

Implications for Operator Interactions in an Agent Supervisory Control Relationship

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Abstract— In order to support a human UAV operator during his mission management task, an artificial cognitive agent (ACU), operated on the basis of high-level tasks, is introduced onboard an unmanned automated aircraft. In analogy to human UAV guidance, the ACU does not interact directly with the aircraft, but rather formulates discrete commands for the automation and continually supervises their execution. In accordance with Sheridan's *Human Supervisory Control*, we describe this relationship between the agent and the underlying automation by the term of *Agent Supervisory Control*. In this role, the ACU performs *Supervisory Functions*, with which the tasks of the operator are supplemented, reviewed and finally decomposed into single actions. These actions are then performed using the onboard conventional automation. The agent considers the automation functions of the UAV as capabilities that are managed and incorporated into its planning and execution process in accordance to their availability and requirements. During task execution, the ACU supplies the operator with information, as to keep him in charge of the aircraft at all times. The extent, form and frequency of the information depend on the necessities of the specific situation and the current task. The information requirements of the operator and a possible operator information-overload due to its detail must be weighed against each other.

I. INTRODUCTION

In most current UAV, the role of the human operator has shifted from an aircraft controller to a mission manager and automation supervisor. A variety of ground and onboard automation systems relieve the operator of high-frequent tasks such as flight-control and support him in tasks, e.g. flight guidance. Sensor management functions or Aided/Automated Target Recognition (ATR) support the operator in clearly defined tasks during mission execution. Higher cognitive tasks such as planning, decision-making and problem solving in complex situation are still solely left to the human operator. The operator controls the aircraft using the available automation. He orders discrete and rather abstract commands, such as waypoint navigation and supervises their execution. He only intervenes in the case of unforeseen events. Sheridan describes this relationship

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between human and machine as *Human Supervisory Control* (HSC) [1]. The human operator interacts with a variety of automation functions, which individually close control loops around the underlying hardware and software components.

Increasing the number of automation functions does not necessarily lead to a better support of the human, but can even increase the operator workload and lead to human-machine interaction problems. Data link degradation can cause signal delays and impede the ability to control the aircraft, while data link loss diminishes the operator's situation awareness and leaves the aircraft without the human capability to react to unforeseen events.

The capacity of the human cognition limit the amount of flight parameters and the number of aircrafts that can be controlled by a single operator. The level of training and experience as well as support by backup personnel and equipment can only raise these limitations to a certain extent [2]. These considerations lead to the question how a UAV system can support the operator adequately in mission planning and execution and how its resilience against the effects of data link loss and human cognitive limitations can be raised.

A. State of the Art

In the past years progress has been made in the guidance of unmanned aircraft using the *Dual-Mode Cognitive Automation* Concept by Onken & Schulte [3]. The concept aims at shifting cognitive tasks from the human to an artificial cognitive unit (ACU), which can be either in a supervisory or in a cooperative relationship with the operator [4]. In this context, Uhrmann & Schulte [5] describe the task-based multi-UAV guidance from aboard a manned helicopter cockpit and the implications for the resulting human-machine relationship. Kriegel et al. [6] propose a division between mission- and machine-specific knowledge of ACUs within a *Knowledge Configured Vehicle* (KCV) concept for UAV. Pecher et al. [7] use a cognitive agent for the knowledge-based management of primary systems within a More Electric Aircraft. In this context, the double role of cognitive agents as mission management components within a UAV and subordinates to the human operator within the work system is still left untouched.

Parasuraman & Riley discuss criteria for the delegation of tasks from the operator to the automation, concerning

their impact on the overall system, in [8]. The criteria are similar to those in an inter-human relationship [9]. The trust of the operator in the satisfactory task execution by the subordinate agent is essential. Lee & See comprehensively discuss the parameters and processes of confidence building within the human operator in [10] and describe implications for a conforming automation design.

In [11], Billings coins the term *Human-Centered Automation* (HCA), which essentially demands to account for human capabilities and requirements in his role as a *Human Supervisor* within the human-machine system. Even though HCA has been discussed critically in [12], [13] its criteria are the basis for many automation interaction concepts. In [14]–[16] criteria for the interaction between humans and artificial agents within a delegation framework or a team are described.

B. Contribution

Building on the concept of task-based mission guidance of Uhrmann & Schulte, a concept for the interaction between a human operator and an artificial cognitive agent within a Supervisory Control delegation framework is presented. The agent is considered as an artificial onboard supervisor, which commands and supervises the underlying automated UAV system. The information flow between the human and the ACU allows the operator to form an appropriate level of trust, which in turn allows him to delegate and supervise tasks according to the current situation and aircraft state. The concept of task-based guidance and the KCV concept are extended to allow mixed task execution, with the operator keeping control over certain automation functions. The supervisory and the subordinate role of the cognitive agent are concretized and joined into a single overall concept. A first implementation of the concept is described and its evaluation is discussed.

II. AGENT SUPERVISORY CONTROL

Expanding the concept of a conventionally automated UAV system, the supervisory control by a cognitive agent shall be described. The human factors concept of a work system is best suited to identify and analyze the elements relevant for this expansion.

Onken & Schulte [3] define a work system as the physical representation of its corresponding work process, that follows a work objective under environmental conditions and achieves a certain work result. The work system distinguishes between the *Operating Force* (OF) and the *Operation Supporting Means* (OSM). The OF knows and understands the current work objective and uses its OSM to achieve it. Furthermore, the OF includes at least one human entity, who possesses the authority to modify the current work objective, making the work system an autonomous system by definition [3]. The OSM include all work site settings, non-powered tools and machines, e.g. automation, available to the OF during the work process.

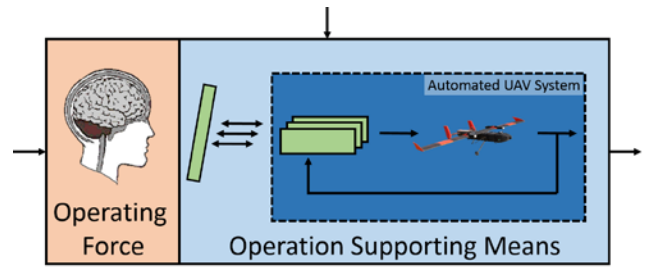


Figure 1. Work system of a conventionally automated UAV

Figure 1 shows the work system for a conventionally automated UAV system controlled by a single human operator. While the OF contains only the human, the OSM encompass the human-machine interface (HMI) and the aircraft including its onboard automation. The automation relieves the operator of the high-frequent senso-motor tasks and provides additional capabilities for mission execution. The operator does not control the aircraft manually, but intermittently through automation that he commands discretely and that he monitors during execution. This type of control relationship was described by Sheridan [1] as *Human Supervisory Control* (HSC). The operator does not interact directly with the underlying machine (the aircraft), but with its automation, that closes individual control-loops around the machine. The human operator does not act as an additional outer-loop controller, but as a *Human Supervisor* who commands intermittently and monitors more or less continually.

