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Designing for the future: A Cognitive-Adaptive-Man-Machine-Interface

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Abstract

The forecasts of the International Civil Aviation Organization envisage a growth in world air travel of 5% per annum until 2020. The air traffic in Europe is therefore expected to more than double by 2020. In order to deal with the growth, the European Air Traffic Management (ATM) system will undergo major changes. The envisaged next generation ATM will require new technologies to meet future collaborative decision making, self separation, precision 4D path following, and closer aircraft spacing. The CAMMI (Cognitive Adaptive Man Machine Interface) program addresses human factors priorities in various domains by developing concepts that balance operator workload, support added future operator roles and responsibilities and resulting new task and information requirements, while allowing operators to focus on the most safety critical tasks. In the aviation domain current pilot interface applications are inadequate to support pilot performance under increased workload and responsibility. The envisioned ATM capabilities will only be realized with increased automation, therefore the development of adaptive information management, display management, and task management aids is a necessity. The paper discusses the CAMMI project and presents concepts to address the challenges presented by future flight operations.

Introduction

The current Air Traffic Management (ATM) system is already operating at its’ limits. New innovations in the structure of ATM will be needed to handle the expected increase in traffic. However, such innovations will necessarily impact the distribution of tasks and responsibilities between the air and the ground, as well as the roles and responsibilities of the automation and human operators. These two bottlenecks lead even under today’s conditions to situations of high workload for all involved. New concepts like precision 4D path following, self separation, and closer aircraft spacing will be needed to increase capacity and efficiency. These types of ATM innovations will necessarily affect aircrews operations and will impact their workload.

In a future ATM environment the aircrew might be designated as those responsible for aircraft separation. Compared to today’s situation this will be a completely new task for the aircrew and will as likely as not represent the biggest change in the role and responsibility of a pilot in the future. The aircrew will heavily rely on new or modified systems which will increase their situation awareness, and will support them in the decision process, by for example automatic filtering and highlighting of conflicting traffic on a display or proposing maneuvers for deconfliction.

The Cognitive Adaptive Man Machine Interface (CAMMI) project definition commenced as a response to the “Human-Centric Design (HCD) of Embedded Systems sub-program (SP-8)” of the ARTEMIS annual work program (ARTEMIS AWP, 2008). The program is expected to establish novel methodologies for design and development with respect to human-in-the-loop adaptive control systems, with special emphasis on the cognitive state of the human operator dealing with safety critical systems in umpteen domains.

CAMMI takes up the challenge to develop a joint-cognitive system which will allow for balancing and optimization of the human operators’ workload under demanding labour conditions. The intention is to design the system in a way that it will be applicable to four different domains, namely aviation (manned/unmanned), civil security, automotive, and agricultural domain. Although these domains seem to be completely distinct on the first sight, there are commonalities on closer consideration. The framework conditions are changing in all domains and become more and more loading for the human operator due to e.g. increasing volume of traffic, increasing information flood, more onboard systems, increased functionality of onboard tools, time pressure, just to name a few. In combination with increasing requirements for improved operational performance and safety, the workload reaches critical levels, which in turn might lead to decrements in the overall system.

Considering the manned aviation domain the changes described above are obvious and various initiatives around the world (e.g. SESAR, 2006; NextGen, 2007) have been launched to accommodate the trend of the air traffic growth and prepare the ATM (Air Traffic Management) for the demand of 2020 and beyond.

Within the framework of CAMMI the manned avionics domain will focus on the Electronic Flight Instrument System (EFIS), which manages all command and control activities in an airplane and is the primary electronic system through which pilots conduct their four high level tasks: aviate, navigate, communicate, and manage systems. CAMMI intends to develop adaptive pilot interface technologies that utilize both, the context and the pilots' cognitive state to trigger automation assistance when needed most. The goal is to keep pilot workload balanced and allow them to focus on the most safety critical tasks, resulting in increased safety, higher capacity, and increased efficiency operations.

Since the introduction of enhanced electronic systems in the cockpit flight crew cognitive skills, situation awareness, and decision making are increasingly critical to safe and efficient aircraft operation. In the future pilots are expected to have more responsibilities in a high capacity air traffic environment. Within such an environment information and task management will compose significant portions of the overall pilot workload.

