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SA-Based Guidance to Aid UAV Swarm Supervisory Control: What do Experts Say?

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Abstract

Recent incident reports reveal that incorrect Situation Awareness (SA) due to deficits in scanning behaviour is a frequent cause of human errors in context of supervisory control of Unmanned Aerial Vehicles (UAV). In the future, the number of UAVs human operators have to supervise at the same time will increase. Thus, methods are needed aiding deficits in their scanning behaviour. Our research focuses on the development of a novel attention assistance system – called Supervisory Guide. Supervisory Guide aims at optimizing the scanning behaviour of a human operator based on the determination of actual SA-needs. These SA-needs are inferred from eye movements recorded and analysed in real-time. In this paper we present the results of an early prototype evaluation performed with three Special Matter Experts (SME). Each SME evaluated the prototype from a different perspective. Overall, the SMEs agreed that Supervisory Guide implements a promising concept to aid deficits in scanning behaviour and SA.

1 Motivation and Background

Today, a complex, Unmanned Aerial Vehicle (UAV) is typically operated by a team of human operators via dedicated Human-Machine Interfaces (HMI). However, the interest of stakeholders in UAV swarms, which can be operated by a single human operator via a dedicated HMI increased significantly (Brian et al. 2005). The expected benefits are, e.g., reduced costs for personnel and higher system reliability and resilience. Key enablers are the ever-increasing levels of machine automation (Parasuraman et al. 2000) and autonomy (Cummings 2004), which release limited cognitive resources of a human operator to redeploy them for managing multiple UAVs at the same time. Consequently, supervisory control becomes a much more substantial task a human operator has to perform. A general requirement for the successful application of a supervisory control task is the human operator's capability to continuously build and maintain good Situation Awareness (SA).

Figure 1: Supervisory Guide assists a human operator supervising a highly autonomous UAV swarm

SA is defined as a state of knowledge including the perception of the elements in the environment (SA_{level1}), the comprehension of their meaning (SA_{level2}) and the projection of their status in the near future (SA_{level3}) (Endsley 1995). Because these levels build upon each other ($SA_{level1} \rightarrow SA_{level2} \rightarrow SA_{level3}$) it is important for building and maintaining good SA on all levels that a human operator supervising a UAV swarm continuously scans relevant information on the HMI. Otherwise, incidents caused by poor SA are likely to occur. However, for single UAV supervisory control it was shown that several human factors (e.g., boredom and distraction) constrain effective and efficient scanning behaviour (Cummings et al. 2013). Further, no prophet is needed to anticipate that supervisory control of future UAV swarms will suffer from the same problems and that the effects will be even worse. This assumption is supported by studies conducted in synthetic environments (Cummings et al. 2013). Thus, there is considerable need for methods, which can be applied to improve the scanning behaviour and SA of a human operator managing a UAV swarm.

In this paper, we present Supervisory Guide – an assistance system that aims at aiding poor SA by guiding a human operator's visual attention during UAV swarm supervisory control to information that he/she should know but actually doesn't know (see Figure 1). Improving SA of human operators in charge of supervisory control tasks has received much attention in the past. Basically, there are two categories of methods for tackling this problem: the first category subsumes methods to design SA-friendly HMIs (Endsley et al. 2003); the second category subsumes methods to assist human operators in real-time to build and maintain good SA. The focus of our research is on methods of the second category. Examples of the second category are, e.g., (1) alarm systems and (2) cognitive assistance systems.