In his role as a *Human Supervisor*, the operator performs the five *Supervisory Functions*. He determines the current objective and explores a strategy to achieve it using the given means (*plan*); he conveys his commands to the automation (*teach*); he monitors the automation to ensure proper execution (*monitor*); if necessary he intervenes (*intervene*); and finally he may learn from experience to perform better next time (*learn*) [1]. These functions, performed by the human operator, allow the overall system to react to individual challenges and thus to be able to compensate for unforeseen events.

As depicted in Figure 1 the operator does not supervise a single automation function, but rather a multitude of different automation components. The operator is presented a multitude of subsymbolic, heterogeneous feedback information, that he interprets using his cognitive capabilities and with which he determines further steps. A conventional approach of introducing more and more complex automation to support the operator may impede his work, as the number of output information increases.

With all cognitive capabilities residing on ground within the human operator, the possibility of a data link loss, e.g. through jamming, leads to their loss aboard the aircraft. The system loses its capability to react to events not considered during design time, which may lead to mission abortion or possibly the loss of the aircraft itself.

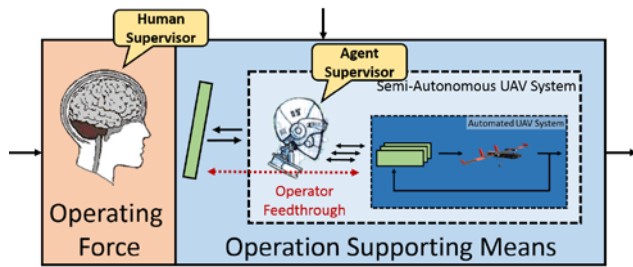


Figure 3. Work system of a semi-autonomous UAV using a Supporting ACU (SCU)

The cognitive automation approach introduces automation components with artificial cognitive capabilities such as decision-making, problem solving and planning, similar to human information processing. Such automation may be implemented in form of *Artificial Cognitive Units* (ACU), symbolized by robot heads in work system figures. Onken & Schulte generally describe two different modes to integrate ACUs into a work system [3]. Either as part of the OSM (Mode 1) or as part of the OF (Mode 2). Mode 2 cognitive automation describes a cooperative relationship between the human operator and the ACU, in which the ACU monitors and assists the operator as a team member. This may be implemented as a knowledge-based assistant system. Mode 1 cognitive automation aims at a higher degree of autonomy for the UAV system and a relief of the cognitive workload for the human operator, as it acts as a subordinate in a supervisory control relationship.

In Figure 3 an ACU is introduced into the work system as part of the OSM (Mode 1), making it a *Supporting ACU* (SCU). The artificial cognitive capabilities of the SCU allow it to derive action plans from objectives set by the human operator. The SCU can also plan and coordinate the application of the underlying OSM. In this sense, the SCU acts goal-oriented rather than procedural, which enables the overall system to adapt to a changing environment during runtime. Still, the SCU does not have authority to modify the objective for the UAV, set by the human. This makes the resulting UAV system semi-autonomous by definition [3].

This modification of the work system influences the interaction between the operator and the aircraft. Instead of step-by-step instructions for multiple automation components, the operator formulates the objective of the single artificial agent. In this context, Uhrmann & Schulte [5] propose a task-based UAV guidance (TBG), where the operator sets the objective (*what?*) for the semi-autonomous system, but leaves the action determination and task execution (*how?*) to the SCU. Such tasks may include *Perform reconnaissance of Area Bravo* or *Land the Aircraft at Airfield Alpha*. TBG stems from an inter-human delegation relationship and relieves the supervisor from the tedious task to derive parametric action instructions from

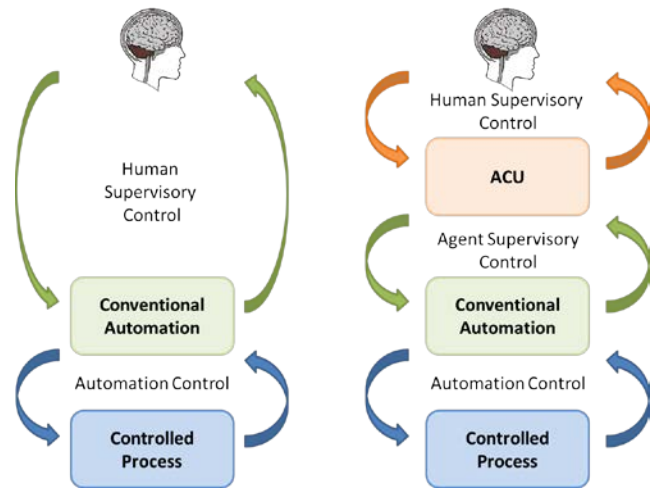


Figure 2. Agent Supervisory Control (ASC) as an additional guidance loop between the operator and the conventional automation

intentions, as SCU tasks are formulated on a symbolic mission level.

The TBG concept is extended to account for situations in which the operator does not want to delegate all aspects of a task to the SCU. The operator may choose to manually control certain actions, within the task execution of the subordinate agent. Criteria for the delegation of tasks and the impact of agent design on the operator's delegation decision are given in section III.

To allow human control of conventional automation components within the concept of TBG, the formulation of tasks has to be extended to include information on what automation is taken from the agent and allocated to the operator. From the SCU perspective, this information differs from automation loss in a sense, that functions cannot be requested and controlled by the agent, but are still supplied by the human. The agent derives action plans to accomplish the given objective, including actions executed manually by the operator. In this situation, the agent depends on the human to execute actions exhaustively during the task. An automation feed through, depicted as red line in Figure 3 allows the operator to manually access the conventional automation components during task execution.

