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OpCog: An Operational Driven Development Approach for Cognitive Mission Management Systems

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Abstract

Future application scenarios for unmanned aerial vehicles (UAVs) especially in the military domain require the operation of UAVs with a high level of autonomy. As Mission Management Systems (MMS) for those high level autonomous UAVs can become highly complex the underlying technologies must be able to cope with this complexity. One promising development paradigm coming from the research community is the cognitive agent technology which is based on the human information processing. A cognitive MMS incorporating this technology is expected to handle unforeseen events, to cope with complex decision-making and to provide long-term planning. Among the biggest problems for the application of cognitive agent technology to MMS are time, budget and available knowledge on the industrial side. Moreover, UAV mission planners and UAV operators should be able to understand the behaviour of the autonomous system at any point of time during mission execution. This paper investigates the application of cognitive agent technology to the development of cognitive mission management systems from an industrial point of view. Furthermore, it presents a design procedure which supports the transition of pure operational requirements and functional specifications into a cognitive agent system. In order to assess the performance of this operational driven development approach, called *OpCog*, it has been applied to the development of a mission management system for UAVs operating in a Suppression of Enemy Air Defence (SEAD) scenario. The outcome of this application and the results of an experimental campaign are presented, too.

1. INTRODUCTION

Development of Unmanned Aerial Vehicle Systems (UAS) has been accelerating throughout the world in the last decade. Today UAS are mainly used for military applications but the demand for deployment of UAS for civil applications gains more and more importance. Here the search for intelligence and autonomy has become more than ever a key driver in the design of the UAS in general and UAS operations in particular since these capabilities outline some significant advantages over conventional UAV systems or manned aircraft operations.

Most of the UAS solutions that are currently in operation comprise unmanned vehicles that are mainly under remote control of a human operator. While the vehicle itself is stabilized via onboard feedback control, the human operator takes over the guidance and all more difficult cognitive tasks like flight and mission management, reaction to unforeseen events, decision making etc. But that form of remote control can only lead to a satisfying system performance assuming that the remote operator has full situational awareness and short reaction time. This poses very hard requirements for the availability and bandwidth of the data link and for the man-machine interface. In addition, many complex military scenarios even require the deployment of swarms or teams of UAVs. It becomes obvious that the control of such a team of UAVs cannot be taken over by a large team of human operators, since this would be too expensive and inefficient. Therefore, future military UAS must comprise vehicles with a higher level of autonomy and the direct ability to swarm or act in teams. Depending on the complexity of the respective application and the required capabilities, different levels of autonomy for UAVs have been defined, see e.g. [1], ranging from level 1, i.e. systems under full remote control, to level 4, autonomous self-learning systems.

Although a lot of work has already been done in that area, see e.g. [2], [3] or [4], the application of new autonomy enabling technologies and algorithmic techniques is still not providing the users with their expected level of performance. The main reasons are the complexity of the required cognitive functions and the required safety, reliability and predictability of such an autonomous UAV system. In addition, there is still a gap between the view of the end user, i.e. the UAV mission planners and operators, and the viewpoint of the researcher that provides the technologies to implement the required cognitive functions. The mission planner has the task to define the operational requirements and the specific UAV functionalities like mapping, navigation, control, communication or coordination. He is mainly interested in a UAV system that fulfils the requirements and offers the required functionalities, and not in details of a technical implementation. On the other hand, many researchers seem to be mainly interested in providing some new agent-related methodologies, where UAVs are welcome as a pure abstract application example. However, these contributions most often neglect questions of practical implementation and operational requirements. The engineers and developers in industry, i.e. those people that are responsible for the development of UAVs and all the subsystems like the onboard Mission Management System (MMS), then have to take into account all of these different aspects. They have to choose technologies provided by research that allows the fulfilment of the operational requirements defined by the customer and the implementation of the core functionalities of the MMS. Hereby, these functionalities have to be designed and implemented in a way that the UAV mission planners and operators should be able to understand the current behaviour of the UAV during the mission execution. Furthermore, aspects of certification as well as time, budget, human resources and knowledge have to be considered, too. Therefore, the industrial development of the core functionalities of a cognitive MMS must be based on a design procedure that supports the transfer of the operational requirements and desired functionalities into a technical implementation in the UAV. Herein, a suitable technology that allows the design of a cognitive system must be chosen first, where one of the most promising solutions is agent-based system. Agents are especially suited to design cognitive autonomous systems, see e.g. [5] and also provide the extension to the multi-UAV case using multi-agent systems. In addition, a lot of contributions related to UAV applications can be found in the literature, see e.g. [3] or [4] to mention only a few, and methodologies, tools and implementation approaches as well as de-facto standards already exist.

