Experimental Evaluation of a Cooperative Automation Approach for Manned-Unmanned Teaming in Future Military Helicopter Missions

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ABSTRACT

This paper describes a twofold approach of cognitive automation in the Manned Unmanned Teaming (MUM-T) domain and explains the concept, implementation and experimental evaluation with pilots of the Bundeswehr. The application includes the guidance of several Unmanned Aerial Vehicles (UAV) by the cockpit crew of a manned transport helicopter in future military scenarios. We introduce two types of artificial cognitive agents to compensate the resulting high and dynamic workload for the crew. Cognitive agents on board the UAVs are in a delegation relationship with the crew and carry out assigned tasks in a highly automated manner. In addition, an artificial cognitive agent in the form of an associate system supports the crew in a cooperative manner. The agent behaves similar to a human crew member and has the task of preventing pilot errors and reducing workload peaks. The support takes place in both mission planning and mission execution. The associate system dynamically adapts the extend of the support to the mental demands and the task context of the crew, as well as the criticality of the situation. We implemented this twofold approach as real-time-capable software modules in a helicopter mission simulator. To evaluate the overall system, an experimental campaign was conducted with crews of experienced pilots of the German Armed Forces. The results show the potential of the approach presented. The reconnaissance continuously ensured safety for the crew of the manned helicopter.

1.0 INTRODUCTION

The guidance of several Unmanned Aerial Vehicles (UAVs) from the cockpit of manned aircraft (Manned Unmanned Teaming, MUM-T) is a highly relevant field of research and technology [1], [2]. In this context, the Institute of Flight Systems conducts research on the guidance of unmanned flight systems by the cockpit crew of a two-seated helicopter. Here, the pilot flying is mainly responsible for the manual control of the helicopter, navigation, communication and system management. In addition to traditional tasks such as mission management, communication and system management, the commander is responsible for the UAVs. The new range of tasks includes the management and monitoring of UAVs, the evaluation of sensor results and the adaptation of the mission and flight plan based on the reconnaissance results obtained. This spectrum of tasks results in highly varying mental workload (MWL) conditions of the crew. Especially phases of high MWL can lead to overtaxing conditions. This can result in reduced crew performance, a significant reduction in situational awareness and an increased error rate. Our approach of *Human-Autonomy Teaming* (HAT) addresses these problems by introducing cognitive abilities on the part of automation. The goal is to increase overall mission performance, balance workload and counteract human factors problems like out-of-the-loop problems [3], complacency and automation bias [4]. Therefore, we use two modes of cognitive automation, as depicted in Figure 1 [5][6][7]:

With the concept of *task-based guidance*, the crew is able to guide the UAVs by delegating tasks to the cognitive agent onboard each UAV (Figure 1, right side). The intelligent agents are able to understand and execute complex mission tasks in a highly automated manner. Thus, they use mission and system knowledge as well as the ability to plan and make decisions in complex scenarios. By delegating high-level tasks to automated systems, MWL is shifted from the crew to the agents. *Adaptable levels of automation* in the UAV guidance enable the crew to add additional knowledge at different levels of detail in order to compensate for the agent's lack of knowledge.

As second mode, a *workload-adaptive associate system* onboard the manned helicopter assists the crew. The associate system acts as artificial crew member and cooperates with the crew (Figure 1, right side). It supports the crew by modifying the task load by own initiative with the aim to correct, avoid, or even prevent pilot errors. To provide workload-adapted support, the agent generates a mental image of the crew and the environment (mission and tactical situation). The agent supports the planning and execution phase of the mission in dynamic environments based on *adaptive levels of automation*, enabling the manned-unmanned team to react quickly to dynamic tactical situations and unexpected events.

