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COGNITIVE AUTOMATION BASED GUIDANCE AND OPERATOR ASSISTANCE FOR SEMI-AUTONOMOUS MISSION ACCOMPLISHMENT OF THE UAV DEMONSTRATOR SAGITTA

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Abstract

Cognitive Automation as part of a UAV provides cognitive capabilities similar to those of a human pilot. These capabilities include planning, problem solving, decision making, and – generally speaking – dynamically reacting to a changing tactical situation and environment. This functional element shall be introduced onboard the aircraft in form of a so-called Artificial Cognitive Unit (ACU).

The application of an ACU shall relieve the operator by enabling him to focus only on high-level mission goals and hence realize the advanced concept of Task-Based Guidance. There, the operator will issue a set of abstract tasks to the UAV. These will be processed by the on-board ACU to create a complete and detailed task agenda which will be dynamically adapted in case of unforeseen events.

In the Mission & Payload Control Station, Cognitive Automation in terms of an Assistant System will support the operator during the guidance process. The Assistant ACU, exhibiting knowledge both in the UAV mission domain and in the operator's cognitive processes, will support the operator by means of Mixed-Initiative Operation and Operator Intent Recognition.

1. INTRODUCTION

1.1. The Project SAGITTA

The SAGITTA UAV (Unmanned Aerial Vehicle) program is a research project funded and supervised by Cassidian. It coordinates several research partners in design and development of a leading edge UAV technology demonstration platform.

Our contribution as described in this article comprises the Mission Management System consisting of the on-board Decision Engine (i.e. the Artificial Cognitive Unit, ACU) and a ground control station supporting the operator with an Assistant System.

1.2. Task-Based UAV Guidance

The means of controlling today's conventional unmanned aircraft range from manual control to a certain degree of automation.

The basic form of remote flight control is achieved by a permanent transmission of joystick and throttle commands to the aircraft. With newer UAVs, this method is gradually being replaced by an automated course or route following. Modern commercial unmanned aircraft are guided by a list of pre-defined waypoints issued by the operator. These waypoints are then being followed fully automatically, hence relieving the operator of a permanent manual flight control.

Automation employing waypoint-following mechanisms can be used to carry out flight missions without intervention of the UAV operator. In case of a loss of the data link to the ground segment, the aircraft is henceforth still able to follow its commanded route. The mission is then carried out automatically.

The behavior of the UAV is then, however, completely predetermined. Should the scenario's conditions change during the absence of new orders or should the issued plan contain flaws, the aircraft will be unable to react accordingly.

It is hence desirable to employ means of flight guidance maintaining a high degree of automation while, on the other hand, granting the UAV the degree of flexibility necessary to react according to unforeseen events.

Therefore, the paradigm of Task-Based Guidance (TBG) [16] is used for commanding Sagitta. In terms of military leadership, a task is a specified goal which grants the recipient freedom to independently find a way to achieve that goal within given boundaries [3]. Accordingly, TBG allows the operator to issue orders to the UAV at the abstraction level of mission tasks (e.g. "Reconnoiter target"). These tasks will then be reviewed, supplemented and decomposed by the on-board ACU to create a complete and detailed task agenda. In case of unforeseen events or tactical situational changes the ACU will adapt this task agenda by changing affected sub-tasks, hence increasing the on-board autonomy of the UAV.

1.3. Outline

Within Section 2 the application of Cognitive Automation for mission guidance will be motivated and conceptually introduced.

In Section 3 the technical implementation of Cognitive Agents, their Cognitive System architecture and the concept of Task-Based Guidance will be described in detail.

Section 4 will motivate and explain the function of an Assistant System for the operator and describe the application of Mixed-Initiative Operation of a UAV.

In Section 5 the research aspects introduced here will be put into the context of past and present research projects at the Institute of Flight Systems.

2. COGNITIVE AUTOMATION FOR UAV MISSION GUIDANCE

2.1. UAV Missions in Military Scenarios

We define two different Use-Cases for military UAV missions: “Reconnaissance of enemy airfield” and “Reconnaissance of mobile enemy units”. As they have a huge impact on the tasks and options which the Mission System will have to process, they will be described in the following.

Figure 1 gives an overview of the first mission that the Sagitta UAV will have to accomplish. Turquoise items represent the “standard solution” for this scenario; yellow items are events that might be introduced to the scenario during mission runtime. In this mission Sagitta has to fly a departure, transit to the FLOT (forward line of own troops) and cross the FLOT. After that it has to cross an area of enemy air defense and is forced to evade those threats in a suitable way (e.g. fly around the threat radius). After another transit to the target area it has to search, identify and reconnoiter a stationary target whose position is known in advance. Afterwards Sagitta has to fly an egress, cross the FLOT again, transit to the Home Base and fly an arrival. Possible events that are not known to the mission system before mission start are: FLOT closed, refueling (may be necessary if the FLOT is closed for too long), sensor damage, and popup threats.

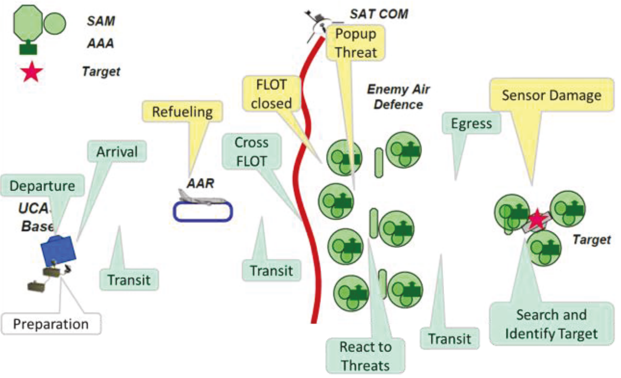

Figure 1: Mission 1: Reconnaissance of enemy airfield

Figure 2 shows the second scenario for the Sagitta UAV. It differs from the first one in the two aspects that the position of the target is not known exactly and that the target is mobile. Only a rough area where the target might be at some time is known to the mission system. Therefore the Sagitta UAV has to fly a search pattern in the target area, wait for the sensors to detect the target and follow the target until it is identified.

