Intelligent On-Board Management of Data Link Based Tactical Information

Prof. Dr. Axel Schulte

formerly:
ESG Elektroniksystem- und Logistik-GmbH
Advanced Avioncs Systems
P.O. Box 80 05 69
81605 Munich
GERMANY

currently:
Munich University of the German Armed Forces
Institute of System Dynamics and Flight Mechanics
85577 Neubiberg
GERMANY

E-mail: Axel.Schulte@unibw-muenchen.de

SUMMARY

This paper describes an approach to cognitive crew assistance (e.g. Onken & Walsdorf, 2000) in the field of tactical combat mission management. A concept for a functional prototype system, the so-called Tactical Information and Mission Management System (TIMMS) will be given. The implementation of a functional prototype, taking the cockpit avionics of the Eurofighter into consideration, and some evaluation results concerning the principal architecture will be described. The approach aims at the conception of crew assistant functions which focus upon the monitoring and if necessary the retrieval of the integrity of superior goals such as safety and mission accomplishment.

Following the conceptual guidelines of the so-called ***cognitive automation*** *approach the Tactical Mission Management System has been implemented as a functional prototype in the Mission Avionics Experimental Cockpit, a development flight simulator at* ***ESG Elektroniksystem- und Logistik-GmbH, Munich****. Similar automation concepts as being already proved successful in other crew assistant programmes such as CAMA (e.g. Schulte & Stütz, 1998; Frey et al., 1999; Stütz & Schulte, 2000) are incorporated in the architecture and extended towards an application for the air-to-ground attack role. In a next step the system has been integrated in a cockpit avionics environment close to the Eurofighter cockpit. This paper gives some information on results of an experimental evaluation of the principal ideas as well as an insight into the weapon system oriented advancements of the functions.*

1.0 INTRODUCTION

Performing military combat missions in an uncertain dynamic tactical environment, presents a potentially intolerable workload for the crew. Therefore, several research and development activities are conducted in order to automate flight crews' tasks in order to support safe and successful mission completion. This is done by use of technical means such as intelligent on-board systems in the context of human-centered flight deck automation. Figure 1 illustrates the expected benefit of an increase of complexity of conventional automation as opposed to a so-called *cognitive automation* approach (e.g. Onken & Walsdorf, 2000; Putzer & Onken, 2001). Investigations of modern aircraft cockpits show that a further increase in use of conventional automation will not necessarily result in increased productivity. Automation itself became a complex element within the already complex environment of the cockpit. In some cases conventional automation has even become the key-factor for decreased safety (e.g. due to 'mode confusion'). (e.g. Wiener & Nagel, 1988) The reason for this seems to be found in the unpredictability of the machine's behaviour due to inconsistencies between the machine function and the pilot's mental model of it.

Paper presented at the RTO SCI Symposium on "Critical Design Issues for the Human-Machine Interface", held in Prague, Czech Republic, 19-21 May 2003, and published in RTO-MP-112.

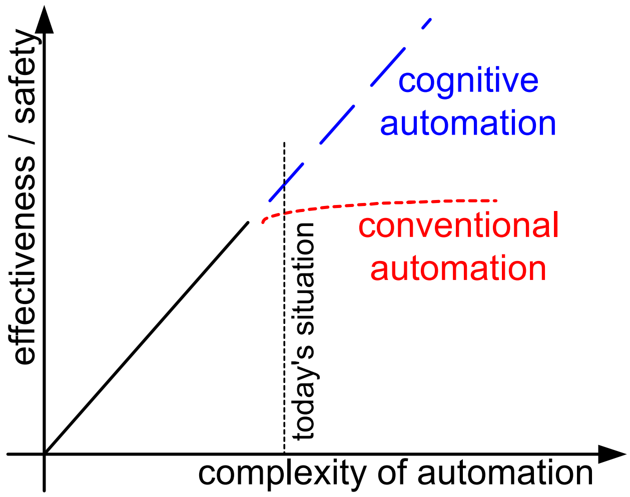

Figure 1: Expected Benefit of Conventional and Cognitive Automation.

This paper comprises some information on an automation approach, which is supposed to provide more intelligible interaction and efficient use. The required functions of such a so-called cognitive assistant system are derived from a concept taking into consideration the process of human information processing. The underlying automation concept has already been proven successful in a crew assistant programme for transport aircraft, the Crew Assistant Military Aircraft, CAMA (Stütz & Schulte, 2000). In the application described in this paper it is modified in order to meet the particular requirements of information management in an air-to-ground attack role, which will presumably become part of the Eurofighter range of application.

The next chapter deals with the refinement of the cognitive automation concept on the basis of the consideration of the human knowledge processing scheme. A generic functional framework will be derived. The following chapter provides the results of a research and development programme being based upon these concepts.

2.0 COGNITIVE SYSTEM DESIGN CONCEPT

In the introduction the issue of changing from a conventional automation philosophy towards a more advanced and promising concept in terms of safety and productivity has been just scratched on the surface. The following sections are meant to discuss the cognitive design philosophy in a more systematically manner.

2.1 Co-operative Automation

The variety of tasks to be performed by the pilot during a tactical flight mission result in a workload spread over all work process levels (see Figure 2), ranging from skill-based manipulatory control (bottom/yellow) through rule-based system interaction (middle/green) up to general knowledge-based problem solving tasks (top/blue). Conventional automation traditionally focuses on relieving the crews from exhausting routine actions, thereby being granted full autonomy in certain well defined areas (Figure 2, left). Expanding this strategy of automation into task domains primarily subjected to rule- and knowledge-based crew action, leads to severe problems in the area of man-machine interaction (Figure 2, middle). Significant for this kind of development are very complex avionics structures and functions taking over full autonomy for comprehensive parts of the flight, while reducing the pilot to a mere solver of abnormal situations (Hollnagel, 1995; Billings, 1997).