Alarm systems are event-based, using sensors to measure and analyse given environmental and/or vehicle conditions. In the case of an event (encoded using thresholds) an alarm is triggered in order to guide the visual attention of the human operator to the relevant information source. Using a visual or auditory alarm to raise the awareness of a human operator in the case of a critical situation is an effective method to prevent an SA-related error or accident. However, determining whether and when an alarm is needed is a difficult issue. Reports reveal that pilots and air traffic controllers ignored alarms (Breznitz 1984) or even turned them off prior to accidents (Wickens et al. 2009). Besides to false alarms, the high number of unwarranted nuisance alarms which human operators are exposed to during routine tasks is a problem, which could consequently lead to annoyance, frustration and distraction. As stated in (Getty et al. 1995) this problem can be approached from two perspectives of the signal detection theory, corresponding to the parameters 'sensitivity' and 'response bias'. However, this approach is no final solution: (1) more or earlier alarms induce more dispensable alarms and (2) less or later alarms induce more critical situations.

A solution lies in the understanding and consideration of human operator SA within the decision making process implemented in the alarm system. Such an enhanced decision making process is a key feature of cognitive assistance systems like the Cognitive ASsistant SYstem (CASSY) (Onken 1999) and the COGnitive cockPIT (COGPIT) (Taylor et al. 2000). A cognitive assistance system takes into consideration the cognitive state and information processing limitations of human operators to optimize the information presentation and human-automation task distribution during task performance in a flexible, context-dependent way. The general philosophy of a cognitive assistance system is twofold: (1) to aid SA by guiding the attention of human operators to the objectively most urgent task or subtask of that situation; (2) to take care that human operators are never overburdened, e.g., by too many parallel tasks (Flemisch & Onken 1998). In order to accomplish the first aspect of this philosophy the cognitive assistance system needs an understanding of the situations in a way that is comparable to the human operator's understanding. In order to accomplish the second aspect the cognitive assistance system needs an understanding of the human operator's cognitive state, which could be derived from psychological theories and psycho-physiological measures.

In the remainder of this paper, we briefly present the concept of Supervisory Guide (Section 2). Then, we present the evaluation of an early prototype conducted with three experts from the perspectives usability, human factors and UAV manufacturing in order to get an impression of the expectable user acceptance, safety impact and market potential (Section 3). Finally, we present our conclusions and future work (Section 4).

2 Supervisory Guide

Supervisory Guide aims at optimizing the scanning behaviour of a human operator based on the detection of actual SA-gaps. Roughly speaking, an SA-gap is a deviation between what the human operator actually knows and what he/she should know about his/her situation. According to Endsley, this knowledge includes knowledge on three levels. Basically, SA-based guidance can be subsumed by the following system's point of view statement: *"Tell me what you know about your situation and then I will show you what you should really know."* This statement consists of two aspects:

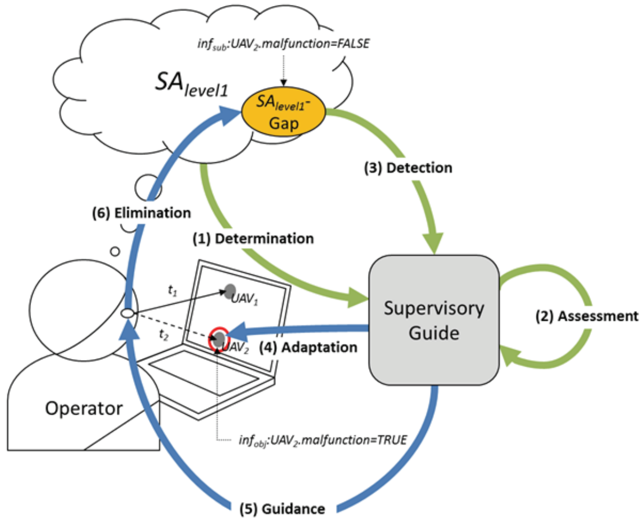

Figure 2: Steps performed by Supervisory Guide

The first aspect (*Tell me what you know…*) refers to the issues (1) determination and (2) assessment of SA, and the subsequent (3) detection of SA-gaps. The second aspect (*…and then I will show you what you should really know*) refers to the issues (4) HMI adaptation, (5) guidance of visual attention and the subsequent (6) elimination of SA-gaps.