Looking at the guidance hierarchy, the SCU is inserted into the work system between the human operator and the conventional automation. Figure 2 depicts the newly created guidance loop, closed by the cognitive agent. As the human, the SCU does not act as an additional outer-loop controller for the automated UAV system, but rather as an agent supervisor, formulating discrete commands for the conventional automation and monitoring their execution. This relationship between the SCU, the conventional automation and the aircraft may be best described by the term *Agent Supervisory Control* (ASC) [17]. The SCU takes the role of an *Agent Supervisor* or an artificial pilot, performing such functions that were formerly solely left to

the human supervisor. The concept of ASC does not aim at a fully autonomous UAV system that acts independently from human input, but rather at an *intelligent* subordinate, using its knowledge to execute human tasks.

In its role as an *Agent Supervisor*, the SCU combines two command relationships. On the one hand, it commands and monitors underlying automation components, on the other hand it is subordinate to the human operator. Its behavior during automation supervision and towards the human are essential for the degree of operator support that can be achieved by Mode 1 cognitive automation and will be discussed in the following section.

III. ROLE-SPECIFIC BEHAVIOR FOR A COGNITIVE AGENT

The SCU, in its subordinate role, has to provide the operator with information that allow him/her to distinguish between tasks that can be delegated to the agent and those that cannot [8], [9]. The operator may then decide which tasks are to be delegated to the SCU and formulate assignments respectively. For monitoring the SCU, the operator requires information about the degree of task execution and an outlook on upcoming steps and events intended by the agent [10], [15]. If the operator decides to keep manual control over conventional automation, he/she also needs respective feedback information.

Figure 4 depicts criteria for the delegation of operator tasks to subordinate automation, i.e. the SCU, given by Parasuraman & Riley [8] and indicates those that can be directly influenced by automation design. The central criterion is *reliance*, resembling the affinity of the operator to delegate a task to the SCU. The human reliance on automation is directly influenced by his *confidence* in manually executing the task, his current level of *fatigue*, the *perceived risk* associated with task failure and the operator's *trust in automation* for it to satisfactorily execute the task.

Most of the criteria in Figure 4 are uncontrollable and depend on the current task its associated *task complexity*, as

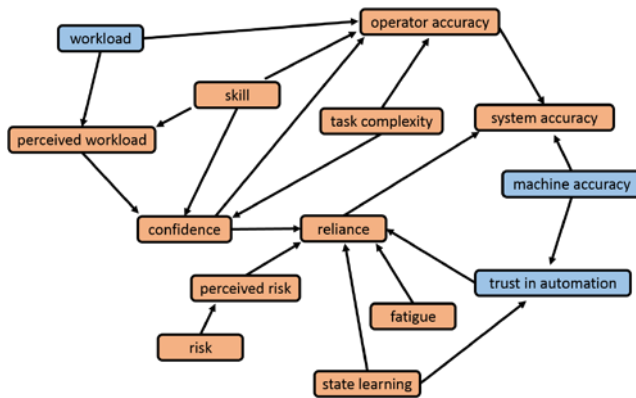


Figure 4. Criteria and their interactions influencing the delegation of tasks from the operator to the automation [8]. Criteria, directly influenced by automation design are color coded in blue

well as the operator's state. Three of them (color coded in blue) can be identified as directly being affected by automation behavior and thus controllable by its design. *Machine accuracy* describes the level of sufficiency with which a delegated task is executed by the automation. *Trust in automation* evolves from the operator's perception of automation behavior and is used to predict behavior in future situations. The operator's senso-motor and cognitive *workload* are directly influenced by interacting with automation during task execution. In the following subsections, these criteria and their implications for the design of the cognitive agent are discussed.

A. Machine Accuracy

The term *machine accuracy* refers to the performance of the cognitive agent, supervising conventional automation components during task execution. The agent's decision and action accuracy is directly rated in comparison with projected human behavior. In this context, the performance of the SCU is rated with regard to directability, predictability and task satisfaction [15]. A more directable automation component is executing operator tasks more accurately on his behalf. *Machine accuracy* directly affects the overall *system accuracy* and the operator's *trust in automation*.

B. Operator's Trust in Automation

According to [10] the significance of trust in subordinate automation rises, if the complexity of the automation does not allow its full understanding and if strategies above predetermined, procedural behavior are required. Thus, the behavior of the cognitive agent within the work system has to allow for the development of *calibrated trust* [10] by the operator. *Calibrated trust* refers to a level of trust, in which the operator does neither over- nor underestimate the capabilities of the SCU and which allows him a sophisticated decision on task delegation. The foundation for trust building regarding the agent's capabilities is the information that is conveyed from the SCU to the operator. This information can be categorized into three different types [18].

- *Performance*: Describes *what* the agent does and the execution status of the current task, given by the operator. The performance history allows the operator to assess the ability, reliability and predictability of the agent.
- *Process*: Focuses on *how* the agent works and to which degree the algorithms match the delegated tasks. The information helps to form an impression of dependability and integrity of the agent and require the understandability of its structure and algorithms.

- *Purpose*: Implies *why*, meaning for which purpose, the agent was developed. If this information is conveyed to the operator, it sustains his trust in the agent, if the purpose of the agent matches the current task.

Trust is not only formed through the content of information conveyed by the agent, but also by how it is conveyed to the operator. The type of interaction can be described by the term *etiquette* [19], which can have either positive or negative effects on the overall system. A suitable etiquette implies a distinct knowledge about the context and the role of the agent within the work system and can enhance the effectiveness and the safety of the overall system [20].

C. Workload resulting from task delegation

The primary goal of inserting an ACU into the work system as part of the OSM (Mode 1) is to support the operator by reducing his cognitive workload. Thus, the workload relief by delegating a task to the SCU has to exceed the (cognitive) effort required for tasking and monitoring the agent. According to [8], [21] the tendency to delegate a task to the SCU rises with decreasing delegation effort.

The operator's workload caused by delegating to the semi-autonomous UAV system can be separated into the decision on which tasks are to be delegated, the delegation task itself and the monitoring task during its execution.

The complexity of the delegation decision depends on the operator's information on SCU capabilities, the requirements resulting from the current task and the compatibility of both information. The task delegation to the SCU is conducted on a task-based level, as described in section II. The human operator can delegate tasks to the agent with partly manual control. The aim of the cognitive agent design has to be to create a most simple and adaptable task-based guidance concept, of which an approach is described in section IV.