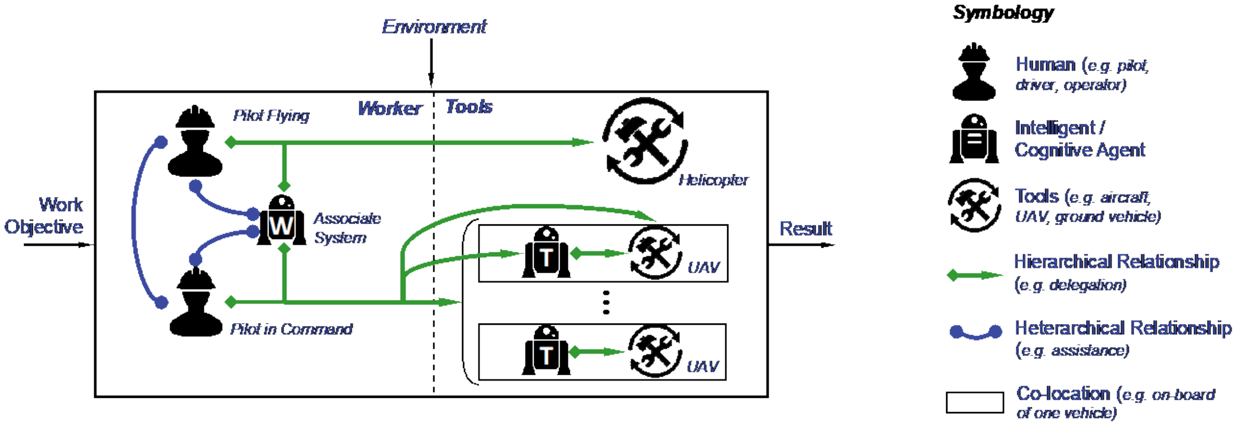

Figure 1: MUM-T work system

2.0 TASK-BASED GUIDANCE

The approach of task-based guidance for unmanned systems [8] offers the possibility to reduce the mental workload of the pilots by shifting cognitive load to the intelligent agent on board the UAVs. Such cognitive loads comprise the decomposition of UAV tasks into subtasks as well as the generation of flight plans and sensor commands. Thereby, the crew is able to manage several UAVs from the cockpit without changing the spectrum of use or usability. The relationship between commander and software agent is a delegation relationship similar to that of a human subordinate (Supervisory Control [9], green arrows in Figure 1). However, cognitive capabilities such as situation assessing, planning and problem solving are essential capabilities for such intelligent agents. Agents must be able to understand the tasks, break them down into subtasks, and execute them automatically. For returning the reconnaissance results obtained, the agent has to use the same, high level and a suitable format.

2.1 Levels of Automation in Task-based Guidance

We use the term *level of automation* in UAV guidance as a measure to describe the scope of necessary work steps of the pilot. A low level of automation (e.g. waypoint specification) can be compared with the direct manual control by the pilot, thus limiting the agent's scope for action. A high level of automation (e.g. task-based guidance) means that the pilot allows the agent more freedom in the implementation and is more interested in the result than in the sequence. Low levels of automation produce a higher workload, but they do allow better control, possibly a higher situation awareness, and the possibility to intervene in case of automation errors. This need for flexibility, especially in military missions, was also identified in earlier experiments on mission-based command and control. [10], [11]. The ability to compensate for automation errors and weaknesses and use human strengths plays a major role, especially in sensor and aerial image analysis. Above all, object recognition and friend-foe classification often push today's automation to its limits. [12], [13].

2.2 Scalable Autonomy in task-based guidance using variable levels of automation

The question now arises how to realize variable levels of automation in UAV management in general and from the cockpit in particular. Offering all available levels of automation at the same time and letting the pilot decide on their use brings some disadvantages. This includes possible unused cognitive resources of the agent, a poor structuring of the use of automation functions and problems if the agent runs in a low level mode and meanwhile losses its data link [14]. Another possibility is the hierarchical approach of scalable autonomy according to [15]. The pilot is able to access low levels of automation within a job in order to take advantage of the variable levels of automation described above. However, the concept ascertains that a task must be given first. The agent uses an HTN planner to break it down into subtasks which the pilot can access and modify in order to influence flight routes or sensor parameters, for example. Through this restriction, the agent knows the operator's intention expressed by the task and can provide appropriate support, for example through an associate system (chapter 3). The interventions are also possible during the plan execution and allow a specific and situation-dependent scaling of the used levels of automation. The agent was implemented as a knowledge-based system in the business rule engine Drools [16]. The system supports specific missions for transport helicopter missions, such as route and area reconnaissance, landing zone reconnaissance and tactical movement. Access to tasks and to low levels of automation are available for both pilots via the multifunction displays in the cockpit.

3.0 WORKLOAD-ADAPTIVE ASSOCIATE SYSTEM

The second mode of our human autonomy teaming concept is a workload-adaptive cognitive associate system that adapts its support to the current task situation and the mental state of the crew. The associate system cooperates with the pilots and thus is able to detect and correct human errors during the planning and execution phase of the mission, or to proactively prevent them.