Currently, Supervisory Guide focuses on aiding SA_{level1} by eliminating SA_{level1}-gaps. The generic concept of Supervisory Guide is shown in Figure 2. Green arrows represent steps of the first and blue arrows of the second aspect. The foundation of this concept is using eye movements as indications of SA_{level1} (Salmon et al. 2006). The theoretic foundation of this approach is the eye-mind hypothesis, which states that where humans look at and what they think about tends to be the same (Just & Carpenter 1980). Although it can be criticized that the hypothesis fails in some situations of daily life we assume that it mainly holds for supervisory control of a UAV swarm. The validity of this approach is supported by recent studies showing that eye movements of human operators in charge of supervisory control tasks are valuable indications of SA. This has been shown, e.g., for air traffic control (Moore 2009), manned (Van de Merwe et al. 2012) and unmanned aviation (Ratwani et al. 2010). We hypothesize that knowing the relevance of information and the human operator's mental picture in context of a situation allows optimizing the scanning behaviour of the human operator with regard to his/her actual SA-needs and therefore reduces the number of unwarranted alarms. In the following, we elaborate more on the individual steps applied by Supervisory Guide.

2.1 Steps 1-3: Determination, Assessment and Detection

Supervisory Guide continuously (1) determines and (2) assesses SA_{level1} based on a formal situation model *Sit*, which is composed on the lowest level of a set of information elements *Inf* (Frische & Lüdtke 2013). In step (1), Supervisory Guide analyses eye movements (recorded by an eye tracker) on the HMI and interprets them in context of the displayed information in order to generate a subjective instance Sit_{sub} (including Inf_{sub}). In step (2), Supervisory Guide compares Inf_{sub} to the information elements Inf_{obj} of the objective situation model instance Sit_{obj}. In step (3), Supervisory Guide identifies individual SA_{level1}-gaps. For a specific information element $inf \in Inf$ an SA_{level1}-gap_{inf} is a deviation between inf_{sub} and inf_{obj}. As shown in Figure 2, this can, e.g., be a sudden UAV malfunction (inf_{obj}:UAV_2.*malfunction=TRUE*), which occurs while the human operator is not looking at the associated information source (UAV_2). Consequently, the human operator might believe that there is currently no problem (inf_{sub}:UAV_2.*malfunction=FALSE*).

2.2 Steps 4-6: Adaptation, Guidance and Elimination

If Supervisory Guide detects an SA_{level1}-gap, the assistance system (4) adapts the HMI characteristics accordingly. Comparable to (Ratwani et al. 2010), our HMI consists mainly of a single screen with a 2D map display. Furthermore, there is an aircraft (A/C) check list and control buttons on the right side (see Figure 3). On the map, information objects (e.g., UAV icons or text labels) are presented, which are associated with information elements (e.g., UAV identity or location). At each point in time, the HMI is in a certain state determining, e.g., the location or salience of information objects and associated information elements. In this paper, we initially investigate the suitability of using three colour codes (green, yellow, red) as a means for displaying SA_{level1}-gaps of three different criticality levels (safe, caution, danger) on the HMI. We decided to use three colours because there is international agreement about how they refer to safety words (Salvendy 2012). The criticality level of a certain gap SA_{level1}-gap_{inf} is calculated based on the relevance of *inf* in context of pertinent goals and the degree of deviation between inf_{sub} and inf_{obj}. On the HMI, each information object is surrounded by a rectangular shape indicating the current criticality level of associated information elements. Using these visual cues, Supervisory Guide (5) guides the human operator's visual attention (within a volume of time $[t_1, t_2]$) to the information object associated with the SA_{level1}-gap. Consequently, the gap will be (6) eliminated on-the-fly.

Figure 3: HMI for UAV supervisory control with coloured shapes for highlighting the criticality of SA_{level1}-gaps

3 Evaluation

The goal of this evaluation was to get an impression of the expectable user acceptance, safety impact and market potential. Thus, the evaluation was performed with Special Matter Experts (SME) in the field of usability engineering, human factors and UAV manufacturing.