The operator's situation awareness and assessment during SCU monitoring are based on the interaction with the cognitive agent. The agent monitors the heterogeneous automation functions and creates a symbolic representation of the situation picture and the system status based on the information. With regard to the operator's workload, he/she is assisted by the SCU, if the cognitive process to interpret the symbolic information is less complex than the processes needed to monitor the conventional automation itself. *Specialized etiquette* [19] implying an established form of behavior in the aviation domain and in its role of a subordinate mission manager impacts this interpretability and has relevance for both mission and safety aspects. The level of detail [10] and the frequency [13] of interaction determine whether the operator's workload is increased or decreased.

IV. SYSTEM CONCEPT

The concept of task-based guidance by Uhrmann & Schulte [5] allows for an adaptable level of rigor, meaning the operator may vary the level of freedom with which the agent can deduce action instructions from a task. The operator may set intermediate steps for the task execution, which increases his effort, but allows him to demand a specific behavior from the agent. According to Theißing & Schulte [22] tasks and step instructions may include boundary conditions. A list containing a specific task, intermediate steps and their respective boundary conditions is called *task agenda*. By the definition of TBG, the operator has to define the task agenda in a way, that the SCU can achieve it using its OSM.

Figure 5 shows the delegation of a task agenda from the operator to the subordinate agent. The figure depicts the shape of the supervisory functions, executed by the SCU in its role as an agent supervisor within the work system. According to the task processing structure by Theißing et al. [23], the *plan*-step can be divided into three sub steps, conducted by the agent to process the task agenda.

First, the task agenda is supplemented with intermediate steps, logically required to reach the goal state and not

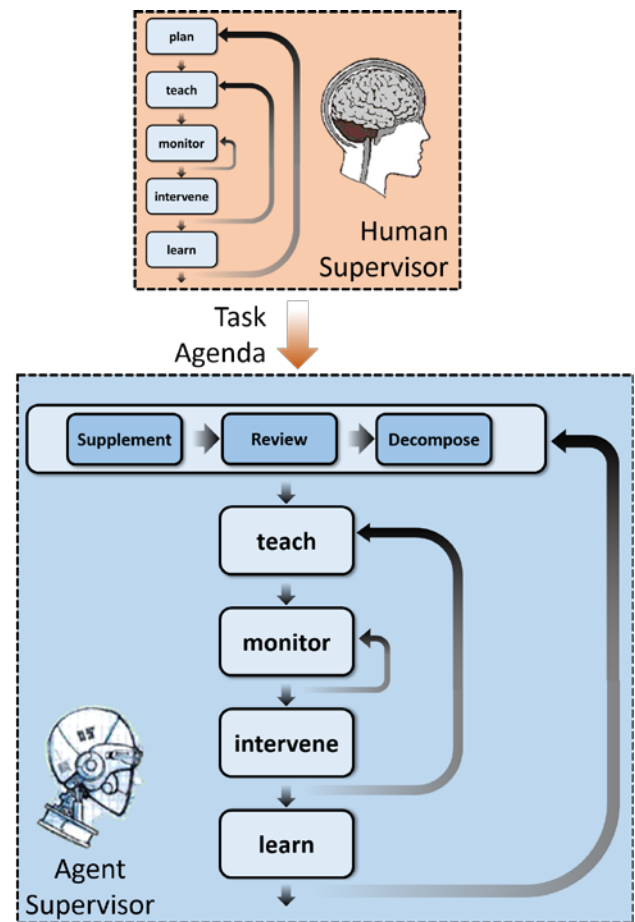


Figure 5. Supervisory Functions of the cognitive agent during its ASC

specified by the operator - *supplement*. The goal is to create a complete task agenda as a means-ends chain from the original state to the end. The boundary conditions, given by the operator set the options to determine steps from. Then the task agenda is reviewed to match task-independent rules (e.g. rules of engagement (ROE) and mission parameters) - *review*. Finally, the agent derives action instructions from the individual steps for the underlying conventional automation - *decompose*.

Figure 6 shows an example for the processing of the task agenda during the *plan* step of the cognitive agent. The SCU requires information about the available resources and capabilities of the UAV to perform the decomposition of the task agenda. In this context Kriegel et al. [6] describe the *Knowledge-Configured Vehicle* (KCV) concept, which enables the SCU to derive abstract capabilities from conventional automation functions and modes and checks them for availability in the specific situation. Desired behavior may be requested from the automation through configuration of the UAV capabilities. For this purpose, the KCV concept uses machine-specific knowledge that allows the determination of supply and vehicle resources from the aircraft. The information is considered during the *review* step, as shown in Figure 6.

During the execution of the action instruction list (*teach*), the SCU formulates desired behavior and requests it from the automation using the KCV concept. The *monitor* task is conducted using the feedback information given by the automation. If the deduced action list turns out to be badly suited due to changes in the UAV state or the environmental conditions, the *plan* step is rerun. If no solution can be found for the current task agenda, the SCU informs the operator about its planning failure and, if known, its reasons.

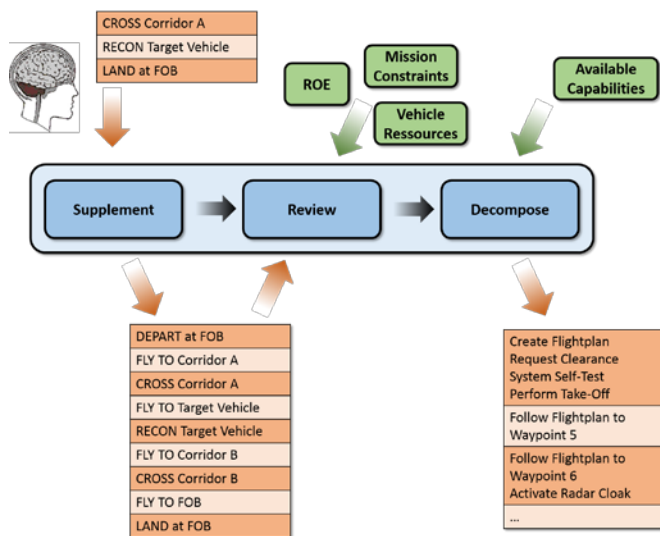


Figure 6. Exemplary description of the *plan* process of the cognitive agent. Derivation of action instructions from the task agenda delegated to the agent by the human operator

If the operator decides to keep control over certain automation functions during task execution, he is occupying capabilities, making them unavailable to the SCU. Still, the operator provides *virtual capabilities* to the agent, executing certain actions manually. Virtual capabilities can even extend the capabilities of an aircraft. For example, if the aircraft is missing an algorithm for vehicle detection, the human can analyze sensory data and provide the capability manually. The decision to keep control over certain automation functions is conveyed to the agent as part of the task agenda. If capabilities are not available e.g. due to system failure, the SCU notices automatically through the KCV concept.

