Task-based Guidance of Multiple UAV Using Cognitive Automation

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***Abstract*—This article discusses different dimensions of automation in the integration of multiple, detached, unmanned sensor platforms into a military helicopter scenario. Artificial cognitive units implement parts of human-like knowledge-rich task execution aboard a highly automated vehicle. Artificial cognition, being the method used, allows task execution beyond pre-scripted and predefined instruction sets, utilizing reasoning about the current situation to support goal-driven behaviour during task execution instead. The tasks assigned by the human operator are formulated at an abstraction level that might as well be used to task human subordinates within a mission. Like human subordinates, the UAV uses its cognitive capabilities to adapt task execution to the currently known situation including knowledge about the task assignments of teammates.**

Keywords – Task-based guidance; goal-driven behaviour; artificial cognititive units; artificial cognition; level of automation.

I. INTRODUCTION

The utilization of UAVs as detached sensor platforms of a manned helicopter in a military scenario requires a change in the UAV guidance paradigm that enables a single human operator to control the UAVs while being the commander of a manned aircraft.

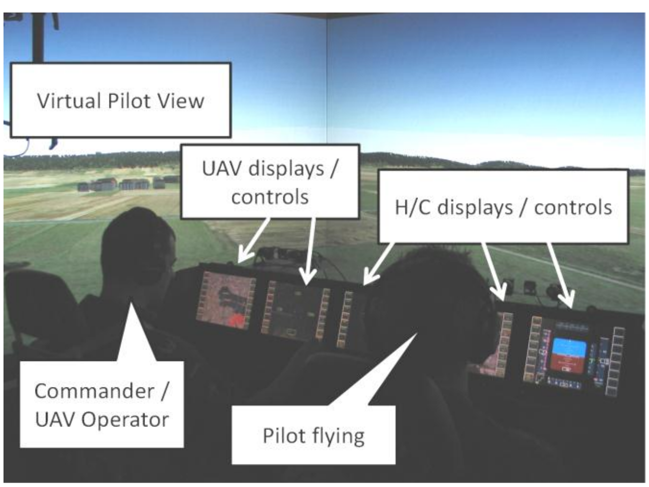

Figure 1. Helicopter simulator of the Institute of Flight Systems

If those UAVs were manned assets, the commander would just assign tasks referring to the mission elements and the current situation and leave the details of task execution as well as the application of "common sense"-knowledge generating local tactical behaviours to the human subordinate.

Some current research approaches concerning UAV guidance allow the definition of scripts or plays [1] to define action sequences for one or multiple UAVs. Moreover, some of these systems also react to changes in the situation like a new threat along a flight route [2]. However, the resulting behaviours of suchlike systems are solely defined at design-time. The goals of the behaviour of the UAVs are not expressed in the system but are implicitly encoded in the implementation of the guidance system. This article describes the system architecture, knowledge and goals driving task-based, cooperative and cognitive UAV automation. The resulting type of supervisory control shall avoid at least some of the issues of conventional automation by taking a step towards human-centred automation [3]. This is integrated in the helicopter research flight simulator of the Institute of Flight Systems at the Universität der Bundeswehr München and evaluated in experiments with experienced German Army aviators. In these experiments, the pilots had to perform several, dynamic troop transport missions including an unscheduled combat recovery task with the support of the manned helicopter and three UAVs.

The following sections describe the task-based guidance approach, its design, the resulting adaptable levels of automation and first experimental results.

II. RELATED WORK

Most current research projects in the area of UAV guidance and mission management focus on solving problems in the field of trajectory generation [4] and management and the achievement of what is mostly referred to as "full autonomy" by the application of control algorithms [5].

This research concentrates on optimizing within a given constraint set. However, such constraint sets and parameters are either static or the definition is left to the human operator or the experimenter. If the handling and monitoring of the control algorithms of multiple UAV is allocated to the commander of a manned helicopter, then the result is error-

 ISBN: 978-1-61208-155-7

prone behaviour and high workload for the operator [6]. Therefore, we present a system that integrates flight control, payload control and radio links into one entity. This entity uses its knowledge about the situation, the mission, the vehicle and its capabilities to provide an interface to the human operator that allows UAV guidance on a situation adaptive task level rather than sub-system handling.

