Introduction of Unmanned Airborne Combat Systems into Future Threat Scenarios: Opportunities and Challenges

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ABSTRACT

In future air combat, the integration of unmanned cooperative systems will be a potentially huge force multiplicator. Key factors for its success will be teaming intelligence, coordinated mission planning and cross-platform mission management. Therefore, the task of conceptualizing the next generation airborne weapon system requires a holistic system-of-systems approach that considers the different air vehicles itself, their avionics mission systems and the overall concept of operation against future threats. For early validation of possible solution concepts and assessment of their operational performance, a dynamic multi-agent combat simulation has been developed over the last years within Airbus Defence & Space Future Projects. In addition to its faster-than-real-time engineering functionality, the simulation allows real-time human-in-the-loop experiments to foster collaboration between engineers, operators and customers. This paper presents our approach to dynamic mission simulation and insights from the application of our tool during the Future Combat Air System (FCAS) studies, during which it became clear what will be a key challenge for future applications: Implementing a robust high-level planning algorithm that generates ad-hoc mission plans for complex air operations while considering reactive low-level agent behaviour, human operators and online user input.

1.0 INTRODUCTION

Every new fighter generation can be defined over one or multiple technological leaps that significantly discriminate the design of its members from the ones of the previous generation. It is without doubt that there have been significant advances in almost all design disciplines since the first 5th generation fighter aircrafts entered service about 15 years ago. Different aircraft manufactures, including Airbus, have already announced that they are currently conceptualizing or working on 6th generation fighter jets [1] [3]. Compared to current state-of-the-art aircrafts, those projects will very likely see improvements in various fields like flight performance, all-aspect and all-modality stealth, low probability of intercept radar and communication or armament. Still the question remains: What will be *the* defining factor of this generation, a true game changer for the battlespace of the future?

A common assumption is that the future battlespace will be “highly networked”, i.e. all involved entities can exchange their situational view and create a shared tactical picture in near real-time. On the one hand, this enables reliable spatial and temporal synchronization of multiple platforms to a degree that has previously not been possible. Many algorithms, especially for emitter localization or target ranging, produce significantly better results if measurements can be generated from multiple positions. On the other hand, a reliable exchange of high-quality data allows more tactical flexibility by distributing tasks that have previously been carried out by a single platform. The major application for combat aircraft is probably the so called cooperative engagement concept (CEC), which is already part of the U.S. Navy’s Naval Integrated Fire Control-Counter Air (NIFC-CA) doctrine against anti-access/area denial (A2/AD) environments [4], but other applications are also possible, e.g. cooperative electronic attack. The mentioned concepts are mainly applicable in the short-term context of a single situation during a mission, e.g. reconaissance or attack of a SAM site, air-to-air (A2A) combat, etc. However, there is also another aspect with respect to mission as a whole that should be mentioned. Given reliable communication between all involved entities, planning algorithms can exchange proposals for mission plan changes and automatically accept or decline them based on their objective and current tactical situation. This is especially useful in situations where one or more unforeseeable events render the original mission plan invalid despite all pre-calculated margins. Instead of estimating if an alternative plan is feasible and aligning it with all other entities via voice communication (which is a challenging and time consuming task given the high workload of the crew during some mission phases and the number of involved entities), a cross-plattform mission management system can quickly calculate alternatives to the current mission plan and evaluate if e.g. temporal constraints like open corridors can still be met. A set of alternatives is then presented to the crews to support their decision if and how the mission can be continued.

Combining the above ideas with the now available on-board computing power, made possible by recent advances in both hardware and software, it can be concluded that the coming fighter jet generation will very likely operate with superior tatctical concepts based on powerful avionics systems and fast and reliable data exchange. However, this is not yet the definite game changer we are looking for – even existing 5th generation fighter jets already apply some of the mentioned concepts, e.g. the F-35 within the NIFC-CA context [4]. Consequently, the next step is to not only improve the avionics of the aircraft but to coherently optimize avionics, tactics and platform design under the premises of a fully networked environment. This approach allows thinking about concepts where not every platform needs to have a full sensor suite and full decision making capability if it is supported by complementary entities within the network. As a consequence, different platforms can be highly optimized to their special tasks, thus reducing the number of trade-offs required in the design process compared to the "single platform does it all" approach. It is quite obvious that a dedicated sensor platform needs no or very limited armament, so the now available space can be used for better sensors or larger fuel tanks. This can already lead to a significant performance improvement for the tasks the platform is specialized on, but there is one thing that can be removed that has the most impact: The pilot. At this point, it has to be clearly noted that there is currently no algorithm or artificial intelligence that comes even close to the situational awareness and decision making capability of a trained aircrew. This is why a human pilot will always be necessary for combat missions in the near future. However, the pilot (or more precisely, the decision maker) does not need to be in the same platform if he/she is provided all required information for commanding his/her unmanned companions. We therefore propose a concept in which one or more manned platforms are supported by multiple unmanned and specialized combat aerial vehicles (UAVs). In the following, we will refer to a group of at least one manned platform and one or more specialized UAVs commanded by the manned platform as package. We claim that the unmanned platforms will function as a force multiplier for the manned platforms due to the following reasons:

- UAVs are expandable and aircrews are not. Thus, UAVs can perform high-risk tasks and allow tactics that would not be acceptable with manned platforms only.
- UAVs are cheaper (even when not considering the value of the crew) because they can be build smaller than manned platforms with same performance. This means that more platforms can fly a mission at the same cost and a higher number of platforms lead to a higher mission success rate: First, because there are more redundancies and second, because some tasks can be performed better if more assets contribute to it, e.g. emitter localization.
- Different UAVs and manned platforms can be combined arbitrarily. Before the start of a mission, packages can be composed as required. During the mission, packages can also be recombined given certain constraints, e.g. maximum distance between the command platforms if the rules of engagement prohibit uncontrolled flight. This allows for greater flexibility in mission planning and execution and is expected to also keep operating costs and material wear low ("use only what you need").