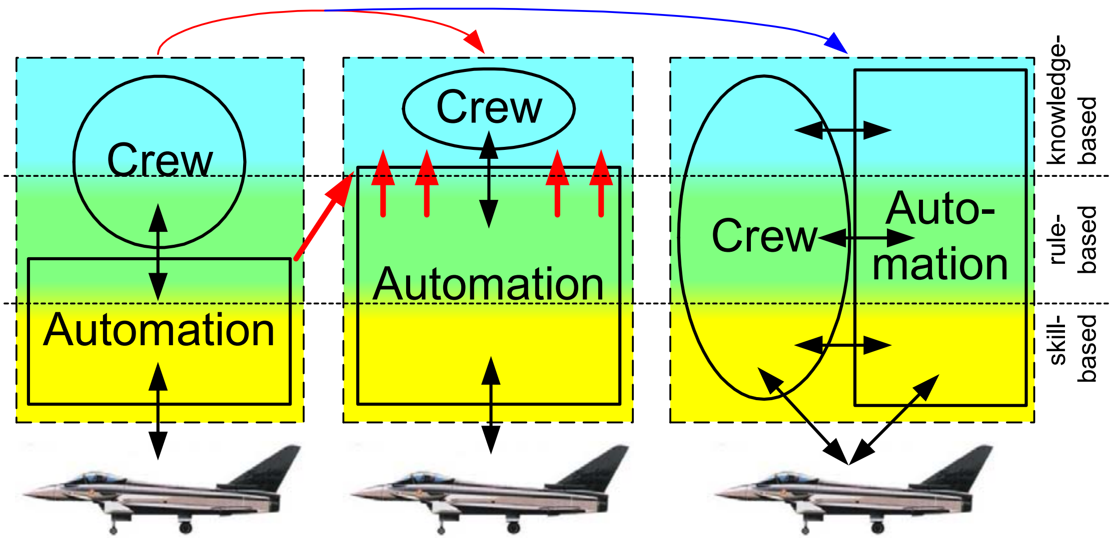

Figure 2: Conventional / Co-operative Automation.

Therefore, new progressive methods are demanded when it comes to expand automation into all aspects of flight and mission management. The most promising way to proceed is the concept of an automated system acting in a co-operative relation rather than separating the crew from the basic aircraft systems (Figure 2, right). Being well aware of the complex task to perform, the crew interprets the output of the automation system as the recommendation of an additional electronic crewmember. The decision-making to accept or reject the machine's advice is allocated to the crew. Proceeding this way, the crew is kept continuously in the decision loop, as according to Billings' principles, and is able to employ the full strength of human performance. At the same time the crew takes advantage of the particular strengths and abilities of the system.

Establishing the postulated co-operative task allocation within a close-partner work relationship between the human operator and the machine requires to qualify the automated system to be an equal and competent team player, as one would expect from a human counterpart. The next section yields a closer look at human performance models in task situations to be used as a paradigm for a technical system's human-like behaviour.

2.2 Human Problem-Solving Strategy and Cognitive Process

Considering the automated functions within today's cockpit avionics and flight guidance systems against the background of Rasmussen's model (1983) of the human knowledge processing scheme (see Figure 3) shortcomings in conventional automation design can be easily identified (Onken & Walsdorf, 2000). It covers only about the half of what has been considered the spectrum of human cognitive functions. Simple automation implementations within clearly-cut task domains such as auto-pilot or flight director systems usually can be seen as immediate instantiations of the processing steps on the skill-based performance level, which are directly connected through functional relations. Planning functions are state-of-the-art in today's Flight Management Systems (FMS). They can be attributed mostly to the rule-based performance level.

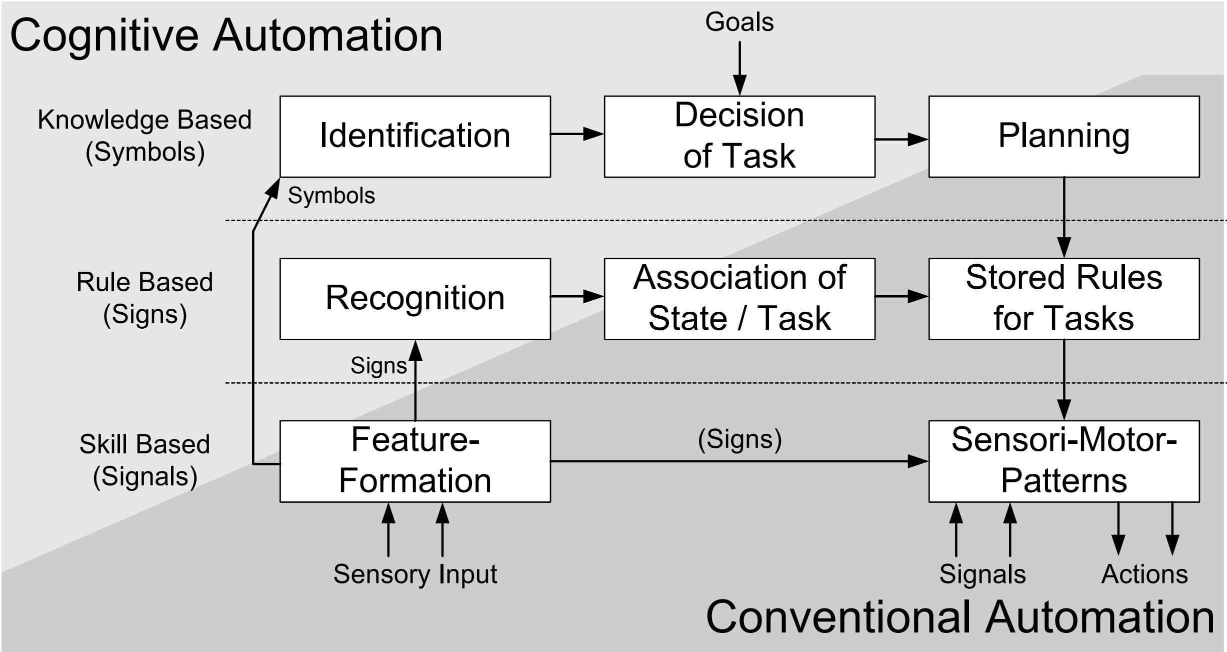

Figure 3: Scope of Cognitive and Conventional Automation within the Rasmussen Scheme.