Adaptive Automation

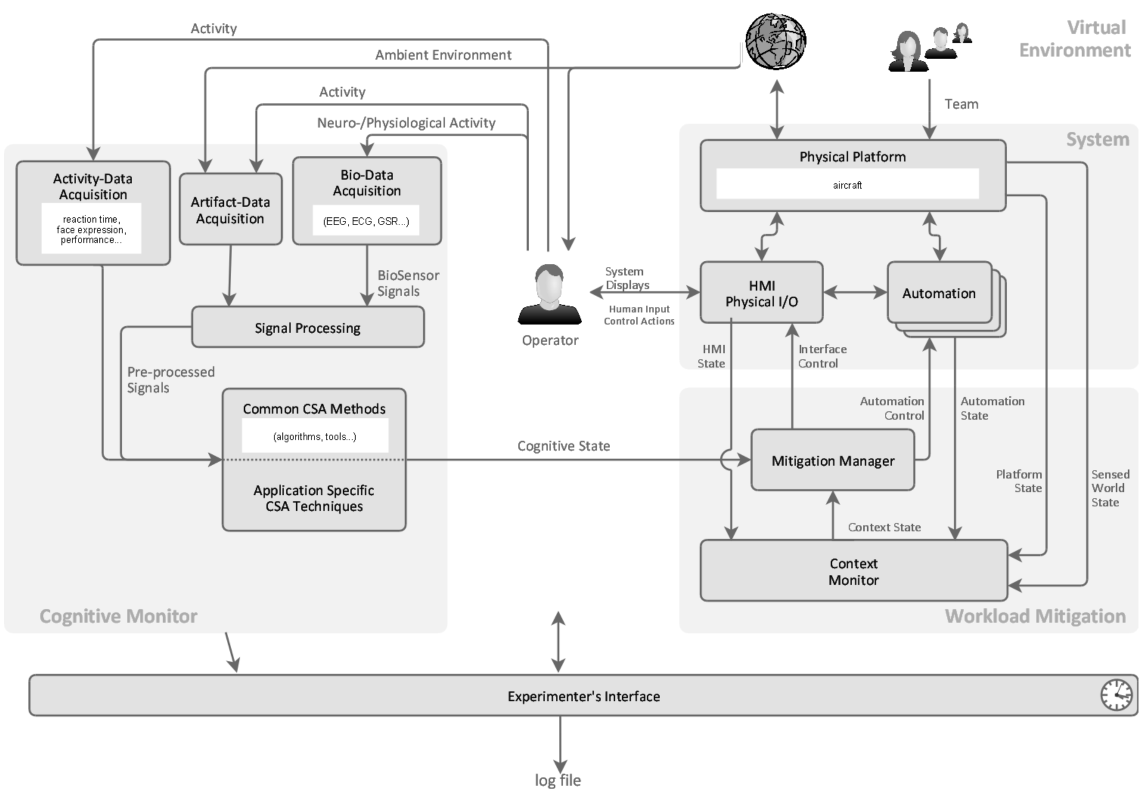
Adaptive systems, where tasks are dynamically allocated between the human operator and a system at the time of task execution, represent an alternative to static automation, where the automation is implemented in a fixed manner at the time of design. The main challenge in designing an adaptive system is arguably to determine *what* should be automated, *when* should automation be activated or switched off, and *which level* of automation should be applied. Based on the human information processing loop, which was introduced by Boyd (1996), a team at NASA Johnson Space Center (Proud et al., 2003), developed a 8-level scale of Autonomy Assessment to determine the appropriate level of automation for specific tasks related to the human information processing stages observe, orient, decide, and act, and provides a useful guide to answer the questions regarding *what* and *which level*. But the most critical question is *when* to invoke automation and when to deactivate automation again. In the literature one can find three main categories of how to deal with this issue (Inagaki, 2003): (1) when modeling-based strategies are applied, operator performance models are used to estimate the actual and anticipated state of an operator and deduce from this whether the workload exceeds a critical level or not; (2) critical event strategies define events which invoke a change in function allocation between the human and automation (it is assumed that the operators’ workload may exceed a critical threshold in the course of critical events); and (3) measurement-based strategies assess the operators’ workload in real time and dynamically allocate functions between the operator and the machine on a moment-to-moment basis. For these strategies neurophysiology and physiological sensors can provide data that can be proceed to estimate operator cognitive state. CAMMI intends to develop a technology which integrates critical event strategies (e.g. related to the mission context; current state of the world; state of the user; goals, tasks, and intent) as well as measurement-based strategies.