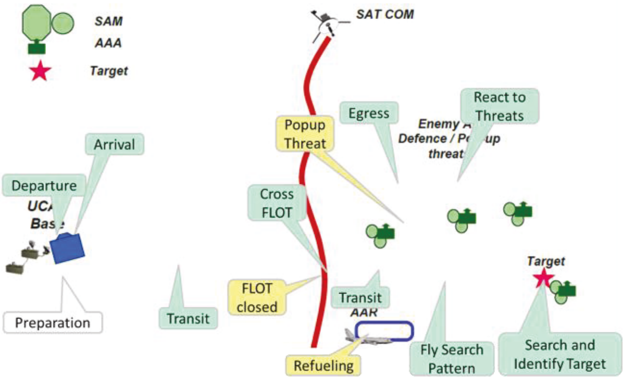

Figure 2: Mission 2: Reconnaissance of mobile enemy units

Both scenarios are characterized by multiple dynamical aspects: Not all elements of the tactical situation are known prior to the start of the mission, new threats can appear suddenly, and the data link can be lost anytime during mission runtime. In the latter case the system shall still be able to make reasonable decisions.

2.2. Necessity of Partial Autonomy in UAV Guidance Systems

2.2.1. Motivation of Autonomy Aspects

The characteristics of the described use cases bear some implications which disqualify the UAV for means of conventional flight guidance.

The assumed realistic military scenario implies a threat situation which is only partially known in advance. Hostile anti-aircraft missile sites or artillery units may be encountered spontaneously. This makes the ability for spontaneous evasive maneuvers and route re-planning necessary. Both could, if slowly, be commanded from the ground segment. This would, however, require a permanently stable data link.

The dynamic environment, however, renders this assumption unrealistic. In practice every radio connection can be disturbed by environmental conditions or enemy jamming. It must be assumed that once hostile territory has been entered a great part of the UAV mission must be executed by the air segment without any contact to the operator on ground.

In modern UAVs employing waypoint following the areas in which the data link ceases to work are crossed along an entirely predefined route. The UAV is then prone to become an easy victim of enemy fire.

A more effective mission execution henceforth requires the UAV to be able to automatically act according to changes in its environment. This entails a certain degree of autonomy on board of the UAV.

Partial autonomy on board of the aircraft has the effect that a part of the tasks formerly carried out by the operator is outsourced to the ACU. The resulting gap of work load of the operator can then be utilized for other tasks [6]. The freed mental resources may e.g. be used for a guidance of multiple UAVs.

2.2.2. The Operator in the Loop

A lot of research in the field of UAV autonomy aims at a fully automated mission execution without any operator involvement at all.

Our research, in contrast, deliberately involves the UAV operator in the process of mission execution. He plays, in fact, the most significant role therein [1].

For once, in the field of military aircraft, giving up control about the situation is not desirable. The ethical implications of an unsupervised, possibly armed aerial vehicle are difficult to handle.

In addition to that, keeping the operator out of the loop equals neglecting a valuable source of information. While certain abilities like computational speed are domains in which machines are generally superior to men, the operator is very likely to offer a broader situational knowledge and better ability to interpret situational changes [13].

Our research therefore aims at a sensible integration of the operator's knowledge and the operator's abilities into the mission system.
While the data link is established and the operator is directly in charge of the UAV, his skills and his knowledge are reflected in his immediate actions.
As soon as the connection is interrupted, the UAV has to resort to prior commands, constraints and decisions given by the operator. Using those as a basis for further action, the UAV then carries out the mission semi-autonomously.

The desired degree of automation is therefore to involve the operator in the mission planning and execution as much as possible while maintaining the ability to carry out the mission semi-autonomously if necessary.

2.3. Integration of Autonomous Components in a UAV Work System

2.3.1. The Work System

Sensible conceptual means have to be found for an integration of systems with autonomous behavior into the mission guidance process.

In this context of military UAV missions the development of all guidance functionality has one superior goal: The achievement of the set of mission objectives. Thereby, the UAV operator is in charge of his aircraft which he uses to achieve the given goal.
A situation like this can be modeled as a *Work System* [9]. In a Work System, a group of agents called *Operating Force (OF)* receives an external *Work Objective* it then attempts to fulfill. It therefore makes use of a set of tools, the *Operation-Supporting Means (OSM)*. In the end, this process creates a *Work Result*.
The OF is in charge of the Work Process and exhibits a sufficient degree of autonomy to modify its Work Objective. It consists of at least one human being. The OSM, in contrast, are simple receivers of commands which they obey.

Modeling UAV mission guidance as a work system can show the conceptual possibilities for an integration of semi-autonomous components with respect to optimizing the fulfilling of the Work Objective.

2.3.2. Conventional UAV Guidance

In conventional UAV guidance via Joystick, throttle, and sensor feedback, the OF is constituted by the UAV operator only. He uses his only OSM, the UAV, in order to fulfill his Work Objective.

He guides the aircraft via continuous control, i.e. permanent maneuvering and a permanent flight state supervision. The process, modeled as a work system, is depicted in Figure 3.

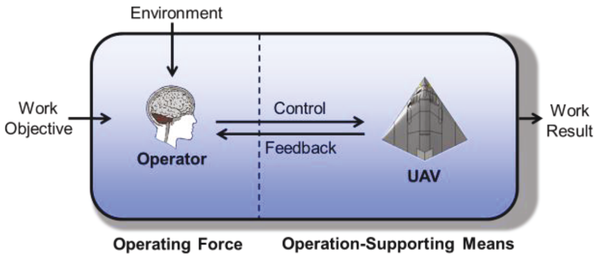

Figure 3: The Work System of Conventional UAV Guidance

2.3.3. Supervisory Control

In order to relieve the operator of the task of permanent manual control, an ACU taking over flight control can be added to the air segment. An ACU is designed to automate certain cognitive capabilities of the human being (the mechanisms will be explained in Section 3.2) and hence resemble the behavior of a human being [11].