As always, there is no such thing as free lunch. In our case, all the above advantages come at a cost for the aircraft designer: Instead of optimizing the performance of a single design to a set of technical requirements, multiple platforms and their subsystems have to be designed such that they maximize the overall system-of-systems performance in various missions and package configurations. In the remaining part of this paper, we will present the FCAS Prototyping Lab (FPL), a simulation environment developed in the FCAS context to tackle this highly complex problem. After outlining its role in conceptual design and interdisciplinary technology prototyping in chapter 2, we will present the concept and architecture of the underlying dynamic multi-agent mission simulation in chapter 3. In chapter 4, results from selected projects are presented to outline the versatility of the tool. The paper will be concluded with what might be one of the biggest future challenges not only for simulation but also for the introduction of unmanned systems in general: Implementing a robust high-level planning algorithm that generates ad-hoc mission plans for complex air operations while considering reactive low-level agent behaviour, human operators and online user input.

2.0 CONTRIBUTION

From a functional perspective, the FPL is an analysis tool for the conceptual design of aircrafts and their subsystems. Many already existing tools are used in the aircraft design process to calculate different performance measures of the platform itself (e.g. range, climb rate, manoeuvrability etc.) or for its subsystems (e.g. sensor range and coverage, datalink bandwidth etc.). However, those tools are often stand-alone and cover only some aspects of the aircraft’s mission. Based on year-long experience of engineers and designers it is possible to combine results from all those tools to maximize the expected mission performance of a new aircraft design. This becomes increasingly complex when not only a single platform concept but different platform and/or subsystem concepts have to be considered in a holistic system-of-systems context. To handle this increase in complexity, the FPL can be used to assess the operational system-of-systems performance by simulating complete combat missions in a highly dynamic environment. Platform and subsystem performance measures calculated from different design tools can be used as input for a detailed physical simulation of current systems and future concepts. Different operational performance measures allow to assess how changes in the concept affect the overall mission success.

Furthermore, the FPL is not only used for internal analysis as it also provides a transparent way to translate customer needs to technical requirements. In the early stages of conceptual design, requirements are usually very limited. It is however very crucial to the success of a product to have a common understanding between customer and manufacturer regarding the desired functionality and how this functionality can be realized. To this end, the customer may define exemplary missions that a future aircraft should perform. Relevant aspects of those missions or even complete missions can then be simulated in the FPL. Measuring the performance of different concepts in those missions helps the customer and engineers to jointly evaluate the impact of different design trade-offs. Based on those evaluations, more detailed technical requirements can be formulated that are traceable back to operational customer needs.

The dynamic mission simulation is the core component of the FPL, but the full scope of the FPL goes beyond that: It is in fact a physical environment with different human-machine-interfaces (HMI) like cockpits or command stations that can be used for human-in-the-loop experiments. Those experiments may range from testing different HMI concepts with a single pilot up to facilitating complete wargaming sessions with multiple operators on own and enemy side. In addition to that, the architecture is based on open-source middleware and designed to allow fast integration of new simulation models in a “plug-and-play” manner. In sum, this makes the FPL a powerful rapid-prototyping tool to foster cooperation between different disciplines and stakeholders. By involving industry partners, experts from different disciplines, customers and operators in early phases of aircraft technology projects it is ensured that novel concepts are assessed from different viewpoints and that all important aspects are covered.

3.0 METHODS

The core of the FPL is a dynamic multi-agent mission simulation which can be run on a single computer or distributed over multiple machines and with different additional hardware components. To facilitate wargaming sessions, to prototype and test HMI technologies or for general demonstration purposes, all manned airborne assets in the simulation can be optionally controlled from hardware cockpits. If no human operators are involved, the simulation has to be capable of running faster than real-time. This is especially required for effective development and trade-off analyses in large-scale missions that might take up to hours. To assess concepts and technologies in an objective and unbiased manner, the course of every simulated mission evolves from pre-defined system properties, simulation of physical effects and configurable agent behaviour and cooperation. There exist no scripted events and the result of every new simulation run is completely open. Blue and red forces are simulated under the same assumptions and with comparable level of abstraction. The following chapters outline how missions of current and future airborne systems can be dynamically simulated in the FPL. We present our simulation architecture, the most important design trade-offs when modelling such systems and a high-level planning/low-level control approach to behaviour modelling.

