Information Fusion supporting Team Situation Awareness for Future Fighting Aircraft

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Abstract – *In the military aviation domain, the decision maker, i.e. the pilot, often has to process huge amounts of information in order to make correct decisions. This is further aggravated by factors such as time-pressure, high workload and the presence of uncertain information. A support system that aids the pilot to achieve his/her goals has long been considered vital for performance progress in military aviation. Research programs within the domain have studied such support systems, though focus has not been on team collaboration. Based on identified challenges of assessing team situation awareness we suggest an approach to future military aviation support systems based on information fusion. In contrast to most previous work in this area, focus is on supporting team situation awareness, including team threat evaluation. To deal with these challenges, we propose the development of a situational adapting system, which presents information and recommendations based on the current situation.*

Keywords: Situation awareness, threat evaluation, team cooperation, adaptive aiding, situational picture, decision support, information fusion, fighter aircraft.

1 Introduction

Consider the following scenario. A team of four pilots is performing a reconnaissance mission, with the goal to fly within hostile airspace and gather information about a weapons factory and fortifications in the surroundings. Previous reconnaissance missions performed within the area have gathered valuable data over the terrain and enemy location, which has been used in the pre-planning process of the current mission. To perform their mission, the pilots have access to passive and active sensors, weapons and countermeasures. One of the aircraft is also equipped with a camera, for collecting images of the factory. During the mission, the pilots communicate with each other via radio and the platforms transmit data within the team over a data link. To achieve a good situational picture, sensor reports from the different aircraft in the team as well as preloaded intelligence data of known enemy locations are fused. When flying inside the hostile airspace, the pilots are endangered by surface-based threats. To avoid being detected, the pilots only use passive sensors. When a sensor in one aircraft detects signals from an unknown threat, another teammember can direct his/her sensors towards the threat in order to get measurements from additional sensors. Fusing information from two or more passive sensors, enables both an estimate of range to the object, as well as reduction of false alarms. Suppose that a previously unknown threat has been detected. To act in response to this new piece of information, the team can make slight changes to the mission plan to avoid being detected. Furthermore, the position of the new threat is stored in the team's threat database, which can be useful information when performing future missions within the area. However, it might be the case that the detected threat is of such magnitude that drastic changes in the original mission plan must be performed. A new division of tasks or roles within the team might be necessary, which requires that the pilots are able to quickly comprehend the new situation.

Fundamental in this scenario is that each pilot constantly has to assess threats in the surroundings that might endanger the individual aircraft, another aircraft in the team or the whole mission. Simultaneously, he/she has to consider the goals of the current mission. Thus, to increase the probability of mission success and survival, the division of tasks between the pilots must be reflected by the current situation as well as by their available resources and opportunities. Furthermore, cooperation within the team is needed to enable an advantageous use of the team's combined resources.

1.1 Perspectives of the Situational Picture

This brief and simple scenario highlights the importance of creating a common situational picture within the team. The quality of the situation analysis for an individual pilot can be increased by information sharing with the other pilots in the team. In order for the pilots to shorten the time for their observation, orientation, deciding and acting activities (as illustrated by Boyd's OODA-loop [1], see Figure 1), and position themselves one step ahead of their enemy, the complete situational picture will enhance the pilots' abilities to analyze and assess the situation as well as making suitable decisions.

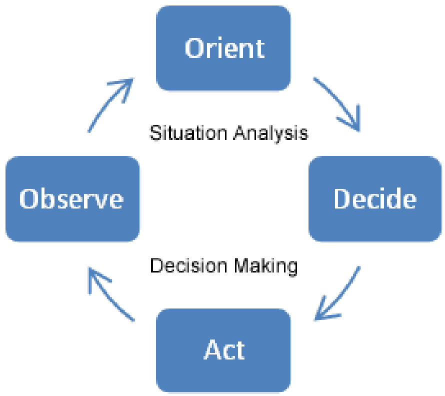

Figure 1: The OODA-loop, adapted from Boyd [1]. Observe and Orient are included in the situational analysis process, while Decide and Act are parts of the decision making process.

Schulte's goal model, presented in Figure 2, considers the pilot's main objectives during a mission: flight safety, combat survival and mission accomplishment. During a mission, these three objectives might conflict each other and the pilot must decide whether to follow the route of the mission or abandon it. These three objectives can be considered as perspectives of the situational picture, of which the pilot must simultaneously be aware in order to effectively reach his/her goals. In the scenario depicted above, the pilot has to consider factors such as the remaining amount of fuel (flight safety), manoeuvring away from surface-based threats (combat survival) as well as concentrating on gathering more information about the weapons factory (mission accomplishment). In order to do so effectively and successfully, the pilots must cooperate and share information so as to generate a more complete situational picture [2]. We anticipate that the creation of a team situational picture will enhance the pilots' abilities to balance between these perspectives. One reason for this is that the pilots can divide tasks (e.g. tasks connected to the mission perspective or the survival perspective) between them.