When taking over flight control tasks, the ACU may be seen as an artificial pilot receiving abstract instructions from the ground. The ACU reduces the operator's work load to giving single commands and supervising their execution. It thereby relieves him of a permanent control. The hierarchical relationship between the human operator and the aircraft remains identical to the one of conventional guidance: The operator issues commands and the ACU obeys. This concept, shown in Figure 4, is therefore referred to as **Supervisory Control**.

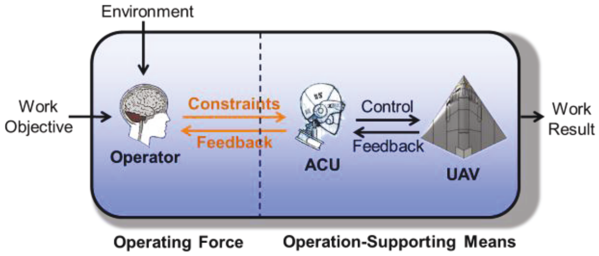

Figure 4: The Work System of Supervisory UAV Control

2.3.4. Cooperative Control

Supervisory control enables the operator to outsource a part of his tasks to an ACU and thus automate them.
In addition to that, it is desirable to have an ACU which does not simply obey orders but supports the operator on an equal level of hierarchy. The analogy to human beings would be that the operator desires not only to have a subordinate following his instructions, but also to have a partner comparable to a co-pilot he is able to have a dialogue with.

The solution is to integrate an ACU inside the OF, hence to place it on the same hierarchical level as the operator. The human operator and the ACU can then both command the UAV as a team. While cooperating to fulfill their shared work objective, they can negotiate about the means necessary and can assist each other in the work process.
This concept is referred to as **Cooperative Control**.

Figure 5 depicts the combination of both concepts as employed in Sagitta.
The airborne ACU is given instructions according to supervisory control from the ground segment. It receives abstracted mission commands and executes them. Its main purpose is therefore the mission guidance of the UAV.
The ACU on ground follows the paradigm of cooperative control and supports the operator in planning and execution of the mission. Its main purpose is therein the assistance of the human operator.

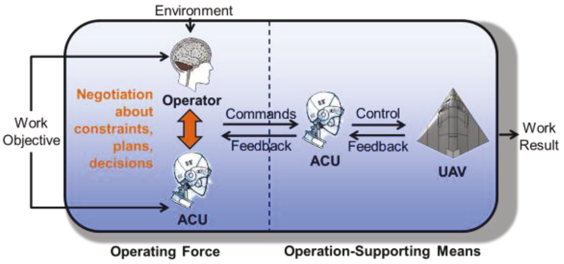

Figure 5: The Work System of Cooperative UAV Control

2.4. The Mission Management System (MMS)

In the following the system architecture of the MMS in the Sagitta project and the roles of the two main elements, the Decision Engine and the Mission & Payload Control Station, will be described.

Figure 6 shows the overall system architecture of the MMS. On the ground segment the operator (Op) is able to interact with and get feedback from the system using the mission & payload control station (M&PCS). The M&PCS uses the mission data link (MDL) to transmit and receive mission data to/from the Sagitta UAV. On-board the decision engine (DE) is able to issue commands to the flight management system (FMS) via a safety module preventing the DE from issuing unsafe commands (MSS). The DE can also make requests to the active perception (AP), which will use the sensors and the hardware acceleration & auto land module (HAAL) to fulfill these requests. Additionally the AP can use the MDL directly to stream live video footage to the M&PCS.

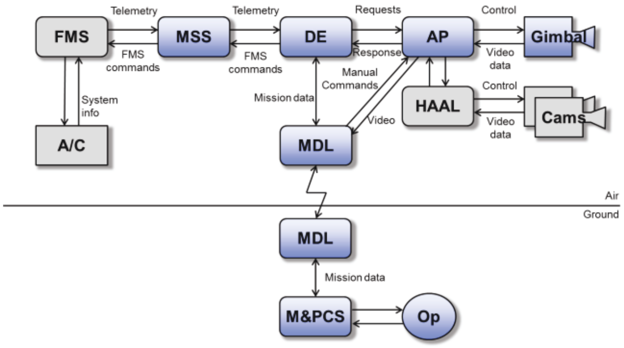

Figure 6: The MMS System Architecture

The DE is the central component of the on-board segment. Its purpose is to make mission relevant decisions during mission runtime based on the current tactical situation and environment as perceived by the AP. For this it has to understand the intents of the Operator, perceive its environment and tactical situation and use the A/C's resources accordingly.

The M&PCS is the Human-Machine-Interface used to command and control the Sagitta UAV during mission runtime. It provides features to enable the Operator to order tasks to the DE and includes an assistant system supporting the Operator in controlling the A/C and planning the mission.

3. DECISION ENGINE (DE)

3.1. Task-Based Guidance

Increasing the level of autonomy is mentioned as one of the main objectives of MMS design within Sagitta. As this shall and will not eliminate the human operator from the system concept, the methods of interaction between the human operator and the mission system have to be revised. In conjunction with cognitive automation, task-based guidance [16] is proposed as a suitable concept of interaction.

A task is, in the context of military missions, characterized by a fixed set of constraints within which the receiver of a task is free to achieve a fixed set of goals [3]. It is therefore considered desirable that a highly automated system with the ability to make own decisions be commanded by tasks given by the human operator.

Highly automated systems guided by tasks are expected to offer greater operational flexibility without overtaxing the operator. On the other hand, introducing task-based guidance to conventional, completely pre-planned missions would hardly be worthwhile. This is the reason why cognitive task-based guidance addresses both, high flexibility in unpredictable mission scenarios, and the reduction of human operator task load, avoiding error-prone excess workload situations even in multi-aircraft mission management configurations.

