML) to fly as a stand alone system in the automatic LATAN TF mode down to 200 feet SCH.

System Design

The system designed by Dasa for low level and terrain following flight is built around a central digital terrain and mission database. This database is critical to the system's functional process and flow of information. Therefore the entire functional LLF process, especially the navigation function, must be treated as flight safety critical (Figure 2).

The key system components and features are as follows:

- Central Mission Database: The database is comprised of all terrain and mission data required to successfully complete a tactical and/or logistical mission. As such, it supplies the navigation, flight planning, 4D flight guidance, and display processes with all relevant data (Figure 3). The terrain data is a fusion of various data sources (DTED, DFAD, LFH, satellite photos, radar imagery, etc.). The pre-processing procedure must verify the data before it is loaded into the onboard sy stem.
- A highly sophisticated navigation system based on the sensor fusion of laser inertial navigation system (LINS), global positioning system (GPS) with military P/Y code, and terrain referenced navigation (TRN). By using the strengths of each individual sensor, for example, the GPS's precision, the weaknesses can be overcome to provide a navigation solution that has a higher reliability, integrity and availability than any single sensor. The fusion is accomplished through the use of 4 stage extended Kalman Filter (1 primary filter for all three sensors and 3 secondary filters for each pair) and an associated failure detection and isolation (FDI) logic for the switching between filters. The result is a precise and reliable navigation vector that can be used for safety critical applications.
- The LLF system has a Care Free Moding (Figure 4) to provide the aircrew with maximum flexibility through various levels of automatic support. The aircrew is able to switch between modes at will. The switching between or coupling to TF routes is always accomplished with full terrain clearance. The modes are as follows:
  - *Standby Mode*: the pilot has full control of the aircraft (stick and throttle) and the system is initialised and ready for use.
  - *Free Track Mode*: the pilot has roll control of the aircraft while the system provides automatic height and thrust control. This mode is intended to support the aircrew in deviating from pre-planned routes, so that threats, obstacles, etc. can be safely avoided without having to climb to the minimum sector altitude (MSA).
  - *Fixed Track Mode*: the automatic flight along pre-planned TF routes. The pilot has the ability to either manually fly the route with auto-throttle support (also known as the Manual Mode) or let the system fully control the aircraft.
- The flight guidance algorithms consist of several elements to accomplish the 4D route planning, Autopilot and Flight Director functions.
  - To generate the 4D routes, an algorithm is needed that takes various factors into account. Ideally suited to this application is the Rolling Stone algorithm, named so because it resembles rolling a stone or disc over a terrain profile to generate the flyable

4D route (Figure 5). Climb/dive angles, push/pull radii, set clearance height, speed limits, dynamic manoeuvring and engine dynamics are some of the more important parameters that can be adjusted. The Rolling Stone algorithm also ensures that peaks and obstacles are over flown in level flight without vertical speed (no "ballooning").

- Energy Management (EM) is very important to providing good TF performance for a transport aircraft, as the thrust-to-weight ratio is low. By setting a speed range, an obstacle can be over flown with a combination of static and dynamic climbing (Figure 6). The aircraft must first accelerate to increase its energy level, then climbs (≈2 deg.) at constant velocity, before climbing dynamically (≈10 deg.). At the peak of the climb, the velocity is again a minimum and a descent is initiated.
- Ride Comfort enables the aircrew to set the vertical acceleration limits, or the hardness, of 4D route. This feature is critical in ensuring a cargo is ready for action or use when delivered to its destination. For example, paratroopers would require a softer ride than a payload of tanks. Two routes over the Harz Mountains in Germany are shown in Figure 7 for comparison of the Hard and Soft Ride.

- The Man/Machine Interface consists primary of inputs to the system (stick, pedals, throttle, control panel) and outputs to the aircrew (displays, system status).
  - The control panel enables to the pilot to select the mode, the TF route, the ride mode and the set clearance height (SCH) and shows the system status.
  - The displays used consist of Head Up (Figure 12), Head Down (Figure 13) and Navigation Displays. This combination provides the pilots with all relevant information and even an enhanced 3D synthetic view of the terrain in the HDD. With increased situation awareness, the aircrew's workload is decreased in demanding situations (IMC, night, etc.).
- An obstacle cueing/detection sensor is critical to the verification of terrain database, as it provides a safety check against unmapped or new obstacles, which are not known to the mission database. The use of a millimetre radar or a FLIR (forward looking infrared) could fulfil the requirements of this function.
- A link to on-board mission planning station provides the ability to (re)plan TF routes in flight, based on new information (threat and scenario updates) received by data link. Additionally, this link serves to upload/update the mission database before the start of a mission.

Technology Demonstration

Work in two separate technology research areas has enabled the low-risk, partial realisation of the concept described above (Figure 8). Each research area has used common computer hardware, so that the future integration of individual projects can be facilitated.

- The development and flight demonstration of the navigation concept in the RAPIN programme.
- The development and demonstration of flight guidance and display concept in the ATTAS and Airbus Simulator to evaluate the handling qualities and TF performance of the LLF system [1].

RAPIN

RAPIN (Reliable Autonomous Precise Integrated Navigation) is a government-sponsored research and development programme to investigate the above mentioned navigation concept. A more detailed description of the RAPIN concept is provided in [2].

The RAPIN flight trials were conducted with a German Air Force C160 Transall ANA/FRA from the WTD61. The aircraft test configuration (Figure 9) consisted of a Collins GPS Receiver (MAGR 3M), a Honeywell LINS (H423), a Dasa Radar Altimeter (DRA100) and the aircraft's Air Data Computer. A reference position was obtained using an Omnistar DGPS and, whenever possible, the tracking radar at Manching, Germany. The flights were flown at low to medium altitude over diverse terrain types (flat to rugged, eg. Black Forest) and over water (Lake Constance, North Sea).

As the flight test series was only concluded in August 1998, the initial results are very positive and a sample is provided in Figure 10. This plot shows a jump that occurred in the GPS position. At this point in time, the pilots noticed something was wrong with the GPS and had to disengage it. RAPIN recognised this error and subsequently ignored the GPS solution, while still providing a very precise navigation solution. Both RAPIN and the reference system remained very close for the remainder of the flight, demonstrating RAPIN's high reliability and precision.

FLA Experiment Cockpit Simulator

The system presented to and demonstrated by German Air Force Pilots in FLA Experimental Cockpit Simulator at Deutsche Airbus in Hamburg, Germany consisted of: mission database, full Care Free Moding, a generic control panel, and 4D flight guidance and display functions. Additionally, the system was coupled to the Airbus Fly-by-Wire (FbW) system for full closed-loop capabilities.

The pilots were not only required to fly a standard tactical transport mission as both pilot flying and pilot non-flying, but required to give comments on a LLF system in general (design driving comments) and feedback on the Dasa system. Although lacking the effects of flight, the TF performance was very good in both the Manual and Fixed Track Modes. A switch of modes or tracks posed little problems to the pilots. Full results including the comments by the pilots are available in [3] and a selection is presented below.

The major design driving comments were:

"...low level flight is the only chance of survival, penetrating a medium/high threat scenario..."

"...especially the freedom to perform spontaneous lateral manoeuvres with terrain clearance is advantageous..."

"...low level flight with terrain clearance requires 90% of a pilot's mental power; a reduction of crew workload is desirable..."

Some comments about the system and positive pilot feedback were:

"...the successful flexibility has been reached, especially under IFR conditions..."

"...this system is superior to a Flight Management System..."

"...the Free Track Mode reduces the crew workload and is better a pull-up onto minimum safe altitude, and therefore minimises exposure to threats..."

ATTAS Flight Trials

The ATTAS flight trials consisted of 3 flight-test campaigns of several flights each in December 1995, April and September 1997. The primary goal was the in-flight demonstration of the display concept (HUD and LCD) and the basic TF system with German Air Force pilots. In each campaign, manual terrain following along pre-planned routes only (no auto-throttle) was performed. This is basically equivalent to the use of the Standby and Manual Modes. The flight altitude over the Harz Mountains in Germany was between 9000 and 12000 ft with virtual offset in displays to simulate 150ft SCH.

Figure 11 shows the left side of the ATTAS cockpit, where the LCD was installed in front of the instruments and a Sextant HUD from above. The FbW sidestick and the throttles are visible on the lower left and right, respectively. The right seat in the ATTAS is reserved for a safety pilot, who can at any time override the FbW system with the original mechanical controls.

The results indicate that low level flight with this system is definitely feasible and the adjustable handling qualities (ie. Ride Comfort) are suitable to diverse mission requirements [4]. The pilot followed the pre-planned route (Figure 14) and stayed within the TF channel without flight critical undershoots (Figure 15). The difference between Standby and Manual Modes has been minimal, even though one would expect that the manual mode with Flight Director would be better. The results show that manual TF along the pre-planned routes requires an auto-throttle, because pilots cannot perform EM manually. Future flights with control inputs to the FbW (Auto-throttle) will address this issue.

Conclusion & Outlook

The low level flight guidance system being developed by Dasa's Military Aircraft Division fulfils the requirements for future tactical transport aircraft, allows low level flying without forward-looking active sensors and can be realised with low technological risks based on available COTS components.

The previous projects are coming to a close and are currently being fused into one. More ATTAS flights are planned for middle 1999, where a system comprised of mission database, integrated navigation, flight guidance and display functions will be flown and tested in the Manual Mode with automatic thrust control. More long-term goals are the full realisation of the system, where the obstacle cueing/detection and sensor fusion for increased pilot awareness is included, and the closed-loop flight testing (fully automatic TF in the Fixed Track Mode).

Abbreviations

ATTAS	Advanced Technology Testing Aircraft System
DFAD	Digital Feature Analysis Data
DTED	Digital Terrain Elevation Data
DLR	Deutsche Zentrum für Luft- und Raumfahrt
EM	Energy Management
FLA	Future Large Aircraft
FLIR	Forward Looking Infrared
FTA	Future Transport Aircraft
GPS	Global Positioning System
HDD	Head Down Display
HUD	Head Up Display
LATAN	Low Altitude Terrain Avoidance and Navigation
LCD	Liquid Crystal Display
LINS	Laser Inertial Navigation System
LFH	Aviation Obstacles (Luftfahrthindernisse)
LLF	Low Level Flight
NAV	Navigation
ND	Navigation Display
PFD	Primary Flight Display
RAPIN	Reliable Autonomous Precise Integrated Navigation
SCH	Set Clearance Height
TA	Terrain Avoidance
TF	Terrain Following
TRN	Terrain Referenced Navigation