3.1 Architecture

The simulation architecture of the FPL consists of three logical components: Applications, simulation control and communication middleware. A central feature of the architecture is that the simulation is split into several applications. Every application runs different models, e.g. there is an application for simulating own (blue) air vehicles, enemy (red) air vehicles, an integrated air defence system (IADS) and many more as shown below. All applications share the same standardized interface and can be combined arbitrarily. This modularization allows running only a selection of models that is required for a certain task or project. All applications are stand-alone executables and can be run in parallel processes on the same computer or distributed over several machines. By exchanging compiled binaries, the integration of models from different companies is possible without exposing the detailed underlying functionality. Fast and easy cooperation between different companies is in general a main driver for the FPL architecture. To this end, a base application class is made available that provides all simulation-related functionality like simulation control state machine, communication middleware interface and common libraries e.g. for geospatial calculations in different coordinate systems. New models can be added to the simulation framework by simply implementing a new base application instance. The execution of all applications is controlled by a central simulation control instance. It provides a graphical user interface to start, stop and speed up the simulation as required. During execution, the runtime of all applications is monitored and the simulation time is dynamically adjusted to the slowest model. This allows distributed faster-than-real-time simulations with adaptive simulation time acceleration. Communication between applications is realized with the Data Distribution Service (DDS) standard [2]. It enables reliable and scalable data exchange in a network using a publish-subscribe pattern. Two different partitions are used for broadcasting simulation data (e.g. entity states, simulation control commands, etc.) and multicasting command and control data (e.g. data actually sent over BUS-systems or data links). An open source implementation of the DDS standard is used to further ease collaboration with external partners.

Figure 1 provides an overview of our simulation architecture including applications that are required for most missions. As previously mentioned, this architecture is not fixed and virtually any application can be removed or exchanged as required. New models can be integrated by registering a base application implementation at the simulation control via the DDS middleware as indicated by the dashed black arrow. Boxes with blue/red background depict own/enemy systems, boxes with mixed colour can be used by both sides. Simulation infrastructure components are coloured grey and user interfaces are coloured orange. Black arrows indicate communication during the simulation, grey arrows stand for data exchange before/after a simulation run. The high-level functionality of all applications shown in ***Figure 1*** is listed in ***Table 1*** below.

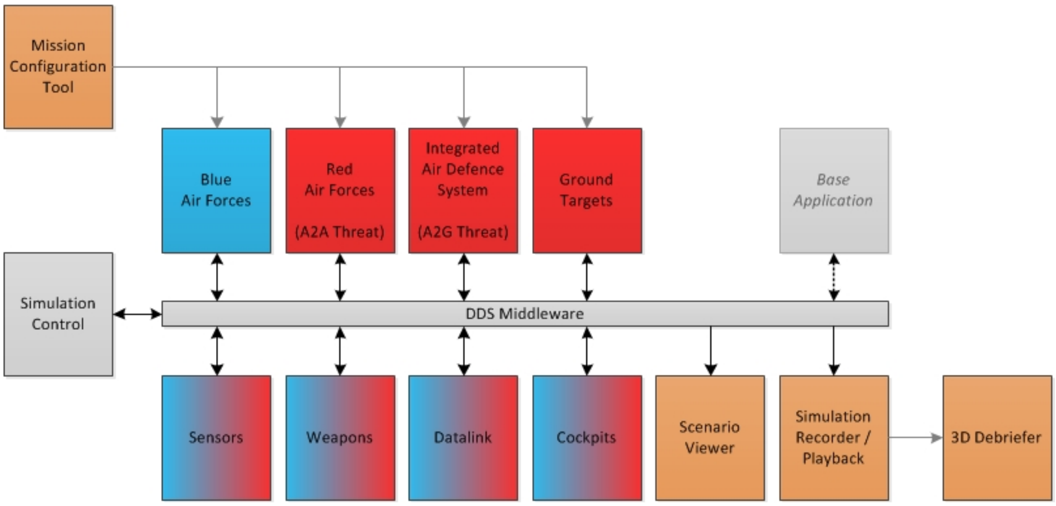


Figure 1: Architecture overview with baseline components.

Table 1: Selected applications and their high-level functionality.

Application	Usage	Functionality
Mission Configuration Tool	Setup	Graphical user interface for setting initial configurations of blue and red forces, mission planning
Scenario Viewer	Visualization	Online mission visualization
Simulation Recorder / Playback	Analysis	Record mission data during simulation to playback missions later for debriefing and further analysis
3D Debriefer	Visualization	3D visualization of recorded missions for debriefing
Blue Air Forces	Blue Forces	Airborne system simulation including 10-DOF* aerodynamic model, flight control system (FCS), manoeuver logic, sensor models, data fusion and tactic module
Red Air Forces	Red Forces	Air threat simulation including 10-DOF* aerodynamic model, FCS, manoeuver logic, sensor models, data fusion and tactic module (A2A only)
Integrated Air Defence System (IADS)	Red Forces	Ground threat simulation including ground-based radar simulation, vehicle motion, data fusion and tactic module
Ground Targets	Red Forces	Static and moving ground targets not integrated in the IADS
Sensors	All Forces	Radar simulation including detection model, radar management and target tracker model; passive emitter localization, EO/IR

Weapons	All Forces	A2A, A2G and G2A weapon simulation including gun model, missile propulsion model, 5/10-DOF* aerodynamic model (missiles and guided munition), seeker head model, guidance laws and damage assessment
Datalink	All Forces	Multi-platform information exchange system, radio simulation
Cockpits	All Forces	Physical cockpit models to optionally take over control of aircrafts from UCAV or interceptor application

* Aerodynamic models with 10 degrees of freedom (DOF) for aircrafts and cruise missile types, 5 DOFs for missiles (roll not simulated).