3.1 Behaviour of the Associate System

The behavior of the associate system is derived from the behavior of a human copilot. The associate system pursues the mission objective independently and on its own initiative and supports the crew only if necessary. The extend of support is scaled according to the attention and mental workload of the crew. Therefore, the associate system follows behavior rules in the form of escalating basic requirements: The basic rule for this interaction is a defensive behavior of the associate system. If the crew is able to perform the task with the given automation tools, there is no reason to intervene in the functioning work process (basic requirement). Only if the pilot's attention is no longer focused on the most urgent task, it should be directed back to it (attention guiding, 1st requirement). If the pilot is overtaxed and therefore not able to solve a task situation, the associate system tries to simplify the task situation by transform it into a task situation, which can be handled by the crew again (task simplification, 2nd requirement). Only in the case of a very high risk the associate system takes over tasks automatically (task adoption, 3rd requirement). In order to transfer the skills and capabilities of a supporting co-pilot to a technical associate system, the system needs knowledge of the domain, cognitive capabilities to interpret and plan based on the knowledge and an interaction model to communicate with the crew. The basis for the interaction between pilot and agent and also between all associate system components is a common task model (subchapter 3.2). The situation interpretation based on this task model is explained in subchapters 3.3 and 3.4. The adaptive support for the crew is described in chapter 3.5.

3.2 A task model for task-centered communication

The basic idea of a task-centered communication approach is that only the name of a task is sufficient for the communicating partners to generate a mental picture of the task, which includes scope, prerequisites and demands [17]. This task-centered communication approach is used for communication between pilots and the associate system on the one hand and between individual modules of the associate system on the other hand. The developed task model contains all mission and pilot tasks in a hierarchical structure. Mission tasks are vehicle-specific, domain relevant tasks. For each mission task, all pilot tasks which are required to carry out the mission task, are also stored in the model. Each pilot task contains the mental resources required to execute the task.

3.3 Mixed-Initiative Mission Planning

The goal of the mission planning process is to generate a plan, containing the necessary and optional plan elements, with which the mission goal can then be achieved. The contained tasks are based on the mission tasks from the task model. The associate system itself must be capable of planning and scheduling in order to derive the necessary action steps with which the pilot shall be supported in (re)planning if necessary. While there is probably sufficient time for detailed manual planning during mission preparation on the ground, unforeseen changes of either the tactical situation or the mission objective/mission constraints during the flight require time-critical replanning. Especially in situations of excessive workload, problems of human performance and errors can occur [18], [19]. For this reason, a manual mission planning is not suitable in most situations. Automated planning, on the other hand, reduces the demands placed on pilots, but can lead to problems such as loss of competence [20], [21]. Additionally, automated systems lack of transparency [22], create comprehension problems [23] and might yield to a loss of plan and situation awareness [24]. In extreme cases, the hierarchy may be inverted during plan execution, resulting in an operator executing a machine generated plan. A mixed-initiative approach enables cooperative planning where both human and automation bring their strength on own initiative [25]. The mission planner can actively propose plan elements to the pilot.

3.3.1 Modes of Automation in Mixed-Initiative Planning

The advantages and disadvantages of various automation approaches described above show that different situations require different characteristics of support by the mission planner. Therefore, our mixed initiative concept provides three modes of automation (Figure 2), varying in type and extend to support in planning phases adaptively. The type can vary between forward planning, flaw correction and optimization, the extend can vary from single plan elements to complete mission plans. The smaller the scope of support, the better the pilot can follow the proposal for plan adjustment. From this point of view, incremental support is suggested. It is difficult to interpret complex segment plans in a short time. On the other hand, several incremental support proposals take more time. For time-critical and complex planning tasks, this process may simply take too long. These can then be adapted to the pilot with the knowledge of the complexity of the planning tasks involved and their time criticality. The adaption process is described in chapter 3.5.