Previous articles focus on the requirements engineering [6] and global system design and test environment including the integration of assistant systems [7] [8] [9]. The main contribution of this article consists of a discussion of the resulting levels of automation gained by task based guidance, a description of the knowledge base to realize task based guidance as well as the first experimental evaluation of the system.

III. TASK-BASED GUIDANCE

Task based guidance aims at integrating multiple unmanned vehicles into a manned helicopter mission in a similar manner as integrating additional manned helicopters into the scenario. Therefore, the guidance of unmanned vehicles should be on an abstraction level that allows the allocation of a series of tasks to each UAV. Suchlike tasks are issued by the human operator and request the achievement of goals, e.g., the request of reconnaissance information about a landing site. The interpretation of the tasks and the use of on-board systems to fulfil these tasks are left to the UAV. The series of tasks is on a similar abstraction level as tasks assigned to a pilot during mission briefing in a conventional, manned helicopter mission.

Moreover, just like a human pilot, UAVs should also use opportunities of supporting the mission, e.g., by getting sensor information of nearby objects, without a direct command from the operator.

This implies UAV guidance and mission management on a level where one or more UAVs are controlled by tasks that use mission terms instead of waypoints and the request of results rather than in-detail configuration of flight control functions and sensor payload. The latter should be generated aboard the UAV by its on-board automation.

The tasks currently implemented in the experimental setup are

- a *departure* task that respects basic air traffic regulations of the airfield and makes the UAV depart via a given, named departure location.
- a *transit* task that causes a flight to a specific, named location. While being in transit, the UAV configures the camera into forward looking mode. Known threats will be automatically avoided, if possible.
- a *recce route* task that causes the UAV to fly a route to a named destination. The sensor payload will be configured to provide reconnaissance information about the flight path. If the UAV possesses knowledge about another UAV also tasked with a recce of the same route, it will modify its flight path to maximize sensor coverage.
- a *recce area* task that causes the UAV to gather recce information about a named area. The camera will be used to provide ortho-photos of the area.
- an *object surveillance* task. While working on this task, the UAV will use the payload control to deliver a continuous video stream of a named location.
- a *cross corridor* task makes the UAV fly through a transition corridor between friendly and hostile territory. To avoid friendly fire and ease cooperation with the own ground based air defence; this crossing is modelled as separate task. Moreover, it is the only task allowed to cross the border between friendly and hostile territory.
- a *landing* task causes the UAV to take an approach route to an airfield and to land at that airfield.

The capability of understanding these tasks at mission level, i.e., understanding the current situation, planning towards task execution, using the flight control system, communication equipment and mission payload of the UAV requires an automation that incorporates certain sub-functions as found in cognitive behaviour of a human [7], thereby creating cognitive behaviour of the automation. The following chapters discuss the resulting levels of automation and describe the architecture and information processing of a so-called artificial cognitive unit (ACU).

IV. LEVELS OF AUTOMATION

Currently, UAV systems operate on a wide range of different guidance modes. That modes cover the whole range from direct manual control [10], flight control based [6], scripted behaviours [1] up to above-mentioned task-based guidance [7]. These guidance modes form a stack of abstraction layers as depicted in Figure 2.

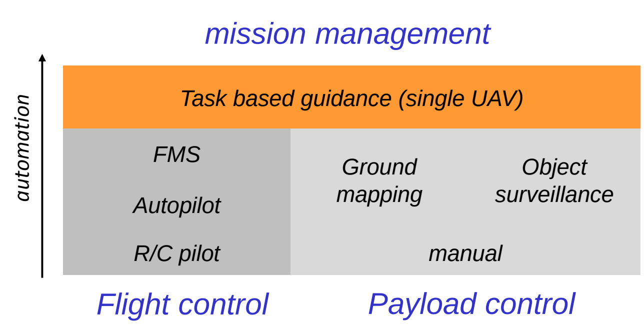

Figure 2. Levels of abstraction in UAV guidance

Sheridan and Verplank [11] describe a different view of levels of automation. These levels are mostly independent from the chosen abstraction layer but focus on task allocation and authority sharing between the human and the automation. They range from barely manual control to automation that does neither allow intervention from the human operator nor provide information about the action taken. In the design of current UAV guidance systems, various levels are present, e.g., in waypoint based guidance

 ISBN: 978-1-61208-155-7

systems, the definition of waypoints is the sole responsibility of the human operator. No automation support is provided in that task. However, automatic flight termination systems do not allow the human to veto on the decision of the automation but merely report the flight termination after its execution, i.e., level 7 according to Sheridan and Verplank [11].

