# OpCog: An Industrial Development Approach for Cognitive Agent Systems in Military UAV Applications

# (Short Paper)


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## ABSTRACT

Future applications of unmanned aerial vehicles (UAVs) especially in military missions require the operation of UAVs with a high level of autonomy. Autonomous UAVs could be developed using agent technologies and therefore this paper investigates such an approach from an industrial perspective. Taking into account time, budget and available knowledge on the industrial side and need for UAV operators to understand the behavior of the autonomous system this paper proposes the application of cognitive agents and a design procedure that supports the transition of the pure operational requirements and functional specification into a cognitive agent system, called *Op*erational driven development approach for *Cog*nitive Systems(*OpCog*).



## Categories and Subject Descriptors

I.2.11 [**Artificial Intelligence**]: Distributed Artificial Intelligence, Intelligent agents

## General Terms

Design, Development process

## Keywords

Agent-oriented software engineering, cognitive agents


## 1. INTRODUCTION

Since four decades or even more, Unmanned Aerial Vehicles (UAVs) are investigated by the research community. As UAVs are operated without any human pilot, they especially provide new applications in the military domain where manned aircrafts cannot operate or can only operate less efficiently e.g. in long endurance or Suppression of Enemy Air Defence (SEAD) missions. Most of the UAV solutions that are currently in operation comprise unmanned vehicles that are mainly under remote control of a human operator.


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However, it is widely recognized that future military UAV systems must comprise vehicles with a high level of autonomy and the direct ability to swarm or act in teams without permanent remote control. Although autonomous UAVs are an important area of research and many contributions can be found in the literature, see e.g. [3], UAVs with such a high level of autonomy are not yet in operation.

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 lack of methodologies and tools to support the UAV mission planners and operators to define the operational requirements and the specific UAV functionalities. Therefore, engineers in industry have to develop UAV mission management systems(MMS) which meet the operational requirements defined by the UAV mission planner while also taking aspects of certification as well as time and budget etc. into account. It becomes obvious that the industrial development of autonomous UAV systems and the core functionalities of the 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, one of the most promising technologies are agent-based systems, see e.g. [3]. In this paper, we focus on the industrial aspects of the design of an MMS for autonomous UAVs using agent technologies. For that purpose, we first describe a suitable application example of a SEAD mission that should be carried out by autonomous UAVs. Hereby, the operational requirements from the UAV operator's point of view have to be derived. These requirements then lead to the identification of the core functionalities of the MMS. This MMS then should be implemented using a cognitive agent architecture, and hence a suitable solution from the industrial perspective had to be identified. Here, we decided to apply the BDI paradigm and to implement the core functionalities with the help of the COGNET architecture. Our experiences with that approach then led to the definition of a development process called OpCog: an operational driven development approach for cognitve agent systems.

## 2. 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 heterogenous 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 are classified and localized.

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 focus 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. Besides the UAV operator at the ground control station, an undefined number of UAVs and targets are assumed in the mission scenario. The targets can be classified according to their threat, size and mobility. The UAVs are already equipped with a flight control unit (FCU), a highly integrated data link (HIDL) for communication and a specific sensor equipment, either a radar or an electro-optical sensor. Both sensors are able to detect a target, whereas the radar sensor can also determine the exact position of a target and the electro-optical sensor can classify a target. Therefore, a target classification and localization can only be achieved by merging both data. For the improvement of the mission performance it has been split in two phases, a coarse find, fix and track (FFT) phase and a fine FFT phase. In the FFT coarse phase all targets in the mission area should be detected. This can be done individually by each UAV. In the FFT fine mission phase, subteams providing at least one radar and one electro-optical sensor are formed to localise and classify the previously detected targets.

The operational requirements describe the needs on mission level in order to accomplish the mission. They can be classified in specific ones differing from one mission phase to another and general ones remaining during the mission course. At the beginning of the mission the UAVs shall share information about their mission goal. If they realize that the achievement of their goals is only possible through cooperation they shall build a team, *Team Building*. Having built a team the mission area has to be divided into parts and distributed among the team members, *Sector Distribution*. Then, the sectors shall be cleared up, *Sector Reconnaissance*, and detected targets should be communicated within the team, *Communication of Detection Results*.

Having finished the FFT coarse phase, the team shall build subteams, *SubTeam Building*, composed of at least one UAV equipped with a radar sensor and one with an electro-optical sensor and allocate the targets among those subteams, *Target Allocation*. For optimal mission execution the subteams shall compute a resource and threat minimizing flight path to cover all targets, *Optimized Path Planning*. Target identification and classification can only be achieved by a fusion of the different sensory results, *Target Data Fusion*. The fusion results shall be communicated within 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 replan their flight path to minimize the threat risk, *Path Re-Planning*.

One general operational requirement is the reconfiguration of the team, *Team Reconfiguration*. 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 behavior by the help of a flight control unit (FCU), *UAV Guidance*.