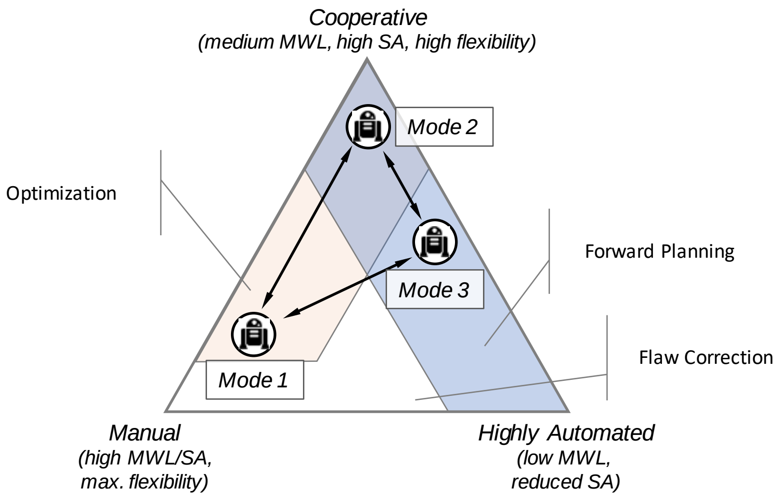

Figure 2: Three modes of automation provided by the mission planner

3.3.2 Mission Planner

To enable planning support, the pilot must inform the system about the desired mission objective. The mission planner then plans on the level of the mission tasks, i.e. links the individual mission tasks logically, spatially and temporally to a mission plan. Therefore, the planner uses knowledge about the mission objective and the task model. For the technical implementation, a PDDL planner [26] and the Constraints Optimization Solver CPLEX [27] are used as planning tools. We modelled the MUM-T domain comprising own, unknown and hostile forces, air space regulations, infrastructures, as well as possible actions in PDDL. Subsequently, the planning result is optimized with regard to various constraints such as threat exposure, time requirements, the resource requirements of the UAVs or the consideration of geospecific features such as the terrain. Pilot planning inputs on the tactical map displays are considered as logical constraints by the planner. Constraint relaxation is used to identify weaknesses in the implemented partial plan.

3.4 Activity and Mental Workload Determination

An activity determination serves as the basis for the determination of the mental resources currently needed. Since many, especially cognitive tasks, cannot be observed directly, the indirect approach of evidence-based activity recognition is pursued. [28], [29]. During the execution of the necessary tasks, the pilots interact with the system in a variety of ways. Interactions include manual interactions via helicopter controls, buttons and multi-touch screens (MFDs), auditive communication via aircraft radio and intercom, and visual attention to individual cockpit instruments. During these interactions, the system observes the pilots with the help of various measurement sensors. It uses these observations to combine the related evidences from the task model, which oppose or reject the execution of a specific task. Thereby, the system deduces the current activity of a pilot. Using the activity and knowledge of the task-specific demand on mental resources from the task model, the associate system estimates the total resource demand, which is necessary to execute the activity [30]. With this resource estimate, acute demand peaks can be detected and the level of support from the associate system can be adjusted accordingly.

3.5 Workload-adaptive Intervention Generation

The goal of the associate system is to avoid mistakes of the helicopter crew through deliberate interventions. For a proactive error avoidance, the estimation of the current demands is not sufficient. Therefore, the associate system uses the mission plan to predict future task situations and demand peaks [31].

3.5.1 Pilot Plan and Projection of Future Workload Peaks

Firstly, mission tasks are broken down into pilot tasks in order to identify which tasks the crew must perform in order to fulfil the mission. These planned pilot tasks are compared with the pilot's actual activities and all completed plan elements are checked. (green tasks in Figure 3). The remaining tasks not completed on time are triggers for intervention. (red tasks in Figure 3). The associate system uses the Constraints Optimization Solver CPLEX [27] to logically arrange all pilot tasks that have not (yet) been completed. The system considers dependencies between tasks and execution times of the individual tasks and simulates the resulting sequence of pilot tasks using the information of demand on mental resources. The system determines when areas of high workload may cause performance losses. These predicted workload peaks are a second trigger for intervention. In situations that are not foreseeable by the plan, such as a sudden change of the tactical situation, the associate system supports firstly to minimize the acute danger of the crew and secondly to create a new valid plan in cooperation with the crew as quickly as possible.

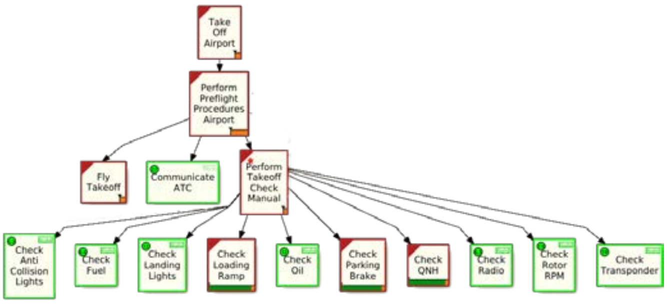

Figure 3: Detailed pilot plan of the mission task TakeOffAirport and corresponding required pilot tasks