For wargaming sessions, the different applications run distributed over multiple rooms in the FPL to mimic the procedure of real air operations: After setting up a scenario, operators on blue and red side use the mission configuration tool to plan their mission in separated rooms. The air operation commanders remain in those rooms while pilots split on two rooms with two cockpits each to fly the mission. Any aircraft from the blue and red air forces application can be controlled from the cockpits, so pilots can take over different roles and fly against each other or as a single team against computer controlled forces. All rooms are equipped with a voice communication simulation. After the mission, the teams come together in the briefing room to evaluate the mission which can be replayed from recorded simulation data. An additional room equipped with multiple PCs connected to the simulation network can optionally be used for project-specific tasks, e.g. hardware-in-the-loop experiments.

3.2 Model Building

The choice of the right modelling paradigm for the FPL is in fact not trivial as it covers aspects of an operational analysis tool (often stochastic) as well as an engineering simulation (usually deterministic or hybrid). The impact of this decision can best be illustrated on an example, namely how to determine if an aircraft is hit by a missile. In a stochastic model, this decision is based on configurable probabilities, e.g. probability of hit (missile) and evasive manoeuvre success (aircraft) and a random number. To make the final mission result less sensitive to a single random number, multiple simulation runs with different random seeds are often conducted in practice. Following the deterministic approach, the missile flyout is simulated based on the missiles' launch direction, guidance law and fixed performance parameters like thrust, maximum acceleration etc. The aircraft's trajectory during the evasive manoeuvre is analogously based on its initial state, aerodynamics, reaction time etc. The aircraft is considered killed e.g. if the distance between missile and aircraft is below a certain threshold when the warhead detonates. In a deterministic model it is per definition already known at the time of the missile launch if the aircraft will be hit. Necessary simplifications in deterministic models are usually done by introducing fixed parameters like the distance threshold in the missile example. Hybrid models allow using random numbers for such simplifications, e.g. a probability of kill as function of miss distance.

To efficiently test and analyse large-scale air operations, the simulation should run faster than real-time by at least factor 10 (on average) with several dozens of blue and red assets in operation on a single machine. This imposes a major restriction on time discretization and runtime complexity of the used algorithms. To also maintain rapid prototyping capability, the time required for setting up the simulation for new projects or developing/integrating new components should be kept low. Models that are too complex impose more restrictions than significantly improving the quality of the results. Under those aspects, (more) stochastic models have the advantage of being faster in both runtime and development time. However, there are two major factors that restrict the use of stochastic models to a minimum in our case: First, the simulation will only be accepted by operators if gives exact reasons why their tactics and manoeuvers were successful or not. Additionally, stochastic models are data driven, but the required data is often not available for future own and/or enemy systems. It is possible to estimate the probability of kill for a missile that has been in service for years and shot multiple times in tests or real operations. It is however very risky to just increase this probability for future missiles, especially because stochastic models are very sensitive to those parameters. From our point of view, a sounder extrapolation of future systems can be achieved by modelling all systems as generic physical models based on technical system parameters. In a first step, the models itself are validated by simulating existing systems with known technical and performance parameters. For future systems, the technical parameters are then extrapolated based on expected technological advances, domain expert knowledge and their tools. To stick with the initial example, the extrapolated evasive manoeuver performance of a future fighter is e.g. based on a higher lift coefficient calculated from CAD and fluid dynamic models or on higher resolution and sensitivity of the missile approach warner.

A key aspect for objectively evaluating the performance of future concepts in simulation is the modelling of environment and threats. It has to be taken into account that the system-of-system approach is leveraged on red side just like on blue side. The danger of modern IADSs comes from combining different systems from very short range to long range. All of those systems have their strengths and weaknesses, but they are organized such that individual weaknesses are compensated by other systems and overall system-of-system performance is maximized. The first difficulty is therefore that a large amount of systems has to be simulated and that the individual strengths and weaknesses of those systems have to be identified. The approach of generic physical models comes to use for both aspects: After a generic air defence system model has been developed and validated, it allows quickly integrating new systems in the simulation. Based on the simulated physical effects, operational strengths and weaknesses of enemy systems or possible future threat concepts can be estimated. The difficulty of using generic models on the other hand is that functionalities from real systems have to be mapped to the generic model such that all significant individual system properties are retained. This leads inevitably to quite complex and detailed generic models. We will outline our approach to balancing complexity and fidelity on the example of the ground based radar component. As exemplary shown in ***Figure 2***, an entity within the IADS simulation is composed of different components. Those components can be combined arbitrarily to quickly configure new systems. From a functional point of view, the ground based radar component is made up of controller, detection model and target tracker. According to the current task of the entity, the controller selects the required radar mode, e.g. surveillance for 360° search or combat search if a specific sector has to be prioritized. To counter jamming or ground clutter, different waveforms can be used. Depending on the radar type, e.g. mechanically or electronically steered in one or two dimensions, the controller has varying possibilities to adapt the search pattern. After the types and numbers of waveforms have been selected for a beam position, the detection model generates measurements based on an aspect-depending radar cross section model of the target, ground clutter, terrain shadowing, atmospheric attenuation and electronic countermeasures. Measurement errors are induced by signal-to-noise depending stochastic models. The hence generated measurements are then processed by the target tracker which performs measurement-track association and track filtering.