To enable the system to perform also on the higher level of goal-driven problem solving and decision-making, some abstract and therefore more versatile task knowledge and processing procedures have to be made available to the machine. Cognitive automation will cover the whole process of building an internal comprehensive representation of the relevant parts of the external world (i.e. the mental picture of the situation), a type of activity which has been mostly left up to the human operator, so far. The so-gained situation picture will be the basis for the crucial goal-driven decision-making process (Putzer & Onken, 2001).

3.0 FUNCTIONAL BREAKDOWN BASED ON COGNITIVE APPROACH

In order to derive a functional breakdown of the TIMMS the abovementioned generic processing steps are translated into specific functions (see Figure 4). The process steps of situation recognition and identification are represented by the functions of flight situation analysis (FSA), tactical situation analysis (TSA) and mission command analysis (MCA), covering the relevant situational domains. The level of goal-driven decision-making is implemented in the module conflict detection and resolution (CDR), while autonomous mission re-planning as an assistant function will be performed by the mission planner (MP).

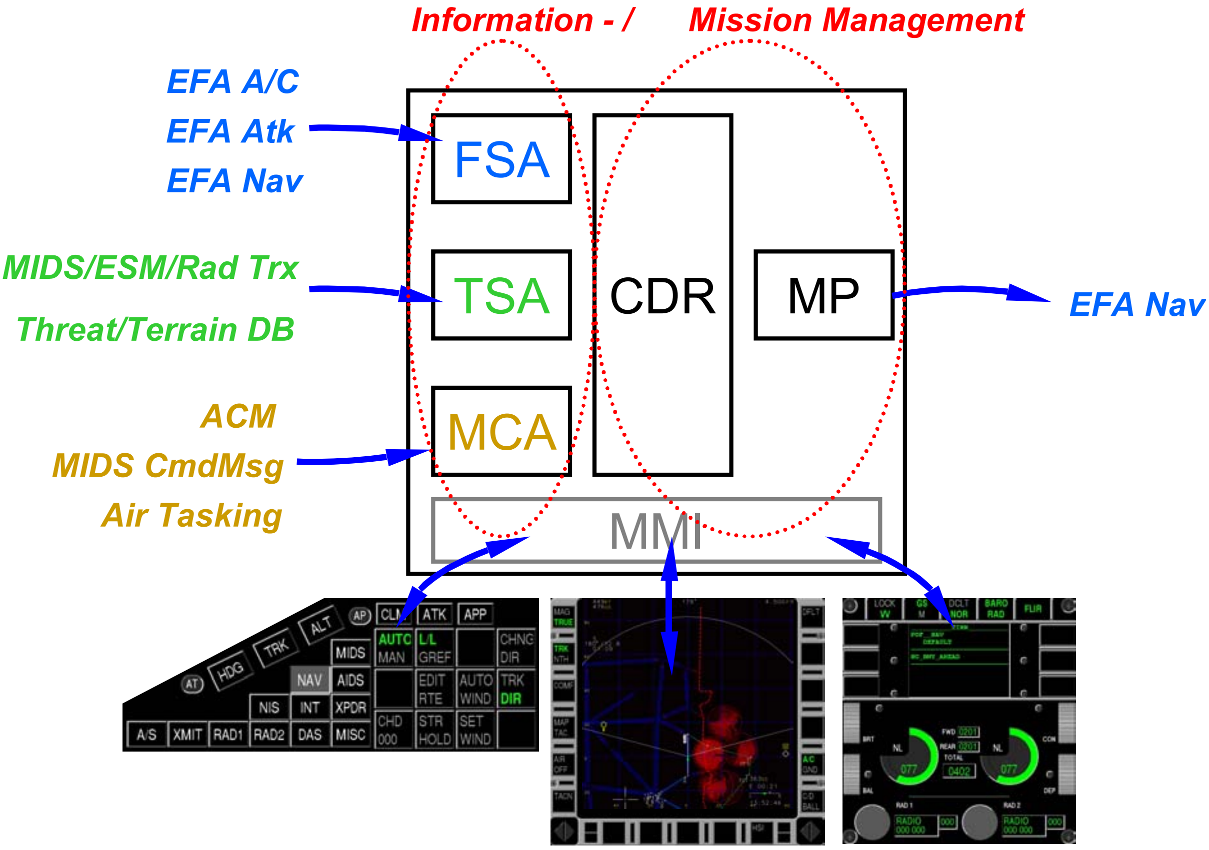

Figure 4: Functions of TIMMS Prototype and Interfaces to Eurofighter Avionics.

The main objective of the module *flight situation analysis* is the determination of the current phase of flight (PoF). Therefore, the already existing PoF-concept integrated in the Eurofighter display moding logic has been supplemented by some intelligent functions. Firstly, the PoF selected by the pilot will be analysed with respect to its plausibility within the mission context (e.g. PoF Landing is not plausible, when no destination airport is nearby). In a second step the corrected Pof will be refined in appropriate sub-phases, and further analyses, such as concerning the current deployment zone will be conducted.

The *tactical situation analysis* generates a threat model on the basis of available threat data from on-board sensor data, data link information, and relevant data bases, such as terrain elevation data. Utilising the so gained threat model a further analysis of the current mission plan will be conducted, in order to detect situations, where relevant tactical changes affect the current mission.

Finally, the *mission command analysis* processes incoming tasking messages broadcasted via data link. Usually these tasking message contain alterations of mission assignment or target allocation. The pilot has to decide, whether to comply with the tasking or not. The module MCA will compute all necessary steps to be performed in order to comply with this new tasking. The resulting sequence of actions will be analysed with respect to the available resources (e.g. time, fuel, airspace control means). A recommendation to the pilot will be generated, in order to facilitate and support his decision.

The *conflict detection and resolution* function builds up a hierarchy of general goals to be followed throughout the mission, such as flight safety, combat survival and mission accomplishment. Utilising the results of the situation analyses, the module figures out violations of these goals. After negotiation with the pilot, a proposal how to resolve the conflict will be passed to appropriate machine agents for conflict resolution. Implementing this human-like goal-task-model ensures machine problem solving strategies which are easy to anticipate for the pilot.