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Figures

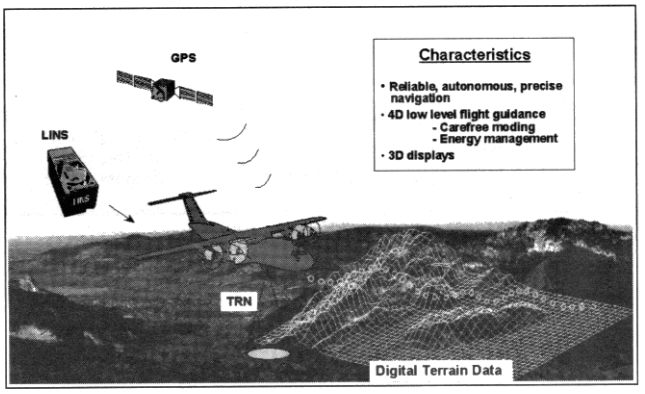

Figure 1: Integrated System

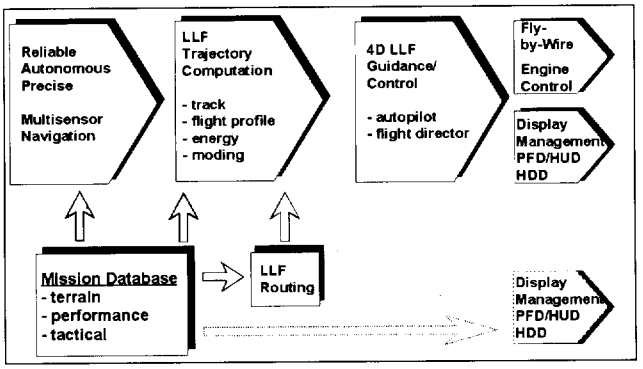

Figure 2: Functional Process

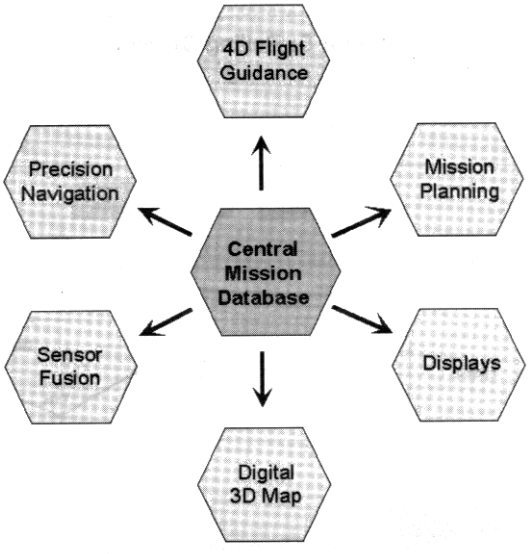

Figure 3: Central Mission Database

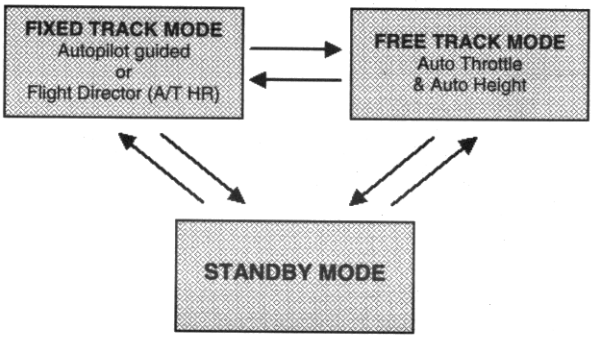

Figure 4: Care Free Moding Concept

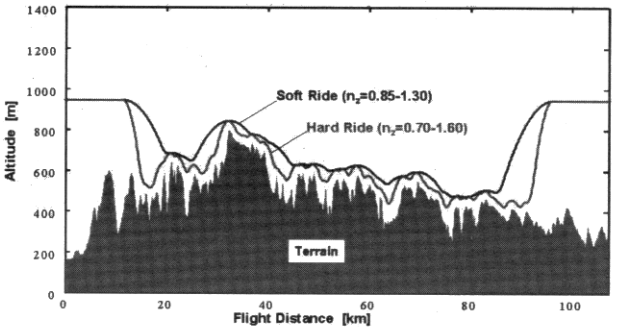

Figure 7: Ride Comfort

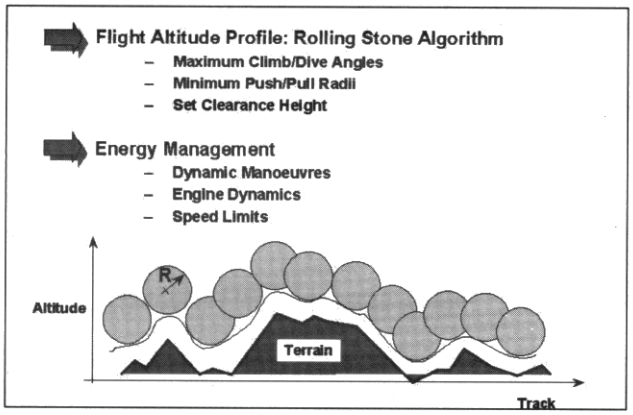

Figure 5: Rolling Stone

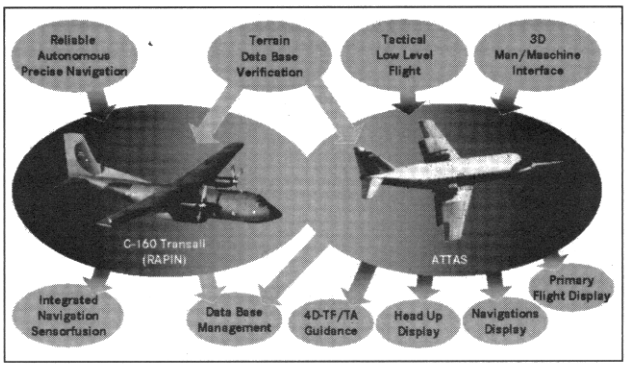

Figure 8: Flight Demonstration

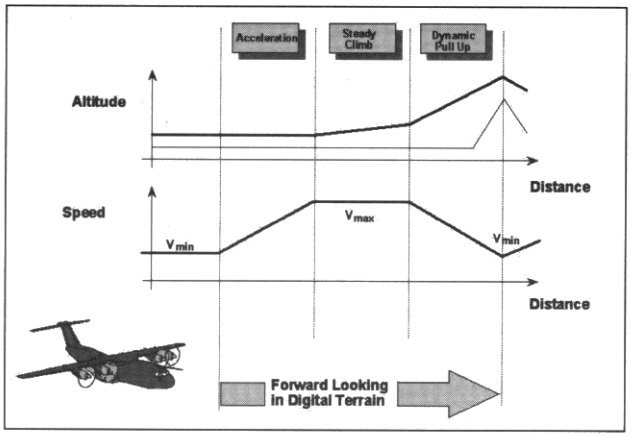

Figure 6: Energy Management

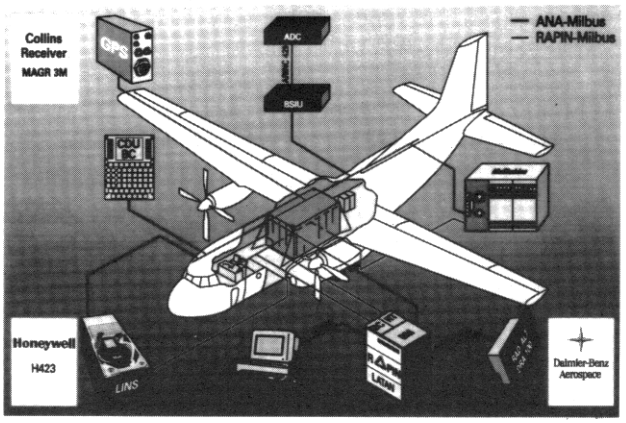

Figure 9: RAPIN in C160 Transall

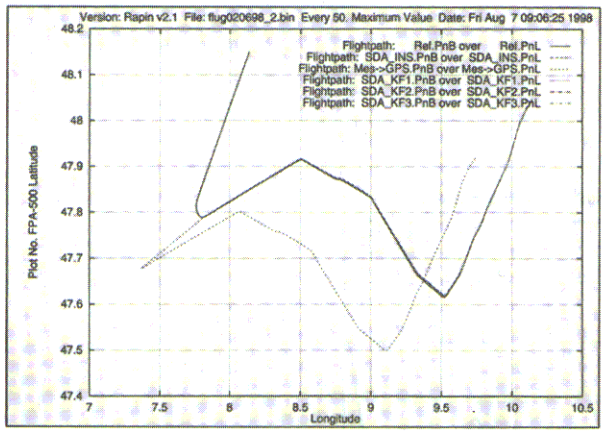

Figure 10: RAPIN Result

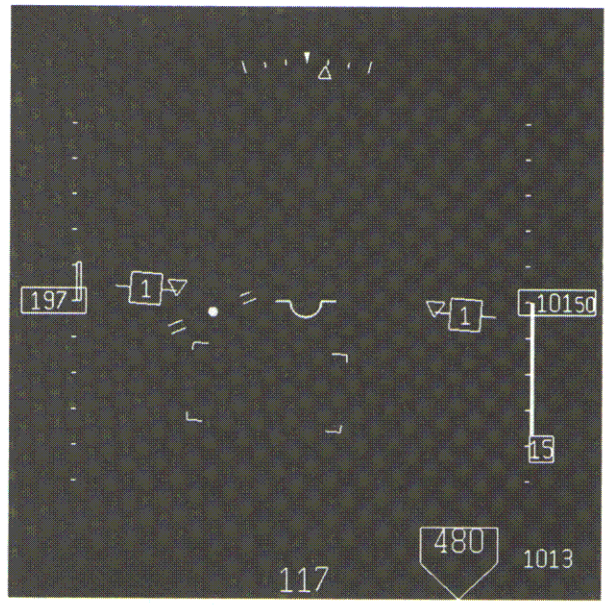

Figure 12: Head Up Display (HUD)

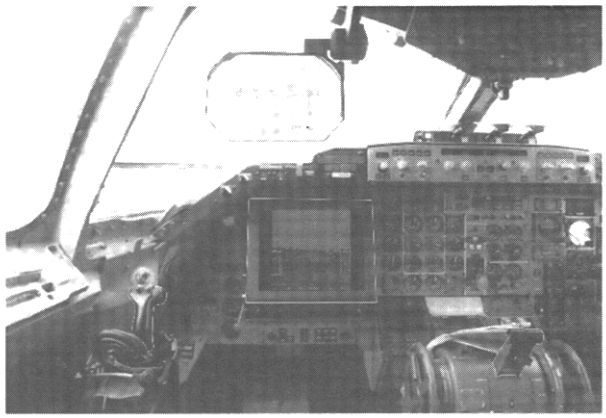

Figure 11: Cockpit Displays in ATTAS

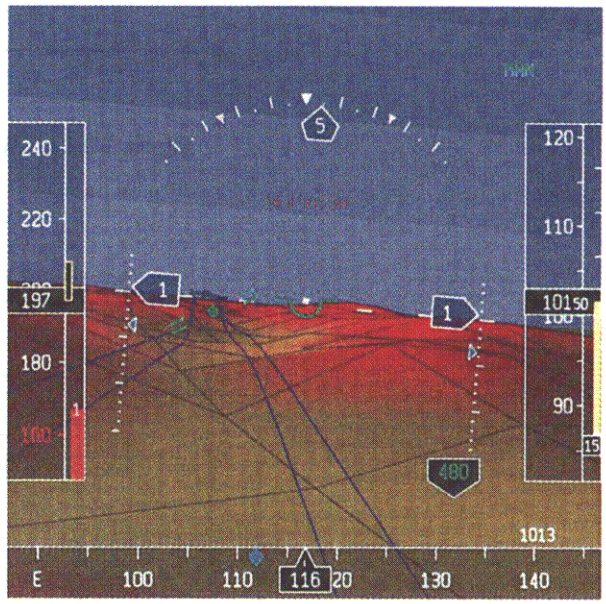

Figure 13: Head Down Display (HDD)

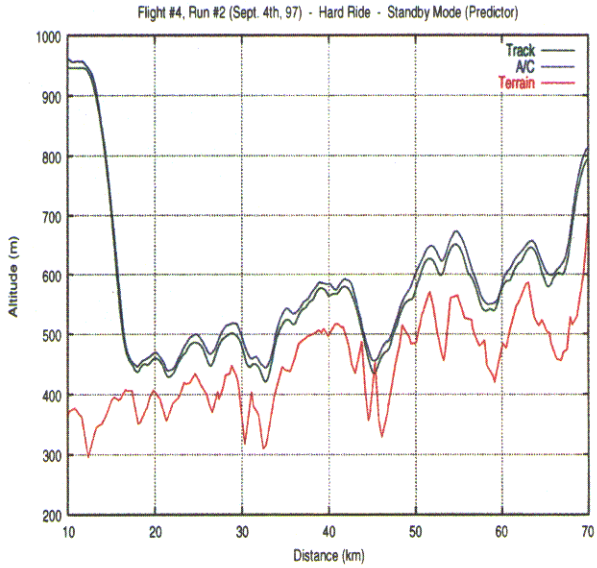

Figure 14: LLF Results - Vertical Profile

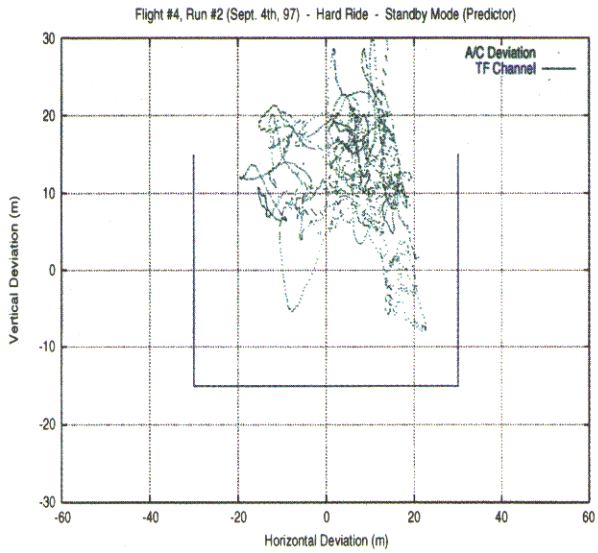

Figure 15: LLF Results – Track Deviations

Utilizing CORBA Concepts for Command and Control Systems

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1. SUMMARY

As Command and Control systems are getting larger and more complex, reliable, modifiable, scalable, platform and operating system independent, distributed and non-proprietary programming environment becomes an important issue for system engineers and developers. Although CORBA (Common Object Request Broker Architecture) concept and its implementations offer a platform and operating system independent software architecture for large scale systems, there are still some important missing issues such as reliability, fault-tolerancy and real-time/fast enough QoS behaviour. In this paper, we present our evaluation results based on our experience and efforts in designing a C2 system utilizing currently available COTS technologies as much as possible and propose an infrastructure to satisfy the reliability and fault-tolerancy requirements of a C2 system software architecture with some additional domain interfaces over CORBA. We also present our overall software architecture that will utilize this infrastructure in C2 system domain.

Keywords: CORBA, Command and Control Systems, Software Architecture, Distributed Programming Environment, Reliability

2. INTRODUCTION

Military Command and Control(C2) system have to be reliable, fault-tolerant and also should meet the real-time / fast QoS criteria in distributed environments. The feature "No single point of failure" makes distributed systems more crucial for C2 system architecture. On the other hand, very rapidly changing operating systems and platforms mandates layered approach between the application software and underlying platform dependent software which makes it easier to modify the application programs for new platforms with less efforts.

With the improvements in the commercial standards and their resultant products, both in terms of performance and supported services, the usage of COTS technologies in military systems becomes more and more important due to especially, the platform and operating system independency, low-cost, non-proprietary and replacability features of such systems.

The main scope of this study is to specify the requirements of the software architecture for C2 systems, and present our evaluation showing that CORBA architecture with some modifications, can be used for this domain. With a system, utilizing a commercial standards as the underlying backbone architecture, we hope that system designers and implementors will have more flexibility and time to deal with their original problems. Being able to use these commercial architectures will also provide third party utilities that will enable the implementors deal with the real-life problems more easily.

As the background information we present the requirement analysis of a C2 system in general and some of the features of the existing distributed COTS architectures including a short explanation on CORBA and its services, especially Event Service, in section 3. We then discuss the frameworks that we built for the evaluation of distributed systems for C2 purposes CORBA and the evaluation results along with the performance evaluation of CORBA based systems in section 4. In section 5, we present the design and the features of the infrastructure which we believe, is especially useful in Event-Based Data-driven C2 system domain, based on CORBA Event Service to provide reliability and fault-tolerancy and its usage in a C2 software architecture. Section 6 will cover our conclusions and possible future work.

3. BACKGROUND

3.1 Basic Requirements for a Military C2 System

C2 systems are the brain of many military computer systems. As an example of a C2 system, consider a frigate with different sensors, weapons and communication channels with different units in the fleet

Paper presented at the RTO SCI Symposium on "Sensor Data Fusion and Integration of the Human Element", held in Ottawa, Canada, 14-17 September 1998, and published in RTO MP-12.

or at the shore. A schematic diagram of such a C2 system is given in Figure 1.

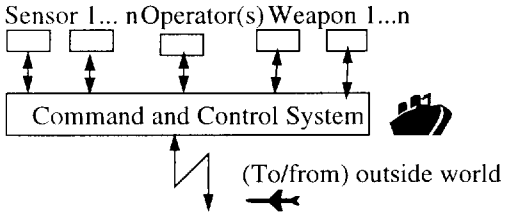

Figure 1.Schematic Diagram of a sample C2 System

The task of the C2 system can be outlined as gathering the information from different sensors, processing these information with some predefined or interactive criteria, and evaluating the information to produce the necessary actions to be taken directly by the system or by the command team.

Due to their vitality in military systems; C2 systems, have to meet the real-time criteria defined for each specific task and have to be reliable in a distributed manner. On the other hand complexity of the applications programs makes it desirable to have a layered apporoach between these programs and te underlying architecture in order to have a more adaptable programs.

3.2 Requirements for a Military C2 System Software Architecture

With the requirements specified in above section and our experience in C2 system, we set a framework indicating the very basic requirements of a C2 system software architecture. We think that these are the system level requirements that can be used in order to evaluate a distributed architecture for our purposes.

Table 1.System Level Evaluation Framework

Requirement Name	Description
Stability	the degree which shows the maturity of the product.
Simplicity	the degree to which the product is straightforward to develop application programs.
Hardware Independence	The degree to which the software is de-coupled from the hardware on which it operates.
Integrable into Hardware	The effort required to embedded into different hardware
Interoperable	The effort required to couple one system to another

Table 1.System Level Evaluation Framework (con't)

Requirement Name	Description
Reliable	The extent to which a program can be expected to perform its intended function with required precision
Scalability	The degree to which a system or application can handle increasing or decreasing demand on system resources without significant performance degradation.k
Real-time	The degree to which the software monitors/analyses/controls real-world evens as they occur
Portability	The degree to which a software source code remains unchanged even when its environment changes. (Ex: change of operating system)
Support by the Industry	The software architecture should be supported by the majority of the industry.

Now that we set a framework for the general evaluation purposes of the distributed systems, we can take a look at to the work done in distributed systems.

3.3 An overview for Distributed Systems

As being a very important area of Computer Science and Information Technology, the studies in Distributed Systems are very popular in both academic and commercial world. Besides the projects/products MACH, AMEOBA, ACE, ISIS, HORUS, ELECTRA developed in the academic studies, there are also very valuable efforts in the commercial world such as DCOM, JavaRMI, DCE, and CORBA. The requirements such as stability, interoperability and portability leads us to focus on the commercial products. Although we covered many academic study in our research, they will not be considered here.

DCOM is the Microsoft's solution for Windows only platforms, hence a single vendor and single platform solution.

JavaRMI (Remote Method Invocation) is Sun Microsystems' distributed computing solution for Java programming Language. Java is an open standard and runs almost on all computing platforms, but it is not mature and stable enough to become a C2 middleware yet.

DCE is an open distributed computing standard and implementation from OSF (Open Software Foundation). It has many similarities with CORBA but the main drawback is its structured programming paradigm and its lack of higher level services such as Naming, Trader, Event or Security services of CORBA.

CORBA as explained in [1] is the core of Object Management Architecture (OMA) introduced by Object Management Group (OMG). The biggest ever software consortium with 800 participating companies. CORBA is also capable for very large scale distributed computing such as in the Internet.

3.3.1CORBA and Common Object Services.

Due to the ever increasing need for reusable components that have well defined interfaces, Object Management Group (OMG) introduced an Object Management Architecture(OMA) to solve some of the problems. OMA has four components. These are Object Request Broker(ORB), Object Services (OS) , Common Facilities (CF) and Application Objects (AO) (Figure 2). ORB, a kind of software bus, is

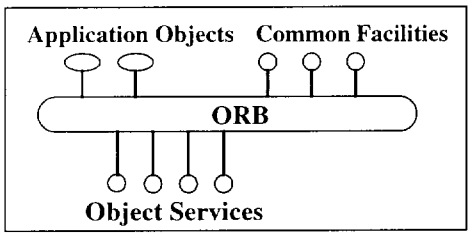

Figure 2. The Components of Object Management Architecture (OMA)

the core of this architecture. CORBA is the arhitectural specification of ORB component. All object interfaces, including common facilities, object services and ORB itself are defined with in an Interface Definition Language (IDL). There are various mappings from IDL to other programming languages such as C, C++, Java, Ada and COBOL. IDL is used to define the interface of CORBA objects. It is the main tool to describe distributed object oriented architecture.

Besides basic functionalities that ORB provides, many services that are found to be useful by OMG are introduced into OMA as Object Services. Basic Object Services can be listed as: Naming, Event, Security, Transactions, Trading, Life Cycle, Externalization, Licensing, Time, Property, Relationships, Concurrency Control, Persistent Objects, Query services.

Out of these services especially Event Service provides a good mechanism for large-scale distributed programs including C2 systems.

Event Service presents a view of an event-based messaging environment. Suppliers generate events and consumers receive them. It models a decoupled communication style.

The Event Service supports asynchronous message delivery and allows one or more suppliers to send messages to one or more consumers. Event data can be delivered from suppliers to consumers without requiring these participants to know about each other explicitly[2]. Event service design is scalable and is suitable for distributed environments. There is no requirement for a centralized server or dependency on any global service[3].

4. EVALUATION OF DISTRIBUTED SYSTEMS FOR C2 PURPOSES

In the evaluation phase, we utilized the requirements that we specified in the last section and our experience on C2 so far. Although performance evaluation has also been considered, more effort has been put into the architectural evaluation.

4.1 Architectural Evaluation

For the architectural evaluation of different distributed systems for C2 purposes, we used the table set in the section 3.2 and the results are given in Table 2.

Table 2.System Level Evaluation Results

	DCOM	RMI	DCE	CORBA
stability	yes	yes	yes	yes
simplicity to build large scale systems	yes	yes	no	yes
hardware independence	no	yes	most	yes
integrable into hardware	yes	yes	no	yes
interoperable with other m/w	no	yes	yes	yes
reliable	no	no	no	no
real-time	no	no	no	no
portability	no	yes	yes	yes

As a result of evaluation of the first framework, it turned out to be that among DCOM, RMI, DCE and CORBA, with some nice services and the support of the industry, CORBA satisfies more requirements than the others.