Missions fully exploiting the potential of task-based guidance should thus be represented by a sequence of operator-given task elements, arranged in a modifiable order. The following list contains the task elements necessary to cover a reconnaissance mission:

- Depart [via]
- Transit [to]
- Cross FLOT [via]
- Fly Search Pattern [x]
- Search [Target]
- Identify [Target]
- Egress [via]
- Arrive [at]

Once a task is issued by the human operator, the cognitive MMS should be able to interpret the given task correctly and initiate the desired system behavior based on knowledge given to it during design time and by use of a knowledge processing architecture on board being good for decision-making. To achieve this, we propose a five-tier architecture consisting of: Supplement, Review, Decompose, Supervise&Adapt, and Execute.

Supplement given tasks, resulting in agenda:
A given task may be a fitting next step to change the current system state, but it might as well be a task which requires several other tasks to be performed prior to the given one. The MMS shall be able to supplement given tasks automatically and assemble a complete agenda without missing steps. If, for

example, the operator issues the task element “Transit to target airfield” with the aircraft still stationary on the runway, the task agenda will automatically be supplemented with tasks “Depart”, “Transit to FLOT” and “Cross FLOT”.

A task element might also be given as an addition to an already existing and consistent task agenda. In this case, the MMS should be able to arrange the existing tasks and the new task in a sensible order, i.e. prioritize them, detect conflicting tasks and drop tasks when deemed appropriate, all of the latter done on the basis of the system’s knowledge about the CONOPS (Concept of Operations).

Review given tasks considering overarching goals, i.e. goals which are valid regardless of mission phase:
The cognitive MMS shall check each given task against a list of overarching goals which shall not be violated, regardless of the mission phase. These overarching goals are common rules in place to ensure safety and mission success. The MMS should actively question a task if that task is found to infringe on an overarching goal. Adherence to the Rules of Engagement is an example of such a goal which e.g. prevents attacking a target which has not been classified.

Decompose given tasks from agenda to a sequence of sub-tasks (tactical behavior):
In this step, the agenda consisting of operator-given tasks shall be broken down to a self-deduced and detailed sequence of sub-tasks. This implies e.g. knowing how to perform tactical maneuvers like reconnaissance or executing the items on the landing checklist, but the MMS should be free to arrange its actions in a different order if there are reasons to do so.

Supervise&Adapt tactical situation & environment:
Whereas the first three steps facilitate the understanding and execution of operator intent, the fourth step introduces the ability and freedom of the system to react to changes in the tactical situation. Whenever the tactical situation changes, the MMS should use its given knowledge to adapt the task agenda and according actions in order to cope with the new situation. This may involve, according to the level of automation to be selected for the human-system interaction, the proposal of a reaction for the operator to choose. This step becomes relevant for example if the aircraft encounters a pop-up threat, experiences subsystem malfunctions or if expectations concerning the target prove wrong.

Execute tasks:
The last step in this process is the actual execution of the current task. Depending on the situation and task there might still be some actions that need to be done before the A/C can start to fulfill the current task. These actions mainly consist of further detailing the task to the capabilities of the A/C. A “Transit [to]” task for example has to be translated to a waypoint for the FMS.

3.2. Cognitive Automation

Conventional automation is not sufficient for an implementation of high-level guidance methods like TBG. The main focus of conventional automation lies in sensory-motor skills [9]. Our intention is to automate cognitive abilities to enable the system to act on a more sophisticated level. Furthermore conventional automation tends to create a very complex system with a clumsy human machine interface which easily leads to an excess of human work demand [9]. Together with the possibility of a lost data link this makes the system vulnerable to a complete loss of control.

Therefore a different approach to automation is necessary: cognitive automation.

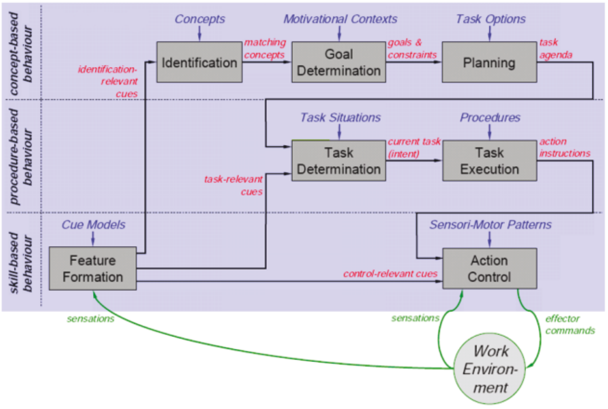

Figure 7: Modified Rasmussen Scheme for Human Cognitive Behavior

Cognitive automation introduces human-like abilities (perceive and understand, find solutions, decide, plan) to a highly automated system by emulating human information processing. Figure 7 shows the scheme we use for information processing. It is based on Rasmussen’s model of human cognitive behavior [10] and was modified by Prof. Onken and Prof. Schulte in [9]. The processing steps are divided into three levels: skill-based, procedure-based and concept-based behavior. The lowest level, skill-based behavior, describes highly automated control tasks which take place subconsciously (e.g. the small corrections a driver’s hands make when keeping his car on the lane). Procedure-based behavior covers actions that take place consciously in a known situation. Here best practices respectively former solutions for a specific situation tell the human what to do (e.g. stopping the car at a red traffic light). The highest level, concept-based behavior, describes actions that take place in an unknown situation. This is the most sophisticated way of dealing with problems since it enables humans to solve problems they have never encountered before (e.g. on January 15th 2009 the Pilot of US Airways Flight 1549 successfully ditches his A320 in the Hudson River after a bird strike although he has never done this before).

Furthermore the model divides the complex process of cognition into several simplified cognitive sub-functions each responsible for a distinct task in the cognitive process. In addition the model introduces two different kinds of knowledge: static a-priori knowledge (blue in Figure 7) and dynamic situational knowledge (red in Figure 7). A-priori knowledge is specified during design time and does not change during mission runtime. On contrast the situational knowledge is generated dynamically during mission runtime.

Using this model of information processing a framework for cognitive automation has been developed at the IFS called COSA².