In order to support the aircrew in their tasks as well as to balance pilots’ workload, the CAMMI system, designed as an Adaptive System, will as such, make timely decisions on how and when best to use varying levels of (adaptive) automation to provide support in the joint human automation system. The adaptive system will make independent judgment and has the authority to initiate changes to the task environment. Adaptations will happen in real-time and will be turned on and off, depending on the need, based on the context and the status of the operator and the system.

The CAMMI System

In the EFIS domain the current aviation system, including e.g. current operational procedures, current avionics will serve as a baseline to assess the functionalities of the CAMMI system. At this stage of the program, the CAMMI system will be developed as from a generic future ATM environment, where assumptions will be made based on current plans for SESAR. The CAMMI system will optimize pilots' workload by helping the pilot to perform onboard tasks, especially those which are connected with higher levels of workload, and facilitate pilots' tasks in future airspace environment where higher responsibilities (and higher workload) are expected to be placed on the pilot. To achieve this, the CAMMI concept requires the installation of new equipment in the cockpit demonstrator (e.g. sensors, Cognitive monitor, CAMMI mitigation manager, etc.), and requires adjustments of current avionics, mainly associated with changes in the Human Machine Interface (HMI).

Throughout the development of the CAMMI system it is envisioned for all four domains to adhere to a basic system architecture depicted in Figure 1.



The system will consist of five main components: the cognitive monitor, the workload mitigation, the system, the virtual environment, and the human operator.

The Cognitive Monitor will combine the psychophysiological measures of cognitive state in order to generate a single cognitive state profile. Various sensors, such as electroencephalogram (EEG), electrodermal response (EDR), electroocculogram (EOG), electrocardiogram (ECG), and electromyogram (EMG) might be the source of neuropsychological date to drive the classification of cognitive state (for an example, see Dorneich et al., 2007). The output of the classification algorithms is the cognitive state profile of the user. An example might be a classification of cognitive workload as high, medium, or low. Domain characteristics and the particular task environment will drive the choice of specific sensors, processing requirements, and the cognitive state classification algorithms. A suite of techniques will be used to derive meaningful measures of the cognitive state from cleaned signals. The cognitive state algorithms should be able to reliably discriminate between multiple levels ("classes") on a moment to moment basis. Initially there will be a wide range of available sensor data (e.g. EEG, ECG) and a host of different algorithms and methods which could be used to assess the cognitive state. Within an iterative process each domain will define a specific subset of sensor data (data will be weighted according to the domain/application specific needs) and a specific subset of cognitive state assessment algorithms, which will be used to assess the actual cognitive state.

The Mitigation Manager module is responsible to make decisions on how to adapt the work environment in order to optimize the joint human-automation cognitive abilities with respect to specific domain tasks. The Mitigation manager has two broad areas of adaptation: the "Human Machine Interface (HMI)" and the "Automation". The Mitigation Manager can adapt the HMI to customize it for the current situation by e.g. varying the information content, modality, or type. In addition the Mitigation Manager can vary the level and type of automation support, and decide when it is applied. The cognitive state from the Cognitive Monitor, as well as the context state from the Context Monitor serves as the input for the Mitigation Manager. In general there are four types of possible mitigation strategies applicable to an EFIS system: 1) task scheduling (e.g. defer lower priority messages, direct attention to higher priority task, Interruption Management), 2) change interfaces (e.g. de-clutter displays, highlight important information, change the modality of incoming information), 3) task offloading (e.g. automate lower priority tasks), and 4) task sharing (e.g. provide automation assistance on tasks – simplify tasks by for example providing audio navigation cues).

The task environment will be changed depending on the current state of the user, the current tasks, and the current context. The Context Monitor will be responsible for tracking tasks, goals, performance, platform state, world state, ambient environment state, HMI state and automation state, and will provide this information to the Mitigation Manager. The Mitigation Manager will in turn be able to interpret the cognitive state in the full context of operations. For example, in certain contexts high cognitive workload is appropriate and no mitigation needs to be triggered, while in other contexts high cognitive workload would indicate a need to mitigate.

The System, e.g. the demonstrator platform, will be domain-specific, and will be a simulation of the respective cockpit, which will be operated in a Virtual environment.

Challenges in the CAMMI system design

Adaptive automation research has been active for decades (Miller & Dorneich, 2006), and much of that work will inform the design of the CAMMI system. However, with the addition of a real-time measure of cognitive state based on physiological data, there is the potential to create fine-grained, closely coupled adaptive automation, where both the user and the system can respond to changes in the task environment quickly and appropriately in a coordinated manner. The Mitigation Manager can potentially realize frequent and subtle adaptations to the joint human-automation system, by arranging levels and types of automated assistance, varying or changing the information presentation to the user, or by taking a strong role in deciding the function allocation between the user and the automation at a given moment. The potential advantage of such systems is in the responsiveness and granularity of the tailoring of automation assistance to the user’s current cognitive capabilities and needs.