# 3. COGNITIVE AGENT SYSTEMS

## 3.1 Why Cognitive Agents?

Cognition comprises phenomena like problem solving, decision making, language, memory, and learning. A cognitive agent will be defined here as *"a technical system embedded in a complex environment, that gathers and processes information in order to act in and thereby alter the environment by own behavior. Herein, the information processing imitates the human cognitive behavior according to the aforementioned phenomena and characteristics,"* i.e. as an agent that processes the information according to a model of human cognition. There are several reasons why the modeling of human cognition in such cognitive agent systems is useful: (1) the actions of cognitive agents should be more human-like and understandable to the people that need to interact with them, (2) the knowledge the agents need should be more readily obtainable from human experts in the same field of work and (3) the agent's internal reasoning and thought processes should be easier to analyze and debug. Because of these properties, the application of cognitive agents is of special interest in industrial applications and led to our decision to use cognitive agents for the realization of autonomous UAVs in the project presented here.

## 3.2 Assessment of Cognitive Agent Systems

There are several candidate architectures based on human cognition and reasoning such as Soar [2], ACT-R [1], BDI [4] and COGNET [6]. In order to decide which of these paradigms fulfills the needs of the industrial developer of autonomous UAVs in the best way, all approaches have been compared and assessed with regard to some suitable evaluation criteria. These criteria are categorized as company-, theory- and application-specific criteria. *Company-specific* criteria comprise already available knowledge and human resources of the company as well as long-term development strategies. *Theory-specific assessment criteria* consider complexity, syntax, flexibility of the approach, modularity, extendability etc. The *application-specific criteria* are criteria like suitability for UAV scenarios, reference projects in the UAV area, requirements wrt practical (programming) knowledge and so on.

Taking these criteria into account, an assessment led to the result that both Soar and ACT-R are not really suitable for the considered application domain. This is mainly caused by the rather complex syntax, the unflexible architecture and the missing tool support. In addition, these paradigms do not really support the formation and coordination of teams. 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. The theory itself is straightforward, but the realization from a practical/industrial perspective is most often rather difficult. The definition of the beliefs, goals and plans most often has to be done with formal languages which are difficult to understand for the UAV planner/operator. The main advantage of the COGNET/iGEN approach is the graphical description and definition of all components of the architecture.

Therefore, the main result of the assessment was the idea to merge the BDI paradigm and the COGNET/iGEN implementation. The BDI paradigm is used as the underlying concept that models the cognitive behavior of the agent. That model of the cognitive agent is then mapped to the components used by COGNET/iGEN and the graphical description of knowledge, goals and plans, see also [5]. For the implementation of belief generation of the cognitive agent, various components are used. One part of the beliefs are not generated during runtime, but are predefined. Those beliefs are stored on the blackboard at the beginning of the mission. Beliefs about the external world are generated by the perceptual demons during runtime, which also transfer and integrate incoming information to the blackboard. The desires of the BDI paradigm can be interpreted as the full set of cognitive tasks, that become intentions if the tasks are triggered according to the current situation. The hierarchy of sub-goals and operators in the cognitive tasks implements the plans that have to be followed in order to fulfill the cognitive tasks and achieve the goals.

From an industrial perspective that approach provides a suitable methodology in order to design cognitive agents more comfortably. As the specific UAV domain has not been considered so far, there remains the question how to transfer the operational requirements of a specific UAV mission into a cognitive agent implemented with COGNET / iGEN. Therefore, we now carry on this approach towards an integrated development procedure based on BDI and COGNET/iGEN.

## 4. OPCOG DEVELOPMENT APPROACH

In this section we present *OpCog* as an operational driven development approach for cognitve agent systems. As the acronym indicates, *Op* stands for "operational" and *Cog* for "cognitive". *OpCog* tries to bridge the gap between the operational requirements derived from the military user and the existing cognitive systems. During the development processes in former projects in the area of UAV applications, we identified three main stakeholders: domain experts, operators and developers. Domain experts like military users are interested in the overall fulfillment of their requirements according to standards and specifications, see section 2. 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 Fig. 1:

**Operational Knowledge Acquisition**: During this phase, domain experts and developers derive potential operational requirements like those described in section 2. For that reason domain experts provide general mission knowledge e.g. military procedures and mission specific schedules.

**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 [5] neither abstract nor real goals are interlocked to concrete beliefs. However, based on the operational requirements obtained in phase one, the developers are able to model the causal and hierarchical relation between abstract and real goals, see also Fig. 2.

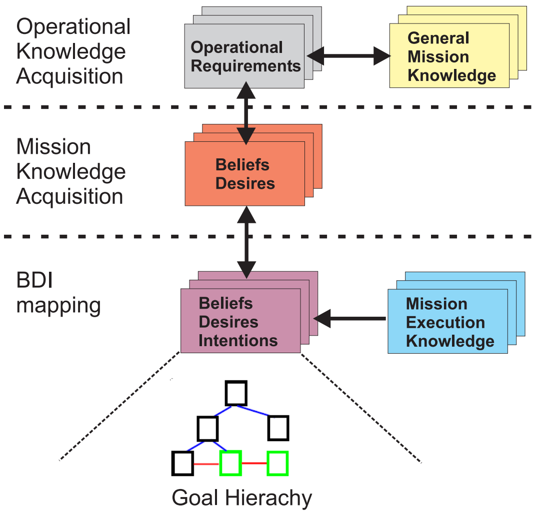


**Figure 1: The development approach.**

**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. 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 leading to the goal hierarchy, see Fig. 2. After a revision of the goal hierarchy the developers start to implement and integrate the proposed system.