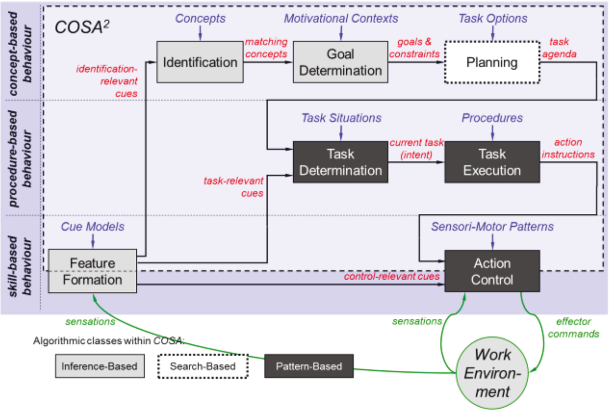

Figure 8: Cognitive System Architecture

Figure 8 shows the parts of the modified Rasmussen scheme which are implemented in the Cognitive System Architecture with Centralized Ontology and Specific Algorithms COSA² (highlighted in the light blue box) [2]. The cognitive sub-functions are implemented using different types of algorithms. Feature Formation, Identification and Goal Determination are implemented using inference-based algorithms, Task Determination, Task Execution and Action control using pattern-based algorithms. Planning uses search-based algorithms.

This framework enables us to develop an ACU (Artificial Cognitive Unit) that is capable of managing the five task processing steps supplement, review, decompose, execute and supervise. Our design consideration about the Decision Engine using a COSA² ACU and the five task processing steps will be discussed in the next section.

3.3. DE System Architecture

The DE will implement the five-tier task processing architecture as described in Section 3.1 by using cognitive automation. There will be an ACU implemented with COSA² which possesses the five steps supplement, review, decompose, supervise and execute as task options. It will use this task options as tools to fulfill its goals which are to have a complete task agenda, have a valid task agenda and have a detailed task agenda.

The task processing structure is shown in Figure 9. The Operator can submit a task agenda (a single task is considered as a task agenda of length one) to the ACU. The ACU will use this task agenda as input for the supplement step. Here a planning module will insert potentially missing elements to the agenda and modify it according to the current tactical situation and constraints. The output will be a complete agenda which would theoretically be flyable. In practice there might still be some overarching goals that need to be considered. A possible scenario for this is a mission plan that is valid but would lead the UAV into airspace outside of the mission area. In the review step the complete task agenda will be checked for violation of such overarching goals. If there are violations the module will reinitiate the supplement step with constraints modified in a way that the overarching goal is not violated any more. If this is not possible a message will be generated stating the reason for the planning failure which will be passed to the operator. If there are no violations of overarching goals the task agenda is considered to be valid.

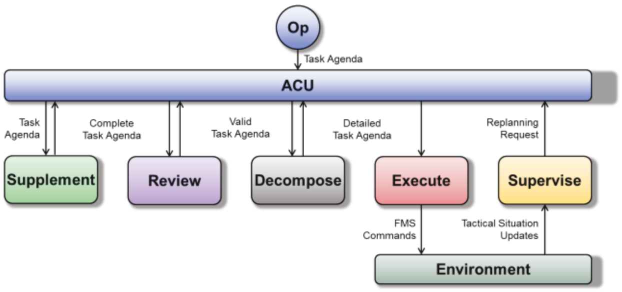

Figure 9: Task Processing Structure

This valid task agenda will then be passed to the decompose module. Here all tasks in the agenda will be detailed further. Task elements that implicitly consist of other tasks will be divided into sub-tasks. For example one task element might be “Cross FLOT”. This task implicitly consists of the two tasks “Transit to FLOT entry point” and “Transit to FLOT exit point”. When all tasks are divided into sub-tasks and a detailed task agenda is created it will be passed to the execute module. Here the detailed task agenda is translated to an even more in-depth level which is specific to the system’s hardware respectively FMS. In our case this module will create a list of waypoints for the FMS or requests to the Active Perception. The supervise module runs in parallel to all others and enables the system to adapt to changes in the environment or tactical situation. It constantly analyses these changes for influence on the current task agenda. If it encounters a change that makes the current plan invalid or provides new possibilities for the mission execution, it reinitiates the task processing procedure which will consider the new tactical situation. This way a new valid plan will be generated and the mission can be continued. Each time the agenda needs to be changed the Operator will be informed. If a change of the environment or tactical situation makes it impossible to achieve the mission goal(s) the DE will ask the Operator what to do.

4. MISSION & PAYLOAD CONTROL STATION (MPCS)

4.1. The Operator Assistant System

The ACU in the ground segment is assigned the same hierarchical level as the human operator. Both the operator and the ACU have, within the concept of cooperative control (Figure 5), the superior goal of fulfilling the Work Objective, i.e. the optimal completion of the assigned UAV mission.

The human operator and the ACU have different strengths and weaknesses. According to [13] man is stronger in improvising, abstracting or selecting relevant information while the machine is superior in speed, precision and the lack of fatigue. In the domain of aircraft guidance, the human being can generally be assumed to exceed the machine in tactical knowledge, ethical reasoning and reactions to unknown situations. The ACU, in contrast, is able to analyze situations, plans and action implications fast, precisely, and with permanence.
While equivalent concerning hierarchy, the human operator and the ACU are therefore destined to differ in their roles in the guidance process according to their described respective strengths.

The human operator is assigned the paramount role of actually guiding the UAV, i.e. deciding about the mission plan and its execution. The tasks of communicating with the UAV and issuing commands are of his responsibility in the first place.
The role of the ACU, instead, is that of assisting the operator in the guidance process. It enables him to work optimally by letting him work on his own in the first place, but providing him with an escalating cascade of information, warnings and proposals once a deviation from an optimal work flow is detected. Onken and Schulte suggest four escalating functionalities an Assistant System should exhibit [9]:

1) Providing the operator with all information necessary. *Or, if that fails,*
2) Guiding the operator's attention to the most urgent task. *Or, if that fails,*
3) Relieving an overtaxed operator by reducing his current task to a manageable one. *Or, if that fails,*
4) Taking over his task.