In this paper, we focus on the industrial aspects of the design of a cognitive MMS for autonomous UAVs using agent technologies. For that purpose, section 2 provides our understanding of a cognitive MMS for autonomous UAVs. Section 3 presents an application example where autonomous UAVs should perform the reconnaissance part of a SEAD. Based on the scenario description the operational requirements from the UAV operator's point of view are derived. The requirements are then used for the identification of the core functionalities of the MMS. As the MMS shall incorporate cognitive features its implementation is based on existing cognitive agent architectures. The chosen architecture, the development process for the transition from operational requirements to system design called *OpCog*, an Operational driven development approach for Cognitive mission management systems, and its application to the application example is presented in section 4. Lessons learned from that application example are described in section 5.

2. MISSION MANAGEMENT SYSTEM (MMS)

The upper part of the figure shown in Figure 1 describes the three control levels of a hierarchical UAV flight guidance system. Based on the flight path containing the specific flight dynamics the first control level is represented by the autopilot/flight control. One level above there is the flight management which provides complex control processes to follow a flight path and therefore generate the commands for the underlying flight control. The highest level in the hierarchical UAV flight guidance system controls the mission execution taking into account all internal and external situation parameters. Taken over by a pilot in a manned aircraft this task is accomplished by the MMS in the UAV.

As in most cases the UAV is controlled by an operator at a ground control station he has to supervise the output generated by the MMS, at least. The supervision becomes more difficult the more complex the MMS is. A cognitive MMS which is based on human information processing can add a lot to the situation awareness of the operator by not only showing the current behaviour of the UAV but also the reason for this behaviour. Therefore, a cognitive MMS shall rely on goal-based behaviour as the human operator is goal driven, too.

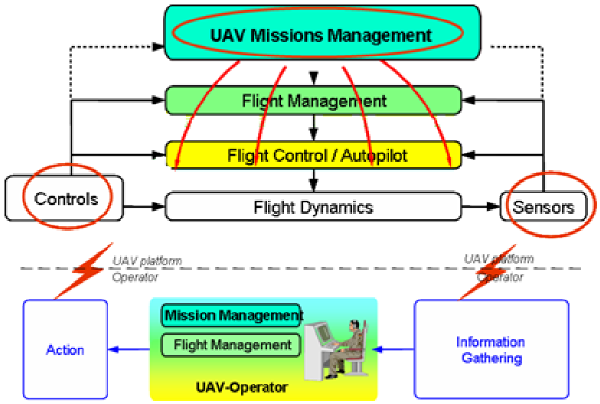

Figure 1 - UAV Flight Guidance System

In the literature approaches for cognitive MMS are already described, see [6]. However, the focus of our approach for a cognitive MMS mainly relies on the traceability and understandability of its output to the operator. Therefore our MMS is based on the Belief, Desire and Intention (BDI) model of human practical reasoning. First introduced by Bratman [7] and later formalised in a computable way by Rao and Georgeff [1] the BDI model provides the description of human goal-oriented behaviour in a more intuitively manner.

The BDI architectures have their roots in the tradition of understanding practical reasoning and comprise two important processes: deciding what goals should be achieved, deliberation, and how to achieve these goals, means-ends reasoning, see [1]. The beliefs represent the information the agent keeps about its current environment. Desires are the main constant goals of the agent. They represent the states of the world which the agent wants to achieve, and must be consistent. The intentions are the commitments to some of these goals according to the current situation. In order to reach a goal, the agent chooses a plan out of a plan library. For further information about the BDI paradigm the reader should refer to the literature [7] and [1].

The main advantage of the BDI paradigm is the fact that it is a well known approach where many examples can be found in the literature and also a lot of tools are available. Furthermore, Norling et al. [8] showed in several case-studies that the BDI model is particularly applicable to domains where deliberation and means-end reasoning about goals are the main issues. But although the theory itself is straightforward its realisation from a practical/industrial perspective is mostly rather difficult and therefore inconvenient. The definition of the beliefs, goals and plans often has to be done with formal languages which are difficult to understand for non cognitive systems experts like e.g. the UAV planner and operator.