The agent feedback serves the operator to monitor the SCU performance, its task execution and the overall system assessment, allowing him to intervene if necessary. The type and form of information needed by the operator stems from the criteria described in section III for trust building and the reduction of (cognitive) operator workload.

The main content of feedback information is formed by details on the performance of the UAV system and the SCU during task execution. Information on the process and the purpose of the SCU are only conveyed implicitly. Process information is easy for the operator to process as the structure of the SCU functions in its role as an agent supervisor are similar those of the human. The performance information correlate with the claim of HCA to keep the operator in the control loop and as the ultimate authority of the work system during the delegation process [12]. It can be separated into event-independent and event-dependent information.

Event-independent information are:

- The current system status of the UAV (resources, (available) capabilities)
- Current tactical situation information and perception results (threats, tactical elements)
- The status and the current objective of the SCU, its (reviewed) task-agenda and its execution progress

Event-dependent information are:

- Messages on standard events during task execution (task acceptance, task completion)
- Messages on situation and system changes with task relevance (The task agenda cannot be successfully completed in the current conditions)

The system status of the UAV and the tactical situation information are used to analyze and assess the performance data of the SCU. The style, in which the feedback information is conveyed, concurs with the level of abstraction on which the operator delegates the agent, thus relieving the operator of additional information processing. The delegation and feedback information (event dependent and independent) both contain symbolically represented

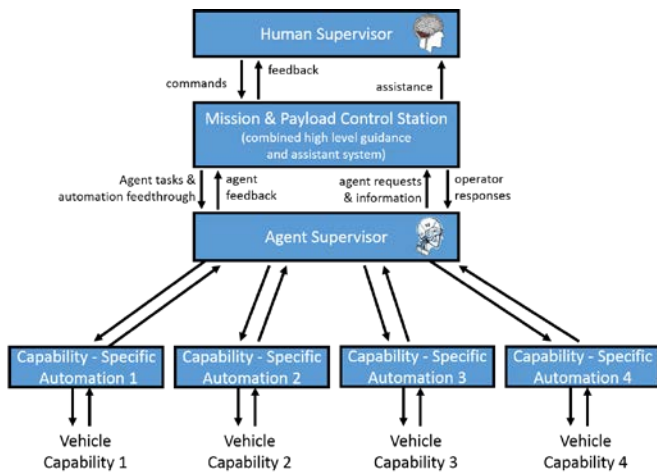


Figure 7. Hierarchical structure of the information flow within the work system implementing ASC

elements and goals on a mission level. Information about the current SCU task agenda is linked with existing tactical elements and their symbolic states. For the example of a vehicle detection task, the operator will be presented the processed perception results linked to tactical elements in the HMI instead of raw video streams. The task progress information is also aligned with the delegation abstraction level. Instead of notifications on waypoint arrival, the operator is informed about the entrance into a flight corridor.

Event-dependent information are conveyed to the operator in form of messages and are comprised of task-relevant, symbolic content. The messages are only triggered on events with relevance for mission execution, distinguishing them from status information of conventional automation elements. Tactical situation changes or system changes only have to be explicitly conveyed if they oppose the current task execution. The regulation of the message frequency and the deployment of messages on standardized events correlate to a specialized etiquette with the goal to ensure the decision-making and problem-solving capabilities of the human operator. At the same time operator, overloading is avoided by the regulation of information that do not directly affect his level of influence.

The interaction between the human operator and the

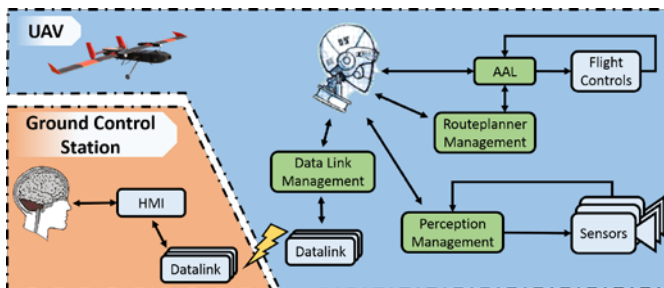


Figure 8. Conceptual design of the overall system. The SCU supervises four automation functions aboard the aircraft in an ASC relationship. The operator supervises the UAV system from inside the ground control station (GCS)

cognitive agent is completed with clearance and assistance requests initiated by the SCU. Certain actions may require clearance from the human operator, as final authority, for mission-relevant or security reasons. Specifications for the necessity of clearances are implemented as task-independent rules (e.g. ROE) or in form of constraints included in the task agenda. The SCU can request assistance from the operator if the agent requires the execution of a certain, (virtual) capability, that cannot be accessed. If, for example, the system is missing an automatic departure and landing procedure, but the agent has knowledge about a specific virtual capability, the SCU may request the execution of a manual landing procedure from the human.

Figure 7 depicts the resulting information flow within the work system implementing ASC. Apart from the operator, the cognitive agent and the conventional automation, the *Mission- and Payload Control Station* (MPCS) is depicted, which serves the human as an HMI and may include additional functions such as an assistant system [1].

V. IMPLEMENTATION

The implementation of the ASC concept comprises the overall work system, as described in section II, including the aircraft as well as the ground control station (GCS). Figure 8 shows the main elements of both segments (air and ground) with the SCU as the central mission-management component onboard the UAV. The operator supervises the UAV system from inside the GCS. Figure 8 identifies four conventional automation functions onboard the UAV, which serve to control the aircraft and its payload. Both the cognitive agent and the human operator can access the automation.

1. Automation Abstraction Layer (AAL)

The AAL provides a standardized access to the Flight Management System (FMS) of the UAV. Functions such as waypoint navigation and autopilot commands for fixed-wing and rotorcrafts are available to multiple users at once. The feedback information of the AAL include waypoint and route events as well as autopilot modes and parameters.

2. Routeplanner Management (RPM)

The RPM includes multiple route planner algorithms, with different qualities and strengths. (A* and Theta* on an equidistant, uniform grid; A* on an adaptive grid based on the quadtree algorithm and a potential field planner.) The route planner algorithms respect threats, no-fly zones and dynamic constraints of the aircraft. Multiple users can chose a specific algorithm, define its parameters and execute it. Generated routes are automatically stored in the AAL, such that eligible users can access and command them to the FMS.