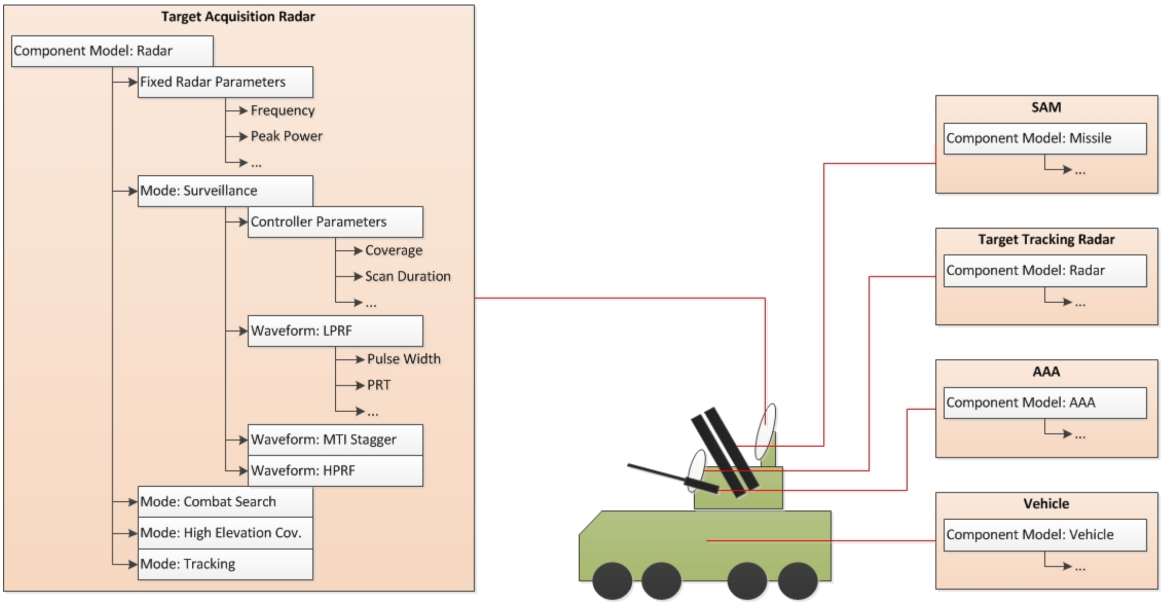


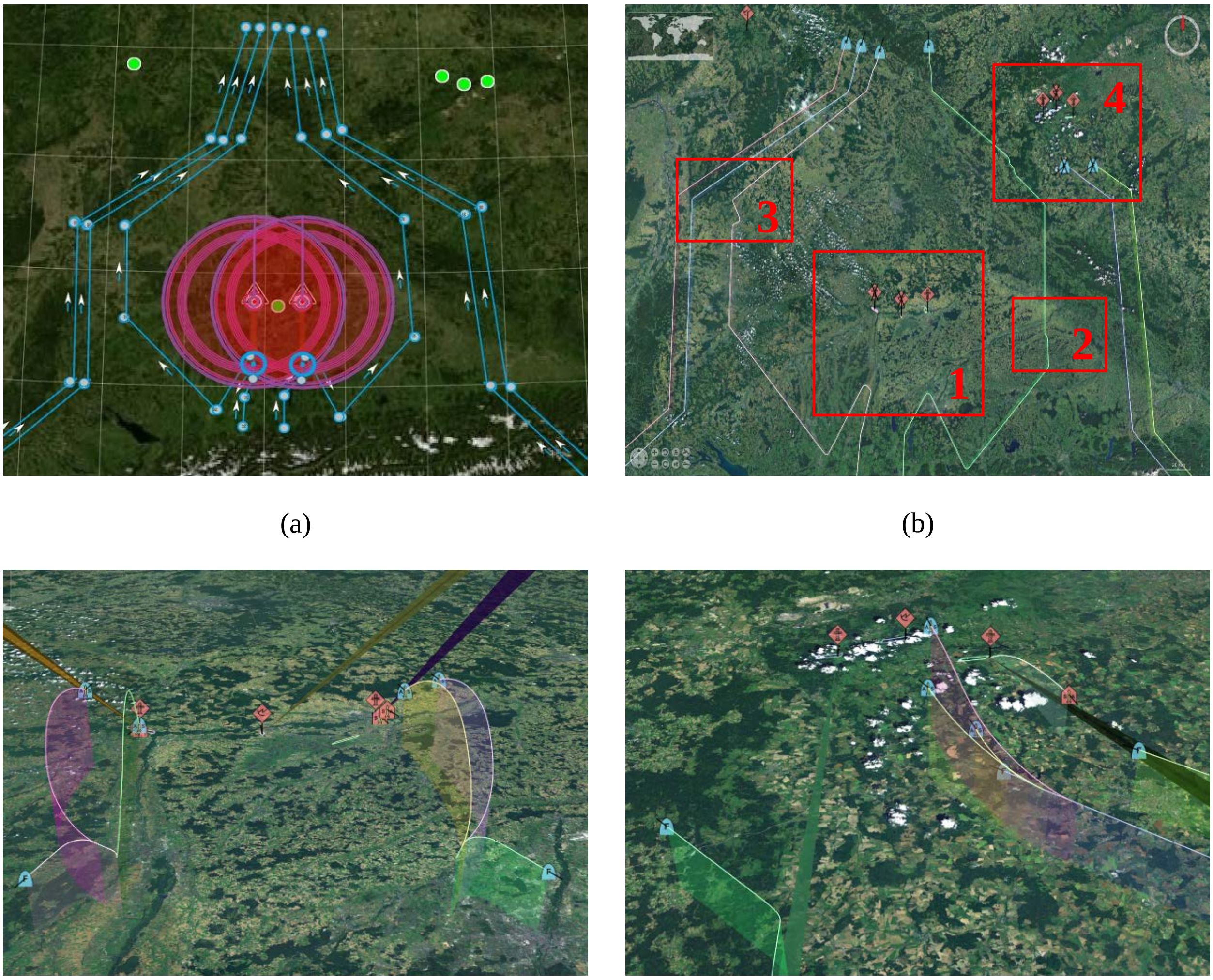
Figure 2: Exemplary mapping of a short-range ground-based air defence system to generic components.