Table 3. Framework for usability of CORBA products in C2 systems

Requirement Name	Description	Visibroker	Orbix
Fault Tolerant ORB	Distributed ORB architecture prevents single point of failure.	Yes	No
Fault Tolerant Application programs	A system wide fault-tolerant service should follow the applications' state and if there is any crashed application, new applications are to be created automatically by restoring the old state of the applications.	No	No
Persistent Data Service (PDS)	There are some data to be kept in the system forever. These data should be saved in the files.	No	Yes
Fault Tolerancy in PDS	These permanent data are to be kept in more than one node or in every node.	No	No
Critical Data Service (CDS)	There are some data to be kept in the system while the system is running. This kind of data is to be cached in each of the nodes for reliability purposes.	No	No
Fault Tolerancy in CDS	These cashed data are to be kept in more than one node or in every node.	No	No
Event Triggering Filter mechanism.	Listener objects could specify on which values of the event information fields they are interested in. These filters might be the source of the event or any field of the information sent by the event.	No, *	Yes

* but interceptors for callbacks can be used

Table 3. Framework for usability of CORBA products in C2 systems (con't)

Requirement Name	Description	Visibroker	Orbix
Event Log key field indications.	Each listener object could specify the "key" fields that it is interested in, in order to avoid overwriting valuable info or stocking unnecessary information.	No	No
Event triggering for more than one event (for an event list)	Each listener could specify a list of events that it is to be invoked in any one of these events occurs.	No	No
Event waiting for a specific time period.	Each listener could specify a time-out value to wait for an event.	No	No
Concept of new and old data in event information	When an event is to be read by the listener, it becomes an old data for it, but it may be still valuable in case of crashes, or for some statistical purposes.	No	No
Time synchronization	All of the nodes in the distributed environment could use the same time values in order to be predictable in their behaviours	No	No
Distributed File management.	For fault-tolerancy purposes, same file structure is to be kept in different nodes of the distributed environment. Hence a file manager which organizes mirror files for the required information is a need.	No	No

For further evaluation, CORBA based products were considered for their suitability against the requirements of a heterogeneous software architecture [4], combining event based, implicit invocation, publish-subscribe, repository and object oriented styles[4], in an harmony. An evaluation framework and evaluation results for two sample implementation is presented in Table 3.

As the result of the architectural evaluation, we see that although CORBA provides a good environment from many perspective, there are still some missing issues in the specifications especially for the real-time, reliable features of C2 systems. Time synchronization, system monitoring and general file management issues are also problematic areas which will effect the design of a such architecture.

4.2 Performance Evaluation:

Another aspect of the evaluation is of course the performance issue. One thing that is to be considered here is that the performance of CORBA applications may differ greatly depending on the usage of the very little details of CORBA implementations. Hence those figures might be misleading. On the other hand, increasing processing power of the platforms and fine-tuning of the CORBA implementations by the companies provide better performance figures every day.

Hence rather than specifying some of the numerical values in tables, (although we have many test cases), we prefer to give the results out of these performance tests.

We have done some tests in two different test environments resulting 10 times better performance. The first test environment was consisting of a Sparc-Ultra1 and a Sparc Notebook with 10B Ethernet. The second environment that we set up very recently consists of 4 Ultra-60 machines with 155MB ATM connections. This reveals the effect of the hardware on the performance. Another effect on the performance is to use the appropriate methods according to the selected ORB. This is actually the fine-tuning part of the ORB. Some implementations of ORB may perform better for some given scenarios.

During these tests, we realized that messaging load is one of the key aspects to consider for the performance, hence it must be carefully monitored. Messaging can be decreased by

1.Grouping objects into a single server process,

2.Using in-process event channels,

3.Keeping request and/or event push frequencies at medium levels (~10Hz),

4.Returning large data structures at once instead of having to make multiple requests for clients on the same host

5.Reducing the number of clients accessing the event channel in the same host.

These methods will help the designed system be predictable without pushing the limits of underlying hardware and operating system.

4.3 Evaluation Summary

As the result of the continuing experience and evaluation, we see that in a CORBA based software architecture for C2 systems, there are two risks areas. (Real-time) performance and reliability features. Time synchronization, system monitoring and general file management issues are also problematic areas which will effect the design of a such architecture.

Out of these evaluations, we concluded that CORBA architecture as currently specified does not support enough features necessary to build reliable, large scale C2 systems. Since CORBA does not provide a completely appropriate software architecture for C2 systems, what we decide is to get out of CORBA as much as we can get and build an intermediate layer on top of this architecture to fulfil our requirements with a minimum size of in-house implementation [5].

4.4 Related Research

There are some on-going research to increase the capabilities of OMA specifications. Adding reliability to CORBA architectures is also a point of interest for many research group. Orbix+Isis is offered to provide a reliable environment for Event Service of CORBA[6]. Server objects are to be used via Object Groups and a log file for the event history is to be kept either in the memory or in the disk. For such an architecture "Event Log key field indication" and "Fault Tolerancy in Persistent Data Service" can be listed as the missing requirements with respect to Table 1. There is also no indication for the "fault tolerant ORB" in their studies. In case of a new receiver arrives to the system, (e.g. due to the crash of the old receiver), they indicate that a user-defined number of events will be backed up from the log file. In our case this approach is not appropriate, the number of the event information to be backed up is not predictable at all.

Another product CyberBus[7], based on source-code free partial CORBA implementation ELECTRA [8], has been announced. It has several differences from the CORBA Event Service. Main subject for our case is that it introduces active and passive replicas of the objects for fault tolerancy. A mechanism will determine the crashed objects and notifies surviving objects of such events. Additionally, CyberBus can be configured to automatically restart a crashed object on a new machine, without having to restart the objects that interacted with the crashed object. In

this study, also virtual synchrony concept has been utilized.

The research group at Washington University evaluated CORBA products for the reliability, flexibility, reusability and performance features. Very well defined performance tests have been applied for the commercial CORBA products and also some solutions for the possible bottleneck points have been suggested by this group. They offer a system which satisfies real-time ORB[14] that can deliver end-to-end QoS guarantees to applications. In their work they propose some extensions to CORBA Event service so that it will be suitable for real-time systems. These extensions support periodic rate-based event processing and efficient event filtering and correlation [2].

The inefficiency of CORBA for reliable and high available systems are explained in detail in [9]. Also in this paper, the interesting methods for building reliable systems namely, Message Queues, Transaction Processing Monitors and Virtual Synchrony methods are explained and evaluated. Orbix+Isis is offered to provide a reliable environment for Event Service of CORBA[6]. Another middleware CyberBus, which runs on source code free partial CORBA implementation ELECTRA[8], has been proposed with similar facilities to Event Service. Experience over the past several years illustrates that CORBA is well-suited for best-effort, client-server applications running over conventional local area networks. However, building highly available applications with CORBA is much harder[9].

Although there are some definitions and evaluations about the methods for building reliable systems on CORBA architectures, in most of the studies, the concept of group communication and virtual synchrony have been utilized. We believe that for our case, in an environment where the data flows between the processes are encapsulated as objects; utilizing object group concept for every object, may be a performance bottleneck. On the other hand methods such as message queues or TP has got little attention. We think that message queues and data redundancy can also be effectively used to build reliable systems.

On the other hand, OMG has published a Request for Proposal (RFP) for the fault tolerant CORBA using entity redundancy[16] on mid April 98, which has a submission due date as October,20, 98. We hope that this will increase the motivation for the implementation of a fault-tolerant, reliable CORBA architecture in the industry.

5. PROPOSED ARCHITECTURE FOR C2 SYSTEMS

Before explaining the architecture itself, we will present some information about the underliying communication mechanism.

5.1 Event-based or Client-server architecture

CORBA IDL operation calls are an ideal mechanism for communicating between a client and a server: an object in a server can advertise its IDL interface and clients can use this interface using simple and familiar programming constructs. A C++ function call can result in the activation of an object on a different node, running on a different operating system, and writtenn in a different programming language.

However, this direct point-to-point communication is not ideal when a client must make the same operational call on a set of objects. Having to make a sequence of operation calls is very expensive for the program, and inefficient to execute. Such communication is also inappropriate if a client needs to make a variable set of objects that the client can not, or should not, be able to enumerate. A client may not know the objects that it needs to communicate with because this set is very variable (so it would be diffucult to maintain a list of object references in the client) or because the client and the target objects should not know of each other.

On the other hand, there are some application level programs and functionalities that they are used by many clients in the system. Track Manager can be given as the best example for such services. This kind of services are accessed by many clients, and they have well-known interfaces. For such purposes, client-server architecture should be the choice. Hence implementing such a functionality as a server object will reduce the amount of processing in the other processes. Time server, File Management Server can also be considered as such services.

Even we design to use client-server architecture for some specific purposes, the implementation of the server on the other end, will also be using Event-service mechanism to keep its information upto date.

As a result, we can say that Event-Service will be the main communication facility in the system, but for specific purposes Client-Server architectures will be utilized.

5.2 Overview of the Architecture

We present a domain specific CORBA based architecture in this section. Our overall design for a C2 system architecture is shown in Figure 3.

In the "infrastructure" layer, we would like to handle all of the communication and data transfer, data adaptation and reliability problems, where in "core services" we plan to perform system management functionalities. "Core applications" are the basic applications that are to be utilized by the application programs very heavily in this domain, and "application programs" are the tactical applications that will be changing mostly according to the platforms and the purpose that the system is used for. Out of these four layers we think that first two can be used for many C2 systems with different purposes, where as for "core applications" some modifications or replacements might be necessary, and "application programs" are very specific for each C2 system.

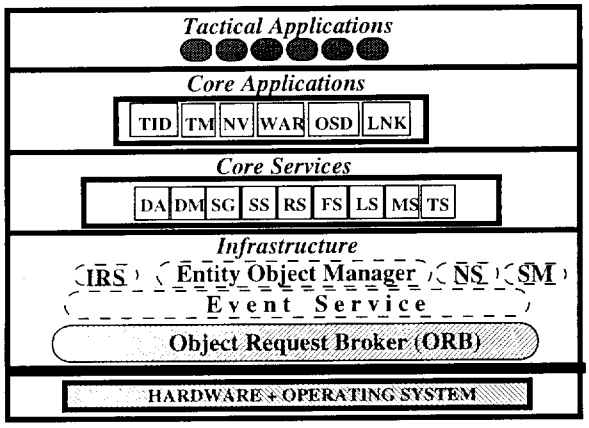

Figure 3. Overall Design for a C2 system

As it can be seen from Figure 3, the infrastructure has a special importance in the overall architecture. Hence, our main concern will be the details of this layer handling the underlying communication and reliability features in a data and event driven system.

5.3 Important features of the architecture.

The layers of "Infrastructure" and "Core services" have special importance since these two layers provide the necessary services for implementing a C2 system regardless of its functionalitiy and its size.

Tactical Applications uses the services provided by the underlying layers and essentially gets the data, performs some actions on the data and output the result into the system or to the user. In some cases, they act as a client of the "core applications".

Core applications are most likely to be implemented as a client-server manner due to their well-known interface for the application programs. But, on the lower level of their interface, they will still be using subscribe-publish mechanism in order to retrieve information from the system.

"Core services" layer is the layer where functionality independent behaviour is embedded, hence we expect a set of general "core services" for each of the C2 system. In our definition a subsystem is a source of or the user of an information in the domain.On the other hand, domain is a collection of subsystems, and a system is a collection of domains. Hence a unique "Domain Administrator" for the whole system is required where as for each domain a "Domain Manager" is used to keep the associated subsystem records in the domain.

As an example for domain concept, platform domain, OTC domain, fleet domain can be given. In each of these domains, there will be different subsystem assigned to this domain.

On the other hand, for the "Infrastructure" layer, data is the key element in the system. The Application programs (tactical / core applications and core services) simply specify their interest with specific pieces of data, and an event (or notification) service with the help of an agent collects (cashes) the data from the overall system for the application program(s).

On the cashed data, the state information of the application programs is maintained, hence in case of crash of an application, the new application can restore its state by utilizing this cashed data in the same or different node of the system.

Due to the special characteristics of the C2 domain, data instances represent mostly continuous quantities [10], which allows a slight relaxation of the consistency requirements normally associated with distributed systems. For this kind of information, there is no need for rigid synchronization of the cashed data.

For the data, that does not fit into the above category, (i.e. not continuous) the delivery time is a major issue. For this purpose, effective notification mechanism is to be provided.

In the cashed data, data is stored according to the key values specified by the producers. In addition to this storage, each application can also specify different key values for other storage structures.

On the other hand, application programs can specify filters for the data that they are interested in. This mechanism is also used to optimize the network message traffic.

Query mechanism can also be set on to the cashed data by the application program. Such a mechanism is especially useful for the effective triggering of the application programs.

Correlation mechanism [2] which gives the opportunity to the application program to specify its interest for more than one events is also a desirable feature of the system.

On top of such an architecture, a system monitoring service is also needed to detect the possible crashed application programs and restart them in the appropriate places.

CORBA and its event service fits quite well for the underlying communication mechanism. The reason that we say "quite" have been explained in section 2, as the missing important features of CORBA system. On top of this basic layer, we are more concerned on:

1. A layer that will satisfy the additional requirements of missing features,
2. A layer that will hide the CORBA interfaces from the application software and provide an interface for the additional requirements, and
3. Design of Business Object Model in the overall architecture. Namely, Process Objects and Entity objects are to be defined and designed in the system.

In a system utilizing publish-subscribe architectures data plays the key role. Data as being the information, passing between the "Process Objects" of the Business Object Model, will be encapsulated as "Entity Objects"

Three different types of "entity objects" have special meanings in the system. "Permanent", "Critical" and "Periodic" entities. These entities will be made accessible by using the IDL interface of the system.

Permanent entity objects are to be stored on each node's disk in the network, so that application software can use this information for the initial start up. (Some default settings, vital information etc.)

Critical entity objects are to be stored in the main memory of each node (heap / shared memory). To avoid unnecessary pile-up of objects, objects with the same values of indicated "key" fields will be overridden by the data produced later (key fields will be designated by the producers of the data). Addionally, each consumer as being a processing object should be able to indicate how the entity object is to be stored for their application purposes, hence rather than a unique producer key list, each consumer is to prepare a key list of that object data to be stored in the memory. Our point is that in order to support the reliability, on each node on the system network, the same data is to be kept as "critical". In case of a node failure, this critical info will be retrieved from one of the other (master) nodes.

Periodic entity objects are the objects for which no storage is required. Such objects constitutes an important amount of data passing around in a C2 system, and due to the continuous nature of such data, the requirement of having all of the data and synchronization of such data in different nodes is not strictly necessary. The current event service implementations fulfil this requirement.

With a good abstraction we expect to have 1500-2000 different entity objects in a large scale C2 system. Out of 1500, approximately 400 periodic, 200 permanent and 900 critical entities are expected. During the design phase, this property of the entity object will be set in the IDL interface as an attribute "type". Hence it will be available through out the system.

The design of event channel usage is also an important concept to consider. The amount of event channels and the amount of different entity objects passed through these event channels, is one of the major design problem.

Keeping these ideas in mind, we present the general schema of the overall architecture in Figure 4.

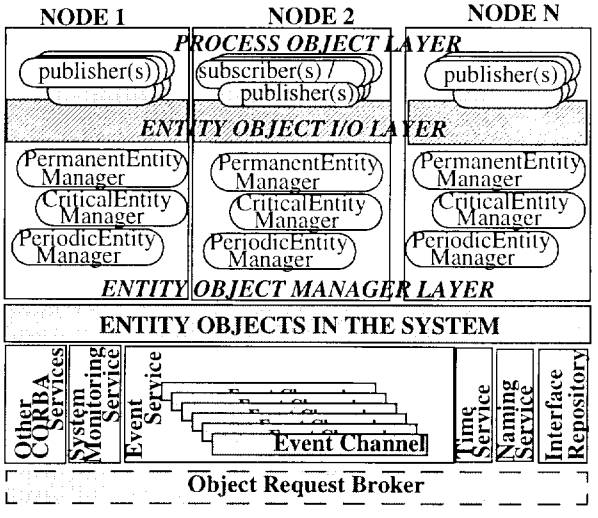

Figure 4.General Schema of the Proposed Architecture

In Figure 4, we illustrate all of the major components of infrastructure layer with respect to the general schema of the overall architecture. Hence, this figure does not reveal the complete architecture, but gives an idea about where the infrastructure lies in the overall architecture. All of the components except

the "Process Object Layer" elements are the elements of the "infrastructure" or "core services" layer.

Especially System Monitoring service has significant importance for the reliability of the system. That service will detect the crashed "entity" or "process" objects and re-start or activate another copy of the crashed object. Since the "critical" entities are available through out the system, the object will restore its state prior to the crash.

Now, there are two questions to be answered for such a nice mechanism.
1. What is the fail detection mechanism?
2. What is the mechanism for the synchronization of the "critical" data in each of the node?

As we will be explaining in later in this section, the answer for these questions is the notification service. For the current prototype purposes, we consider that each object will report itself to the subsystem manager by sending a heart beat. Subsystem manager will evaluate these information acc. to a dynamic time criteria set w.r.t the cpu usage and may declare the crash of an object. On the other hand, we postponed the synchronization problem until a good notification service becomes available.

Entity Object Manager Layer (ML) and I/O Layer (IOL) in Figure 4 support the idea of layered approach and provides necessary caching mechanism and application interfaces for reliability and fault-tolerancy that are missing in standard CORBA specs for C2 system domain.

The main idea is to store the "critical" entity objects required by the consumer applications (process objects) in a redundant manner, so that a crushed objects can recover to its original state prior to crush by utilizing these data in the same node or in another node. For "persistent" entity objects, the storage is to be made to the disk for initial, default set up values. For "periodic" entity objects basically there is no storage requirement and CORBA Event Service fits quite well for this purpose.