4.2. Mixed-Initiative Operation

The cooperation between the operator and his Assistant System implies a scheme of interaction in which both equal partners may take the *initiative* over the conversation (as opposed to relationships of supervisory control, where all initiative emanates from the supervisor).

The process-based model of scaled initiative [5] defines the concept of initiative as a two-dimensional entity varying in the *process* in which it is applied as well as in the *strength* it exhibits. Let several partners engage in several processes, e.g. work steps or dialogues. Each partner engaged in one of those is then said to have a certain degree of initiative in the respective process depending on how much he is in charge of its progress.

The degree or strength of initiative varies with the escalating Assistant System functions as listed above. It may increase from a simple provision of available information to a seizing of command authority.

The processes in which initiative can be applied resemble the operator's cognitive processes employed in the actual flight guidance. They constitute a subset of the overall cognitive process according to the Rasmussen scheme (cf. Figure 7) in omitting the procedure-based behavior and reducing the skill-based layer to simple input and output interfacing. After all, only high-level planning is concerned and procedural or reactive behavior is left to the aircraft.
The resulting scheme is depicted in Figure 10.

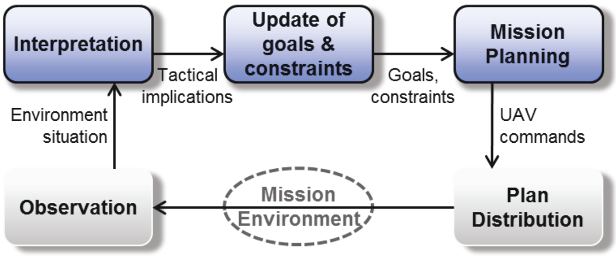

Figure 10: The cognitive processes involved in the Operator's UAV guidance.

4.2.1. The Operator's Work Process

A detailed analysis of the complex "Mission Planning" block in Figure 10 reveals the actual work flow of the operator while planning and supervising a UAV mission. The result, shown in Figure 11, will be described in the following paragraphs.

The operator's guidance process begins with an OBSERVATION of the available environmental data and an INTERPRETATION resulting in his understanding of the current tactical situation. From his knowledge about the general domain of UAV guidance and about the current mission, including the tactical situation, mission objectives or Rules Of Engagement, he deduces GOALS AND CONSTRAINTS for his mission plan.

The next set of steps, marked blue in Figure 11, constitutes the process generally understood as **Mission Planning**, i.e. the production process receiving goals and constraints as inputs and generating a set of commands, in our case a task agenda, as output.
In addition to the given inputs, planning requires the operator to make assumptions about the development of the tactical environment. It is the combination of the commanded tasks and the environmental influence, after all, which leads to the future tactical situation. Planning a mission therefore includes optimizing the plan with respect to an assumed set of SCENARIOS possible to be encountered (refer to Figure 12). The operator

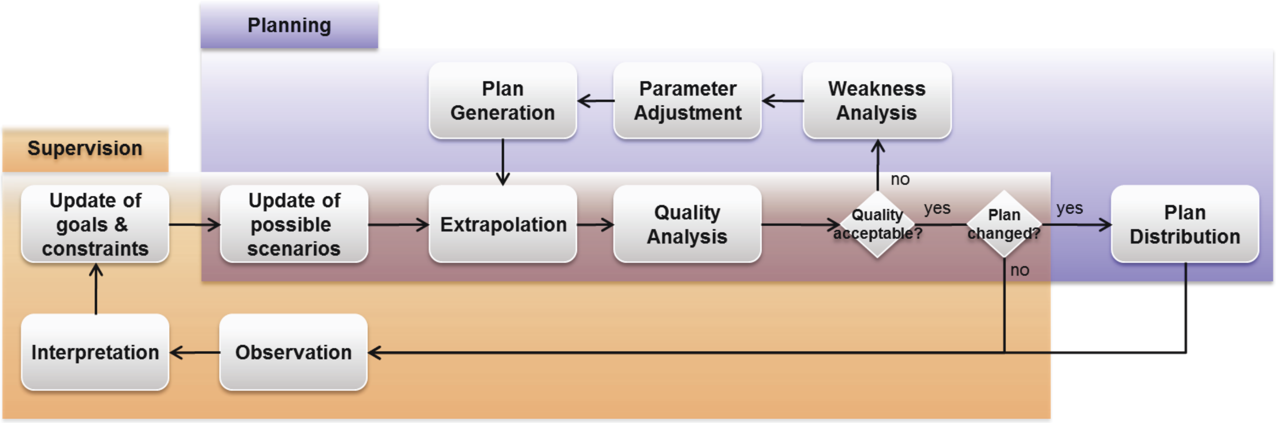

Figure 11: The UAV Operator's Work Flow during mission planning and mission supervision.

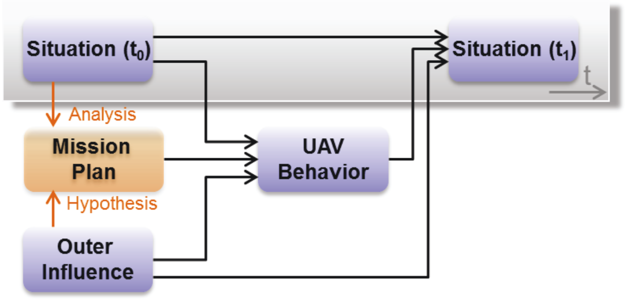

Figure 12: The relationship between the mission plan, the known situation and unknown outer influence.

hence deliberates events which have a significant probability of occurrence and which are sensible to be kept in mind during the planning process. The awareness about the risk of enemy anti-aircraft artillery spontaneously coming up in a non-surveilled area, for example, might let the operator plan a route differently in an otherwise identical configuration of goals and the observed situation.

By a mental EXTRAPOLATION of the current situation over the possible scenarios and the currently contemplated task agenda (which might be empty at the time) the operator estimates the outcome of his plan. The subsequent QUALITY ANALYSIS of the outcome reveals whether the plan is promising or not.