Another difficulty arising from such detailed models is the total number of parameters that have to be estimated. It is also important to note at this point that all data in the simulation is non-restricted. This is on the one hand due to constraints from most projects, but on the other hand it also has practical advantages in daily work. One has to keep in mind that the simulation is used for concept validation and not for detailed system design, so using classified threat data at this early stage would impose major restrictions to infrastructure and development processes without adding significant value to the results. Based on that, all threat data had to be estimated based on publicly available sources or non-restricted data from internal projects and external partners. This again led to a large amount of data which is often on a very different level of detail or inconsistent, e.g. due to de-classifying restricted data. With the continuous development of our models and the engineering expertise gained over many years, it was possible to estimate consistent parameters for different current and extrapolated future threat systems. This was mainly done in an iterative bottom-up process: Based on available technical and performance parameters, missing model parameters are estimated to fit the component performance. Behaviour and interplay between the different components of a single system is then tuned to achieve the desired system performance. Finally, coordination of those systems within the IADS is tested in different scenarios to maximize the overall system-of-system performance.

3.3 Behaviour Models and Coordinated Tactics

The topic of behaviour models has already been touched in the context of model building and threat simulation. Compared to the threat simulations, which are in most scenarios only reacting to blue force actions, the blue air force simulation requires a high-level mission plan to achieve the desired mission goals. In addition to the high-level mission plan, all agents in the blue air force simulation have a low-level behaviour model that defines how high-level tasks are executed based on the current situation and how to react to unplanned events. We will demonstrate the interplay between high-level planning and low-level agent behaviour on a simple example mission as shown in ***Figure 3***. It has to be noted that this mission is mainly for illustrative purposes and does not necessarily reflect a realistic combat mission. The different red force components of the scenario are a known and alerted SAM site in the south, a pop-up threat in the north-east and a long-range surveillance radar in the north-west. Blue forces ingress from the south in 3 groups of 2 fighter aircraft each. The centre group is tasked to attack the known SAM threat before splitting up and joining the other groups. To further illustrate temporal coordination between agents, all aircrafts should merge into a single formation after traversing the mission area from south to north. The above behaviour is defined in the high-level mission plan that consists of waypoints, pre-defined target and weapon assignments as it can be seen in ***Figure 3***a. It is further possible to define e.g. sensor-optimized patterns or electronic attacks on pre-defined targets.

Figure 3b shows the actual course of the mission. Low-level agent behaviour can be explicitly observed in different mission phases that are framed red and numbered in chronological order. Mission phase 1, the attack on the known SAM site by the centre group, is shown in ***Figure 3***c in more detail. Agents fly a weapon release manoeuver that maximizes the energy of the released weapons based on target type, selected munition and pre-planned attack point before turning away to escape the SAM engagement envelope. It can further be observed how the target tracking radars of the SAM site track the incoming A2G missiles and multiple SAMs are launched for self-defence. This results in 2 of the 3 vehicles surviving the first attack. After having executed their attack manoeuvers, both blue aircrafts return to the pre-planned trajectory. Depending on the defined rules of engagement, a re-attack can simply be carried out if a radar is still emitting after it was attacked (as it is the case here) or it might require battle damage assessment with imaging sensors. In mission phase 2, the agent decides to re-attack the remaining vehicles in the SAM site. As the A2G missiles fired by the aircraft are again intercepted by the SAM site, another re-attack is carried out in mission phase 3. The assignment of such unplanned attack tasks is based on the prioritization of threats with respect to their estimated impact to own mission success and current role, remaining ammunition and relative position of all own assets to the target. ***Figure 3***d shows the beginning of mission phase 4. This time, there is a tactical advantage for the red side: All incoming aircrafts are tracked by the long-range surveillance radar, thus the pop-up SAM is able to engage as soon as targets are in the no-escape range. As the radars of the SAM site switch on, their coarse positions are estimated by passive emitter localization and 3 radar-homing A2G missiles are launched in direction of the threat. It can be seen in ***Figure 3***b that both outmost aircrafts have performed an evasive manoeuvre, but due to their tactical disadvantage and no simulated electronic counter measures they have been engaged by the pop-up threat in this scenario. However, the third aircraft of the right group is still able to successfully attack the target acquisition radar of the SAM site before returning to its pre-planned trajectory and merging with the other aircrafts as initially planned.