The task based guidance described further in this article introduces an additional dimension in the levels of automation. While the abstraction layer is fixed in the current setup, i.e., only the task based layer is available to the human operator, the operator can choose to provide different tasks to the UAV. The UAV will check the tasks for consistency and may insert additional tasks to restore a consistent task agenda. The consistency check and completion of the task agenda is based on a planning scheme, which behaves deterministic with respect to the current tactical situation and the task elements known so far. Thus, the operator may choose to specify only task elements relevant to him or her and leave the specification of other tasks to the UAV. This particular type of adaptable automation allows the specification of strict task agendas, i.e., the human operator defines every task of the UAV. However, also loose task agendas may be defined, i.e., the human operator only defines the most important tasks and leaves the details to the UAV.

Moreover, this kind of automation also can reduce the chance of human errors, because unintentionally omitted tasks are also completed by the automation.

V. System Architecture

In order to implement suchlike machine behaviours, this chapter will provide an overview of the design principles and information processing architecture enabling task based guidance capabilities.

A. *Design of knowledge-based Artificial Cognitive Units*

Based on models of cognitive capabilities of human pilots, artificial cognitive units (ACUs) were designed. As depicted in Figure 3, these units become the sole interface between the human operator and the vehicle [12] in the work system [13]. This additional automation allows the desired shift in the guidance paradigm from the subsystem level, i.e., separate flight guidance and payload management, to commanding intelligent participants in the mission context.

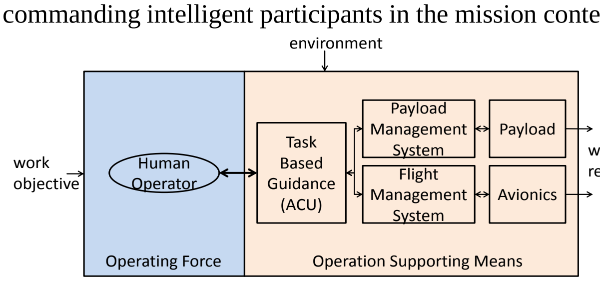

Figure 3. Work system "UAV guidance"

To understand and execute tasks with respect to the current situation, the ACU requires relevant parts of the knowledge and capabilities of human pilots. That knowledge can be grouped into system management, understanding and evaluating mission objectives in the context of the current scenario as well as knowledge to interact with the human operator [14]. This knowledge is derived by formalization of domain specific procedures defined in documents like the NATO doctrine for helicopter use in land operations [15]. Furthermore, interviews with experienced helicopter pilots revealed relevant knowledge. The interviews and the additional evaluation of recordings of training missions used the Cognitive Process Method [16]. For every phase, the human's objective is evaluated. Moreover, all possible and hypothetic action alternatives to pursue the objective are determined. Furthermore, all environmental knowledge is gathered, which is used to select a particular action alternative or which influences the execution of a chosen action. At last, the procedures to execute the actions are evaluated.

B. *Human-Machine Interface*

To support the guidance of multiple UAV from a manned helicopter, the human-machine interface (HMI) has to integrate into the manned helicopter. Moreover, using an audio interface, i.e., speech recognition, to guide the UAV was rejected by a majority of the interviewed pilots due to the already high radio traffic that has to be handled by the helicopter crew.

Therefore, a graphical interface was chosen to interact with the UAV. This interface is integrated into two identical multifunctional displays available to the commander of the manned helicopter. Figure 4 depicts the implemented multifunctional display format.

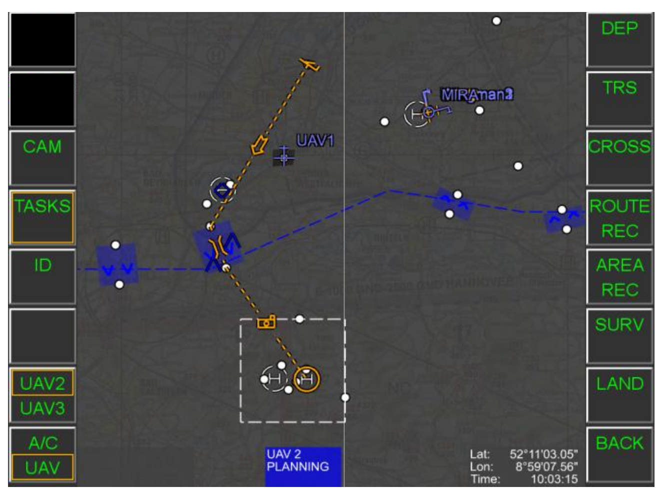

Figure 4. UAV tasking interface

On the lower left of the multifunctional keyboard, the operator can switch between UAV control and the displays of the manned helicopter (A/C / UAV). Above, the current UAV can be selected. On the top left, the operator can select three different modes: CAM, TASKS, and ID. The right multifunctional soft keyboard shows the context sensitive options for the current mode chosen on the left.