Mission Planning is the most important conflict solving agent activity. The Tactical Information and Mission Management System offers a fully autonomous mission and route planning capability to the crew, including terminal operations planning, transit flight planning, tactical low-level flight trajectory optimisation and the use of attack procedure templates.

Finally, the Tactical Information and Mission Management System provides an appropriate man-*machine interface (MMI)* on the flight deck, in order to manage the information flow and the crew interactions. The MMI has been designed using the Eurofighter-given resources in the cockpit of multifunctional head-down displays, manual data entry keyboard and so forth.

4.0 PROTOTYPE EVALUATION

After having formulated the cognitive system approach in the field of crew assistance and tactical mission management, this chapter deals with the evaluation of an experimental prototype. The prototype for the Tactical Mission Management System (TMM) has been developed according to the described design principles of cognitive automation, but not yet implying the Eurofighter-specific man-machine-interface.

4.1 Experimental Design

In order to prove the approach, the TMM has been implemented as a functional prototype and integrated in the flight and scenario simulation environment. It has undergone an experimental evaluation with operational personnel in spring 2001. The following sections give details on the apparatus, scenario and tasks as well as the subjects.

4.1.1 Apparatus, Scenario and Tasks

For the evaluation of the Tactical Mission Management System a comparative study was chosen. Two different simulator set-ups were configured, on the one hand representing the basic functions of a reference combat aircraft cockpit (e.g. Tornado) and on the other hand demonstrating the TMM functions and displays (Figure 5).

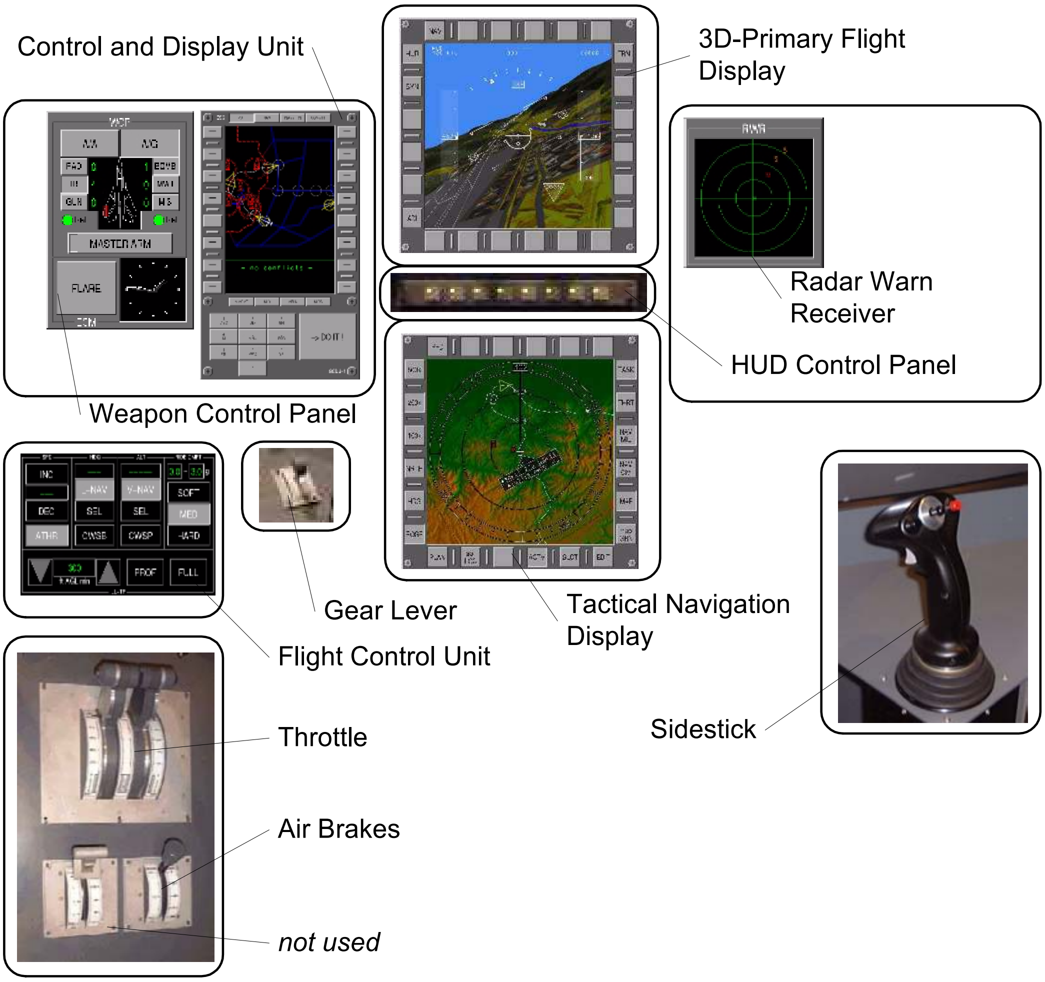

Figure 5: Cockpit in the TMM Configuration.

Following the experimental procedures the pilots had to perform a dedicated test mission with each of the cockpit configurations. Figure 6 shows the phases of the test mission located in the south-west regions of Germany i.e. (1) tactical transit, (2) low-level ingress, (3) attack, (4) low-level egress and (5) tactical transit. During the low-level phase the mission was supported by computer-generated units such as SEAD-forces for suppression of enemy air defence and AWACS. Using the TMM-configuration the aircraft was participant of a tactical data-link network (i.e. MIDS) providing data on other participants and surveillance information. During the mission the tactical situation (i.e. hostile SAM sites) was supposed to change several times forcing the pilots to react accordingly (e.g. route adaptation, re-planning, threat avoidance), thereby workload being imposed on the operator.