3. Perception Management (PM)

The PM allows for the intelligent, situation-dependent deployment of sensor and image processing functions. Abstract perception capabilities are made available for the SCU to request and trigger. The perception capabilities that are offered to the agent strictly depend on the hardware and software components implemented on the aircraft. For this purpose the system uses modifiable perception chains that are created and configured to perform a requested task [24]. The feedback information of the perception management varies between raw sensor output and pre-processed perception results on a symbolic level.

4. Data Link Management (DLM)

The DLM offers functions to choose and configure the data link connections aboard the UAV. Telemetry data, tactical situation updates as well as image and video streams can be transmitted according to the available data link bandwidth. A function for data buffering allows for delayed transmission of data to compensate for data link loss or to reduce electromagnetic emission.

The knowledge of the SCU completely determines its capabilities and behavior, as it is a knowledge-based acting cognitive agent. The SCU requires appropriate knowledge to be able to execute tasks through respective capabilities. It also requires knowledge how to derive symbolic information from parameters and back. Our implementation of the SCU uses the *Cognitive System Architecture with Centralized Ontology and Specialized Algorithms* (COSA²) [25] as a cognitive framework for knowledge-based planning, scheduling and task-execution. COSA² offers a three-layered information processing structure, based on a modified scheme of human behavior from Rasmussen [26]. The framework includes cognitive subfunctions with increasing abstraction, according to their level of behavior. Behavior ranges from simple skill-based and rule-based behavior in known situations to knowledge-based behavior in unknown situations for which no rules exist. The knowledge of an SCU is split into a priori knowledge of the

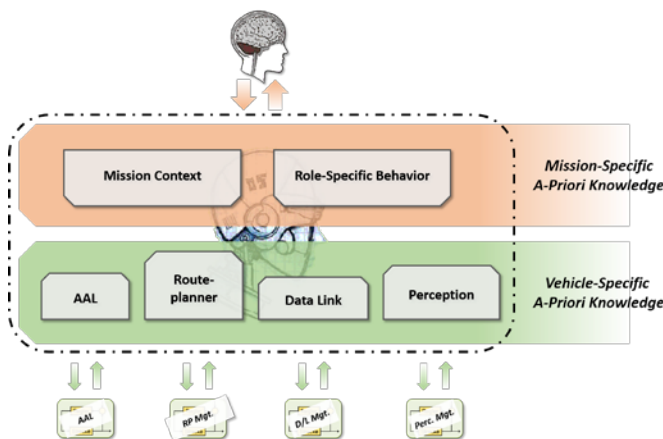


Figure 9. The static a priori knowledge of the SCU can be split into mission-specific and vehicle-specific knowledge components

agent, which is implemented during design time and available to all cognitive subfunctions and situational knowledge, which is derived from current information during runtime using existing a priori knowledge.

Figure 9 shows discrete a priori knowledge components of the SCU, which constitute its behavior as an interactive subordinate to the operator and an agent supervisor within the work system. The knowledge is divided into 2 layers, as suggested by the KCV concept in section IV. Mission-specific knowledge includes information to understand tasks in the current mission context and to constitute roll-specific behavior as a subordinate. Vehicle-specific knowledge allows to command and monitor conventional automation aboard the UAV. The information allows the SCU to abstract capabilities from the four automation functions, to use during task execution. The amount of knowledge that the SCU holds about each automation function determines the level of detail with which the capabilities can be mapped inside the agent and thus on which level it can interact with the automation.

Knowledge-based information processing demands an

Table 1. Capabilities, abstracted from conventional automation functions by the SCU. Parameters are used to request desired behavior from the automation

Automation Element	Capability Name	Parameters
AAL	Fly to Position	- Geo Position - Behavior (En Route & On Arrival)
AAL	Fly Route	- Starting waypoint
AAL	Fly Route to Element	- Starting waypoint - Final waypoint - Behavior on arrival
RPM	Calculate Distance	- RP algorithm - Algorithm specs - Node Geo Positions
RPM	Plan Route	- RP algorithm - Algorithm specs - Node Geo Positions
PM	Start Perception	- Tactical Element - Perception type - Perception specs
PM	Stop Perception	- Perception ID
PM	Process Perception Results	- Perception IC - Processing type
DLM	Start Recording Data	- Data stream ID - Record specs
DLM	Stop Recording Data	- Data stream ID
DLM	Transmit Data	- Data stream ID - Data link specs
DLM	Request Authorization	- Tactical Element - Action Type
DLM	Request Assistance	- Tactical Element - Action Type
Virtual	Conduct Departure	- none
Virtual	Conduct Landing	- none

extensive amount of resources. An increasing number of symbols within a world model representation increases the number of links between the symbols and raises the processing time. Scenarios with limitations on decision time require a restriction of the level of detail for the a priori knowledge and the creation of procedures for certain fixed tasks. This restriction is balanced with the necessity of planning flexibility for the SCU during task performance. Actions of which the SCU does not possess any explicit knowledge have to be solved rule-based, meaning in a fixed manner. If no such rules exist, the action cannot be executed.

An action plan may include further subsymbolic planning and optimization actions to account for parametrical problems not considered during the symbolic mission planning. This parametrical processing raises the overall optimality of the agent solution. The complementary use of knowledge-based behavior and optimization functions [27] allows a calibration of balance between the flexibility and optimality of system behavior.

The cognitive agent is completed through the integration of a reactive behavior layer (*Reactive Extension for COSA² - ReX*) below the knowledge-based planning component. The symbolic planning process of COSA² creates a procedure list to solve the given task. The procedures are stored inside the ReX and hold the action plans specific to each procedure. These procedures are called upon by COSA² during runtime and executed through ReX. The technical connection with the conventional automation also runs through ReX. Furthermore, ReX holds capabilities to dynamically react to changes in a predefined manner, if the situation is time critical and needs immediate reaction.

Table 1 shows a list of the capabilities the cognitive agent can abstract from conventional automation elements to complete its tasks. During the mission, the SCU checks whether the capabilities are available and employs them as necessary. The capabilities can be used as desired behavior, specified by the agent by referring to a specific capability and setting its parameters. Virtual capabilities in Table 1 refer to such actions that can only be performed by the

human operator, as the onboard automation offers no such functions.