In genereal each entity manager for the consumer application programs will collect the requests for each of the entity, from the application programs, establish the event channel connections accordingly, and notify the consumer application programs, if the application program requests also a notification for a specific entity. It will also cache the incoming entities according their specific natures.

Besides these common services of the managers, there are two more services that we evaluate as necessary for "critical" and "periodic" entity object managers. These are query and correlation functionalities. Application programs should be able to specify their queries for the related entities.With correlation mechanism [2], the opportunity to specify its interest for more than one events (OR operation) will be provided to the application program. Other than these, filtering mechanism is another feature that we consider as necessary but we know that notification service will take care of this functionality. Still entity object managers will have to provide an interface for this feature.
The interaction of Critical Entity Manager(CEM) with other units is given as an example in Figure 5.

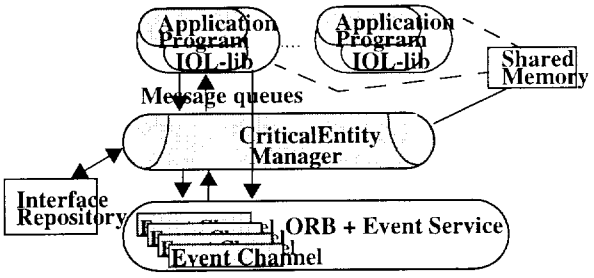

Figure 5.Detailed representation of the CEM part of the proposed infrastructure

On every node, there will be a CEM server, one of them acting as a Master. In case of new node coming up, this master will supply the current critical entity object info to the new CDM with only producers' key values.

Currently, we are working on a prototype that has consumers and producers which are not object oriented application programs. It is due to the risk management concept arising from a quite amount of people which are happy with their programming API and environment and design logic. That is why, at the first stage, a conversion from entity object to object data is essential at least when presenting the entities to the application programmer. This kind of adapter functionality has to be taken care of by the entity manager too. As noticed in Figure 5, we are using shared memory and message queue for the interprocess communication between the application programs and the CEM. effective data structure utilization is also a must for performance reasons.

On the other hand, IOL-lib (Entity Object Input/ Output Layer) provides a mechanism to hide the details of accessing the Entity Object Data. This layer is implemented as a dynamic library and handles the communication between the CEM and the application layer.

For the producer application programs, each of the programs will have a interface hiding the details of the CORBA and Event Service, provided by the IOL-lib, but via IOL-lib will utilize the Event Service or ORB directly, without any services of Manager Layer. In order to decrease the network load, we might consider to add another functionality into the manager layer to take care of the buffering issues for publishing big chunks of data, rather than many small data into the Event Service.

Although being able to cache the redundant "critical" entity objects is a big step, we still need two more, very important services to provide a reliable infrastructure. These are system monitoring and management services. An example of such a system has been presented in [9].

5.4 Effects of New COS Services for the Design of Infrastructure

Since OMA and its services are rapidly evolving, we need to consider the new possible services and their effects for the design of the infrastructure. As it is pointed out through the explanation of the infrastructure, there are some problematic areas, which we think new service specifications will be useful.

One of the main services that we think it will be useful is Objects-by-value. This service will provide better efficiency for the underlying communication mechanism and will let us to encapsulate the data structures as objects. Currently we are using data structures to pass this data among the process objects.

Another important service is the notification service. With this service QoS, Assured Notification, Prioritization and Filtering features will be added to the system. We think this service will be useful for the detection of faulty application programs and the synchronization of the cashed data with its assured notification mechanism. If the performance of the notification service becomes a problem, we might use event service and notification service concurently serving different entity objects, namely "periodic" and "critical" respectively.

We do not want to go through for the real-time service of OMA. It will definitely effect the deterministic behaviour and hopefully the performance of the system.

For Fault-tolerant service by using redundant entity, we would like to stick with our design unless a very good implementation or proposal comes out. Because, with this infrastructure we, not only define a reliability service but also a key component of an architecture, that provides query, caching, filtering service interfaces to the application programs, hiding the details of underlying in-house and OMA structures.

Persistency service may also be used by the "permanent" entity manager if an easy to use service is implemented. On the other hand, externalization service can also be utilized in order to achieve the data storage in the cashe with some modifications.

Time service is also another very important service in the overall architecture. Currently, we are planning to use NTP for time alignment. It gives sufficient resolution and accuracy for the console domain operations but not for the weapon-sensor domain. Hence, better time services are expected to evolve or a hardware timer may be utilized in the eventual system.

We believe that it will take some time for the new services to be mature enough to be used in such an architecture, and we will continue to utilize the existing ones, and since they are modular and as long as we define the application program interfaces correctly, changing the underlying mechanism will not be a big problem.

6. DISCUSSION AND CONCLUSIONS

In this paper, after the evaluation phase, we have first presented a reliable CORBA infrastructure based on redundant entities, and secondly, presented domain specific CORBA based architecture for C2 purposes. We utilized the ideas in [10], [2] and our experience in this domain.

Although our main concern is the reliability feature of the architecture, with the infrastructure we provide, we present a layer which also supports query, filtering, typed event channels and notification services. Although, these services are handled in the infrastructure layer in one entity object manager, depending of the type of the entity object, if the performance results permits, we can easily divide these different services, into different modules according to their fuctionalities.

We believe that publish-subscribe mechanism establish a good infrastructure for large-scale software systems. CORBA, even with some its missing features, provides support for this mechanism. Encapsulating the data as the entity objects in such a mechanism, allows the usage of object features for pure data in the system, such as type-checking and inheritance.

Our proposed module on top of the event service of the CORBA architecture gives us the opportunity to introduce:

- reliable programming environment by using redundant data,
- typed event channels for application programs,
- better performance expectance due to the less number of consumer programs, and effective in-node communications.
- query mechanism for the application programs which will in many case increase the performance,
- an effective access to the information for the application programs.

Since the implementation is not ready yet, currently we can not give any performance results, but from an architectural point of view, the design support the idea of independent modules, utilizing COTS products to the extend possible which causes easy modifications and little in-house implementation, letting the application designers and programmers concentrate on their application functions for C2 system domain. We hope to present the performance results of the prototype which will not include the query and filter mechanisms soon.

After setting the first prototype, we would like to build an API for object-oriented application programs. This will enable us to use some of the software patterns in our architecture more easily.

Investigating the possible connection mechanisms of agent based systems into this architecture is another issue that we consider for further study.

Using Java based programs for especially user-interface programs in connection with CORBA architecture will support adaptability, maintainability and industry support features of the proposed architecture. Hence this kind of joint usage will be a matter of future progress.

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INTEGRATING VOICE RECOGNITION AND AUTOMATIC TARGET CUEING TO IMPROVE AIRCREW-SYSTEM COLLABORATION FOR AIR-TO-GROUND ATTACK

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SUMMARY

Automatic target cueing and pilot voice recognition were integrated into a single-seat fighter cockpit simulator and were evaluated. Pilots were required to fly a pre-planned route to an airfield, where they identified and designated for attack, six tanker aircraft from a group of fifteen aircraft that were parked on the airfield. During navigation and weapon delivery segments of the mission, simulated Airborne Warning and Control directed the pilots to: 1) modify their flight route, 2) change radio frequencies, 3) respond to various tasks and instructions, and 4) attack the airfield. During half of the data collection sessions, data input tasks were performed manually by the pilots using an "upfront" keypad; during the other half of the sessions, data input was accomplished by voice. Additional independent variables were: 1) auditory interference—number of communications requiring pilot response, and 2) workload—maintain altitude at either 300 feet or 1000 feet above ground level. Objective measures of performance for data input (speed and accuracy) and for aircraft control (deviations from commanded course, airspeed and altitude) were collected while pilots navigated along the fight route. Objective measures collected during ground attack included speed of target designation, total number of targets correctly designated, and stand-off distance from the airfield at target designation.

INTRODUCTION

Today, two-seat weapon systems are required to successfully accomplish the most demanding ground attack Air Force missions because cockpit labor must be divided between a pilot and weapon system operator to mitigate task saturation and to maintain adequate aircrew situation awareness. In large measure, task saturation and inadequate situation awareness occur because current cockpit technologies perpetuate three main behaviors that reduce aircrew effectiveness: 1) frequent transition from head-up to head-down displays, 2) cross-check of information that is presented on multiple displays, and 3) mental translation of two-dimensional display information into a three-dimensional environment.

A series of simulation experiments at the U.S. Air Force Research Laboratory (AFRL) have quantified the advantages of integrating various human-computer interface (HCI) technologies to achieve the goals of reducing aircrew workload, increasing aircrew situation awareness, and permitting accomplishment of the most demanding types of ground attack missions with one crewmember instead of two. In early evaluations, HCI technologies integrated into a single-seat fighter cockpit simulator were a helmet-mounted display (HMD) with head-steered sensor capability, a directional-audio threat cueing system and large-screen, head-down displays. Results showed that an HMD integrated with head-steered sensor capability significantly increased pilot accuracy and speed to acquire threats and targets positioned off-axis of the aircraft centerline, and also dramatically improved pilot situation awareness over a baseline, non-HMD system. A head-down cockpit configuration with a centrally-located, 8"- square, primary display and 6" x 8" displays on the left and right promoted more efficient instrument cross-check and provided the requisite display area for pilots to accomplish time-critical ground target search and identification tasks when compared to cockpit configurations that used larger, but fewer, display screens (Ref 1, 2, 3).

Background

Most recently, automatic target cueing and pilot voice recognition were integrated and evaluated in the simulator. Voice control has been researched extensively over the past 20 years. Several researchers (Ref 4) have proposed voice control as a natural and intuitive method by which pilots can communicate with the complex interfaces found in the cockpit. Voice control could allow pilots to manage various sources of information more efficiently by reducing resource competition (e.g., visual attention requirements), freeing the pilot's hands and eyes to fly the aircraft, simplifying complex strings of control actions through the use of "voice macros," and taking advantage of a natural, well-learned human behavior—speech.

Voice can also provide an alternative, simplified control method to complex, overloaded hands-on throttle and stick (HOTAS) implementations. According to an Advisory Group for Aerospace Research & Development published report (Ref 5), cockpits are becoming increasingly complex because of the heavy reliance on programmable, multifunction displays and controls, and advances in communications, data link, weapon and sensor system capabilities. With today's more complex cockpits, "the ability to control aircraft sensor and weapon functions through software-driven keys has increased with a commensurate increase in functions controlled by HOTAS." AGARD concludes that "HOTAS switches have reached practical limits... and will force future use of alternative methods [of input]." Voice control offers an alternative method of control input that retains many of the benefits provided by HOTAS, including the ability to execute control actions without removing hands from primary flight controls, and without distracting visual attention from other critical tasks.

Many of the proposed benefits of voice control have been demonstrated in part-task simulation environments. Compared with traditional manual control methods (e.g., switches, keyboards), voice control can improve crew performance and simplify operations for some tasks. For example, the use of

Paper presented at the RTO SCI Symposium on "Sensor Data Fusion and Integration of the Human Element", held in Ottawa, Canada, 14-17 September 1998, and published in RTO MP-12.

voice control has been shown to decrease input times for selected data entry and concurrent flying tasks (Ref 6, 7), increase input accuracy (Ref 8), and permit the user to simultaneously attend to relevant visual tasks (Ref 9). Other studies suggest that speech recognition technology can potentially reduce operator workload, and may improve the operator's ability to manage multiple, simultaneous tasks in a high workload environment (Ref 8, 10).

State-of-the-art voice systems are capable of accurately recognizing continuous speech, which allows the user to speak naturally using normal inflections and pauses between words. The systems have also matured to the point where they can achieve high recognition accuracy in an operational cockpit environment. Williamson, Barry and Liggett (Ref 11) performed flight tests of a continuous speech recognition system in an OV-10A, measuring speech recognition accuracy with the engines on and off, and during continuous 3-g turns. They also measured recognition accuracy in a laboratory environment for a baseline. No differences in recognition accuracy were found across the different conditions, and at no time did accuracy drop below 97%. They concluded that speech recognition could be used effectively within a high noise/mid-G environment.

Objective

While the benefits of voice control have been demonstrated in part-task environments, and speech recognition systems have matured to where they can perform well in severe environments, a voice interface has not been demonstrated within operational contexts. The overall objective of this experiment was to address the operational context issue by: 1) measuring how the use of voice control influenced the pilot's ability to multitask in a high task load environment, 2) investigating potential interference between voice control and other vocal communication tasks, 3) determining how voice control could influence mission effectiveness in a simulated air interdiction mission, and 4) assessing the utility of voice control when used in conjunction with automatic target cueing. Mechanization of the voice interface was based on recommendations from several previous researchers and fell into five categories: programming, interrogation, data entry, switch and mode selection, and continuous/time-critical action control (Ref 7, 12, 13). Speech recognition has been successfully used in fighter aircraft simulations and flight tests for setting radio frequencies, setting steerpoint coordinates and weapons release parameters, and controlling flight displays (Ref 14, 15). The voice control tasks in this experiment covered this range of applications.

METHOD

Subjects

Twelve male pilots with fighter aircraft experience participated in the experiment. Their total operational flight times ranged from a low of 650 hours to a high of 3800 hours. Their cumulative aircraft experience included significant hours in the A-10, F-4, F-111, F-15, F-16, B-52, B-2, OV-10 and T-38.

Simulator

The experiment was conducted in the Reconfigurable Single-Seat (RS2) simulator in the Vehicle-Pilot Integration Laboratory at Wright Patterson AFB. RS2 consisted of a single-seat cockpit shell with side-console mounted F-15E stick grip and throttles and a 21" × 16" color monitor for showing the head-down display formats. The standard F-15E hands-on-throttle-and-stick (HOTAS) switch mechanization was slightly modified to support the research requirements of the experiment. A Barco Retrographics 801 projection screen, which was located directly in front of the cockpit, displayed F-15E head-up display symbology and simulated, out-the-window, forward field of view imagery. The RS2 simulator is shown in Figure 1.

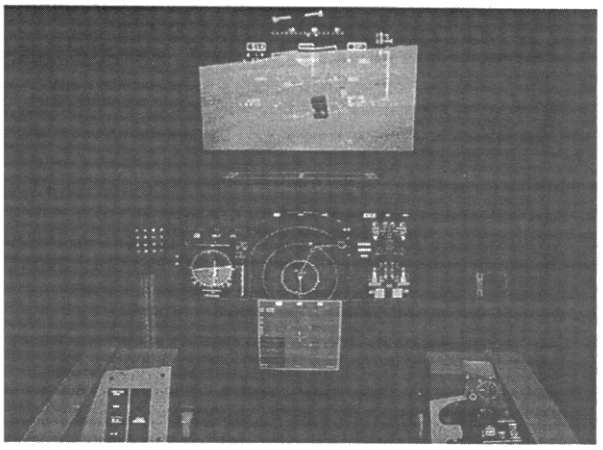

Figure 1. RS2 Simulator

Head-Down Display Layout

The head-down suite consisted of an 8" × 8" top center display and a 6.7" × 6.7" bottom center display on which sensor information (tactical situation display—TSD, air-to-ground radar, targeting pod video, weapons) was provided. Two 6" × 8" displays on either side of the top center display provided primary flight information, system status information, and engine/weapon information. The left 6" × 8" display was divided into two separate areas measuring 6" × 2" and 6" × 6" respectively. The 6" × 2" area provided communication and navigation information (CNI) and the 6" × 6" area was a multifunction display (MFD) capable of presenting system status and flight information. A keypad was positioned next to the 6" × 2" display to allow the pilot to manually enter communication or navigation data. Figure 2 shows the head-down display size configuration and lists the main formats available on each display.

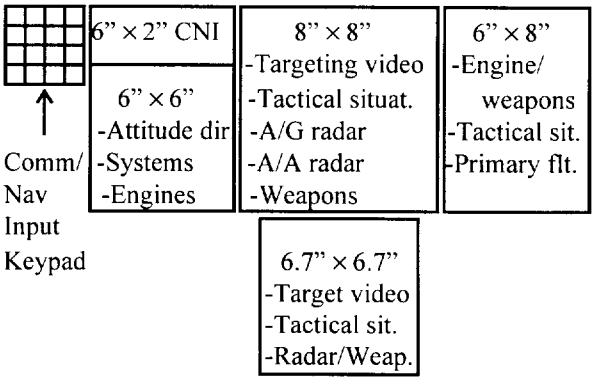

Figure 2. Head-Down Display Configuration (Ref 16)

Test Operator's Console

A test operator's console was located to the side of the RS2 and was used to supervise and control the simulation. It consisted of one Silicon Graphics 21"

monitor, three 13" high-resolution monitors, an intercom system and a desk/writing area.

Voice Control System

To enable the pilots to use voice commands in the cockpit, a Verbex Portable continuous speech recognition system was used with an M-162 microphone that was affixed to standard issue USAF aircrew headsets. The speech recognizer included training software that generated speaker-dependent reference template files for the entire voice control vocabulary. These individualized templates served as the basis for interpretation of the pilot's voice commands. To activate the speech recognition system, the pilot was required to pull aft on the HOTAS microphone switch and then speak the desired voice commands. The recognizer compared these inputs to the stored template, and then sent the interpreted command to the simulation software.