While BDI is only a modelling paradigm for goal-oriented behaviour there are cognitive architectures describing the human information processing as interacting modules. COGNET which stands for COGnition as a NEtwork of Tasks is such a cognitive architecture where human information processing is modelled as the parallel execution of three mechanisms: perception, cognition and action.

– Perception gathers information from the external world and stores it as symbolic or semantic information in an extended working memory.
– The cognitive process analyzes and evaluates the symbolic representation of the world according to predefined goals. In the case that conflicts between the current situation and the goals are found a conflict resolution is taking place. The cognitive process is split up in several cognitive tasks competing one with each other for attention. Note that only one task at one point of time can be executed. Each CT represents one or more sequence of actions in order to achieve its associated goal.
– An Action is a result of cognition and is either an internal action or an external (motor) action. The former alters the internal symbolic representation of the world whereas the latter is used to act in the real environment.

COGNET is mainly based upon the work of Zachary et. al [9] and was especially developed for tactical decision making (TDM) in military missions. TDM is characterised by real-time requirements, decision making under non-predictable events and multi-tasking. iGEN is a cognitive agent software toolkit which implements the COGNET theory and provides an execution engine as well as an integrated development environment for developing and running COGNET based agents.

Advantages of COGNET/iGEN making it an interesting approach are the blackboard architecture used to store the mental model of the world and the agent itself, the traceability of the current actions of the agent and the parallel execution of the three mechanisms, perception, cognition and action. The parallel execution provides the feature that while an agent is reasoning about a current situation it is still receptive for new input from the outside world. Furthermore, the blackboard architecture make it feasible to organise the knowledge in a hierarchical way with semantic connections between knowledge elements. Other more practical advantages of the COGNET/iGEN approach are the possibility to model the components of architecture by a graphical interface, the defined interface for the input and output to the model and the good documentation. On the other hand there are also drawbacks of the approach like e.g. the only implicit representation of goals and the direct binding between goals and sequences of actions for their achievement leading to less flexibility.

Therefore, the main idea presented in this paper is to merge the BDI paradigm with the cognitive model COGNET/iGEN in order to combine the strengths of both approaches which is similar to the proposal presented in TACOP [10]. But instead of using BDI for the description of a model based on COGNET like done in TACOP [10], OpCog uses BDI for the formal description of a cognitive MMS whereas its implementation in software is carried out using the iGEN toolset and therewith parts of the COGNET theory.

3. UAV APPLICATION SCENARIO

Within the scope of a SEAD mission, data about possible targets like surface-to-air-missiles (SAM), including their current activities, capabilities and resources shall be gathered by operating reconnaissance flights. The mission task is the co-operative reconnaissance of the defined mission area by a heterogeneous team of UAVs, i.e. a team of UAVs with different sensory capabilities. The mission is successfully accomplished when all targets in the mission area have been classified and localized.

3.1. Mission Profile

In general, a complete reconnaissance mission consists of several phases spreading from “pre-flight mission planning” and “start from base” to “return to base” and “mission debriefing”. In this paper we concentrate on the central mission phase, the aerial reconnaissance in the mission area, because it illustrates at best the operational complexity of a real UAV application scenario as well as the performance of a co-operative team of UAVs in such an environment.

3.1.1. Participating Entities

Besides the UAV operator in the ground control station an undefined number of UAVs and targets is part of the mission scenario. The targets can be classified according to their threat, size and mobility, ranging from large-size radar stations to small-size and highly dangerous, mobile SAM units. The UAVs are small and agile aircrafts which are already equipped with a flight control unit (FCU) and a highly integrated data link (HIDL) connecting them with the operator and among themselves. Moreover, each AV carries specific sensor equipment, either a radar or n electro-optical sensor. Both sensors are able to detect targets, whereas the radar sensor can also determine the exact position of a target and the electro-optical sensor can classify and hence identify a target. Therefore, a target classification and localization can only be achieved by merging both data.

3.1.2. Mission Phases

For improving the mission results it is reasonable to split up the mission in two phases, a coarse find fix and track (FFT) phase and a fine FFT phase. Goal of the FFT coarse phase is the detection of all targets in the mission area by segmenting the area in several sectors, distribute them among the UAVs and clearing them up individually by only one UAV. In the FFT fine mission phase, sub-teams are formed whose task is the localization and classification of targets which have been detected during the previous phase. Hence, each team has to consist of at least one UAV providing radar sensor equipment and one UAV providing electro-optical sensor equipment. The allocation of sectors to UAVs as well as the targets to the sub-teams shall be accomplished according to the optimal application of all available resources.