CAM provides a live video stream from the camera of the currently selected UAV. The TASKS can be used to monitor the current tactical situation and to manipulate the task elements of the currently selected UAV.

In TASKS, the current tactical situation is displayed as well as the task elements of the UAV. The currently active task is highlighted in yellow. A task can be inserted into the task agenda of the UAV by choosing the task type as shown on the right in Figure 4, optionally choosing the predecessor of the task on the map and selecting the target position of the task. A task can be selected for immediate execution. This functionality can be used to start the execution of the first task as well as for skipping tasks. Additionally, tasks can be deleted and moved, i.e., the target area description of the task is altered. If tasks are added, deleted or modified, the UAV will maintain a consistent task agenda by inserting missing tasks depending on the current tactical situation. As long as this planning is in progress, it is indicated on the bottom of the display as shown for UAV number 2 in Figure 4. To prevent immediate re-insertion of deleted task elements, the consistency checks are delayed after the operator deletes a task element. This allows further modifications of the task agenda by the human operator without being interrupted by the UAV.

The ID display mode is used to review photos taken by the UAV and to classify the objects on the images into pre-defined types (car, military vehicle, ground based air defence) and hostility, i.e., neutral, friend or foe. Those classifications are also reflected in the tactical situation shown in the task mode as well as the electronic map displays available to the pilot flying. Furthermore, those classifications will be transmitted to the UAVs in order to support reaction to the changed tactical environment, e.g., to plan flight routes around hostile air defence.

The combination of those display functionalities shall allow the human operator to guide the UAVs to support a military air assault mission that involves operation over hostile areas and support of infantry troops. Moreover, by tasking the UAVs using mission terms, e.g., by selection of “area reconnaissance of the primary landing site”, the control of three UAVs shall be feasible and enhance mission safety by providing valuable information about mission relevant areas and routes without risking exposure of own troops to threats like ground based air defence and other opposing forces.

C. *Information Processing*

The implementation of artificial cognitive units is based on the Cognitive System Architecture (COSA) framework [16]. This framework is based upon Soar [17] and adds support for object-oriented programming as well as stereotypes for structuring the knowledge into environment models, desires, action alternatives and instruction models.

This (a-priori) knowledge constitutes the application specific part of the Cognitive Process, which is described in detail by Putzer and Onken [16] as well as Onken and Schulte [13]. Information and knowledge processing as well as interfacing with the environment is depicted in Figure 5.

The following describes the information processing steps using examples of the knowledge of the UAV’s on-board ACU.

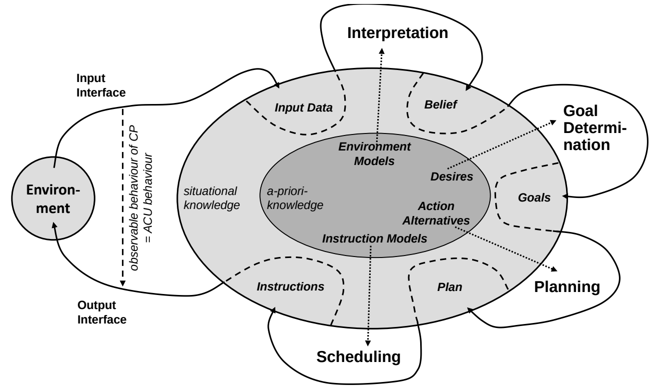

Figure 5. Knowledge processing in the Cognitive Process [16]

Input data are retrieved from the environment by input interfaces. There are three types of input interfaces: (1) reading sensor information from the sensors of the UAV, (2) reading information from the communication link of the UAV and (3) providing results from on-board automation, e.g., information about flight routes generated by an external route planner.