## 5. APPLICATION EXAMPLE

The *OpCog* development approach has been applied to the mission scenario described in section 2 in an experimental development and validation process of an MMS carried out together with UAV mission planners. Herein, the formal system description using the BDI paradigm has been mapped to COGNET/iGen for the implementation.

**First**, the operational requirements have been identified together with the domain experts, see section 2.

**Second**, from the operational requirements we derive the beliefs and goals needed to accomplish the mission. Furthermore, the causal relations between the goals are identified and used to setup the goal hierarchy for this mission (see Fig. 2). The goal hierarchy is based on an AND/OR goal graph 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 Fig. 2, respectively. They only

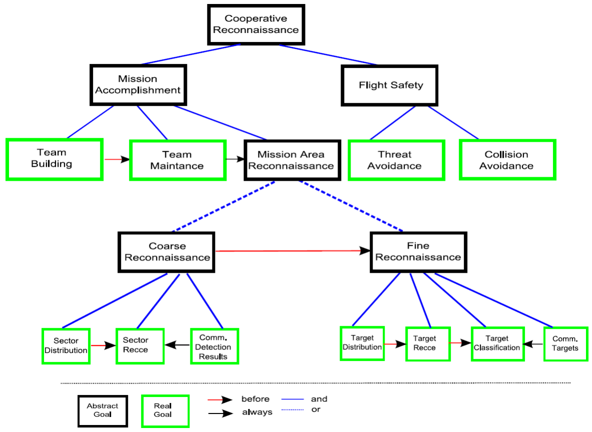


**Figure 2: The goal hierarchy.**

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*.

**Third**, using the mission execution knowledge extracted with the operator we setup the temporal relations between the goals on the same level in the goal hierarchy. Hereby, we use the relations '`BEFORE`' in case a goal has to be achieved once before another one and '`ALWAYS`' in case a 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.

**Forth**, after having modelled the behaviour specification of the UAVs, the BDI paradigm has to be mapped to the COGNET/iGEN architecture and toolset. The declarative part of the beliefs as well as the desires have been implemented using the blackboard structure. The reasoning cycle and the procedural part of the beliefs have been described by COGNET/iGEN cognitive tasks (CT). 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. This add-on reasoning cycle has been 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 behaviors.

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 then can be carried out using different test cases. Part of the evaluation was the input from a UAV operator who monitored the execution of the test cases. The main result was the fact that the mission was generally executed according to the operational requirements. However, the evaluation of bigger scenarios turned out to be rather difficult because of the complex overall behavior of the UAVs. Therefore, future work should consider the visualization of the complex behavior of a multiagent system.

## 6. CONCLUSIONS, LESSONS LEARNED

This paper proposes the *OpCog* methodology that allows the mapping of operational requirements extracted from the domain experts to current cognitive agent approaches. Here, the BDI paradigm has been chosen for the description of the system behavior and COGNET/iGEN for the implementation, similar to [5]. In contrast to [5], our generic approach leads to a separation between behavior 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 behavior specification is visual (see e.g. Fig. 2) one can easily understand and refine it. The approach has been successfully tested in an application example also including the domain experts. However, the developers still must have appropriate background knowledge in cognitive and agent systems technology, which is a drawback from the industrial perspective. Therefore, further work must comprise a separation between the cognitive technology itself and its application.

## 7. REFERENCES

[1] R. Anderson and C. Lebiere. *The Atomic Components of Thought*. London: Lawrence Erlbaum Associates Publishers, 1998.

[2] A. Newell. *Unified Theories of Cognition*. Cambridge, MA: Harvard University Press, 1990.

[3] M. Pechoucek, S. Thompson, and H. Voos. *Defence Industry Applications of Autonomous Agents and Multi-Agent-Systems*. Basel: Birkhauser Verlag, 2007.

[4] A. Rao and M. Georgeff. Bdi-agents: from theory to practice. In *First Int. Conf. on Multi-Agent Systems*, 1995.

[5] W. A. van Doesburg, A. Heuvelink, and E. L. van den Broek. Tacop: A cognitive agent for a naval training simulation environment. In *Proc. of the fourth international joint conference on Autonomous agents and multiagent systems AAMAS 05*, 2005.

[6] W. Zachary, J. Ryder, and J. Hicinbothom. Cognitive task analysis and modeling of decision making in complex environments. In *J. Cannon-Bowers; E. Salas (Eds.): Decision making under stress: implications for training and simulation*. Washington,DC: American Psychological Associations, 1997.