3.5.2 Intervention Planning

If the associate system detects need for action in the form of intervention triggers (neglected tasks, acute and future workload peaks, as well as critical changes in the situation), it plans the intervention. The aim is to find an intervention strategy which, depending on the attention and demands on the crew and the criticality, leads minimally intrusively to the solution of the problem. With the help of activity recognition, the system first determines whether the pilots themselves are already working on a solution to the problem, i.e. whether their attention is directed correctly. If this is not the case, the consideration of mental resources determines whether the crew is able to solve the problem on their own. If so, only attention must be drawn to the most urgent task, otherwise support through task simplification or task assumption is necessary. It is only necessary to take over tasks if the crew cannot solve a mission-critical problem themselves. The described decision-making process, from the identification of the triggers, through the selection of an appropriate intervention strategy, to its realization, is implemented in the cognitive framework Soar [32].

3.5.2 Intervention Strategies

The associate system uses warning sounds, voice output and the multifunctional display of the helicopter to direct attention (Figure 4). The task simplification and adaptation to the task situation is achieved on the one hand by pointing out solution strategies and on the other hand by changing levels of automation (subchapters 2.1 and 3.3). By selecting a higher level of automation, the associate system transfers task components from the pilot to the associate system, thus reducing the overload on the pilot. The cognitive agents on board the UAVs, the mission planner and the sensor and perception management provide these levels of automation. In the event of a high risk of serious consequences, the associate system can take over partial tasks or entire tasks on its own initiative as the highest escalation level. Extreme examples are the intervention in flight control to avoid collisions or the adoption of an uncompleted landing checklist. The associate system adopts planner proposals if otherwise the successful achievement of the mission objective is highly unlikely. The strategy for simplifying and adopting tasks is illustrated using mission planning process as an example: If the system determines that the mental demands of the planning task are high, it adapts the extend of support to the situation taking the time criticality of the planning problem into account. If the pilot does not react despite a high degree of criticality, the system decides to take on a task at the latest possible time. The proposed solution is then automatically accepted.

Figure 4: Detailed Dialog to direct the pilot's attention including the highlighting of the interaction element (here: button) that solves the problem (pink) and the overlayed gaze tracking data (green dot at the top edge)4

4.0 EXPERIMENTAL EVALUATION

To evaluate the overall system, an experimental campaign was conducted with pilots of the Bundeswehr in the helicopter mission simulator of the Institute of Flight Systems at the University of the Bundeswehr in Munich. Seven trained military pilots at an age between 31 and 59 years (M = 50.4, SD = 9.2) and a flying experience between 535 and 6850 (M = 3933, SD = 1807) total hours served as test persons. The pilots were divided into four crews. One of the pilots took the role of commander, while the other pilot took the role of pilot flying.

4.1 Missions

We designed five realistic MUM-T missions, which are based on current missions of the German military (see Table 1). These missions included the transport of own forces into or from military operation areas in hostile territory, each conducted by a single transport helicopter accompanied by three sensor-equipped, unarmed UAVs. The crew of the manned helicopter managed the UAVs under their own responsibility. The commander used the sensors of the UAVs for area and route reconnaissance. Unknown and clearly hostile forces appeared within the operating area, which had to be located and identified by the UAVs. In addition to such sudden changes on the tactical situation, 4 out of 5 missions involved at least one change of the mission objective in order to create alternating workload conditions. Each mission has individually defined airspace regulations in order to avoid accustoming effects.

Table 1: Mission overview.

Mission name	Content	Events	Duration [min]
1 Special Observation	EOD-Transport	-	45
2 Golden Hour	MedEvac	Change of Destinataion	40
3 Desert Shield	Troop Transport	CasEvac	50
4 Rocket Raid	Troop Transport	Change of Target	65
5 Mosahi Konvoi	Troop Transport	Pers. Recovery	45

4.2 Experimental Procedure

Due to the complexity of the experiment, the sequence of missions was maintained throughout the entire experiment. Each crew completed a two-day training course with tutorial and two complex training missions. All crews then flow the five missions in the same order. The mission time varied between 31 and 71 minutes (M = 45.77 min SD = 10.25 min). The pilots evaluated the scenarios using seven-stage Likert scales ranging from 1/negative to 7/positive. They rate the realism of the scenarios as very well (M = 5.6, SD = 0.7) and rate the course of the missions also very positively (M = 5.3, SD = 0.83). The pilots evaluate the simulation environment also positively (M = 5.0, SD = 1.0). After each mission, we conducted a detailed debriefing of selected situations, in which use cases of the UAVs or the associate system occurred.