3.2. Operational Requirements

Operational requirements describe the needs on mission level which have to be met in order to succeed the task of the mission. They can also be referred to as the goals which have to be achieved or maintained during the mission course. The operational requirements can be classified on the one hand in those that are specific for each mission phase. On the other hand, general requirements exist which have to be fulfilled at any time during the mission course.

3.2.1. Mission Phase FFT Coarse

At the beginning of the mission the UAVs shall share information about their mission goal. In case they realize that they can only achieve their goals by working together they shall build a team, thus having the goal of *Team Building*. Once a team is built, the mission area has to be divided into parts and distributed among the team members, *Sector Distribution*. Furthermore, the sector shall be cleared up, *Sector Reconnaissance*, and the detected targets should be communicated within the team, *Communication of Detection Results.*

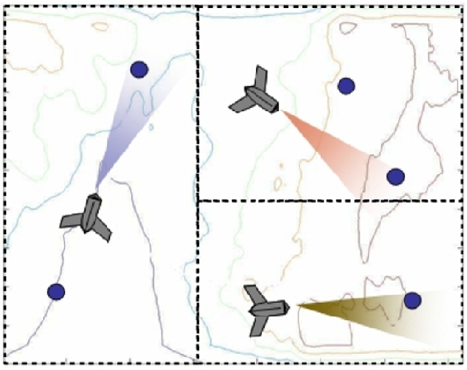

Figure 2 - Mission Phase FFT Coarse

3.2.2. Mission Phase FFT Fine

Having finished the FFT coarse phase, the team shall build sub-teams, *Sub-Team Building*, composed of at least one UAV equipped with a radar sensor and one with an electro-optical sensor. The whole team shall be able to allocate the targets among the different sub-teams, *Target Allocation*. In order to provide optimal mission execution the sub-teams shall compute a resource and threat minimizing flight path to cover all targets, *Optimized Path Planning*. The classification and localization of targets can only be achieved by a fusion of the different sensory results, *Target Data Fusion*. The outcome of the fusion shall be communicated in the team as well as to the operator to prevent target data loss in case of an UAV loss, *Target Data Communication*. As new threats could be identified hereby, the UAVs shall re-plan their flight path to minimize the threat risk, *Path Re-Planning*, see also Figure 3.

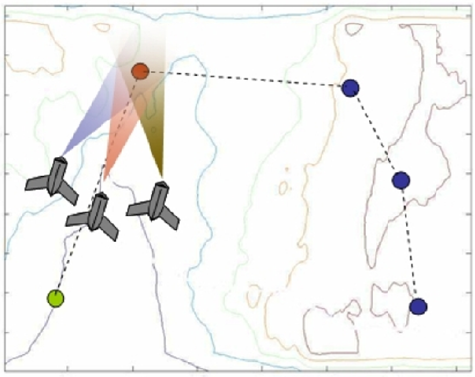

Figure 3 - Mission Phase FFT Fine

3.2.3. General

One general operational requirement is the reconfiguration of the team and the sub-team, *Team Reconfiguration* and *Sub-team Reconfiguration*. This indicates that the UAVs are able to identify the non-reachability of their mission goal with the current team or sub-team configuration and hence rebuild the team and sub-team. In addition, the UAVs shall end the mission and dissolve the team when either the mission goal has been accomplished or can not be achieved any longer, *Mission Ending*. Ensuring the flight safety, each UAV must avoid collisions with other aircrafts or the ground, Collision Avoidance, and provide adequate handling of its flight behaviour by the help of a flight control unit (FCU), *UAV Guidance*.

4. OPCOG

In this section we present OpCog as an operational driven development approach for cognitive agent systems. As the acronym indicates, Op stands for “operational” and Cog for “cognitive”.

4.1. OpCog Development Approach

The OpCog development approach tries to bridge the gap between the operational requirements derived from the military user and the existing cognitive systems. Following the development processes in former projects in the domain of UAV applications, three main stakeholders have been identified: domain experts, operators and developers. Domain experts like military users are interested in the overall fulfilment of their requirements according to standards and specifications, see section 3. Operators are the real users of the system and know exactly the real mission course. The third group of stakeholders comprises the industrial developers which have to capture and transform the knowledge from operators and experts into a working UAV system. Our development approach consists of three development phases, see Figure 4.