The vocabulary contained a total of 91 words and short phrases, i.e. utterances, and was developed with the aid of several experienced pilots to ensure that commonly accepted terminology was incorporated. To make the system more flexible, and therefore more robust with respect to individual pilot styles, selected tasks could be accomplished with multiple voice commands. For example, to slew the targeting pod to the next steerpoint, the pilot could say 'slew next steerpoint' or 'slew next'.

Procedures

Pilots were given an introductory briefing, followed by "ground" training, simulator practice sessions and, finally, data collection sessions. Training and practice were designed to help the pilots understand their roles and responsibilities during data collection and took approximately four hours to accomplish. The sessions included control interface training (voice control and manual control instructions) while "free-flying" the simulator, auto-target cuer practice, and flying the mission scenario to become familiar with the cockpit tasks and experimental procedures. For conditions which used voice recognition, training concluded with a 30 minute template-building session for the speech recognition system. In addition, pilots were briefed on the Subjective Workload Assessment Technique (SWAT), which was used to collect workload data (Ref 17).

A "part-task" approach was used for training the pilots. During the experiment, the pilots performed nine tasks while flying the aircraft. These were: changing the radio frequency, inputting new latitude/longitude coordinates for a mission redirect, correcting a malfunction in the flight control system, updating Global Positioning System (GPS) coordinates in response to a GPS failure, responding to a pop-up threat, aligning the synthetic aperture radar (SAR) to map the target area, identifying ground targets, designating ground targets, and launching weapons. Each of these tasks was introduced and practiced individually prior to flying the entire mission scenario to give the pilot the opportunity to train each single task repeatedly. Each task was practiced until the subject matter expert (a pilot on the research team) determined that the participant was proficient in completing that task. Criteria used in determining proficiency included correct responses to system changes and task completion without cueing from the research team.

Data collection sessions began after the research team had determined that the pilot was proficient in simulator flying and performing the various tasks with each HCI. Each pilot flew eight simulation runs; four using manual HCI and four using voice HCI in a within-subjects design, i.e. all subjects received all combinations of the independent variables. Presentation order for the independent variables was counterbalanced across pilots and data collection trials.

Mission Scenario

The scenario was a low-altitude, night interdiction mission. The initial mission objectives were to destroy an enemy tank column and then proceed to destroy an enemy petroleum site. The scenario was divided into two segments.

1) During the navigation segment, simulated Airborne Warning and Control radioed new mission objectives to the pilot. These objectives required the pilots to reroute to new Initial Point (IP) and target coordinates and use onboard munitions to destroy enemy aircraft parked at an airfield. The pilot was required to manually fly the simulator and keep the HUD flight path marker centered in the terrain-following (TF) box during the low altitude ingress as the navigation segment primary task. Dependent upon the experimental condition, navigation segment secondary tasks were performed using either the manual or voice interface and required the pilots to: 1) modify the flight route by changing the steerpoint latitude/longitude coordinates, 2) change radio frequencies and 3) respond to various other tasks and instructions. During half of the data collection sessions, the pilots performed data input tasks manually by using the upfront keypad and HOTAS switches. During the other half of the sessions, data input was accomplished by voice interface—the pilots read/recited strings of latitude/longitude coordinates, asked for the desired radio frequencies, and/or asked for the desired display format. Additional independent variables during the navigation segment were: 1) auditory interference—the number of communications into the cockpit which required the pilot to respond, and 2) workload—maintaining TF altitude at either 300 feet or 1000 feet above ground level. Objective measures of performance for data input (speed and accuracy) and for aircraft control (deviations from commanded course, airspeed and altitude) were collected along the fight route.

2) During the weapon delivery segment, the pilots used the head-down displays to view a simulated infrared image of the airfield where fifteen aircraft were parked. As the pilots flew closer to the airfield, their primary task was to find and identify six tanker aircraft out of all the vehicles parked on the airfield, designate them as targets, and launch weapons against them. The weapon delivery segment independent variables were: 1) manual versus voice control of target designation tasks, and 2) auto-target cueing (ATC) versus no auto-target cueing. With the manual interface, the pilots used conventional HOTAS slew and designation switches to assign weapons to targets; with the voice interface, the pilots spoke the appropriate commands to cue and designate the targets for weapons assignment. For the trials with ATC, a symbol (circle) and a number (1 through 15) highlighted each potential target (Ref 18). ATC also provided a "proximity highlight" feature that allowed the pilot to manually designate (using HOTAS) without having to center the targeting pod cursor on a specific target. The cuer symbology of the target closest to the targeting pod cursor, at any given time, was highlighted. This indicated that location coordinates for the highlighted target would be sent to

on-board, directed-attack munitions if a designation was performed. Figure 3 illustrates the target designation task with ATC; target 7 is proximity highlighted. Without ATC (Figure 4), no circles or numbers were shown around any of the aircraft. The pilot slewed the target pod cursor over the desired target and then pressed the designate button. There was no proximity highlight feature; pilots positioned the cursor over some portion of the desired target and then designated. Once designated, a square with a dot in the center marked the position of the designation.

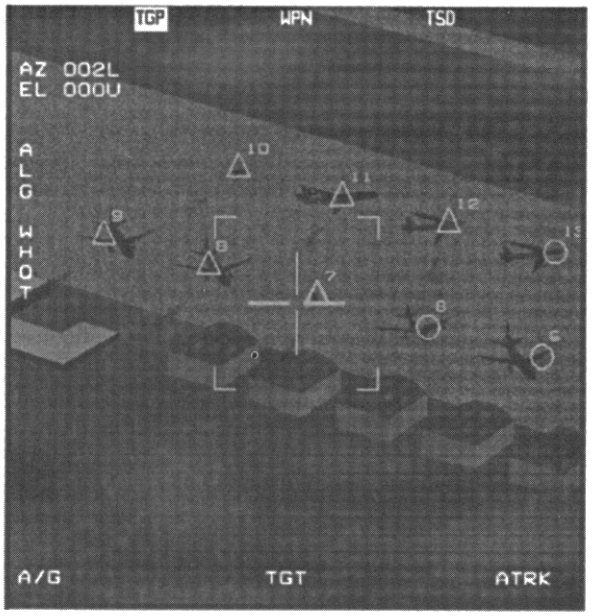

Figure 3. Target Designation Symbology with Auto-Target Cuer (ATC)

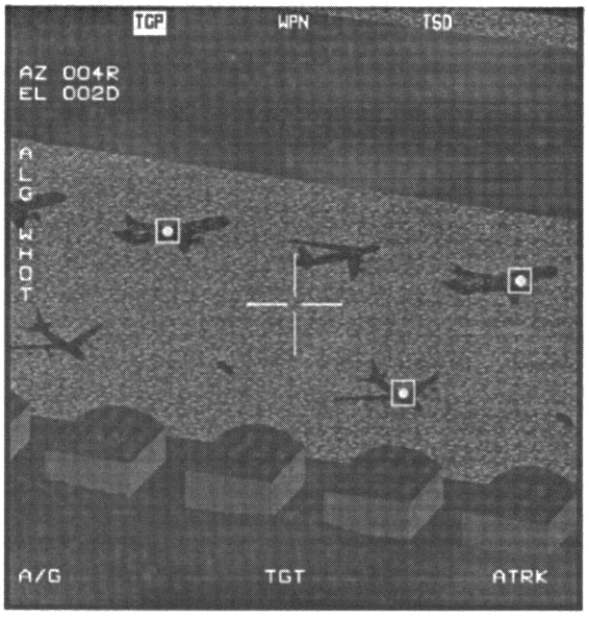

Figure 4. Target Designation Symbology without Auto-Target Cuer (ATC)

For weapon delivery, objective measures of performance included the speed with which pilots could designate targets, the total number of targets correctly designated, and the pilot's distance from the airfield at the time of target designation. Table 1 presents an experimental design overview including the mission segments and their respective tasks and independent variables.

Hypotheses

In general, the use of speech recognition was expected to: 1) improve system effectiveness by decreasing the time required for the pilot to perform mission re-route under high TF Task Load during navigation and by increasing the number of bombs released per pass during the weapon delivery segment, 2) increase pilot ability to multi-task by decreasing the time required to complete the navigation secondary tasks and the weapon delivery primary tasks, and 3) reduce pilot workload by providing a more natural and intuitive interface when compared to the manual interface.

Table 1. Evaluation Overview

Mission Segment/Tasks	Independent Variables
Navigation 1. Primary Task: • manually fly in terrain-following (TF) mode 2. Secondary Tasks: • monitor/respond to radio • change radio frequencies • troubleshoot failures • display reroute info • input reroute data	1. Control Type: • manual • voice 2. TF Task Load: • low: 1000 feet AGL • high: 300 feet AGL 3. Auditory Task Load: • low: lead aircraft + 1 wingman No response required • high: lead aircraft + 4 wingmen Responses required
Weapon Delivery 1. Primary Tasks: • detect, acquire, and designate multiple targets with and without auto-target cuer • release weapons	1. Control Type: • manual • voice 2. Auto-Target Cuer: • present • absent

RESULTS

Summary

Navigation segment results showed that voice recognition significantly improved the speed and accuracy of pilot data input during re-route when compared to manual input. Weapon delivery segment results showed that pilot performance was significantly improved by integrating auto-target cueing features with voice recognition when compared to the manual, throttle-mounted switches. In fact, in all but one of the voice interface cases, pilots were able to correctly designate all six of the tanker aircraft in a single pass on the airfield at significantly greater distances from the airfield than when they used the manual interface.

Navigation Segment

Specific objectives of the navigation segment were:

1. Determine the effects of voice control on the pilot's ability to complete secondary tasks while performing the primary TF flying task.

2. Determine the word error rate of the speech recognition system under simulated operational conditions.
3. Determine pilot acceptability of the mechanization and effectiveness of the speech recognition system.

It was hypothesized that the voice interface would not provide significant improvement in secondary task performance compared to the manual interface during low manual TF Task Load conditions, especially under high Auditory Task Load conditions. However, for high TF Task Load, a significant improvement in secondary task performance was expected with the voice interface. It was further hypothesized that this performance improvement would decrease or become insignificant under high Auditory Task Loading. The accuracy of the speech recognition system was expected to be sufficient so as not to hinder task performance.

To measure these expectations, objective Measures of Effectiveness (MOE) and Measures of Performance (MOP), and subjective Measures of Workload (MOW) and questionnaire data were collected and analyzed for the navigation segment. Descriptions follow:

Navigation Measure of Effectiveness
1. Time to complete the secondary task: Defined as the time interval which started at the onset of a secondary task and ended when all necessary functions had been completed.

Navigation Measures of Performance
1. Flight path control: Commanded flight path, course deviation, and groundspeed data were collected for the manual TF task to determine the acceptability of each data collection run. Pilots were required to keep the flight path marker within the TF box on the HUD, maintain the course displayed on the TSD, and maintain groundspeed of 480 knots. For data analysis, Root Mean Square Error (RMSE) was calculated for each parameter. (Note: Tolerance bands for commanded flight path, course and groundspeed deviation were established to ensure that the pilots treated the flying task as primary. If, while performing a secondary task, a pilot's flight time outside of these tolerance bands exceeded 10% of the total, the data collection trial was repeated.)
2. Communication accuracy: Pilots were required to answer radio calls under high Auditory Task Loads. Response accuracy was monitored by a subject matter expert to determine if performance was commensurate with procedures that would be followed during actual "check-ride" situations. Although this "commensurate-ness" was a subjective measure, the goal was to ensure that the pilots responded in a manner to signify that the message was heard and understood.
3. Speech recognition error rate: Word recognition error rate was collected to evaluate system performance.

Navigation Measures of Workload
1. The Subjective Workload Assessment Technique (SWAT) was used to collect pilot workload data. During navigation, three separate SWAT measurements were collected at unobtrusive points along the route and the resultant SWAT values were analyzed using the sum-percent method (Ref 19).

Navigation Questionnaire Data
1. Subjective data regarding voice interface effectiveness, acceptability, and mechanization was collected via a post-mission interview and a post-study questionnaire.

Navigation Analysis
Statistical comparisons of the performance levels and workload ratings, using Multivariate Analysis of Variance (MANOVA) techniques, were performed against the three independent variables: Control Type, TF Task Load, and Auditory Task Load. Replication was collapsed across all conditions and post hoc Analyses of Variance (ANOVA) and Tukey's multiple pairwise comparisons were performed on the significant effects to identify the nature of the statistical differences. For the questionnaire ratings, frequencies and averages were computed and non-parametric statistical tests were performed to compare differences in questionnaire response means. The SWAT values were analyzed using the sum-percent method (Ref 19), which combines the traditional workload elements associated with time, mental effort, and psychological stress into a scale from zero to one-hundred.

Navigation Results
For the mission rerouting task, the main effect of Control Type was significant ($F[1,11] = 6.77$, $p < .05$). By using the voice interface, pilots completed the rerouting task almost 14 seconds quicker that when using the manual interface.

Although all of the flight performance parameters met the predefined performance criteria, the analysis showed a significant two-way interaction for Control Type × Auditory Task Load ($F[1,11] = 7.01$, $p < .05$). Post hoc tests of this two-way interaction showed that: 1) during low Auditory Task Loading, Control Type had no effect on TF performance during rerouting, but 2) during high Auditory Task Loading, pilots more accurately followed the TF cue when using the voice interface to accomplish rerouting than when they used the manual interface.

More importantly, the three-way interaction for Control Type × Auditory Task Load × TF Task Load was also significant ($F[1,11] = 4.72$, $p < .05$). It showed that: 1) during low Auditory Task Loading and regardless of Control Type, pilots flew the TF task more precisely in the low TF Task Load condition than in the high TF Task Load condition during rerouting (Figure 5), and 2) during high Auditory Task Loading, using the voice interface for rerouting decreased TF deviations compared to the manual interface when TF Task Loading was high, but had no effect on TF deviations when TF Task Loading was low (Figure 6).

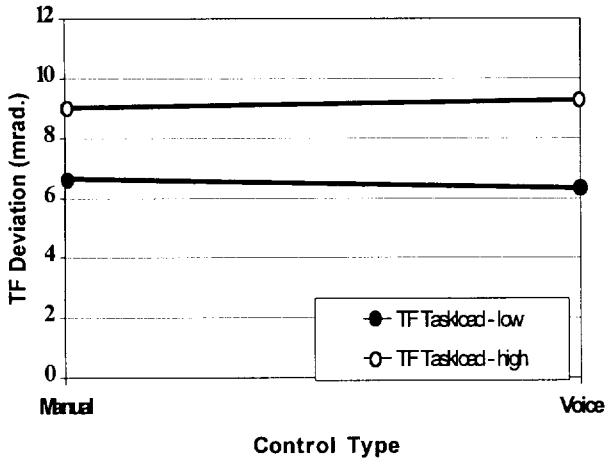

Figure 5. Terrain Following (TF) Deviation during Navigation as a Function of Control Type With Low Auditory Task Load

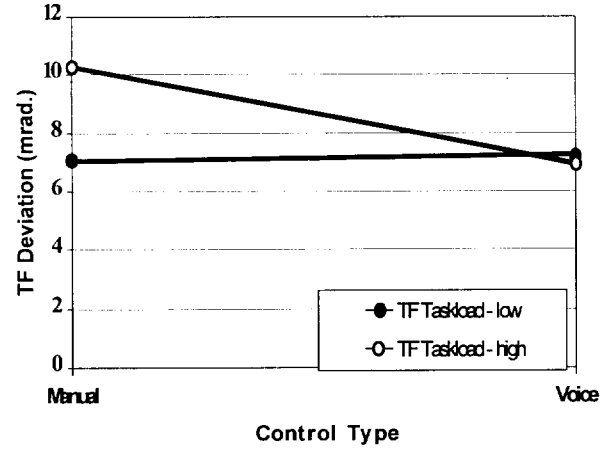

Figure 6. Terrain Following (TF) Deviation during Navigation as a Function of Control Type With High Auditory Task Load

In regard to workload during rerouting, there was a significant two-way interaction for Control Type × TF Task Load ($F[1,11] = 4.84$, $p < .05$). Post-hoc tests showed that: 1) during high TF Task Loading, when the voice interface was used to accomplish mission rerouting, it decreased pilot workload by 31% compared to using the manual interface, and 2) during low TF Task Loading, Control Type had no effect on rerouting. During high TF Task Loading, the pilots' average SWAT ratings to reroute the mission dropped from a 39 with the manual interface to a 27 with the voice interface, whereas during low TF Task Loading, pilots' average SWAT ratings remained virtually constant at 34.

Pilot questionnaire responses confirmed that the voice interface was significantly more effective in completing the mission reroute than the manual interface. The effectiveness scale ranged from 1 (Poor) to 5 (Very Good). Across pilots, the manual interface was rated as neither a hindrance nor an advantage for accomplishing the reroute task (average rating = 3.2). Across pilots, the voice interface was rated as highly effective for accomplishing the task (average rating = 4.8).