Inside the GCS, the operator interacts with the system using his HMI for mission- and vehicle management. The implementation of the HMI uses the *MPCS* to supervise the semi-autonomous UAV as described in [22]. The operator creates a task agenda by interacting with tactical element symbol on a tactical situation map. The level of detail of the task agenda and thus the stringency of task execution can be controlled by the operator through the specification of intermediate tasks on the map. As a response to the task agenda command, the operator is displayed the reviewed task agenda by the SCU. The current degree of task execution is also marked on the agenda and linked to elements on the tactical map.

If new tactical elements or changes are perceived by the UAV, the information is automatically synchronized with the *MPCS*. This allows the human to react to new perceptions and situational changes. The SCU-initiated interaction is constituted by dialogs, displaying the requests for clearance and assistance inside the *MPCS*. The manual control of conventional automation functions is available through additional *MPCS* capabilities. For example, the operator may control the sensors of the UAV manually using an additional sensor display inside the *MPCS*.

VI. EVALUATION

The implementation was evaluated in a flight test campaign conducted in 2013 at UBM. The target application of the UAV system is a reconnaissance mission with an aircraft controlled by a single UAV operator from inside a mobile GCS. The mission conducted during flight-testing comprises a tactical situation with multiple predefined elements prevalent during the course of the mission and dynamically adaptable by the flight test instructor. The airspace is separated into a friendly and hostile territory by a *Forward Line of Own Troops* (FLOT), which can only be crossed using one of two existing flight corridors. The mission goal for the UAV system is to perform reconnaissance of a building located outside of data



Figure 10. GCS with the operator workplace (left) and flight-test environment (right).



Figure 11. UAV demonstrator Explorer as aircraft platform for flight-testing

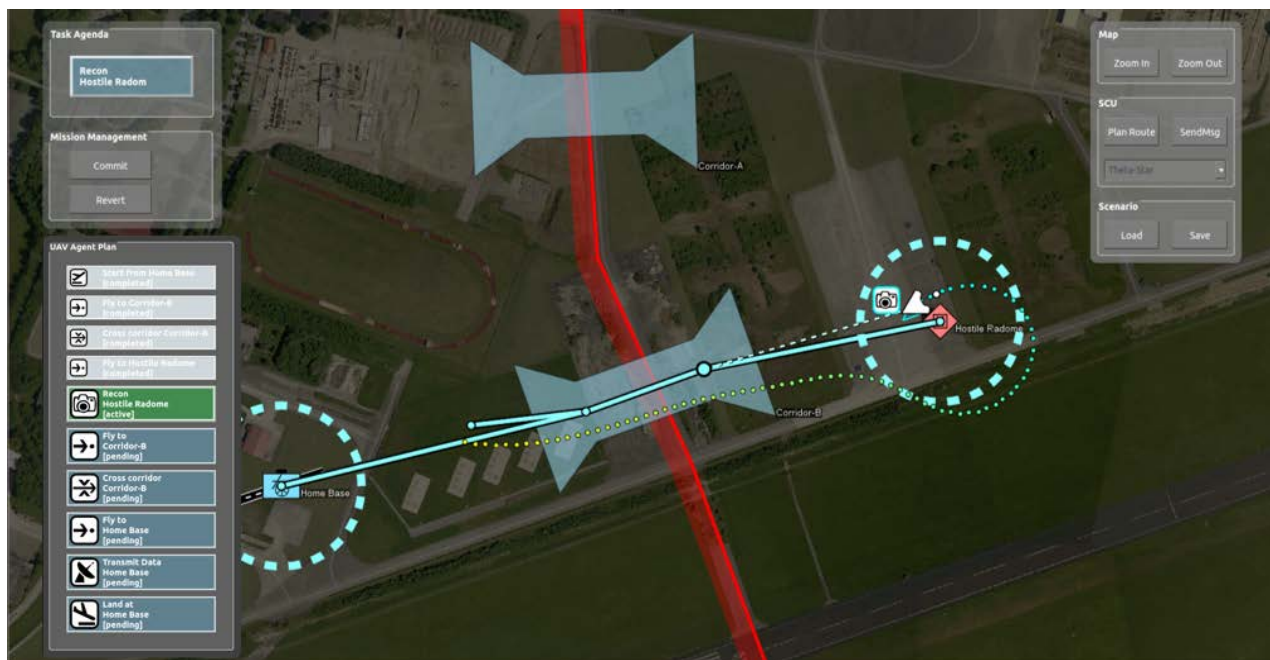


Figure 12. Tactical map display showing the initial mission phase. The (reviewed) task agenda is shown on the left. The blue line indicates the flight plan created by the cognitive agent. The dots are showing the actual flight path of the UAV.

link range.

Flight tests are conducted using a fixed-wing UAV demonstrator, based on a Bormatec airplane model with a maximum payload capacity of 2.5kg (cp. Figure 11). The aircraft is equipped with a Cloudcap Piccolo autopilot system offering waypoint based flight guidance. The onboard sensors include two lightweight full HD cameras, one of which is mounted looking forward and the other one pointing downwards. The downward looking camera serves as a reconnaissance sensor for the UAV. A core i7 powered computer board hosts the conventional automated software elements onboard the aircraft and is connected to all

hardware components used for mission execution.

The mobile GCS is located inside a modified Mercedes Sprinter utility vehicle with two operator workplaces, of which one holds the MPCS (cp. Figure 10 left) and the other is used for the control of flight test equipment (cp. Figure 10 right). Each workplace comprises two multi-touch touchscreens, with the MPCS having one screen for the tactical map and the other for the sensor control software. The GCS holds a tracker platform with two directional and one unidirectional antenna, for extending the data link range of the Wi-Fi network and to visually track the aircraft in flight. A safety pilot is able to control