In case of inferior quality, the WEAKNESS ANALYSIS reveals where and how the operator has to improve his PARAMETERS for planning in order to carry out the next iteration of a PLAN GENERATION. The loop of extrapolation, analysis and re-planning is repeated until a feasible solution is found. After that, the PLAN DISTRIBUTION among the set of agents (i.e. Sagitta) takes place.

The operator then begins the phase of **Mission Supervision**, marked orange in Figure 11. While supervising the correct execution of his mission plan, he continuously OBSERVES and INTERPRETS the situation, updates his GOALS AND CONSTRAINTS and verifies if the current plan still satisfies his goals within the currently perceived environmental situation. He does this by updating his internal list of possible environmental SCENARIOS, EXTRAPOLATING the situation and ANALYZING the quality of its extrapolated outcome.

If the operator thereby determines that the existing mission plan still satisfies his goals, the supervision loop is repeated. If a significant change is detected (i.e. the current plan is assumed to no longer satisfy the operator's goals), the operator switches from supervision to re-planning by continuing with the WEAKNESS ANALYSIS of his plan and completing the planning phase as described above.

This continuous work process and its single sub-processes are now to be cooperatively executed by the operator and his Assistant System.

Within the concept of assistance-based interaction [12], the initiative of problem-solving is primarily subjected to the operator while the ACU's initiative is focused on providing assistance. Inside each of the sub-processes described above, the initiative is therefore shared between man and machine. This concept of cooperative guidance via mixed levels of initiative is referred to as **Mixed-Initiative Operation (MIO).** In the scenario described here it splits up into the two main components of **Mixed-Initiative Planning (MIP)** and **Mixed-Initiative Supervision (MIS).**

4.2.2. Mixed-Initiative Planning

During the process of Mixed-Initiative Planning, the phase of Mission Planning or Re-Planning (cf. Figure 11) is performed by the compound team of the human operator and the assisting ACU [14].

During the first step of SCENARIO GENERATION, the Assistant System can support the operator by providing him with probable scenarios to take into account, for example by showing him possible routes for incoming enemy troops or displaying areas of high radar visibility. Hereby a sensible equilibrium between providing too little information (and hence being useless) and overtaxing the operator with dozens of scenarios must be found.

The two subsequent steps – EXTRAPOLATION of the current situation into the future and then ANALYSIS of the projected future for accordance with the operator's goals and restrictions - are where the operator usually resorts to making only qualitative conclusions. Quantitative information, e.g. if there is enough fuel remaining in the tank, can only be vaguely estimated.

The Assistant System can help here by making fast as well as precise calculations. The simulated outcomes of the current mission plan with respect to some probable scenarios can be displayed to the operator to help him oversee the consequences of his planning. The analyses of these outcomes can show the operator why and how his plan might potentially fail.

The sub-processes of WEAKNESS ANALYSIS and PARAMETER ADJUSTMENT are where the Assistant System uses its planning capabilities to show the operator where a weakness is hidden in his plan and how it can possibly be circumvented.

The actual plan generation is left to the operator as long as possible and only taken over by the Assistant System if everything else fails.

These processes, executed in the given order, reflect the four levels of escalation of the Assistant System as described in Section 4.1:

1) The Assistant System provides the operator with all necessary information by suggesting him possible scenarios to be considered and informing him about possible outcomes of his actions. *Or, if that fails,*
2) The Assistant System guides the operator's attention to the most urgent task by informing him that his plan leads to a mission failure and needs to be changed. *Or, if that fails,*
3) The Assistant System relieves an overtaxed operator by telling him where the weakness is located in his plan and which part he has to fix. *Or, if that fails,*
4) The Assistant System takes over his planning task and replaces the erroneous plan by a working one.

4.2.3. Mixed-Initiative Supervision

During Mixed-Initiative Supervision, the ACU assists the human operator in the process of supervising the UAV mission, i.e. monitoring the execution of his mission plan (cf. Figure 11).

The operator's observation of his environment is prone to errors due to his limited attention span. A fatigued or distracted operator may, after many hours of mission guidance, exhibit deteriorated situation awareness [7]. It is then the task of the permanently vigilant ACU to guide the operator's attention to new events and keep him updated on the tactical situation.

The step of INTERPRETATION of new events is where the operator maps the observed situation, e.g. incoming hostile troops, to abstract concepts, e.g. a threat to the UAV. The Assistant System can display such information in cases in which the operator might be assumed not to have drawn the respective conclusion himself. This is likely to be the case either in unclear situations or in situations in which the interpretation involves numeric calculations, e.g. that of an intercept course.

The subsequent step of UPDATING GOALS AND CONSTRAINTS is where the operator checks if his goals or the constraints to his mission planning have changed, e.g. because a temporary goal has been reached and will have to be replaced by another one or because the mission objective or the Rules Of Engagement have changed. The Assistant System can support the operator by making him aware of reached goals (e.g. the completion of a task and the subsequent necessity to issue a follow-up task) or of a change in the externally assigned mission objective.

Throughout the following chain of UPDATING SCENARIOS, EXTRAPOLATING the situation, and ANALYZING the consequences the operator is supported in the way he is during MIP. The Assistant System may recognize the necessity to switch to the re-planning process and take initiative in making a WEAKNESS ANALYSIS and displaying its results unasked, hence pushing the operator towards reconsidering his plan.

Analogously to MIP, the process chain of MIS mirrors the escalating functionalities of the Assistant System according to Section 4.1:

1) The Assistant System provides the operator with all necessary information by making him aware of situational changes and helping him recognize their tactical implications. *Or, if that fails,*
2) The Assistant System guides the operator's attention to the most urgent task by notifying him about tactical events considered important, about the imminent change or violation of goals or constraints, and about an imminent plan failure. *Or, if that fails,*
3) The Assistant System relieves an overtaxed operator by displaying the MIP functionality described above and guiding him through the process of re-planning.