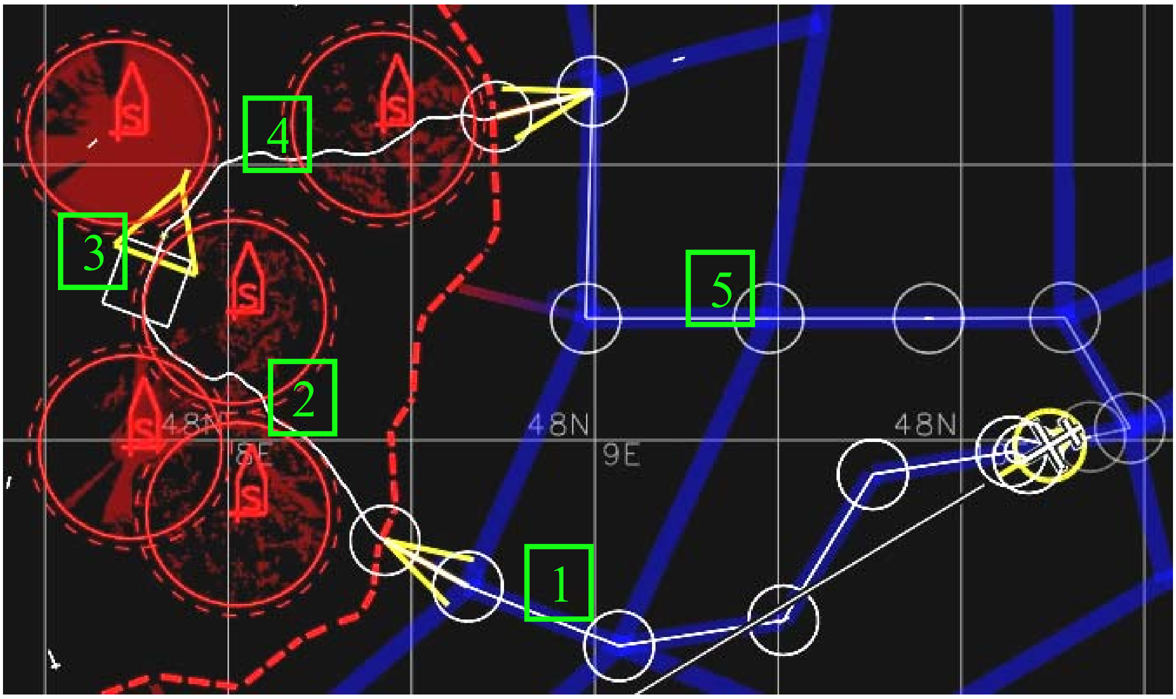

Figure 6: Scenario of the Test Mission for System Evaluation.

4.1.2 Subjects

The subjects were four German Air Force pilots (partly flight instructors) from the Fighter Bomber Wing 34, Memmingen at an age of 30 to 38 years. Their flight experience ranged from a total of 900 to 3000 flying hours on Tornado and other NATO combat aircraft. During a one day familiarisation phase the pilots had the opportunity to train the handling of the simulator and the interaction with the TMM before the test mission had to be performed. Due to organisational constraints pilot 4 had only passed through a shortened training session on the TMM system.

4.2 Evaluation Results

The main scope of the evaluation of the Tactical Mission Management System was to account for improvements in comparison to the reference system in terms of categories as described in the following paragraphs.

4.2.1 Pilot's Performance

The investigation of the pilot's performance has been conducted under the consideration of the three abstract goals: flight safety, combat survival and mission accomplishment.

With regard to *flight safety*, the area of low-level flight guidance has been investigated. During the experiments it could be observed that pilots frequently took the risk of dangerous ground and obstacle proximity in order to avoid military threats. Therefore, it was investigated how often certain given above-ground-level minima were violated while performing low-level flight. Table 1 gives the results of the comparison between the reference system (REF) and the Tactical Mission Management System (TMM). The assessment of ground collisions and the frequency of AGL minima violations make clear that the TMM caused a significant risk reduction by a better ground separation. In a deeper investigation of the terrain following performance it is evident that the flown vertical profile becomes significantly smoother (i.e. less vertical acceleration at an order of magnitude of about 20% to 30%, less variation in altitude) in the TMM configuration. Thereby, the pilot's comfort level could be increased.

Table 1: Violations of Minima during Low-Level Flight

	Pilot 1		*Pilot 2*		*Pilot 3*		*Pilot 4*	
	REF	*TMM*	*REF*	*TMM*	*REF*	*TMM*	*REF*	*TMM*
< 150 ft AGL	39	2	17	5	19	5	36	23
< 50 ft AGL	5	-	-	-	3	-	9	1
< 0 ft AGL	1	-	-	-	1	-	1	-

An important feature of the TMM is the ability of situation-dependent in-flight re-planning of the mission plan for threat reduction. In order to quantify the effect of this assistance function in terms of *combat survival* the mean threat exposure was evaluated along the actually flown trajectories (Figure 7). Obviously, a massive reduction effect on the threat exposure could be noted by use of the TMM. It should be emphasised that the improvement of threat avoidance with the TMM could be achieved in combination with a much better ground separation (see Table 1).

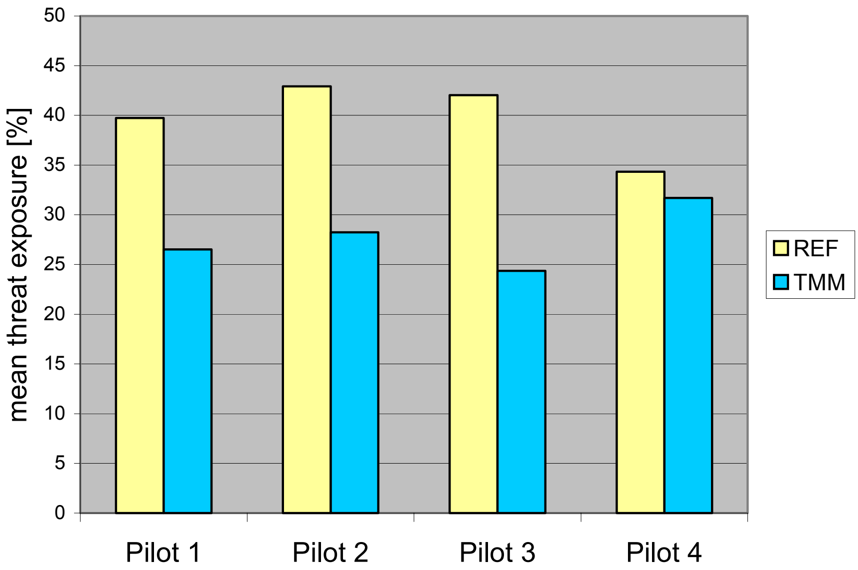

Figure 7: Mean Threat Exposure in Comparison.