(a) (b) (c) (d)

Figure 3: (a) Mission plan generation in the mission configuration tool. (b) Mission execution with 1. pre-planned attack on known SAM site, 2. and 3. re-attack and 4. pop-up threat. (c) Close-up view of pre-planned attack. (d) Close-up view of pop-up threat situation.

4.0 RESULTS

The FPL has already been used in different projects within Airbus Defence & Space or in cooperation with industry partners on national and European level over the last 10 years. Although those projects vary largely in their scope, unmanned systems have always been in focus. In the following, we present several stages and aspects of conceptual design in the context of FCAS and show how the FPL serves as versatile analysis and engineering tool on the way to the next generation airborne weapon system.

4.1 Technology Identification

Technology identification is a continuous process to monitor research and technology advances in aerospace relevant domains and to analyse their possible impact on design and operation of future products. On the one hand, it should cover all technologies that can be used to enhance the capability of the platform or its subsystems. On the other hand, it is at least equally important to deal with various other technologies that might affect the future operational environment and thus require different platform capabilities and operation. Results from this process serve as starting point for new concept designs. Hence, they should answer the question: What are potential game changers for aircrafts that will be in service decades in the future and what technological gaps have to be filled to make those technologies fully available by that time?

Technology identification was also the focus of the early FCAS phases in a national cooperation involving the German armed forces and over 10 different aerospace companies. Besides other technological fields regarding aircraft design and operation, several key enablers for future air combat with unmanned systems were under investigations. The FPL supported those investigations by providing a testing and analysis environment for advanced mission planning, autonomous mission execution, communication management and minimizing emitting signatures. Results from those studies were used to shape technological roadmaps for research and technology activities and serve now as input for the European FCAS cooperation. The flexible “plug-and-play” and open-source architecture as outlined in section 3.1 was crucial for integrating various models from different industry partners in a common prototyping framework.

4.2 Concept Validation

The subsequent stage of FCAS is to conceptualize more concrete designs and analyse their operational performance in relevant mission environments based on the identified technological advances. As outlined in section 2, the FPL provides the operational analysis capability to perform design trade-offs in a holistic system-of-systems context. Together with our customer and industry partners, an exemplary mission that challenges different aspects of the concepts was defined to be simulated in the FPL from start to end. In an iterative process, the different concepts were evaluated in the selected mission and refined together with operators and customer representatives. The selected mission did not only impose several challenges to the concepts but also to the simulation itself. It required faster-than-real-time simulation of several dozen entities on blue and red side including a fully integrated future IADS that incorporates a variety of systems from short to very-long-range. Therefore, not only the blue side concept was subject to change, but the threat simulation was also improved based on input from subject experts from customer side and industry partners. Showing the simulation on various occasions led to a productive and interactive exchange about the expected performance and behaviour of future threat systems. As a result, behaviour models on blue and red side became more and more competitive and robust during the project due to changing behaviour on the opposing side. To guarantee unbiased results, blue and red side models were developed based on a common set of assumption and level of abstraction but by different teams and only with limited knowledge about the tactics of the opposing side. Next to the actual data generation for operational analysis, an important contribution of the FPL was to serve as basis for discussions between engineers, operators and customer. After several development iterations, the simulation environment and its modelling approach was accepted by the customer and could be used for the final assessment of selected concepts. From those assessments it can be concluded that the initially claimed force multiplication effect by unmanned assets as presented in section 1 can be supported by simulative results from the FPL.

4.3 System Prototyping

A key enabler for the succesfull use of unmanned assets in the different FCAS concepts is a cross-plattfrom mission managament system. This system serves two main purposes: First, it controls and coordinates mission execution of multiple UAVs. By automatically distributing tasks and planning manoeuvers it aims to maximize the operational performance of the whole UAV package while minimizing workload of the commanding aircrew. In contested environments with possibly limited communication between manned and unmanned platforms, the cross-plattfrom mission managament system needs to reliably control all unmanned assets such that they do not interfere with each other or the manned plattforms. Additionally, the cross-plattfrom mission managament system serves as command and control interface to the aircrew. It has to receive high-level tasks from the aircrew and present plans to solve those tasks in a fast and intuitive way.With its capability to simulate multiple unamnned assets in future threat environments and the available HMIs for command and control, the FPL provides the environment for prototyping different concepts and algorithms of the cross-plattfrom mission managament system. Based on a set of evaluation vignettes it could already be shown that the efficiency of A2G missions could be significanlty improved when using highly-coordinated package maneuvers compared to conventional flight planning, e.g. for precise localization of threats with distributed sensors on low-cost platforms or cooperative approach and attack manoeuvers to exploit specific threat weaknesses. The so far tested algorithms include cooperative path planning and swarming approaches, but also more experimental approaches like reinforcement learning. This shows how the FPL with its faster-than-real-time simulation capability can be used as training environment for modern machine learning algorithms.