Figure 7 illustrates the incidence of three types of speech recognition errors for the navigation segment: insertions, deletions, and substitutions. Insertions are errors where the voice system inserts commands that the pilot did not speak. Deletions are errors where the voice system did not recognize what the pilot correctly spoke and took no action. Substitutions are errors where the voice system misrecognized what the pilot spoke and executed the wrong command. The figure illustrates the voice interface error rate during the navigation segment for nine of the twelve pilots—data from three pilots were not recorded. The figure shows voice interface error rate overall averaged 2.2%.

Many of the errors were "single-repeat" errors. These were recognition errors that were resolved with a single repeat of the command. Most of these single repeat errors could have been avoided through more extensive voice template training, so another analysis was performed on an adjusted data set in which these errors were removed. This analysis revealed that voice interface overall average error rate drops to 0.6% and is also shown in the figure.

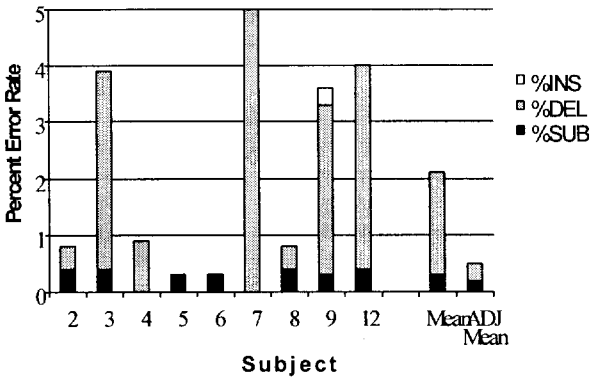

Figure 7. Voice Interface Error Rate (%) for the Navigation Segment

Other tasks during the navigation segment in which the voice and manual interfaces were compared included: 1) correcting system malfunctions, and 2) changing radio frequency channels to place radio calls. For changing radio frequencies—a task similar in nature to rerouting in that a string of alphanumerics was entered into the simulator, the voice interface improved pilots' speed and accuracy to accomplish the task compared to the manual interface ($F[1,11] = 7.63$, $p < .05$). However, the improvement was less than what the voice interface provided for the mission rerouting task. For one system malfunction—flight control pitch fault—voice and manual interfaces demonstrated no differences for accomplishing the pitch fault reset task; for another malfunction—Global Positioning System (GPS) failure—the voice interface increased the time to complete the GPS failure task compared to the manual interface. Possible reasons for these results will be explained in the discussion section.

Weapon Delivery Segment

Specific objectives of the weapon delivery segment were:

1. Determine the effects of voice control on the pilot's detection, acquisition, and weapon delivery performance with and without auto-target cuer (ATC) while attacking multiple targets during a single pass.
2. Determine the word error rate of the Verbex Portable speech recognition system under simulated operational conditions.
3. Determine pilot acceptability of the mechanization and effectiveness of the speech recognition system.

It was hypothesized that incorporating the voice interface alone would not provide significant performance or workload improvement over the manual interface. However, when mechanized with an ATC, the voice interface was expected to provide significant performance and workload improvement over manual interface alone and manual interface with ATC.

To measure these expectations, similar MOEs, MOPs, and MOWs to those identified for the navigation segment were collected and analyzed. Descriptions follow:

Weapon Delivery Measures of Effectiveness

1. Range to first target: Defined as the distance from the aircraft to the center of the airfield at the time of the first correct designation.
2. Range to last target: Defined as the distance from the aircraft to the center of the airfield at the time of the last correct designation.
3. Target designation rate: The amount of time spent designating per the number of correct target designations.
4. Target designation accuracy: The total number of correct targets designated per total number of designated targets for each trial.

Weapon Delivery Measures of Performance

1. Flight path control: Course and groundspeed data were collected to evaluate aircraft control performance. Pilots were instructed to maintain the course displayed on the TSD and maintain groundspeed of 480 knots. RMSE was calculated for each parameter.
2. Speech recognition error rate: Word recognition error rate was collected to evaluate system performance.

Weapon Delivery Measures of Workload

1. As in the navigation segment, SWAT was used to collect pilot workload data. One SWAT measurement was taken per pilot after completion of the weapon delivery segment.
2. On the post-study questionnaire, pilots were also asked about voice interface effectiveness and mechanization as applied to weapon delivery.

Weapon Delivery Analysis

Statistical comparisons of the performance levels and workload ratings using MANOVA were performed against the two independent variables: Control Type and Auto-target Cueing. Replication was collapsed across all conditions and post hoc Analyses of Variance (ANOVA) and Tukey's multiple pairwise comparisons were performed on the significant effects to identify the nature of the statistical differences. For questionnaire ratings, frequencies and averages were computed and non-parametric statistical tests were performed to compare differences in questionnaire response means. As in the navigation segment, the SWAT values were analyzed using the sum-percent method (Ref 19).

Weapon Delivery Results

For weapon delivery, the main effect of Control Type was significant ($F [1,11] = 5.68$, $p < .05$) for airspeed deviation: MANOVA results showed that pilots had greater deviations from the designated airspeed of 480 knots when using the voice interface for target designation than when using the manual interface.

MANOVA analysis also showed a significant two-way interaction for Control Type × ATC ($F [1,11] = 4.79$, $p < .05$) for the time required to designate each target. Post hoc analysis showed that: 1) without ATC, Control Type had no significant effect on target designation rate, 2) with ATC, target designation rate was significantly faster with the voice interface than with the manual interface, and 3) target designations were accomplished more quickly with ATC than without ATC regardless of the Control Type. The weapon delivery two-way interaction is depicted in Figure 8.

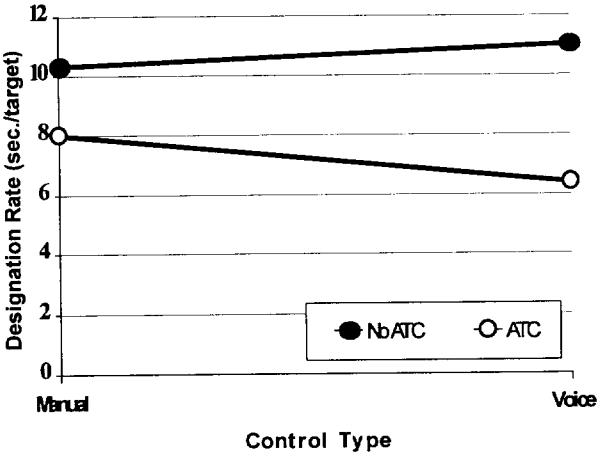

Figure 8. Target Designation Rate during Weapon Delivery as a Function of Control Type With and Without Auto-Target Cueing

MANOVA results also showed a significant Control Type × ATC interaction for workload ($F [1,11] = 4.73$, $p < .05$). Post hoc tests showed that: 1) without ATC, Control Type had no effect on pilot workload, and 2) with ATC, average pilot workload ratings for using the voice interface were 22% lower (average rating = 46) than those for the manual interface (average rating = 59). The weapon delivery workload results are depicted in Figure 9 (next page).

Results of the weapon delivery questionnaire data were consistent with the navigation segment questionnaire data. During weapon delivery, pilots rated the voice interface combined with the auto-target cuer as most effective for identifying targets when compared to the manual or voice interfaces alone or the manual interface combined with ATC. For designating targets, pilots rated both control types effective regardless of whether or not ATC was used, but they rated their performance most effective and gave their highest ratings for the voice interface combined with ATC.

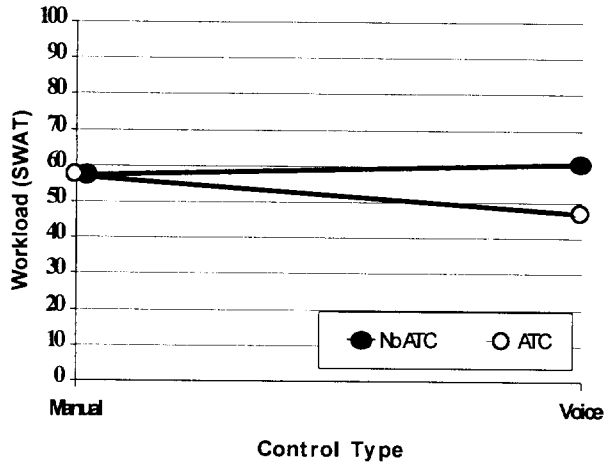

Figure 9. Pilot Workload during Weapon Delivery as a Function of Control Type With and Without Auto-Target Cueing

Figure 10 illustrates the speech recognition error rates for weapon delivery. Insertions, deletions, and substitutions (see navigation segment for descriptions of these error types) are shown for nine of the twelve pilots. The voice interface had an overall error rate during weapon delivery of 3.9%.

The figure shows that subject two contributed a relatively large number of insertion errors. The reduction in the insertion error rate for subsequent subjects was due to a change made in the voice interface mechanization. This will be referenced in the Discussion section. When the single-repeat errors were removed from the data set, the adjusted overall mean error rate dropped to 1.9%.

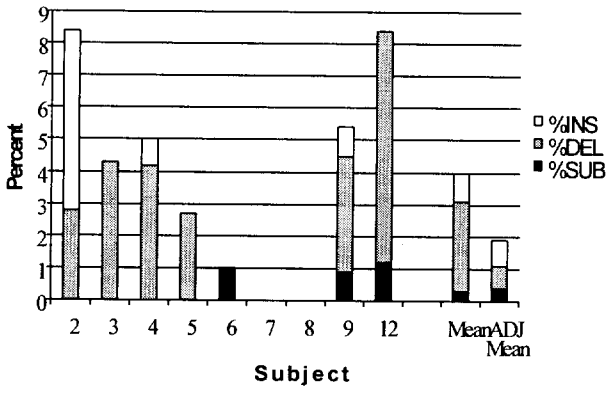

Figure 10. Voice Interface Error Rate (%) for the Weapon Delivery Segment

DISCUSSION

Navigation Segment

It was hypothesized that voice control would enhance secondary task performance when the pilot was under the visual and manual demands imposed by the high manual Terrain Following Task Loading. It was also hypothesized that the high Auditory Task Loading would interfere with the pilot's ability to perform the secondary tasks using voice control. A secondary purpose of the experiment was to determine if voice control could act as a viable substitute for some manual tasks, so it was of interest when no differences in performance were found between voice and manual control conditions.

The results showed that voice control decreased the amount of time it took to complete the mission reroute task and the radio frequency change task. Mission reroute results further showed that voice control reduced workload under high TF Task Loading conditions. Finally, the subjective data analysis showed that pilots rated the voice control interface as significantly more effective than the manual control interface for mission reroute and radio frequency change tasks. At least two factors may have contributed to these results. First, the voice interface enabled the pilots to multitask more efficiently than was possible with the manual control interface. This is consistent with the hypothesis that voice control reduces competition for human resources such as visual attention or manual control actions. When applied appropriately, voice control may aid in distributing task demands across the operator's visual, manual, and voice/auditory resources, thereby aiding the pilot in dividing attention among the concurrent tasks. Second, voice control simplified the data entry tasks by reducing the number of control actions required to complete the task. When these tasks were performed manually, mission rerouting required 39 and radio frequency changes required 7 key strokes to complete. Voice implementation required only 8 and 1 utterances respectively. This reduction was achieved by grouping many of the serial keystrokes into spoken strings.

The results also showed that the voice interface increased the time to complete the GPS failure task, but had no effect on pilot performance of the Pitch Fault task. The characteristics of these tasks provide some insight into these results. In both tasks, manual switch hits were replaced with voice commands on a one-for-one basis. Also, control feedback for each switch hit was provided visually for the manual interface and visually and auditorally for the voice interface. Several sources of time delay are possible for the voice implementation. First, the pilot was required to press a switch to talk to the voice system, and follow this action with a voice command. At least two actions were required, then, when a single manual switch hit was replaced with a voice command. Second, it often takes more time to speak a one or two word command than to manually activate a switch, especially if the switch is immediately accessible, such as in HOTAS. Third, the voice messages which were provided as feedback to voice commands were serial in nature and took more time to present than the visual feedback, which was displayed immediately. If pilots chose to wait for the verbal feedback rather than rely on the visual feedback, their task times would have necessarily been increased. Although voice feedback during the GPS failure was not extensive, it is possible that it contributed to the difference. Finally, because speech recognition systems are not 100% accurate, one would expect to see more errors with a voice interface than with a manual interface, even if the correct input (or voice command) is made by the pilot. In fact, the voice command "Mark," which was used during the GPS failure task, yielded the highest observed deletion error rate (20%). The need for pilots to repeat this command undoubtedly increased the average task completion time.

While these four potential sources of time delay may increase task performance time, the results also show

that they will not always do so (such as with the Pitch Fault task). It is clear that the effect of these time delays is highly dependent upon the specific nature of the task and the pilot's strategy in performing the task, and, in some cases, may be so small as to be undetectable and inconsequential.

Although statistically significant differences were found in the analysis of aircraft flying performance, all pilots were able to stay within the prescribed performance criteria. With the exception of course deviation during the GPS failure task, all significant differences show that the voice interface yielded performance better than or equal to the manual. This result further supports the notion that voice, when implemented properly, can facilitate pilot performance in a multitasking environment by reducing resource competition. More specifically, using the voice system may have enabled the pilots to allocate more attention to critical flight displays (i.e., the terrain following guidance symbology) by reducing the visual demand associated with the secondary tasks.

An unexpected result of the navigation segment was the lack of significant effects for Auditory Task Loading. The performance data indicated that voice control was equally effective (or ineffective) regardless of the level of Auditory Task Load. However, several pilots commented in the questionnaires that using voice had the potential to interfere with their ability to monitor radio communications.

Finally, many of the statistical comparisons performed on the performance and subjective data from the navigation segment yielded no statistically significant differences. Overall, then, the navigation results indicate that voice is a viable control method that can serve to compliment or relieve an overloaded manual control interface. The results also indicate that, when implemented to take advantage of the automated processing characteristics of voice, voice control can enhance performance. Conversely, voice does not improve—and may actually hinder—performance when used for single switch-hit tasks that are easily accomplished via HOTAS.

Weapons Delivery Segment

It was hypothesized that incorporating the voice interface by itself would not provide significant performance or workload improvement over the manual interface. However, when mechanized with an ATC, the voice interface was expected to provide significant performance and workload improvement compared to the manual interface alone and the manual interface with ATC.

The results verified the hypotheses and showed that the pilots were able to designate targets more quickly using voice control coupled with the ATC than with manual control coupled with the ATC. Further, pilots reported a decrease in workload when using the voice versus manual interface in combination with the ATC.

These differences can be attributed to the voice mechanizations of the cueing and target designation functions. The cueing function allowed the pilot to automatically slew the targeting pod onto any target by saying "cue" and then the target number. Once the target was cued, it could be designated by commanding "designate (target number)"; if desired, the pilot could designate up to three targets at a time using this method, e.g. "designate targets *x*, *y*, *z*". This mechanization provided immediate, "random" access to desired targets. With the manual interface, on the other hand, pilots were required to slew the target pod across the airfield to locate the desired target. Once located, additional slewing was required to precisely position the cursor on the desired target (without ATC) or slew the cursor such that the desired target was highlighted (with ATC proximity highlight feature). The additional slewing associated with the manual interface was significantly more time-consuming than the voice interface method.

After removing subject two's data, the largest sources of error during weapon delivery were substitutions and deletions. Although both types of error only occurred 0.4% of the time, it can still be accounted for. Closer examination of the data showed that the substitution errors occurred when designating multiple targets. The voice control mechanization prior to subject three allowed pilots to designate up to six targets in a single utterance. It was found that the voice recognizer was confusing phrases such as "Designate Fourteen, Eight, One" as "Designate Eight, Four, Ten, Eight, One". It would designate five targets instead of three. When the system was limited to three designations, it "knew" that the latter phrase was invalid. Further software modifications also enabled the voice recognizer to eliminate certain words as possible matches due to context. Since the pilot was designating, the voice recognizer could exclude any words not associated with designating (such as "Flares" being substituted for "Five"). This is an example of the Verbex's ability to take advantage of selective vocabularies.

Deletion errors during weapons delivery were attributed to the voice recognizer not being able to match the verbal command(s) to any commands in the template. In fact, the deletion error rate was the predominant cause of errors throughout the entire experiment. These deletion errors can be substantially decreased with more aggressive and repetitive training of the voice templates for "problem words".

LESSONS LEARNED

This experiment offered a variety of lessons learned for future voice control implementations. The lessons learned are based upon experimenter observations and a synthesis of the objective results.

1) An extensive vocabulary was developed with the aid of several pilot subject matter experts, who attempted to make it as intuitive as possible. However, commonly used terminology for some functions and systems vary across different aircraft platforms, and therefore across pilots. To account for this, designed-in software flexibility enabled the pilots to use terminology that was most familiar to them. But even with this precaution, several cases were observed where pilots had difficulty remembering the command or syntax associated with some functions. In these cases, performance obviously suffered, and the limitations of the vocabulary detracted from the intuitiveness of the interface. To minimize such effects, voice commands should be simple, consistent across different functions, and easy for the user to remember.

2) For many of the tasks, the voice interface was implemented as a one-for-one replacement of manual switch actions. This was done to facilitate an "apples to apples" comparison of voice and manual control techniques, and to allow an assessment of the ability of voice control to reduce resource competition in

multitasking conditions. The design team recognized that this approach did not take advantage of using voice "macros" to simplify the interface. Voice macros offer the potential of executing a long string of switch actions through a single voice command. The performance advantages of macros are obvious, and should be considered during voice interface design.