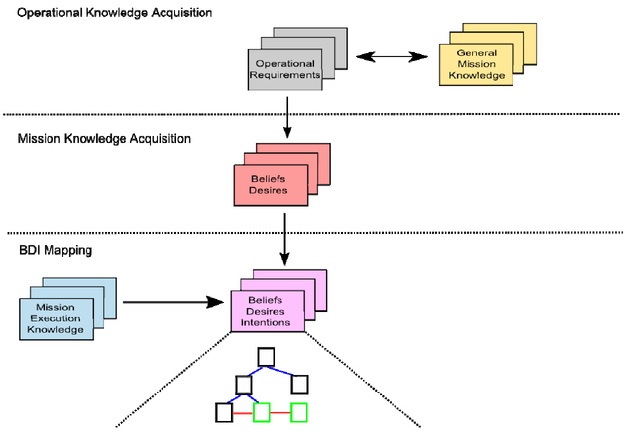

Figure 4 - OpCog Process

1) Operational Knowledge Acquisition

During the knowledge acquisition phase domain experts and developers emerge potential operational requirements like those described in section 2.2. For that reason domain experts provide general mission knowledge e.g. military procedures and mission specific schedules. In general, domain experts have no deep understanding of cognitive technologies. Therefore the developers consult the domain experts in technology related questions which are important in the overall design of the cognitive system.

2) Mission Knowledge Acquisition

Based on the operational requirements the developers then have to derive the beliefs and desires of the cognitive system. Beliefs represent the knowledge which is required to accomplish the mission and can be categorized in a priori knowledge and knowledge which is generated and updated at runtime. Desires represent the goals which the agent wants to achieve. In our approach we distinguish between two types of goals: non-measurable and measurable goals called abstract or real goals, respectively. The two-fold distinction of goals is decoupled from the underlying cognitive system. Unlike [10] neither abstract nor are real goals interlocked to concrete beliefs. However, based on the operational requirements obtained in phase one the developers are able to model causal and hierarchical relation between abstract and real goals.

3) BDI Mapping

In the third development phase the operators provide mission execution knowledge which is used to complete the BDI model of the cognitive agent. Note that up to now only the beliefs and desires have been derived. According to the theory of the BDI paradigm, intentions are instanced desires at a certain point of time. Based on the provided mission execution knowledge, the developers derive the temporal relations between goals and their circumstances. Adding this information the goal hierarchy is completed and provides now the goals and their temporal and causal relations.

This complete OpCog process is passed through several times refining the goal hierarchy each time. Based on this formal system description the developer designs a MMS and implements its functions required for achieving each real goal.

4.2. Application Example

In the following the OpCog process is presented in more detail by designing a MMS for the UAV application scenario described in section 3. Please remind that for the application of OpCog the BDI paradigm used for the formal system description has to be mapped to iGEN for the implementation.

In the “Operational Knowledge Acquisition” phase the operational requirements are identified together with the domain experts like presented in section 3.2.

Using those operational requirements the beliefs and goals needed to accomplish the mission are derived during the “Mission Knowledge Acquisition” phase. This information is used to identify the causal relations between the goals and setup the basic goal hierarchy for this mission, see Figure 5. The goal hierarchy is based on an AND/OR goal graph as proposed in [11] where AND/OR links represent causal relations between goals. Thus, a goal depending on two lower level goals which are linked with the AND annotation can only be accomplished if the two lower level goals are accomplished. The two types of goals, real and abstract ones, are presented as black and green boxes in Figure 5, respectively. They only differ with regard to the determination of their accomplishment. The accomplishment of real goals can be measured, e.g. *Team Building* → a team has been built or not, whereas the accomplishment of abstract goals has to be derived from lower level goals in the hierarchy, e.g. the accomplishment of *Flight Safety* can only be derived from the measurable accomplishment of *Threat Avoidance* and *Collision Avoidance*.