4.3 Results of the Overall Approach

During the missions studied, the helicopter covered an average flight distance of 92 km (MW=92.15 km, SD=28.77 km in a time of 46 minutes (MW=45.82 min, SD=9.97min). The UAVs investigated an average of 172 km^2 per mission (MW=171.96 km^2, SD=70.33 km^2). This results in an average reconnaissance performance of 3.75 km^2 per minute. This high reconnaissance performance also justifies the average time and distance during which the helicopter was over reconnaissance area (Figure 5). The helicopter was over 90% of the time and distance over reconnaissance area. Since enemy forces could be detected over a wide area, the helicopter stayed over 90% of the time and distance over confirmed enemy-free areas, which shows a very large increase of mission security compared to today's missions.

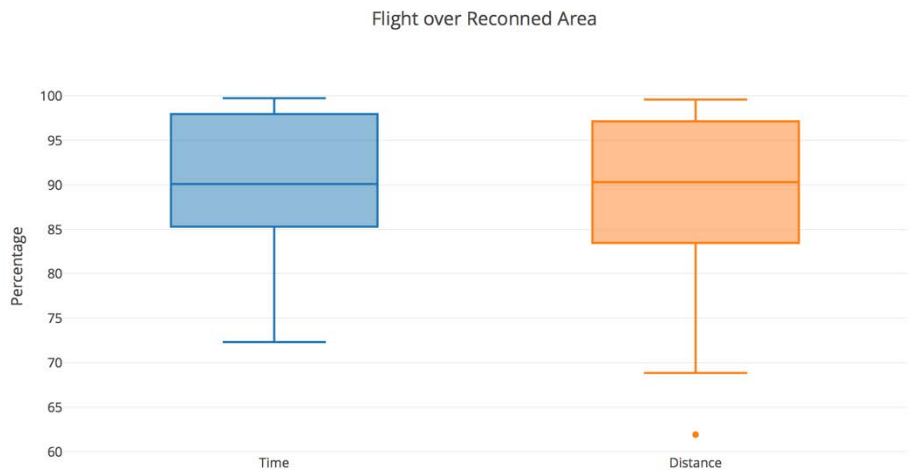

Figure 5: Flight over confirmed cleared area

4.4 Results Task-Based UAV Guidance

The high level of reconnaissance services listed under the overall results is primarily due to the use of UAVs. A recording of the subjective evaluation of the UAV system with the aid of an adjusted Cooper Harper rating according to [33] brought the result shown in Figure 6. After each individual mission, the same questionnaire was presented to the subjects and the values averaged (individual evaluation). After completion of all missions, the questionnaire was presented to the subjects again, with the request to incorporate their experience over the entire week (overall assessment). The subjects evaluated mission aptitude between 2 and 4, with 1 being the best and 10 the worst. This means that a sufficient mission performance (rating 3-6) is guaranteed in any case and in most cases a satisfactory mission performance (rating 1-3) has been achieved. It is also interesting that the overall evaluation, which took place after the completion of all missions, is slightly better than the average of the individual evaluations. This could be due to a learning effect. With greater familiarity with the UAV system, the mission performance and thus the evaluation increases.