Table 2 provides a collection of criteria concerning the global idea of *mission accomplishment*. The results make evident that the pilots performed notedly better with the TMM than without. Due to a better threat avoidance with the TMM the SAM shots could be reduced and thoroughly avoided respectively. Performance criteria such as meeting the Time-over-Target (TOT), hitting the target or reaching the destination could be mostly fulfilled by the pilots quite well. Only pilot 4 did not reach the destination with the reference system due to a flame-out condition. With the TMM he could manage to divert to an alternate destination at least. In general it was found that fuel consumption could be decreased significantly with the TMM during the mission. Another observation was made concerning the number of violations of the Airspace Co-ordination Order (ACO) routing, which could be totally eliminated by the use of the TMM. So, the risk of being hit by friendly fire was minimised.

Table 2: Global Criteria of Flight Safety, Threat Avoidance and Mission Accomplishment

		Pilot 1		*Pilot 2*		*Pilot 3*		*Pilot 4*	
		REF	*TMM*	*REF*	*TMM*	*REF*	*TMM*	*REF*	*TMM*
Safety	Ground crash [#]	1	-	-	-	1	-	1	-
	Fuel on Board @ Touch down [%]	4.4	14.3	9.1	13.8	4.3	12.5	0.0	8.8
Threat	SAM shots [#]	-	-	-	-	1	-	1	-
	ACO violations [#]	5	-	5	-	5	-	8	-
Mission	ΔTOT [s]	L 8.0	E 0.4	E 0.3	E 2.1	E 2.3	E 0.2	L 3.8	L 2.1
	Target hit	E	E	E	E	E	E	E	E
	Destination reached	E	E	E	E	E	E	no	(E)
Mission accomplished		**no**	**yes**	**(no)**	**yes**	**no**	**yes**	**no**	**(yes)**

4.2.2 System Performance

One of the most important features of the TMM is the pilot assistance in optimising a threat minimal route under a dynamically changing hostile threat theatre. Figure 8 shows the total and mean threat exposure computed with an underlying worst-case scenario. Comparing the threat exposure of a direct routing (1st column) with the result of the low-level route planner of the TMM (3rd column) makes the advantage obvious. The total threat accumulation could be decreased from about 8500 to 5700 *%km*. Due to the longer flight trajectory, the effect on the relative threat exposure is even more noticeable (55 down to 30*%*). The columns 2 and 4 in Figure 14 show the threat values of the actual flown trajectories, again under consideration of a worst-case scenario. It is obvious that the co-operation between the system and the pilots yields another improvement in terms of threat avoidance due to synergetic effects.

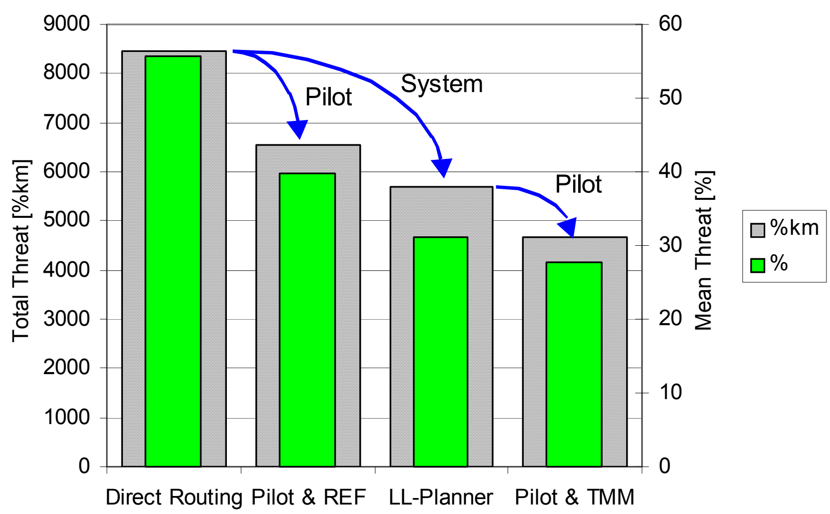

Figure 8: Threat Exposure Reduction.

4.2.3 Workload and Situation Awareness

The TMM was designed to reduce the operator's workload by providing functions to support a better situation awareness and particular automation functions. During the experiments measurements of situation awareness and workload were conducted. Therefore, the experiment was stopped at dedicated points of time in order to perform the NASA Task Load Index (TLX) and the Situation Awareness Global Assessment Technique (SAGAT) (Endsley, 1988).

The evaluations were conducted four times each experimental run (reference system and TMM). The measuring points were the task situations 1 (Transit Ingress), 2 (Low-level Ingress), 4 (Low-level Egress) and 5 (Transit Egress) according to Figure 6. Figure 9 shows the results of the assessments averaged over the four subjects. Concerning the NASA TLX rating (see Figure 9, left) it was found that the overall workload could be reduced massively by use of the TMM with an expected slight increase of workload during the low-level phases of the mission.

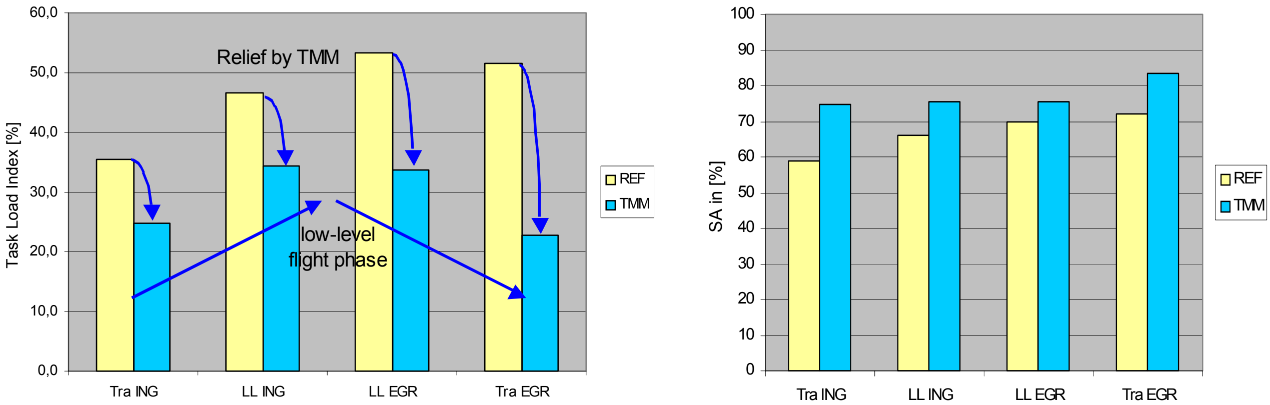

Figure 9: NASA TLX (left) and SAGAT (right) Results over Mission Phases.