3.1 Participants

We invited three SMEs of three different areas to evaluate Supervisory Guide. SME#1 was a researcher in the field of human factors in safety critical systems working at the OFFIS – Institute for Information Technology in Oldenburg. SME#2 was a researcher in the field of usability engineering and interactive human-machine systems working at the University of Oldenburg. SME#3 was an aerospace and astronautics engineer working at the UAV manufacturer Rheinmetall Airborne Systems GmbH in Bremen.

3.2 Setup and Equipment

A notebook was used to run the UAV simulation, the HMI and Supervisory Guide. The eye movements of the participants were recorded with the Dikablis head mounted eye tracking system from Ergoneers (see Figure 1). A 24-inch monitor was used to display the HMI. Two eye tracking markers were attached to the display (bottom left and top right). The participants were seated approximately 0.6 meters from the display and used a mouse device to manage events that occurred during the scenarios.

3.3 Procedure

Each participant evaluated Supervisory Guide in a separate session. Each session took about an hour. First, each participant was introduced to the concept of SA-based guidance and Supervisory Guide. The participants SME#1 and SME#2 were also introduced to UAVs and UAV supervisory control tasks. Then, each participant was calibrated for the eye tracker. After the successful calibration, each participant participated in an experiment which consisted of two comparable scenarios, where they had to manage a swarm of highly automated and autonomous UAVs using our HMI (see Figure 3). In the scenarios, a swarm of three UAVs was managed to extinguish fires in an area which was not accessible by human fire fighters using ordinary equipment. In order to extinguish the fire sources each UAV had to load water at a water source and unload water at one of the fire sources. During mission execution each UAV had to frequently recharge energy at a base. The human operator could not influence the UAV task selection. However, at random times two distinct types of events were induced, which the human operators had to handle manually. First, UAV malfunctions were triggered which had to be detected and resolved by the participants by clicking the UAV icon and then pressing the „Repair UAV“ button on the HMI. Second, intruders entered the mission area, which had to be classified (using the aircraft (a/c) list on the HMI). Intruders could either be fire fighting aircrafts or civil aircrafts. Fire fighting aircrafts had to be allocated to the fire sources by clicking the aircraft icon, a target fire and then pressing the “Allocate Target” button. Civil aircrafts had to be detoured by clicking the aircraft icon and pressing the “Detour Flight” button. In the first scenario Supervisory Guide was deactivated.

Thus, the visual attention of the participants was not guided (control condition). In the second scenario Supervisory Guide was activated. Thus, the visual attention of the participants was guided (experimental condition). Each participant tested each condition for 20 minutes.

3.4 Measures

After each condition, the participants rated their SA using SART (Situation Awareness Rating Technique). SART is the most widely known SA self-rating technique. We used a shortened version of the technique (SART-3), which consisted of three statements. Each of the statements had to be answered on a Likert scale ranging from 1 (strongly agree) to 5 (strongly disagree). The statements were: "*The task was mentally demanding*", "*I could have managed more UAVs*" and "*I was able to keep track of what was going on*". After the experiment, a semi-structured interview was performed.

3.5 Results

The results of the SART-3 questionnaire are depicted in Figure 4. In average, the participants agreed that performing the supervisory control task was more mentally demanding when Supervisory Guide was activated (M=2.3) as compared to when the system was not activated (M=4). Further, they agreed that they could have managed more UAVs when Supervisory Guide was not activated (M=1.7) as compared to when the system was activated (M=2). However, they also agreed that they were better able to keep track of what was going on when Supervisory Guide was activated (M=1.3) as compared to when the system was not activated (M=2.3). Due to the fact that three subjects are not enough to make a strong statement we can only carefully assume that Supervisory Guide increases the mental demand but improves SA.