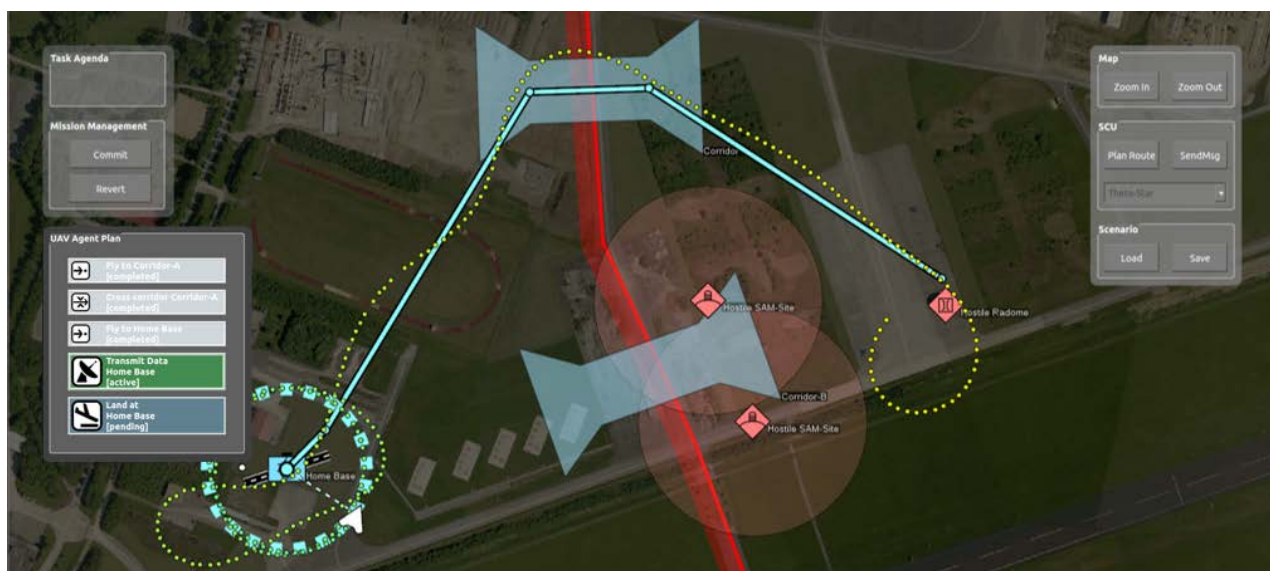


Figure 13. Tactical map display showing the second mission phase after replanning due to changes in the tactical situation. The initial flight corridor is blocked by multiple SAM sites. The figure shows the flight path using an alternate corridor and the aircraft transmitting its data to the operator in the GCS

the aircraft manually at any time during mission execution.

In general, the cognitive agent can access conventional automation functions, as capabilities have been implemented, for them. The availability of the capabilities is determined by the underlying hardware elements and their functions. Virtual capabilities are assumed available through the human operator. The safety pilot performs departure and landing through manual control. The SCU recognizes the aircraft to be airborne / landed when the autopilot is turned on / off.

Figure 2 and Figure 3 show the course of the mission execution on the tactical map display. Upon reception of mission orders, the operator formulates a task to recon the target building on hostile territory (cp. Upper left corner in Figure 2). The recon task comprises the collection of reconnaissance data and its transmission to the GCS. The SCU derives an initial task agenda and begins its execution. The agent creates a flight plan (cp. Blue line in Figure 2) and approaches the target object crossing the FLOT at Corridor B. After arriving at the target object, the SCU initiates its reconnaissance using the PM perception capabilities. Since no data link is present to transmit the reconnaissance data directly to the GCS, the data is stored onboard the UAV for later transmission.

After reconnaissance data about the target building has been gathered, the SCU initiates its return to home base. The tactical situation changes with two threats being detected close to Corridor B, prohibiting its crossing and thus invalidating the initial task agenda. The agent initiates a replanning and returns to home base using the alternative Corridor A, as depicted in Figure 3. The reconnaissance data is transmitted to the GCS and displayed to the operator on the MPCS. Task execution is completed with the UAV landing at the home base.

During mission execution, multiple forms of interaction between the operator and the UAV system take place. After commanding the reconnaissance task to the SCU, the operator is displayed its reviewed task agenda in the tactical map display. During the course of the mission, the status of each action within the task agenda is continually updated and displayed to the operator. Each action is marked with its specific symbol, the name of the element to perform the action on and its status information (cp. Lower left side in Figure 2 and Figure 3). Completed tasks are color coded as grey, current tasks are green and pending tasks are color coded as blue.

The position of the UAV is displayed on the tactical map. The tactical elements within that map form the element pool, which the agent is using during mission planning and is thus visible to the operator. Sensor output happens on the external sensor data display.

Messages for clearance and assistance requests are presented to the operator as dialogs, which can be accepted or denied. When the SCU successfully creates a flight plan

to perform its task agenda, it sends a clearance request to the operator to gain authority for its execution. Assistance requests are transmitted on departure and landing, as their capabilities are purely virtual, thus only available through the operator. For departure, the safety pilot puts the aircraft in a steady flight position and turns over control to the onboard autopilot. For the landing procedure, the safety pilot takes control from the autopilot and lands the aircraft manually.

The agent has to adapt its behavior during task execution, whenever the communication to the human operator is disrupted. In areas where data link is missing, the operator has no possibility to respond to an SCU request. During flight tests, this takes effect when the SCU initiates a replanning after threats have been detected. Since the human operator cannot authorize the flight plan, the SCU configures the route-planning algorithm with a different parameter set, accounting for higher level of safety.

VII. CONCLUSION

The utilization of a cognitive agent for the support of a human operator during mission guidance requires a consideration of its double role as an agent supervisor onboard the aircraft and as a subordinate to the human in charge. In this context, the two concepts of *Agent Supervisory Control* (ASC) and role-specific agent behavior are introduced and described.

An SCU supervises conventional automation systems comparable to a human operator, as it formulates discrete commands and continually monitors their execution. It relieves the operator of the tedious task to derive step-by-step instructions and allows for a task-based UAV guidance, formulated in a task agenda with intermediate steps and constraints.

The operator's perception of the SCU significantly influences his decision to delegate tasks. In this context, the operator's trust in the satisfactory task execution by the SCU is of central importance. The decision is also influenced by the additional effort resulting from delegation.

An overall concept considering both roles of the SCU and its implementation have been described. The abstraction of capabilities from automation functions allows the SCU to dynamically incorporate knowledge about the vehicle into its symbolic mission planning. An adequate combination of event-independent and event-dependent information allow the operator to build an appropriate trust level in his subordinate.

A first flight test has proven the capabilities of the ASC approach in a reconnaissance scenario with data link limitations. Mission execution was made possible even in areas without data link coverage, as the onboard SCU acted goal-oriented, reacting to unforeseen changes in its

environment. A basic implementation of role-specific performance has been tested through task agenda feedback and agent messages to the human operator.

In the future, experiments will focus on the human-agent interaction to evaluate the impact of different types of role-specific behavior on the operator's trust in the cognitive agent and his decision to delegate tasks. More complex task agendas and the impact of mixed task execution, with the operator keeping manual control over certain parts of the aircraft automation have to be tested. The effect of operator support can be evaluate in multi-UAV scenarios with a single operator supervising multiple UAV in a combined mission.

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