4.2.4. Operator Intent Recognition

Mission plans issued by UAV operators rarely cover all possible scenarios of outer influences. As could be seen with man-machine-experiments at the Institute of Flight Systems, a significant share of operators tend to plan a mission under the implicit assumption that they could, if necessary, modify their plan according to a changing environment. They plan, for example, only part of the mission, wait for a partial execution, and then plan the remaining steps.

In the schematic in Figure 11, the sub-process UPDATE OF POSSIBLE SCENARIOS is only superficially executed.

The problem arising by this behavior is that in case of a data link loss (which may occur at any time) the UAV would be left on its own with an insufficient set of instructions.

This may lead to a situation in which the UAV faces a new situation but keeps following the old (and possibly deprecated) instructions given by the operator. The intent of the UAV and the collective intent of the operator and the UAV begin to deviate [8].

The desired case when facing a data link loss would be that the UAV acted according to the operator's actual intent. Its behavior should be determined by the question "What would the operator do?" i.e. which commands would probably be issued by the operator if he had the chance to?

The process of deducing the answer to this question is known as **Operator Intent Recognition**.

Since the operator is not available anymore after the data link disruption has occurred, any information needed has to be retrieved beforehand. If the operator does not deliver a sufficiently exhaustive set of instructions on his own, it is the task of the Assistance System to query this information:

- It may show the operator several outcome scenarios of his plan in order to sharpen his situation awareness and make him reflect about the completeness of his plan.
- It may ask the operator if a certain way of executing a certain task would be acceptable in order to ensure the given instructions go into sufficient detail.
- It may ask him questions in the sense of "Would action X be acceptable if situation Y were encountered?" in order to ensure the given planning constraints go into sufficient detail.

The resulting set of instructions and restrictions given by the operator still constitutes a valid plan for the current situation, but is as well applicable to an extended set of additional scenarios.

Since this process involves querying information by the operator artificially, i.e. without imminent necessity in the current tactical situation, we refer to it as **Operator Information Harvesting**. It takes place implicitly during MIP and MIS.

The compound Operating Force of the Operator and his Assistant ACU command the aircraft via TBG. The actual guidance information expressed by the operator, however, is only partially constituted by explicitly issued tasks. Instead, the operator's UAV guidance takes place in expressing information explicitly and implicitly by means of the processes described above. The operator's intent directly reflects in his mission guidance.

This process of mapping the operator's intent to vehicle guidance commands is referred to as **Intent-Based Guidance**. In this case the operator's intent, expressed by means of cooperation with his Assistant ACU, forms the foundation on which TBG is carried out between ground and air segment, (cf. Figure 13).

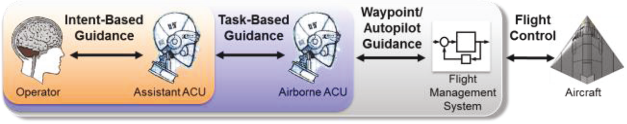

Figure 13: The hierarchical UAV guidance levels

4.3. M&PCS System Architecture

In addition to providing complex Assistant System functionality, the MPCS has to offer the UAV operator the necessary means of Command & Control (C^2). These non-cognitive means of guidance are distributed between two main components.

The first one, the Command & Control Module, lets the operator command the aircraft via tasks and constraints and monitor the mission execution on a tactical map.

The second module lets the operator control the sensor gimbal of the UAV and presents him the sensor image on a screen.

Data exchanged between the air segment and both modules includes sensor imagery and data, sensor commands, telemetry and status messages, commands, and tactical data. Both latter data structures, i.e. the tactical data and the C² data, are permanently synchronized between the ground and the air segment in order to keep valid copies of the current tactical situation and the current set of commands at both the MPCS and the airborne UAV.

The Assistant System plays the role of the obscure third component not directly visible to the operator. It will, if necessary, make use of the other two components and the Human-Machine-Interface in order to assist and negotiate. It needs access to any exchanged data in the same way the operator does in order to make decisions. It is therefore able to listen to any data traffic between air and ground. In addition, in order to monitor the operator, it has access to the Human-Machine-Interface.

The resulting overall system architecture of the MPCS is depicted in Figure 14.

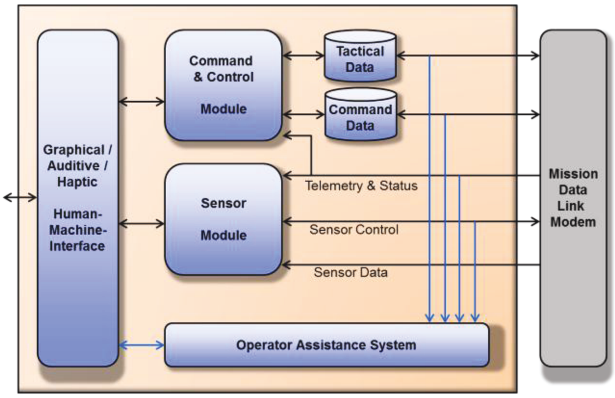

Figure 14: The System Architecture of the Mission & Payload Control Station

5. RESULTS

Sagitta combines several areas of research into one novel project. In each of these areas, the Institute of Flight Systems has been accumulating profound know-how during research, development and experiments in past and present projects.

In the course of the Project *Manned-Unmanned Teaming (MUM-T)* research was conducted on compound missions of human helicopter pilots and UAVs. Thereby multiple UAVs were successfully commanded by a human pilot via TBG [16].
While the evaluation of this project took place in an extensive simulation environment allowing for a multitude of man-machine experiments, TBG could also be successfully applied in real-flight experiments during the Project *CoCampus.* There, a UAV carried out a mission semi-autonomously, guided only via abstract operator-issued tasks [4].
Both CoCampus and MUM-T incorporated the development of intelligent agent frameworks for the airborne ACUs. They made use of two versions of the Cognitive System Architecture [2].
The UAV operator in MUM-T as well as the helicopter pilot in the related MiRA-T project [15] was successfully supported by Assistant Systems. Operator Assistance incorporating MIP (among other concepts) could be proven advantageous in practical military missions.

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