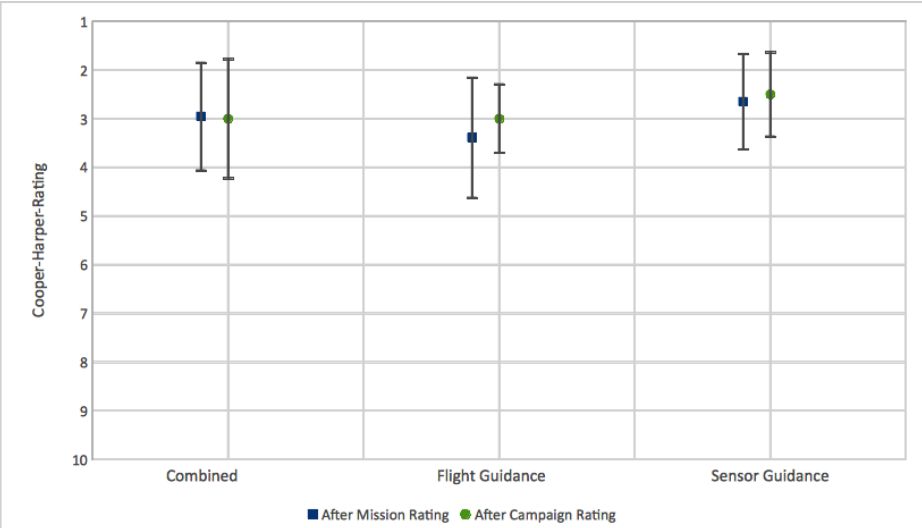

Figure 6: Cooper-Harper Rating for UAV Guidance

4.5 Results Mixed-Initiative Planning

Three use cases with different planning complexity and time criticality were investigated for each mission: At the beginning of the mission, a complete planning has to be be carried out with little time criticality. A pop-up threat makes it necessary to replan the manned helicopters and UAVs locally with high time criticality. A change of the overall mission objective during the existing mission requires a complete time-critical replanning. The results of the intervention behaviour for the described use cases are shown in Figure 7. During initial planning, in 14 out of 20 cases, the system remained silent. A total of 25 pop-up threats appeared, which required an active reaction from the pilot. In 18 cases, a proposal generated by the agent was accepted by the pilot. In 4 cases the pilot switched to a pre-planned alternative route and in 3 cases the pilot carried out a replanning himself. In all these cases, the system offered support on the second level of automation. For the third use case, in 19 out of 20 cases the system supported on the highest level of automation. In 18 cases the system's proposal was accepted. This can be explained by the fact that the planning effort for manual replanning by the pilot would have been very high. After each mission, the pilots evaluated the different extend of intervention for each of the three use cases (Figure 8). The extend was assessed as very suitable by the test persons. Overall, the results show that the mixed initiative approach with adaptive extend of support was very positively received.