However, the same traditional pitfalls that beset human-automation interaction in complex systems can be exacerbated when automation and human form such a closely-coupled system (Sarter et al., 1997; Mathan et al., 2006). Some of these issues will be discussed here, and how they have the potential to be more pronounced in a CAMMI system.

Workload Distribution

Many automated systems rely on humans to input information about the task environment. Thus the human plays the role of a system integrator, required to specify task parameters in order for the automation to be able to execute effectively. Often these “extra” tasks are required during the busiest phases of work, and thus can actually degrade the joint human-automation performance in high workload conditions – precisely when automation assistance may be most needed. This can lead to errors. In aviation this is best seen in the fact that workload with automated flight decks has actually increased during takeoff and landing, the busiest phases of flight (Wiener, 1989). In the CAMMI system, the mitigations will be designed to be invoked with little or no explicit involvement of the user. Real time assessments of cognitive state will allow the system to increase automation assistance precisely when workload for the user is reaching a critical level. Thus the likely benefit of a CAMMI system is during these high workload periods.

Automation surprises

Automation surprises are the result of a breakdown in mode awareness, the ability of the human user to predict and understand the behavior of an automated system (Sarter et al., 1997). Lack of mode awareness can cause the human user to fail to respond appropriately when the automation behaves in an unexpected or undesirable manner, and can cause users to misinterpret automation actions (current or future). While the invocation of mitigations with little or no explicit human input may be beneficial in high workload situations, it also has the potential for providing assistance to the user in such a way that the user is unaware that the system behavior has changed. Furthermore, the CAMMI system may have many different types of mitigations, each of which offers assistance to users in different situations, and assumes control of certain aspects of the user’s tasks. Thus the CAMMI system will have to make users aware of its current mode of operation, and be as transparent as possible about its current state.

The likely result of invoking mitigation is a lowering of workload. However, while the mitigation may have been triggered when workload reached an unacceptable limit, it is not necessarily the case the same mitigation would be “turned off” once workload falls. This could lead to a situation where workload is constantly fluctuating as mitigation is cycling on and off. In addition, turning off mitigations based solely on a drop in workload may return full task responsibility to the user in difficult task conditions. Thus the criteria used to turn off mitigations may be very different from the criteria to turn them on. For instance, a mitigation triggered by high workload may remain on until the task is finished (Dorneich et al., 2006).

New Coordination Demands

As automation becomes more prevalent in the cockpit, and takes on more and more responsibility for pilot functions, the automation itself effectively becomes another crew member responsible for critical tasks on the flight deck. An important aspect of crew members is that they keep others informed of their intentions and the current task status. However, as Sarter and colleagues suggest, automation often performs tasks autonomously and silently, but return control to users abruptly when things fail. Thus is it up to the user to make additional efforts to keep informed about automation status. These new coordination requirements can add to cognitive load. The CAMMI system will be designed with the assumption that the automation is fallible, and will allow a human to intervene if the system was unable to handle a situation effectively. Task status of the automation (as well as its mode, as described above) will be communicated to the user in a way to minimize the humans’ coordination demands.

Trust

The appropriate calibration of human trust in an automated system is vital to optimizing joint human-computer performance. Trust the system too little, and humans run the risk of under-utilizing automation assistance. Trust the system too much, and humans can become complacent and fail to monitor the system appropriately (Lee & See, 2004). This can be a critical factor in accidents (Sarter et al., 1990). The CAMMI system design will need to address both issues. Acceptance among the pilot community must be overcome by demonstrating the operational benefit to be derived from the system, allowing its full potential benefit to be realized. However, issues of complacency must be countered by a carefully thought out design. There are many ways to address this, from automation feedback to the user during task execution, to better training to help users understand the appropriate level of reliance on the system.

Conclusion

Even if the expected benefits of adaptive automation and human-centered automation are encouraging, there are several unresolved issues regarding the design of adaptive automation as pointed out in the present paper. CAMMI will take up the presented issues in order to develop adaptive automation strategies which will offer the opportunity of leveraging the strengths of humans and machines, and augmenting human performance specifically when the assessed human cognitive capacity falls short of the demands imposed by task environments.

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