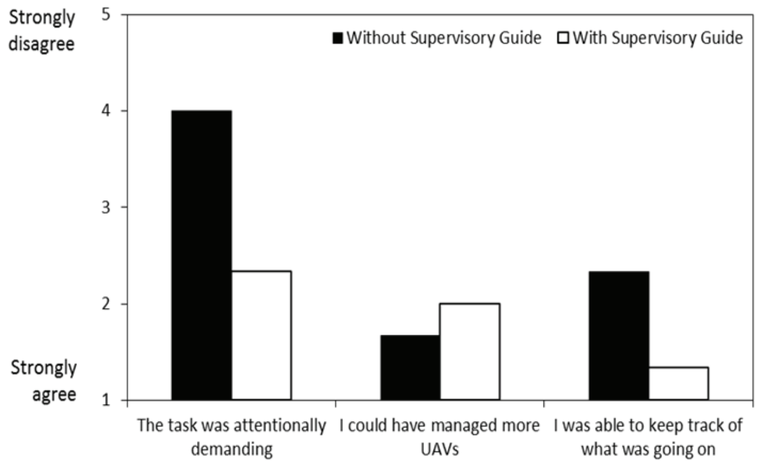

Figure 4: Results of the SART-3 questionnaire

During the interviews, we received further valuable qualitative feedback from the participants. Overall, they agreed that SA-based guidance is a very interesting and useful concept and that further effort should be invested in the research of Supervisory Guide. Although they mentioned that being observed by the eye tracker while performing the supervisory control task was an unpleasant feeling at first, they agreed that they could adjust after some time of using the system.

SME#1 mentioned that wearing the eye tracker was uncomfortable. The uncomfortable feeling could potentially distract users from the supervisory control task. Thus, he recommended replacing the head mounted eye tracker by a screen based eye tracking system to improve the comfort. An important remark was that the calibration of the eye tracker is essential for the trust that users have in the system. Sloppy calibration would cause the cry-wolf effect (Breznitz 1984). It has to be assessed whether it will be possible in the future to guarantee good calibrations with acceptable effort. Further, he mentioned that Supervisory Guide seems to increase workload because the transitions between the criticality levels were very fast. He assumed that better adjustment of threshold parameters would reduce the perceived workload.

SME#2 suggested that using green, yellow and red rectangles is not very useful for the given context of use. She argued that green rectangles are not needed at all and that not displaying green rectangles would also de-clutter the HMI allowing for better supervisory control performance. For the same reason, she suggested colourizing the icons itself instead of using rectangles. A major remark was that using red and green is problematic due to colour blindness. Colour blind users have no chance to distinguish between the criticality levels because the shapes are similar. Further on, she suggested using halo effects as a means to increase the obtrusiveness of visual alarms. Currently, green, yellow and red rectangles are similar in its obtrusiveness. Using the halo effect could also reduce the perceived workload.

SME#3 agreed that bad scanning performance is actually a problem of human operators in charge of UAV supervisory control. He pointed out that using eye tracking and SA-based guidance could have impact on safety. However, he stated that the trade-off between cost and value has to be kept in mind. Current eye tracking systems are very expensive. But if prices fell down the technique would be much more attractive for manufacturers. It would also add a new selling point to the company's portfolio.

4 Conclusions and Future Work

In this paper, we presented Supervisory Guide - an assistance system for SA-based guidance of visual attention for UAV swarm supervisory control. An evaluation of the Supervisory Guide prototype was conducted with three SMEs from the perspectives usability, human factors and UAV manufacturing to get an impression of the expectable user acceptance, safety impact and market potential. Overall, the results showed that Supervisory Guide increased mental demand but also improved SA. The interviews revealed that the SMEs think that SA-based guidance is a very interesting concept and that more research of this concept is desirable. The SMEs also provided valuable feedback to improve guidance of visual attention. The evaluation served as first proof-of-concept. In the future, we will investigate how guidance of visual attention could be improved. The experts gave a lot of valuable feedback how this could be done. Within an iterative design process we will improve our prototype along these results and prepare it for a user study with the target group to investigate the effects on SA.

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