5.0 OUTLOOK

Previously, we have presented a framework for dynamic multi-agent combat mission simulation. Vital aspects of such a simulation are not only a good architecture choice and adequate system modelling but also robust mission plans and behaviour models for those systems. Robustness is of major importance especially in a rapid prototyping environment where all models have to cope with changing system properties or completely new systems on own and enemy side. Our approach with separated high-level planning and low-level manoeuvre control as presented in section 3.3 has been proven to work with missions of different scope and complexity. With experienced operators and enough time, it is possible to create a consistent mission plan that is also robust to some extent to deviations due to unforeseen events. A problem in the context of simulation however is that it is often used by analysts and engineers only, thus no operators are available to provide their expertise in combat mission planning. It is therefore desirable to fully automate the process of mission planning including e.g. multiple subsequent coordinated attacks in many-to-many engagements with optimized assignments of weapons and targets. The general problem of multi-agent mission planning is not specific to our simulation, but applies to a wide range of simulations and unmanned systems in general.

A mission plan can most easily be described by “who will when be where to do what?” This applies to almost all missions independently of being carried out with manned platforms or UAVs, with one or many participants, in the real world or in simulation. As already pointed out, plans have to be robust against unforeseen events. Such events can be handled by reactive low-level agent behaviour, but they often require adaptions to the original mission plan. In easy cases, it is possible to realign the plan after a disturbance by simply tasking all agents to wait for the slowest agent (given they still have enough fuel). As this exposes the waiting agents unnecessarily to enemy threats, it is usually desired to find a better solution by changing the original mission plan. There are also situations where adapting the original plan is not only desired but necessary, e.g. when own platforms get shot down before achieving their mission goals. Adapting the plan, i.e. online re-planning for multiple coordinated assets, requires different techniques than purely reactive agent behaviour and is a challenging research task.

First off, the task is highly complex and the search space for the planning algorithm is accordingly huge. Recalling the description of a mission plan from the previous paragraph, it is composed of a set of usually heterogeneous agents, a set of possible actions that can be performed anywhere in a continuous 3D space and on a set of different targets. Many actions require cooperation of multiple agents and the outcome of those actions is often highly dependent on where it is carried out and on the world state when it is carried out. Additionally, the world is dynamic, partially unknown and can be explored and altered by the agents over time. Depending on the modelled depth, cooperation between agents can be hindered by limited to partially no communication. As already mentioned, it is not only desired to find a feasible plan but also to optimize it with respect to a desired cost function, e.g. minimize total mission time to reduce exposition to enemy threats. A more complex cost function could in turn try to maximize the probability of mission success, measured e.g. by the threat level of the entities, the number of munition available for the primary targets etc. The optimization problem has both logical and kinodynamic constraints, e.g. rules of engagement and the vehicles’ motion models. Given the complexity of the problem, it is in practice not possible to obtain a globally optimal solution within a reasonable amount of time (especially in the context of online re-planning). A common approach is therefore to split the multi-agent mission planning problem into subproblems and solve them in a top-down or iterative way. Those subproblems usually relate to the fields of task planning, task assignment, task scheduling and motion planning.

In practice, there are even more requirements to the planning algorithm regarding its HMI. It is desired that mission plans and tactics can be adapted based on a high-level language. This applies to the simulation context where analysts want to quickly alter the course of different simulation runs without changing the source code as well as to real world applications where pilots might want to adapt the behaviour of supporting unmanned assets to a changed tactical situation on-the-fly. It is crucial for the acceptance of unmanned assets operating close to the manned platforms that they can be commanded (almost) as flexible as a manned wingman via voice communication. Furthermore, the output of a planning algorithm has to be transparent and human-interpretable as well. As by now, artificial intelligence systems have superior performance in very specific tasks but often lack awareness of the higher context compared to humans. To at least partially compensate this issue, a mission planning algorithm should be able to present a set of alternatives to an operator, e.g. the fastest plan, the safest, etc.

To our knowledge, there is currently no practically usable mission planning system that fully considers all the above points. The multi-UAV mission planning problem is without doubt very challenging, but with the recently increased number of different projects towards human-machine teaming it will surely see significant advances over the next years. In this context, the FPL can be used to integrate promising research approaches and to estimate how they scale to environments of increased complexity.

6.0 SUMMARY

Unmanned systems supporting manned platforms in future air combat environments will have a possibly huge force multiplication effect. The task of conceptualizing those platforms and the required subsystems like cross-platform mission management systems becomes however increasingly complex. To deal with this complexity, the FPL serves as a versatile tool to assess the operational performance of new concepts in a holistic system-of-systems approach. We have presented the core component of the FPL, a dynamic multi-agent simulation that allows simulating complete combat missions in realistic future threat environments and how it was used to answer questions in the fields of technology identification, concept validation and system prototyping. Based on our experience from those tasks, we have outlined what might be one of the biggest future challenges not only for simulation but also for the introduction of unmanned systems in general: Implementing a robust high-level planning algorithm that generates ad-hoc mission plans for complex air operations while considering reactive low-level agent behaviour, human operators and online user input. As we are already working on solving this challenge, we expect the FPL to be further of use as efficient and realistic prototyping environment over the next years.

7.0 REFERNCES

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