The *environment models* of the a-priori knowledge of the ACU drive the interpretation of input data into instances of semantic concepts. Those concepts form an understanding of the current tactical environment including knowledge about existence and positions of threats, areas, bases, landing sites, routes, waypoints etc. Environment models instantiate on the arrival of matching input data and matching situational knowledge. All instances of environment models, i.e., *beliefs*, form the picture of the current situation of the UAV. Notable examples for environment models are instructions, tasks and roles. Instructions represent requests sent from the operator to the UAV and instantiate upon the arrival of the corresponding input data. Instructions can request to insert, delete or immediately execute a task in the task agenda. If the instruction is to insert a new task into the agenda of the UAV, the corresponding task environment model becomes active and creates an instance. This instance will refer to the environmental models describing the target area of the task, the task type, and the state of the task, e.g., “scheduled for execution”. For every task, there is an instance of a precondition and a postcondition. The precondition builds a representation of all required prerequisites of a task, e.g., being airborne and being near a specific location to start the task. The postcondition builds a representation of particular effects of the task, e.g., a transit flight has the postcondition of being airborne at the target location. A role is an environment model describing the specific part of the current UAV in a task shared among multiple UAV, e.g., if multiple UAV have the common task to retrieve recce information about a flight route, a role can tell the UAV to fly in a certain distance left from the route to maximize sensor coverage.

Desires describe world states the UAV should maintain. If a desire detects the violation of the state in the belief, then it activates by instantiating into an active goal. One example of a desire is “know what to do next”, i.e., to have a belief that designates the current task at hand. Whenever the UAV does not have the situational knowledge about its current task, this desire activates and makes the UAV act towards the determination of the next task. Another desire is to comply with the current task, i.e., to actually take the steps necessary to fulfil the task. The desire to “have a unique role” in common tasks enables multiple UAVs to work on the same task by sharing parts of it, i.e., roles in the task. For example, if three UAVs share the task of retrieving visual sensor information about a flight route, then the systems infer from this situation that the roles of flying the centre line of the track and to fly left and right of the track exist. Each UAV selects a role either random or – if selection knowledge is present – it selects a role that fits best for the UAV. To avoid duplicate roles for a single task, every UAV that has a non-unique role re-selects a role. This technique has shown to be sufficient for real-time conflict resolution of at least three UAV.

“Having a consistent agenda” is one of the central desires of the ACU. This desire activates if there is a mismatch between the aforementioned postconditions of a task and the preconditions of its successor. Moreover, it activates, if tactical restrictions are violated, e.g., if a task other than “cross corridor” crosses the border to the opposing terrain or if an area is not entered or left at the designated entry/exit points. The activation of this desire is reported to the human operator as “UAV planning” as depicted for UAV2 in Figure 4. Moreover, the desire of having a consistent agenda also provides knowledge about the severity of violations. This guides the resolution of inconsistencies from the most important violation to the least important violation. “Using opportunities” as they arise makes the UAV exploit chances of gathering additional reconnaissance information, if this does not lead to a neglect of the current task. For instance, if there is a sensor footprint of an unidentified force, then the ACU can decide to use the sensors of the UAV to generate additional information about that location to support the identification of that force. The ACU combines its knowledge about the type of sensor information, i.e., “unidentified sensor-hotspot”, the availability of its sensors, the availability of sensor information from its own sensors and from other UAV and its relative position to the unidentified force. This combination of knowledge enables the UAV to safely detect and use the chance of getting more information about the location. Moreover, the UAV also behave cooperative as the decision to generate additional sensor information is suppressed if another UAV has generated that sensor information from a similar angle to the unidentified force.

Action alternatives provide ways to support active goals. They instantiate if a corresponding goal is active, but only if the current situational knowledge allows the selection of the action alternative. If more than one action alternative can be proposed, then the action alternatives model selection knowledge to prefer one alternative over the other. To maintain a consistent agenda, action alternatives can propose to add additional tasks like recce route, transit or cross corridor. If the crossing of a corridor can be inserted, it is preferred over the other action alternatives to provide a separation between “tasks over own territory” and “tasks over opposing territory” for subsequent action alternatives. Depending on the tactical situation, further tasks are inserted until a consistent agenda is achieved, i.e., all active goals of having a consistent agenda are fulfilled. As mentioned in Section IV, the human operator can exploit this behaviour of the ACU by skipping tasks on purpose and thereby shifting the completion and specification of missing tasks to the ACU.