3) When integrated into a cockpit, voice control should be incorporated only as a redundant method. This will allow pilots to choose the most compatible control method for a given situation and will prevent interference between voice control and radio communications tasks. It also offers the pilot an alternative in the event of degraded speech recognition performance.

4) Using voice control for single HOTAS switch actions should be approached with caution. As shown here, performance may be degraded for such applications for a variety of reasons. On the other hand, voice can be a good alternative to HOTAS when the manual control interface is overloaded and during heavy multitasking situations. Replacement of single manual switch hits with voice commands should be considered when these conditions exist.

5) Initial integration of voice feedback in response to voice commands was extensive during pre-experimental check-out. Feedback—such as repeating the "entered-in" radio frequencies and steerpoint coordinates—proved operationally ineffective and added no value to the interface. In fact, the initial voice feedback design substantially increased task completion times for voice control because pilots had to wait for the voice feedback before issuing the next command. Voice feedback should be used only when it increases pilot performance and/or situation awareness.

6) Finally, speech recognition error rate can be decreased by using selective vocabularies. For example, when changing radio frequencies, the voice recognizer should reference a separate template with that specific vocabulary. Speech recognition error rate can also be decreased through repetitive training of the voice templates of "problem words". This will give the voice recognizer a greater chance of matching what the pilot says with the proper command in the template. Even with just limited use of these two methods, the overall speech recognition error rate for this experiment was held to around 1%!

CONCLUSION

In this experiment, voice control was found to be a viable control method for single seat fighter cockpits. On the plus side, for most tasks, voice provided at least equivalent performance to the manual control interface. However, the effectiveness of voice will also depend upon the nature of the tasks, the voice implementation and software architecture, and the context in which it is used. Where the voice implementation takes advantage of well-learned behaviors (e.g., reading strings of alphanumerics), or can reduce the number of command inputs required to complete a task, performance is enhanced and workload is reduced. Voice also has benefits under multitasking conditions, where it reduces resource competition by offering an alternative data entry/control method when the pilot's hands and eyes are busy. Voice also showed significant performance improvements when it was combined with automatic target cuer symbology and mechanized to enable the pilot to directly access (target cue function) and select (target designate function) critical information (targets) on a display.

On the minus side, a voice interface has the potential to degrade performance and increase workload when used to replace single switch hits that would normally be easily accessible, e.g. via HOTAS. Also, pilot comments indicated that a voice interface may interfere with radio communications monitoring.

Even with the potential shortcomings of voice control, pilots unanimously stated that they would want speech recognition capability in the cockpit. They commented that it allowed them to stay head-up and "do several things at once" while simultaneously reducing workload—especially during keyboard entry tasks. Furthermore, and somewhat unexpectedly, pilot acceptance of voice control was very high and this acceptance would be key to successfully integrating any new technology in cockpits.

As with any conceptual research, the results are highly dependent upon the specific evaluation design and technology baseline, and the conditions under which the testing occurred. For example, voice may not be advantageous when used to replace discrete switch hits, but may be highly effective when combined with other advanced technologies, such as decision aids or automated subsystems, that facilitate the use of voice "shortcuts" (such as the automatic target cuer in this experiment). Similarly, in this experiment, voice was used in an artificial environment that attempted to induce high workload, multitasking, high visual and manual task loading and/or high auditory task loading on the pilot. The results may have been significantly different in a more benign task environment or with different workload "inducers". These factors must be taken into account when generalizing the results of this experiment to other cockpit applications.

The author gratefully acknowledges the human factors, pilot expertise, experimental design and data analysis support provided by Veda, Incorporated under United States Air Force Contract F33615-93-D-3800 and the hardware fabrication and maintenance services provided by UNC-Lear Support Services under United States Air Force Contract F33601-93-D-J019. Government software development and configuration management for this experiment were provided by Mr. Gregory Feitshans (AFRL/HECI) and Mr. David Williamson (AFRL/HECA). The author sincerely appreciates their ideas and recommendations for conducting the experiment and for designing an effective cockpit voice interface. The success of this experiment is in very large measure a result of their tireless effort and commitment.

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THE EFFECTS OF IMAGE RESOLUTION ON THE UTILITY OF TARGET RECOGNITION AIDS

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ABSTRACT

To enable aircraft to respond to time-critical targets during a mission, efforts are underway to develop systems that provide pilots access to imagery-based information from offboard sources. Previous research has shown that annotated imagery of the target area improves target recognition, and that the usefulness of Imagery-Based Target Recognition Aids (IBTRAs) depends on factors such as viewpoint, image complexity, and coverage. This report describes a study that compared the utility of IBTRAs generated from high-resolution and low-resolution databases and identified the impacts of each on operator target recognition performance. Differences in performance were found for both the high- and low-resolution imagery caused by variations in the sensor distance from the target area and by the cross-range extent of the image. The best performance, both in speed and accuracy, was observed when the cross-range extent of the IBTRA was similar to that of the sensor image. IBTRAs developed from high-resolution data provided a significant increase in target recognition accuracy at all reference image cross-range extents when used with imagery taken close to the target. The operational significance of these findings is dependent on the scenario; for a weapon release relatively close to the target, the use of IBTRAs generated from high-resolution data may be of greater value than for a weapon release from longer ranges. A model is presented that describes target recognition performance as a function of the cross-range extent of the imagery being used.

INTRODUCTION

In recent years efforts have begun to develop various systems which would provide pilots with access to imagery-based information from either ground stations or other airborne platforms. As currently envisioned, aircraft would be redirected after takeoff in response to newly discovered time-critical threats. The planning for these new missions would be conducted at a remote ground station and, upon completion of planning, the information needed for a successful attack would be transmitted to the pilot in the aircraft. Upon receiving this information, the pilot would alter course and attack the newly assigned target.. The utility of imagery in improving target recognition was verified in the research described in reference 1. Further research (references 2, 3, and 4) however, has indicated that the usefulness of Imagery Based Target Recognition Aids (IBTRA's) depends on many factors including viewpoint, image complexity, and coverage.

The study described in reference 4 demonstrated that one of the critical parameters affecting the utility of IBTRA's was the area of coverage provided in the image. The IBTRA's used in reference 4 were generated from an image database with a resolution of 30 feet per datum. However, examination of the IBTRA's used in that study revealed significant degradation in image quality when producing IBTRA's of limited cross-range extent. While unavoidable, this raised the question of whether generating the IBTRA's from a high resolution database would significantly improve performance. The purpose of the study described in this

Paper presented at the RTO SCI Symposium on "Sensor Data Fusion and Integration of the Human Element", held in Ottawa, Canada, 14-17 September 1998, and published in RTO MP-12.

report was to compare the utility of IBTRA's generated from high resolution sources with those generated from low resolution sources and identify the impacts which these sources would have on operator target recognition performance. There are currently two classes of "high resolution" databases available. The first includes databases containing imagery which is created from high resolution sources. The second type are collected from sources with lower resolutions and then post processed to produce a database which contains interpolated values for points not contained in the original imagery. The imagery contained in these "interpolated databases" are of inherently lower and users of digital data must take care to ensure that the type of database selected will meet the needs of the intended application.

METHOD

Participants

The participants for this experiment consisted of thirty male and female employees of the NAWCWPNS.

Equipment

The experiment console for this study was implemented on a 166 MHz Pentium computer. The imagery was stored in digital format on the local hard disk and was displayed on a Mitac 17-inch monitor. The monitor resolution used for the experiment console was 1280 pixels wide by 1024 pixels high. This resolution was chosen because it provided a pixel density (number of pixels per inch) close to that of a tactical aircraft display.

Stimuli

FLIR Imagery

The sensor imagery used in this study was culled from videotapes recorded in the local area during exercise and training flights using a Forward Looking Infrared (FLIR) system. The FLIR imagery was categorized as either "close", "medium", or "far" based on the range from the FLIR sensor to the target. Since the actual ranges for the FLIR imagery used in this study were unavailable, the cross-range extent of each image was measured directly from the image. The term "cross-range extent" as used in this report refers to the distance between the two points on the ground displayed at the opposite center points of the vertical sides of the image. The "close" FLIR imagery had cross-range extents varying from 0.5 miles to 0.75 miles. The "medium" images included cross-range extents from 1 miles to 2 miles. The cross-range extents of the "far" images varied from 3 miles to 4 miles. FLIR images with cross-range extents which did not fit one of these categorizations were not used.

Reference Imagery

The low resolution reference scenes were extracted from commercially available SPOT imagery. This product has a resolution of 10 meters per datum. For each target used in the experiment, a plan view image was generated for each of five cross-range extents: .25 miles, .5 miles, 1.5 miles, 3.5 miles, and 5 miles. The high resolution reference scenes were extracted from United States Geologic Survey (USGS) aerial reconnaissance imagery. This is a film product and was digitized by use of a high resolution drum scanner. The resulting digitized imagery has a resolution of 3 feet per datum. For each target used in the experiment, a plan view image was generated for each of four cross-range extents were: 0.125 miles, .25 miles, .5 miles, and 1.5 miles. The resolution of the reference images was 500 pixels vertically and horizontally and the images were displayed at a resolution of approximately 100 pixels per display inch.

Procedure

Description of the Experimental Task

The task during the experiment trials consisted of a target recognition task. In each trial for this task, the subjects were presented with two images; a FLIR image (either close, medium, or far) and a reference image. In each reference image a target was indicated by a box circumscribing the object, which the subjects were required to locate in the FLIR image. The subjects indicated their response in this task by placing the mouse cursor over the location of their choosing in the FLIR image and pressing the left mouse button. The subjects were allowed to take as much time as they needed to designate the target. The data collected for this task consisted of the location of the mouse when the subjects indicated their choice and the time which had elapsed since the onset of the images.

Design

This study was structured as three separate sub-experiments. The first consisted of two fully crossed within factors; FLIR sensor distance with 3 levels (close, medium, and far) and low resolution reference image extent with 5 levels (.25, .5, 1.5, 3.5, and 5 miles). The second consisted of two within fully crossed factors; FLIR sensor distance with the same 3 levels and high resolution reference image cross-range extent with four levels (.0125, .25, .5, and 1.5 miles). The third consisted of three fully crossed factors; one between factor, database resolution, with 2 levels (high and low), and two within factors; FLIR sensor distance, with 3 levels (close, medium, and far) and reference image cross-range extent, with three levels (.25, .5, and 1.5 miles). The additional FLIR sensor distance for the high resolution cross-range extents (0.125 miles) was included to permit examination of any shifts in performance which might be observed in relation to the use of the high resolution images.

RESULTS

Analysis of the Low Resolution Data

Speed

The response times for the low resolution cases were tabulated and subjected to an Analysis of Variance (ANOVA). The results of the analysis indicated that there were significant main effects for both FLIR sensor distance (FSR) ($F2,28 = 6.65$, $p < 0.0043$) and reference image cross-range extent (CRE) ($F4,56 = 3.25$, $p < 0.0181$). There was also a significant interaction between FSR and CRE ($F8,112 = 3.46$, $p < 0.0013$). Further analysis indicated that the Far FSR condition was significantly different from the Close and Medium FSR conditions ($F1,14 = 79.25$, $p < 0.0009$) but that the Close and Medium conditions were not significantly different from each other. Analysis also indicated that response times for the 0.5 mile and 5.0 mile CRE conditions were significantly different from the response times for the 0.25 mile, 1.5 mile, and 3.5 mile CRE conditions ($F1,14 = 8.04$, $p < 0.0132$). The results of this analysis are presented in figure 1.

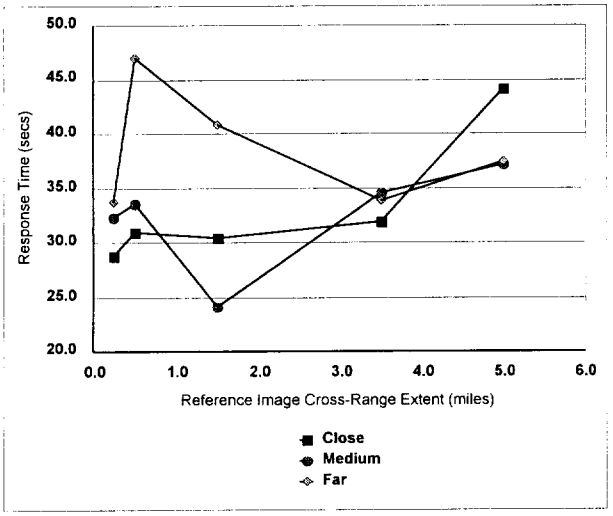

Figure 1. Response Time as a function of Reference Image Cross-Range Extent and FLIR Sensor Distance for the Low Resolution Data

Accuracy

The percentages of correct responses for the low resolution cases were tabulated and subjected to an ANOVA. The results indicated that there were significant main effects for FSR ($F2,28 = 15.98$, $p > 0.00001$), CRE ($F4,56 = 6.24$, $p < 0.0003$), and a significant interaction between the two ($F8,112 = 4.14$, $p < 0.0002$). Contrasts indicated that the accuracies for the Close and Medium FSR conditions were not significantly different but that the percentages of correct responses for these two condition were significantly different than those for the Far FSR condition ($F1,14 = 34.16$, $p < 0.00001$). Further analysis indicated that the observed accuracies divided into three groups with respect to CRE. The first group included the 0.25 mile and 3.5 mile CRE conditions which differed significantly from the 5.0 mile CRE condition ($F1,14 = 4.78$, $p < 0.0462$) and from the group containing the 0.5 mile and 1.5 mile CRE conditions ($F1,14 = 10.42$, $p < 0.0061$). The results of this analysis are presented in figure 2.

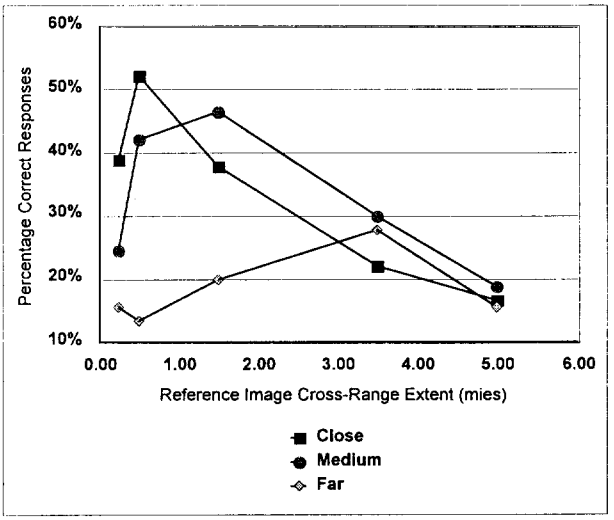

Figure 2. Percentage Correct Responses as a function of Reference Image Cross-Range Extent and FLIR Sensor Distance for the Low Resolution Data

Analysis of the High Resolution Data

Speed

The response times for the high resolution cases were tabulated and subjected to an ANOVA. The results of this analysis indicated that there were main effects for FSR ($F2,13 = 12.61$, $p < 0.0001$) and CRE ($F3,42 = 4.28$, $p < 0.0101$) and a significant interaction between FSR and CRE ($F6,84 = 2.32$, $p < 0.0404$). Contrasts indicated that there was a significant difference between the response times for the Close and Medium FSR conditions ($F1,14 = 20.20$, $p < 0.0005$) but only a marginal difference between the response times for the Medium and Far conditions ($F1,14 = 4.42$, $p < 0.0541$). Further analysis indicated that the response times divided into two groups with respect to the CRE conditions. Significant differences were found between the response times for the first group (which consisted of the 0.125 mile and 0.25 miles CRE conditions) and the second (which consisted of the 0.5 mile and 1.5 miles CRE conditions) ($F1,14 = 7.15$, $p < 0.0182$). The results of this analysis are presented in figure 3.

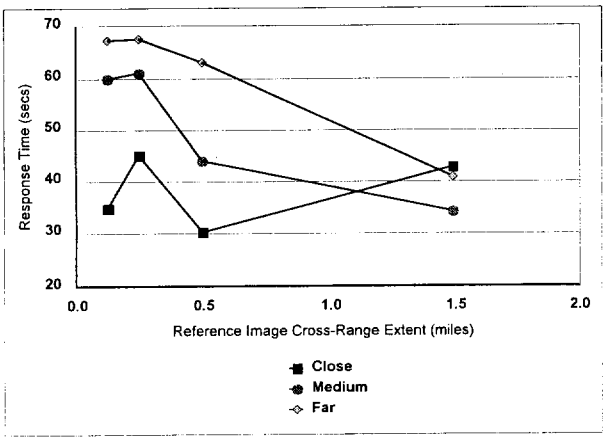

Figure 3. Response Time as a function of Reference Image Cross-Range Extent and FLIR Sensor Distance for the High Resolution Data

Accuracy

The accuracies for the high resolution cases were tabulated and subjected to an ANOVA. The results indicated that there were significant main effects for FSR ($F_{2,28 - 145}$, $p < 0.00001$) and CRE ($F_{3,42} = 3.07$, $p < 0.0382$) and a significant interaction between the two ($F_{6,84} = 5.54$, $p < 0.0001$). Further analysis indicated that there were significant differences between the accuracies for all three FSR conditions (Close v. Medium: $F_{1,14} = 40.19$, $p < 0.00001$ Medium v. Far: $F_{1,14} = 127.88$, $p < 0.00001$). Contrasts also indicated that the accuracies for the 0.125 mile CRE condition were significantly different from the rest ($F_{1,14} = 4.78$, $p < 0.0462$), but that the accuracies for the 0.25 mile, 0.5 mile, and 1.5 mile conditions did not significantly differ from each other. The results of this analysis are presented in figure 4.