The situation awareness assessment was based upon the evaluation of a total of 26 multiple-choice questions concerning situational features. Figure 9 (right) shows the weighted results. An increase in situation awareness of about 10 to 15%, in particular during the early mission phases, can be observed.

4.2.4 Subjective Ratings

In order to assess the pilot's overall acceptance of the approach and benefits offered by the TMM, a de-briefing session concluded the two day evaluation period, where the pilots were asked to fill out subjective ratings. Therefore, the survey presented was structured according to the following aspects:

- *System performance of the TMM*

  The effectiveness and the benefit provided by the assistance functions were evaluated by listing several relevant tasks and sub-tasks throughout the mission. The subjects had to comment on the quality of assistance provided by the TMM with respect to these tasks.

- *Acceptance of the TMM by the user*

  To evaluate the degree of acceptance, the pilots had to refer to a list of statements characterising the system behaviour and handling features.

- *Overall assessment*

  In order to obtain a result concerning the overall evaluation of the system, the subjects had to express their degree of accordance with some general statements about the TMM.

The rating scales covered a range of values from 1 to 7 and were each labelled by a pair of antithetic terms (e.g. good – bad; agree – disagree). The following paragraphs report on some selected results.

Figure 10 shows the pilots' evaluations of the quality and *performance of the assistance functions* offered by the TMM. The overall assessment can be regarded as very positive. Although, there can be identified some minor objections caused by unfamiliar display of timing and system information, insufficient training with the system and some shortcomings in pilot's behaviour modelling. Despite these (easy to remove) deficits the assessment of the implemented prototype was almost optimal.

Figure 10: Evaluation of Assistance Quality.

Figure 11 provides the results of the acceptance evaluation. It could be found that the handling of the Tactical Mission Management System was regarded to be mostly easy, pleasant and predominantly not cumbering. It was found to behave well balanced between a reserved and an intrusive attitude and generally pleasant and well adapted. Hints and warnings issued by the system were found to be not so pleasant to some extent (Who wants to be reminded of his own mistakes?), but also sometimes inadequate and slightly too often. The latter criticism can be directly attributed to the shortcomings in pilot's behaviour modelling with respect to the applicable mission timing procedures, as already mentioned earlier. Disruptions of the operators attention were to some extent caused by an automatic display format change in the case of a detected conflict. It seems to be advisable to find a way of communicating conflicts without the necessity of switching graphical display formats.

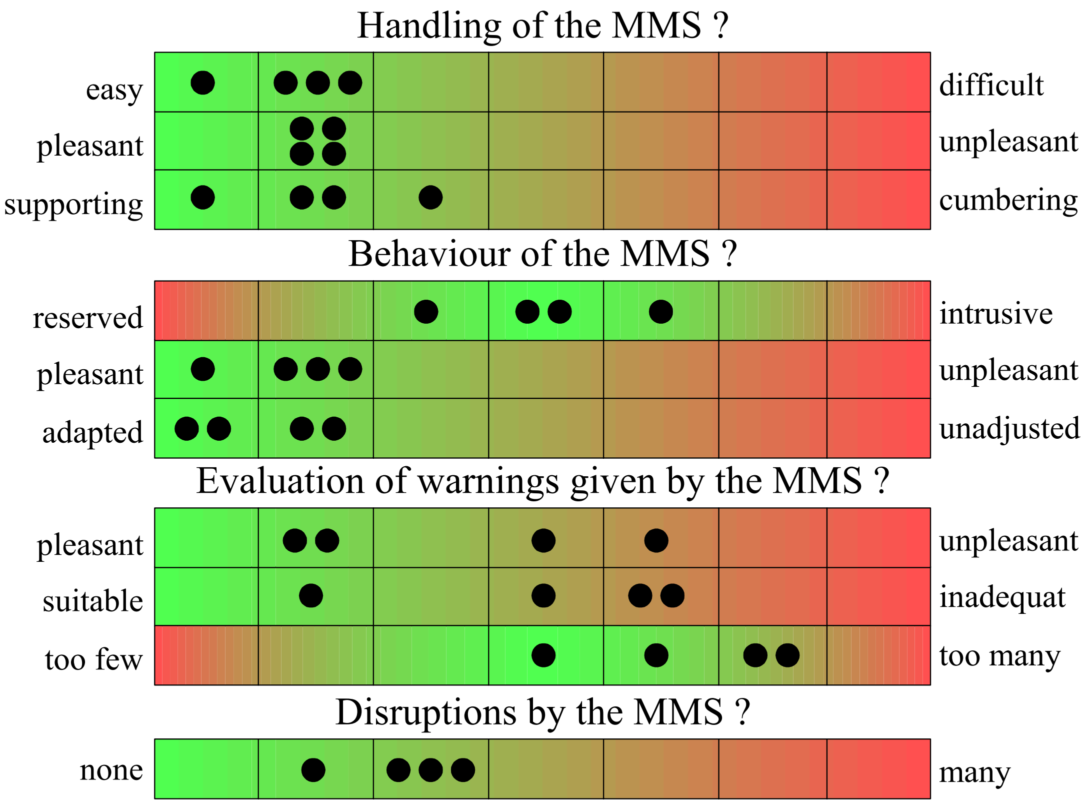

Figure 11: Evaluation of Acceptance.