Every task of the ACU has its corresponding action alternative that supports the execution of the task in case of an active goal to comply with the current task.

After one or more action alternatives are chosen, the *instruction models* become active and support the action alternatives by generating instructions on the output interface of the ACU. Those instructions are read by the output interface and cause the transmission of radio messages, configuration changes at the flight control system or the payload system or activate on-board automation, e.g., a route planner.

In combination, all those processing steps depicted in Figure 5 generate purely goal-driven behaviour that allows reasoning over the tactical situation and the task elements entered by the human operator to provide situation-dependent actions, which are consistent with tactical concepts of operations.

VI. EXPERIMENTAL SETUP AND FIRST RESULTS

Experiments were conducted with experienced German Army helicopter pilots in order to evaluate the task based guidance approach. The simulator cockpit shown in Figure 1 has been used to perform military transport helicopter missions. The objective of the missions was to pick up troops from a known location and to carry them to a possibly threatened destination. According to the briefing, three UAVs should be used to provide reconnaissance information about the flight routes and landing sites in order to minimize exposure of the manned helicopter to threats. In addition to the tasks to perform in previous baseline experiments without task based guidance [6], in this experiment an unscheduled combat recovery task was issued to the crew as soon as the main mission objective had been accomplished.

Prior to the measurements, every test person had been given one and a half day of system training. The test persons acted as pilot flying and pilot non-flying. This configuration was chosen to evaluate the effects of the UAV guidance to crew cooperation and crew resource management.

The following data were recorded during the experiment:

- Interaction of the operator with the system
- Commands sent to the UAV via data link

In every simulation run, the simulation had been halted twice, i.e., in the ingress and during a demanding situation while the helicopter is near the hostile target area, to get measures of the operator’s workload using NASA TLX [18].

 ISBN: 978-1-61208-155-7

During the simulation halt, all displays and the virtual pilot view were blanked and the intercom between pilot flying and pilot non-flying was disabled. To get an indication of the test persons' situation awareness, the test persons were simultaneously questioned about the current tactical situations, system settings, e.g., radio configuration, and the upcoming tasks of the UAV and the manned helicopter. This measure is an adaption of the SAGAT technique [19]. After every mission, a debriefing follows which includes questions about the system acceptance, system handling, interface handling as well as feedback about the degree of realism of the simulation environment.

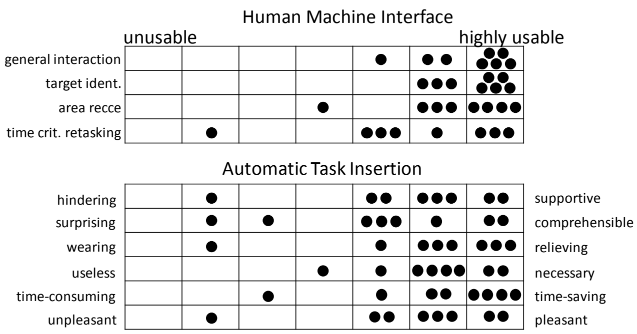

Figure 6. Subjective Pilot Ratings for HMI / Consistency Management

Figure 6 shows some of the subjective ratings of the test persons. The chosen type of human-machine interface and the automatic insertion of task elements to maintain a consistent agenda are generally accepted by all test persons. The test persons stated that handling the UAVs consumed an average of 62% of the time while 34% remained for acting as commander of the manned helicopter. Evaluation of the simulation data shows that test persons used less than 50% of the available time for UAV guidance.

TLX measures of the pilot non-flying range from 23% of subjective workload during the ingress over friendly territory up to a value of 60% during time-critical re-planning of multiple UAV in the target area.

While in hostile areas, the manned helicopter operated within the terrain mapped by ortho-photos 94.5% of the time.

VII. CONCLUSION

The experiments showed that artificial cognitive units make the guidance of multiple UAV in a military helicopter mission feasible with moderate workload. It was shown that artificial cognition aboard the UAVs effectively support the human operator in his/her task of increasing mission safety by providing recce information about flight routes and operation areas. Moreover, depending on the desired level of control over the UAVs, the test persons stated that they instructed the UAVs on a detailed or rough level, i.e., specification of every task element or skipping tasks on purpose and leaving the detailed planning to the UAV and its cognitive capabilities.

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 ISBN: 978-1-61208-155-7