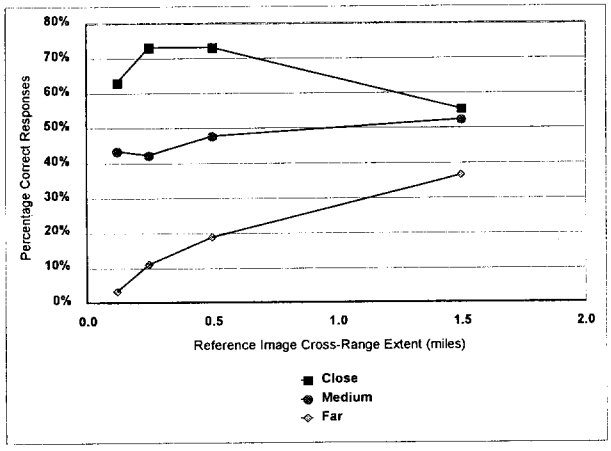

Figure 4. Percentage of Correct Responses as a Function of Reference Image Cross-Range Extent and FLIR Sensor Distance for the High Resolution Data

Comparison of the High and Low Resolution Data

The following analyses were conducted on those FSR and CRE conditions which were observed for both the high and low resolution conditions. The common FSR conditions included Close, Medium, and Far. The common CRE conditions included 0.25 miles, 0.5 miles, and 1.5 miles.

Speed

The response times for the common conditions for the high and low resolution cases were tabulated and subjected to an ANOVA. The results of this analysis indicated that there were main effects for FSR ($F_{2,56} = 27.69$, $p < 0.00001$) and CRE ($F_{2,56} = 4.34$, $p < 0.0176$). There were also two significant two-way interactions; Resolution (RES) x CRE ($F_{2,56} = 5.59$, $p < 0.0061$) and FSR x CRE ($F_{4,112} = 5.20$, $p < 0.0007$), and a marginally significant three-way interaction: RES x FSR x CRE ($F_{4,112} = 2.42$, $p < 0.0522$). Contrasts indicated that there was a significant effect for CRE at the Medium and Far levels of FSR (Medium: $F_{2,56} = 6.15$, $p < 0.0039$, Far: $F_{2,56} = 5.85$, $p < 0.0049$) and a significant interaction between RES and CRE at the Far FSR level ($F_{2,56} = 7.83$, $p < 0.0010$). Further analysis indicated that there were significant effects for FSR at each level of CRE (0.25 mile: $F_{2,56} = 7.96$, $p < 0.0009$, 0.5 mile: $F_{2,56} = 16.13$, $p < 0.00001$, 1.5 mile: $F_{2,56} = 7.14$, $p < 0.0017$) and a significant interaction between FSR and RES at the 0.25 mile level for CRE ($F_{2,56} = 3.21$, $p < 0.0481$). Simple effects comparisons indicated that there was a significant difference between the accuracies observed for the High and Low RES conditions at the 0.25 mile level of CRE for the Far FSR condition ($F_{1,28} = 8.03$, $p < 0.0084$). Figures 5 through 7 present the comparisons of the high and low resolution data for each of levels of FSR. The mean values of all of the levels of CRE for both the high and low resolution cases have been presented in these figures to provide the reader with a better understanding of the data. The reader should keep in mind, however, that the analysis comparing the high and low resolution cases involved only those levels which the two had in common (0.25 mile, 0.5 mile, and 1.5 mile).

Accuracy

The percentages of correct responses for the common conditions for the high and low resolution cases were tabulated and subjected to an ANOVA. The results of this analysis indicated that there were main effects for RES ($F_{1,28} = 9.90$, $p < 0.0038$), FSR ($F_{2,56} = 73.51$, $p < 0.00001$), and CRE ($F_{2,56} = 4.47$, $p < -.0158$). There were also two significant two-way interactions; RES x FSR ($F_{2,56} = 5.31$, $p < 0.0077$) and FSR x CRE ($F_{4,112} = 7.52$, $p < 0.00001$), and a significant three-way interaction: RES x FSR x CRE ($F_{4,112} = 2.79$, $p < 0.0298$). Contrasts indicated that there was a significant effect for CRE at each level of FSR (Close: $F_{2,56} = 7.48$, $p < 0.0013$, Medium: $F_{2,56} = 4.85$,

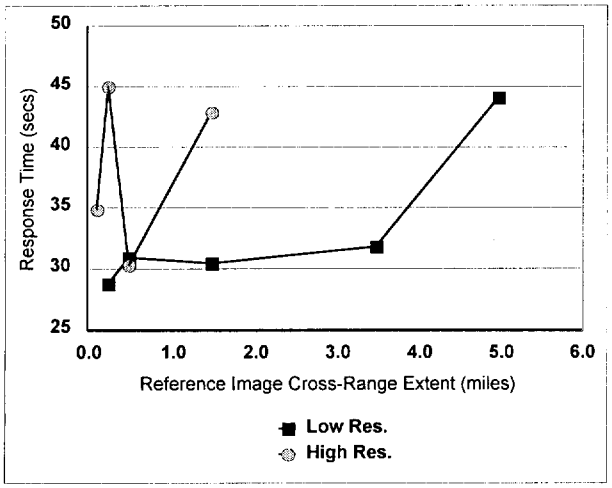

Figure 5. Response Time as a function of Reference Image Cross-Range Extent and Source Database Resolution for the Close FLIR Sensor Distance.

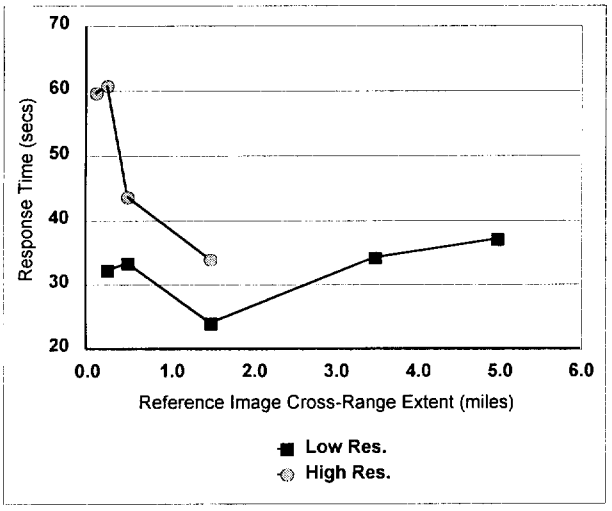

Figure 6. Response Time as a function of Reference Image Cross-Range Extent and Source Database Resolution for the Medium FLIR Sensor Distance.

$p < 0.0114$, Far: $F2,56 = 7.99$, $p < 0.0009$) and a significant interaction between RES and CRE at the Far FSR level ($F2,56 = 3.50$, $p < 0.0371$). Further analysis indicated that there were significant effects for FSR at each level of CRE (0.25 mile: $F2,56 = 52.13$, $p < 0.00001$, 0.5 mile: $F2,56 = 56.09$, $p < 0.00001$, 1.5 mile: $F2,56 = 9.07$, $p < 0.0004$) and a significant interaction between FSR and RES at the 0.25 mile level for CRE ($F2,56 = 10.83$, $p < 0.0001$). Simple effects comparisons indicated that there was asignificant difference between the accuracies observed for the High and Low RES conditions at all levels of CRE for the Close FSR condition (0.25 mile: $F1,28 = 23.04$, $p < 0.00001$, 0.5 mile: $F1,28 = 7.78$, $p < 0.0094$, 1.5 mile: $F1,28 = 5.65$, $p < 0.0245$), at the 0.25 mile level of CRE for the medium FSR condition ($F1,28 = 5.50$, $p < 0.0264$), and at the 1.5 mile level of CRE for the Far FSR condition ($F1,28 = 7.29$, $p < 0.0116$). Figures 8 through 10 present the comparisons of the high and low resolution data for each of levels of FSR. The mean values of all of the levels of CRE for both the high and low resolution cases have been presented in these figures to provide the reader with a better understanding of the data. The reader should keep in mind, however, that the analysis comparing the high and low resolution cases involved only those levels which the two had in common (0.25 mile, 0.5 mile, and 1.5 mile).

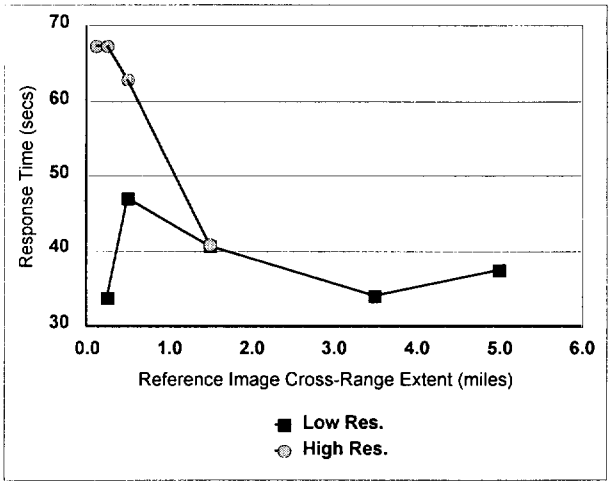

Figure 7. Response Time as a function of Reference Image Cross-Range Extent and Source Database Resolution for the Far FLIR Sensor Distance.

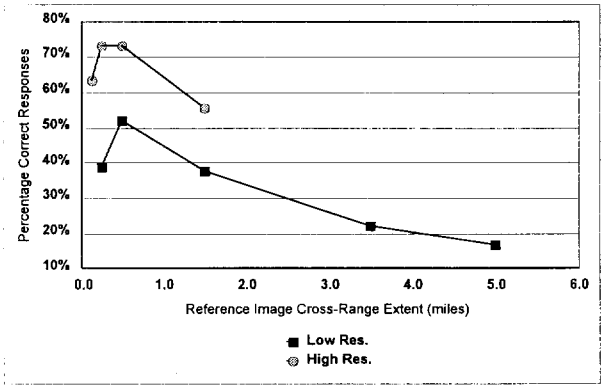

Figure 8. Percentage of Correct Responses as a function of Reference Image Cross-Range Extent and Source Database Resolution for the Close FLIR Sensor Distance.

SUMMARY

The findings from this study indicate that operator target recognition performance using IBTRA's developed from both high and low resolution sources corresponds fairly well to the model described in the early sections of this report. The best performance, both in speed and accuracy, was observed when

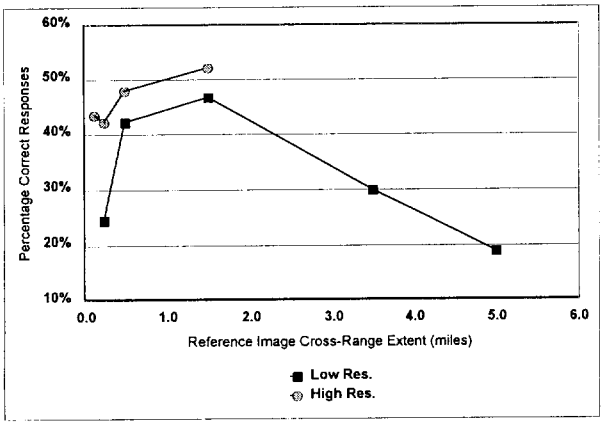

Figure 9. Percentage of Correct Responses as a function of Reference Image Cross-Range Extent and Source Database Resolution for the Medium FLIR Sensor Distance.

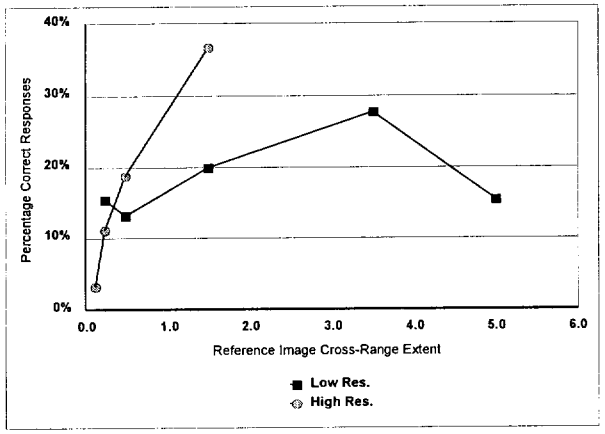

Figure 10. Percentage of Correct Responses as a function of Reference Image Cross-Range Extent and Source Database Resolution for the Far FLIR Sensor Distance.

the cross-range extent of the auxiliary image (the IBTRA) was similar to that of the FLIR sensor image. As expected, the peak performance for the low resolution IBTRA's was better for conditions where the cross-range extent of the images was smaller and degraded gradually as the cross-range extents increased. The shape of the curves associated with the high resolution IBTRA's would seem to indicate that, had higher cross-range extents been examined in this study, a similar pattern might have been observed. However, further research would be required to substantiate this. Overall, the correspondence between the model and observed performance appears to be closer for the observed accuracies than for the observed response times. While the model predicts a relatively flat, wide central region where operator performance is relatively unaffected by either lack of context or resolution, the actual regions observed in the data appeared to be quite narrow.

IBTRA's developed from high resolution data provided a significant increase in target recognition accuracy at all reference image cross-range extents ranges when used with FLIR imagery taken close to the target. However, this benefit only appeared at the 0.25 mile IBTRA cross-range extent for the medium sensor distance, and at the 1.5 miles IBTRA cross-range extent for the far sensor range. There appeared to be no affect on response time due to the use of high resolution data except at 0.25 mile IBTRA cross-range extents with far sensor ranges where operators took significantly longer to use IBTRA's derived from high resolution data than to use IBTRA's derived from low resolution data. This may have been due to a tendency on the operators to spend time examining the detail in the high resolution aids which was unavailable for examination in the low resolution aids. Another explanation may be that the subjects may have more readily "given up" when presented with a severely degraded low resolution image as a reference. The extra time spent on using this imagery, though, did not yield a significant increase in accuracy.

The operational significance of these findings is dependent on the scenario under discussion. If the mission in question involves a weapon release relatively close to the target, then the use of IBTRA's constructed from a high resolution source may be of value. If, however, the weapons involved will be released from longer ranges, high resolution aid may not be as useful. What ranges constitute "relatively close" or "longer" would depend on the field of view of the sensor in use. For example, if the sensor has a 5 degree field of view, then IBTRA's constructed from higher resolutions might be useful at ranges within about 15 - 20 miles from the target. However, if the field of view of the sensor was 30 degrees, these IBTRA's might not be useful until the pilot is within 1-2 miles of the target. An interesting point which is evident from examination of figures 30 - 35 is that, when operator accuracy was better using a high resolution aid, the region of best performance did not change. This would lead to the conclusion that, if designers were restricted to the choice of a single cross-range extent for generating both high and low resolution aids, then a cross-range extent close to that of the sensor would produce the best performance. Also, if designers were limited to a single cross-range extent for all IBTRA's regardless of the range to target, then IBTRA's with a cross-range extent of between 1.0 to 3.0 miles would probably be best.

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REPORT DOCUMENTATION PAGE

1. Recipient's Reference	2. Originator's References	3. Further Reference	4. Security Classification of Document
	RTO-MP-12 AC/323(SCI)TP/4	ISBN 92-837-1010-X	UNCLASSIFIED/ UNLIMITED

5. Originator Research and Technology Organization
North Atlantic Treaty Organization
BP 25, 7 rue Ancelle, F-92201 Neuilly-sur-Seine Cedex, France

6. Title
Sensor Data Fusion and Integration of the Human Element

7. Presented at/sponsored by
the System Concepts and Integration Symposium held in Ottawa, Canada, 14-17 September 1998.

8. Author(s)/Editor(s)	9. Date
Multiple	February 1999
10. Author's/Editor's Address	**11. Pages**
Multiple	244

12. Distribution Statement There are no restrictions on the distribution of this document. Information about the availability of this and other RTO unclassified publications is given on the back cover.

13. Keywords/Descriptors

Data fusion
Multisensors
Operators (personnel)
Decision making
Human factors engineering
Artificial intelligence
Man machine systems
Cockpits
Integrated systems
Man computer interface
Systems engineering
Algorithms
Image processing
Data displays
Command and control
Target recognition
Cognition

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The papers presented covered the following headings:

- Characteristics of Operational Requirements
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Government Reports Announcements & Index (GRA&I)
publié par le National Technical Information Service
Springfield
Virginia 2216
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(accessible également en mode interactif dans la base de données bibliographiques en ligne du NTIS, et sur CD-ROM)

Imprimé par le Groupe Communication Canada Inc.
(membre de la Corporation St-Joseph)
45, boul. Sacré-Cœur, Hull (Québec), Canada K1A 0S7

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Printed by Canada Communication Group Inc.
(A St. Joseph Corporation Company)
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ISBN 92-837-1010-X