Figure 12 shows some selected but representative results of the overall assessment given by the pilots. The subjects fully agreed with the hypothesis that the TMM provides a better big picture in terms of global situation awareness. The TMM is qualified to increase mission efficiency according to the pilots. The operators regarded the presented technology of Tactical Mission Management and crew assistance to be absolutely necessary, suited and adequate.

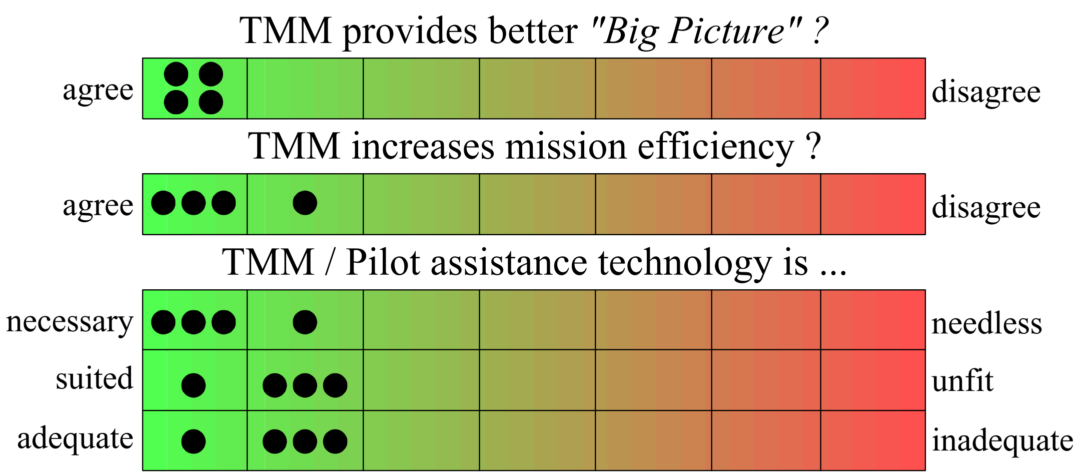

Figure 12: Overall Assessment of the TMM.

5.0 CONCLUSIONS

After having gathered years of experience in cognitive flight-deck automation and crew assistance, the time has come to gain the results of exceedingly successful efforts in the field of military transport as well as combat aircraft. This paper presents the results achieved in the field of military attack aircraft. The functional breakdown of the *Tactical Mission Management System* has been derived from a model of human information processing, in order to approach a co-operative automation principle. A laboratory prototype system has been evaluated with German Air Force fighter-bomber pilots in simulator trials. Besides the fact that the system was very well appreciated by the pilots, objective measures evidence a significant increase in performance in terms of threat avoidance and mission efficiency. These results could be achieved in conjunction with a noticeable reduction of the terrain collision risk and the operator's workload. Therefore, the system approach is highly recommended for application in the advancement and automation of future combat aircraft as well as other military and non-military application domains, where ever operator situation awareness and decision-making is crucial.

6.0 LITERATURE

Billings, Charles E. (1997). *Aviation Automation. The Search for a Human-Centered Approach*. Lawrence Erlbaum Associates: Mahwah, NJ.

Endsley, Mica R. (1988), Situation Awareness Global Assessment Technique (SAGAT). National Aerospace and Electronics Conference.

Frey, Andreas; Lenz, André & Onken, Reiner (1999). Core Elements of the Cognitive Assistant System CAMA. In: *Advanced Mission Management System Integration Technologies for Improved Tactical Operations*. NATO System Concepts and Integration Panel Symposium. Florence Italy. 27-29 Sept. 1999.

Hollnagel, Erik (1995). Automation, Coping, and Control. In: Post HCI'95 Conference Seminar on *Human-Machine Interface in Process Control*. Hieizan, Japan. July 17-19, 1995.

Onken, Reiner & Walsdorf, Anton (2000). Assistant Systems for Vehicle Guidance: Cognitive Man-Machine Cooperation. In: *4th International Conference on IT for Balanced Automation Systems – BASYS 2000*. Berlin, Germany. 27-29 September 2000.

Putzer, Henrik & Onken, Reiner (2001). COSA – A Generic Approach towards a Cognitive System Architecture. In: *The Cognitive Work Process: Automation and Interaction*. 8th European Conference on Cognitive Science Applications in Process Control, CSAPC'01. Munich, GE. 24-26 September, 2001.

Rasmussen, Jens (1983). Skills, Rules, and Knowledge; Signals, Signs, and Symbols, and Other Distinctions in Human Performance Models. In: *IEEE Transactions on Systems, Man, and Cybernetics*. SMC-13(3):257-266.

Schulte, Axel & Stütz, Peter (1998). Evaluation of the Crew Assistant Military Aircraft (CAMA) in Simulator Trials. In: NATO Research and Technology Agency, System Concepts and Integration Panel. Symposium on *Sensor Data Fusion and Integration of Human Element*. Ottawa, Canada.

Schulte, Axel; Stütz, Peter & Klöckner, Wolfgang (1999). Cognitive Concepts in Tactical Mission Management. In: NATO Research and Technology Agency, System Concepts and Integration Panel. Symposium on *Advanced Mission Management and System Integration Technologies for Improved Tactical Operations*. Florence, Italy. September 27-29, 1999.

Schulte, Axel; Stütz, Peter & Klöckner, Wolfgang (2001). Cognitive Automation for Attack Aircraft: Concept and Prototype Evaluation in Flight Simulator Trials. In: *The Cognitive Work Process: Automation* *and Interaction*. 8th European Conference on Cognitive Science Applications in Process Control, CSAPC'01. Munich, GE. 24-26 September, 2001.

Stütz, Peter & Schulte, Axel (2000). Evaluation of the Cockpit Assistant Military Aircraft CAMA in Flight Trials. In: *Third International Conference on Engineering Psychology and Cognitive Ergonomics*. Edinburgh, UK. October 25-27, 2000.

Walsdorf, Anton; Putzer, Henrik & Onken, Reiner (1999). The Cognitive Process and its Application within Cockpit Assistant Systems. In: *IEEE / IEEJ / JSAI International Conference on Intelligent Transportation Systems*. Tokyo, Japan. 5-8 October 1999.