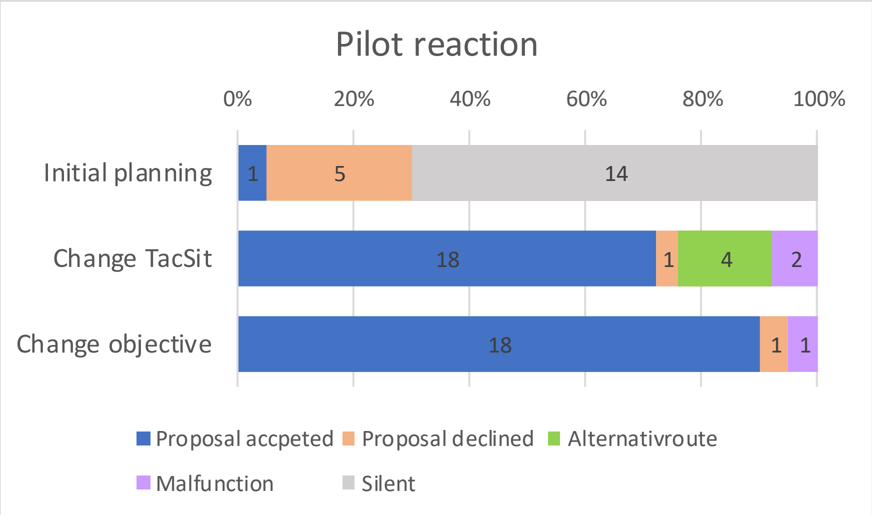

Figure 7: Agent action for different use cases and corresponding pilot reaction

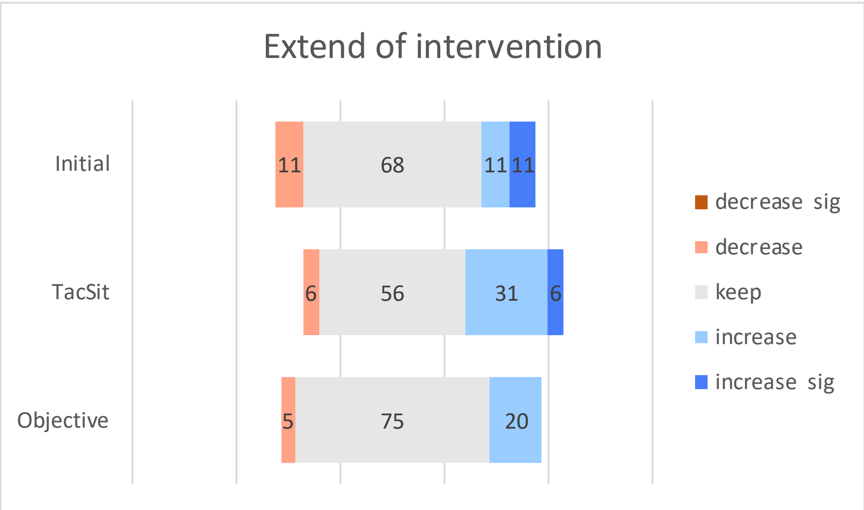

Figure 8: Pilot's subjective ratings for extend of intervention

4.6 Results Adaptive Associate System

An example of an associate system intervention is explained below. In the specific situation the commander fails to assign a reconnaissance task to a UAV on time (pink route segments in Figure 9 and pink highlighted pilot tasks *Plan Mission* in Figure 10). In addition, he is currently involved in an ongoing route reconnaissance task (task blocks highlighted in green in Figure 10). The parallelism of these two task situations leads to high workload (orange plot in Figure 10). The associate system detects a workload peak for the immediate future. Due to the fact that a planning task is jointly responsible for the workload peak, the mission planner is commanded to solve these planning tasks on a high level of automation in order to reduce the task load on the crew for the identified high-workload period. The planner then generates a task proposal for the forgotten route reconnaissance (the associate system dialog with a yellow border in Figure 9). Because of the high criticality and urgency of the problem and the high demands on the crew, the associate system decides to accept this proposal without further notice. The commander assessed this intervention of the associate system as very helpful and appropriate for the high-risk and time-critical situation. Overall, the pilots assessed the associate system interventions as expedient and mostly helpful. The type of intervention selected – attention guiding, task simplification and task adoption - was assessed as mostly situation-adaptive and appropriate. The interventions were considered justified, which is why it can be assumed that there was an understandable reason for support by the associate system in most cases. The scope of the intervention was mostly correct, only one subject found that the interventions took too much work off. Two subjects tended that the interventions must support more (Figure 11).

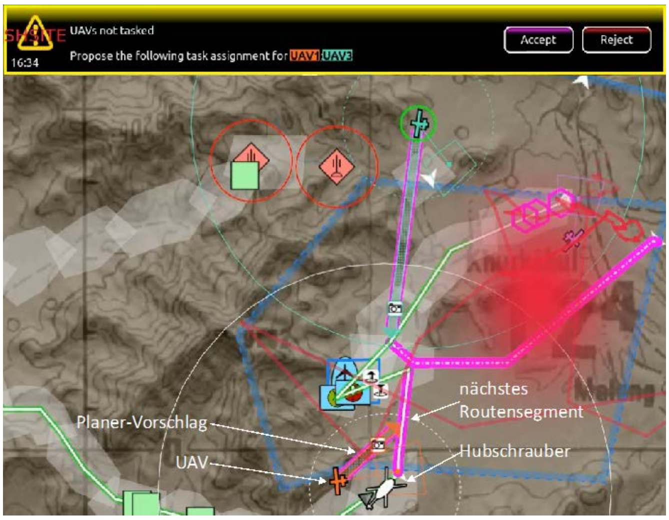

Figure 9: Tactical map of helicopter mission simulator and dialog of associate system informing about missing tasks

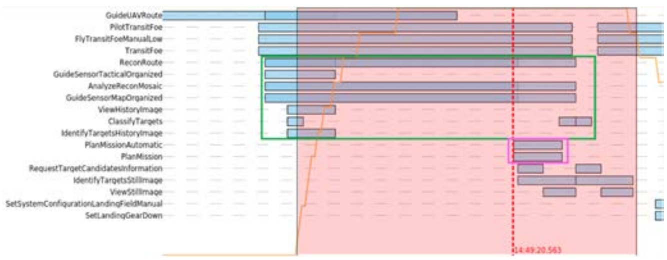

Figure 10: Projected pilot workload (orange line) und detected workload peaks (red area) calculated based on future task situation (blue blocks)

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Die Art der Interventionen ist situationsangepasst.		•		•		••••	••
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Figure 11: Pilot’s subjective ratings of associate system interventions (n=8).

5.0 CONCLUSION

In this paper, a concept of adaptive assistance with cognitive automation was presented. The proposed concept was demonstrated using the MUM-T as an example containing The presented implementation was successfully evaluated with pilots of the German armed forces, the results show the potential of the two-tier approach. Both flight time and route over reconnoitered area show that the developed system can significantly increase crew safety compared to today's systems. The support provided by the associate system was also very well received. Through its interventions, the crew's scope of action was increased to the extent that cognitively demanding tasks were temporarily simplified or taken over by the associate system. Especially in situations of high workload, the system was able to reduce human erroneous performance. Further experiments to evaluate specific research questions are currently being conducted. The concept presented here can also be applied to other domains, such as civil defense, autonomous driving and maritime use cases.

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