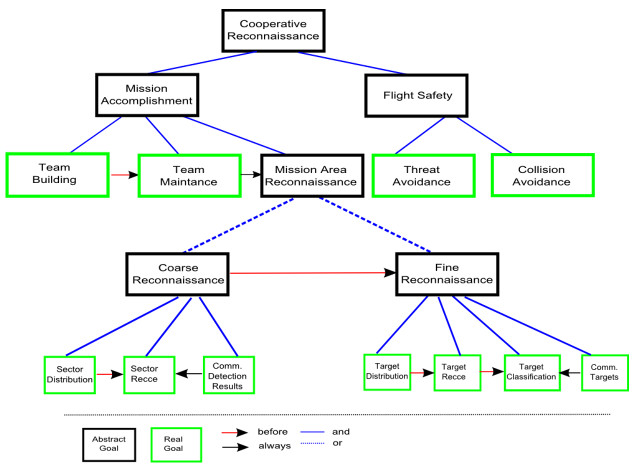

Figure 5 - Goal Hierarchy

During the third phase the mission execution knowledge extracted with the operator is used to setup the temporal relations between the goals on the same level in the goal hierarchy. Hereby, the relation ’BEFORE’ is used in the case that one goal has to be achieved once before another one whereas ’ALWAYS’ is deployed in the case that one goal has to be achieved and maintained before another goal can be pursued. So, the goal *Team Building* has to be achieved once before the goal *Team Maintenance* can be pursued. But if e.g. the goal *Team Maintenance* is no longer achieved the goal *Mission Area Reconnaissance* can not be pursued. This could happen if one UAV in the team is destroyed. It is obvious that the remaining UAVs have to rebuilt the team in order to achieve the overall mission goal.

Finally, after having modelled the behaviour specification of the UAVs, the BDI paradigm has to be mapped to the COGNET/iGEN architecture and toolset for the implementation. The declarative part of the beliefs as well as the desires is implemented using the blackboard architecture. The reasoning cycle and the procedural part of the beliefs have been described by COGNET/iGEN cognitive tasks. The COGNET/iGEN framework itself already includes a reasoning cycle based on the current priority and trigger conditions of CT. In order to fulfil the behaviour specification it is necessary to design an add-on reasoning cycle working only on the goal hierarchy which is implemented using a high priority goal evaluation CT. That goal evaluation CT examines the current achievement of the goals according to the causal and temporal relations between them. Based on the current achievement values of the goals and their relations the goals are prioritized. The add-on reasoning cycle is repeated at each update of the system. The great benefit of this approach is the generality of the add-on reasoning cycle. Therefore, it is completely independent of any goal hierarchy. That enables us to adapt the system rapidly to new desired behaviours. The developed cognitive system has been integrated in a simulation framework providing the core functionalities of the SEAD mission like sensor simulation or flight dynamics simulation. Using the simulation framework, an evaluation of the cognitive system implementation and herewith the OpCog development approach has been carried out, see following section.

5. CONCLUSION AND LESSONS LEARNED

From the developer's point of view, we had to deal with the complexity to map operational requirements which have been extracted from the domain experts to current cognitive system approaches. Although the BDI paradigm generally allows that mapping, no current BDI implementation meets our needs described in section 2. On the other hand, there is the powerful COGNET/iGEN approach supported by the software toolkit as described in section 3. Therefore, we had to setup a work around the BDI paradigm for the description of the system behaviour and COGNET/iGEN for the implementation similar to [10]. But unlike [10], our generic approach leads to a separation between behaviour specification and actual execution. Thanks to the temporal and causal relations in the goal hierarchy one can determine three main issues related to the achievement of the goals: which goals have to be achieved, why these goals have to be achieved and when they have to be achieved.

Moreover, as the behaviour specification is visual like shown in Figure 5, one can easily understand and refine it. This was very helpful during the incremental validation process carried out together with the domain expert and the operator. During the evaluation period we simulated the SEAD mission using different test cases. Those cases differed in the parameters e.g. number of available UAVs, sensor equipment, fuel resources. Part of the evaluation was the input from a UAV operator who monitored the execution of the test cases. As a result it can be stated that in general the mission was executed according to the operational requirements. But the operator stated as well that given a number of UAVs higher than six it was difficult to maintain an overall mission view. The main reason for this drawback can be found in the unsuitable man-machine-interface and not in the comprehensibility of the behaviour specification. Hence, future work should consider the visualization of the complex behaviour of a multi-agent system.

Furthermore, the operator was impressed that he could change the behaviour specifications according to the current mission goal. So, he once changed the temporal relation between flight safety and mission accomplishment in a way that the latter always has to be achieved instead of the former. From the industrial point of view, another drawback of our OpCog approach is still the requirement for the developer to have appropriate background knowledge about cognitive systems in order to model such a complex system. Therefore, further work must contain a separation between the cognitive technology itself and its application. Ideally, this development leads to an industrial standard. Moreover, future investigations should also consider the questions of validation and verification of such cognitive agent systems as this is one of the most important points for certification of cognitive MMS, see [13] for first considerations.

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