1.2 Military Aircraft Support Systems

A support system that aids the pilot achieve his/her goals has long been considered vital for performance progress in military aviation [3]. Research programs within the domain such as the US Pilot's Associate (PA) and French Copilote Electronique (CE) have been concerned with developing support systems that help the pilot through the whole mission - from situation assessment to evaluation and execution of possible actions [3]. The focus of the PA program was to develop different modules with different responsibilities, such as a "Mission Planner", helping pilots dynamically plan a new route [3]. The CE program had a different approach and

Figure 2: Three different perspectives for the pilot to handle: Flight Safety, Combat Survival and Mission Accomplishment.

focused on providing support that was designed for the individual pilot's cognitive characteristics [3]. Another project within the domain, the POWER project, focused on developing a "crew assistant" designed to help the pilots through adapting which information to present and recommending which weapons to use [4]. However, to our knowledge, not much research has been focused on developing decision support for fighter aircraft that takes team performance and team collaboration into account.

This paper presents our suggestions for further improvements of military aircraft support systems with the focus on supporting team situation awareness. Section 2 presents the challenges of creating team situation awareness and Section 3 describes challenges for team threat evaluation, which is a central part of the situation awareness for fighter pilots. Our suggestions for how to meet these challenges through a situational adapting system is described in Section 4. Finally, in Section 5, conclusions and future work are presented.

2 Team Situation Awareness

The concept of situation awareness (SA) has received much attention during the last two decades (cf. [5, 6, 7, 8]). According to Endsley [5], SA is achieved when an operator has perceived the elements in the environment, within a volume of time and space, has understood their meaning and can project their status in the near future. As proposed by Nofi [9], shared, or team, situation awareness takes the concept of SA one step further to integrate mission-essential overlapping features of the individual pilots' situation awareness to form a group dynamic mental model of the current situation. Having achieved team situation awareness, it is anticipated that the pilots will be provided with a clear and true common situational picture [9]. The process of achieving team situation awareness requires that the individual pilots build and maintain their own SA during the mission as well as share their individual SA to the team and become aware of relevant actions of other team-members [9]. In the scenario depicted in Section 1, mission success and survival imply that the pilots are able to fly inside the hostile airspace and gather valuable information about the weapons factory, hopefully without being detected and attacked. To enable the creation of a ”complete” situational picture, pilots must share information with each other and cooperate during the mission. For example, the position of enemy radars and weapons can more accurately be estimated if the pilots gather information together, hence creating a more accurate threat picture. Thus, it is important that the pilots create and maintain an individual situational picture as well as a common one, in order to accurately assess the situation. Figure 3 illustrates how the pilots together contribute to the creation of the team situational picture.

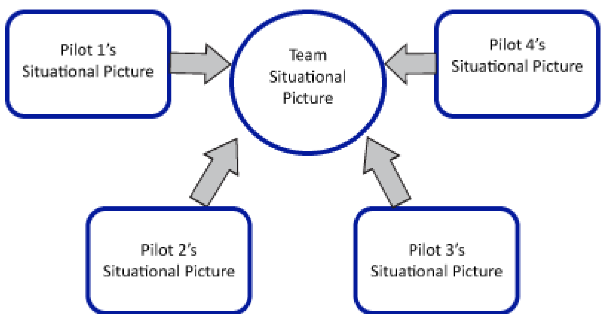

Figure 3: Fusion of information from all team-members enables the creation of a team situational picture.

We anticipate that a support system that provides accurate recommendations reflected by the developing situation is needed. Relevant information must be presented so as to enhance the pilots’ abilities to correctly assess the situation. Crucial information in relation to the pilots’ goals, tasks, roles in the team, threat situation and according to the current phase of the mission should be highlighted. This will make it easier for the pilots to gather information about and understand the current situation as well as anticipate future actions. These fundamental aspects of future military aircraft support systems are elaborated upon in the following subsections.

2.1 Information Presentation

In previous research, the importance of presenting relevant information, at the right time and at the correct level of detail according to the needs of the decision maker has been highlighted (cf. [4, 10]). In the Pilot’s Associate program, a ”display agent” was developed which was responsible for prioritizing which information to present in relation to the pilot’s workload [3]. According to Castor [11], the concept of workload has received much attention in the aviation domain ever since its relation to pilot performance and safety issues was highlighted. Indeed, the notion of workload has been used as a common criterion when evaluating new cockpit designs and predicting pilot performance, and the term is often used to refer to the degree of operator information processing capacity [11]. To keep the pilots’ workloads at an acceptable and suitable level, research has focused on presenting information reflecting the individual needs and workloads of the pilots. However, when deciding upon which information to display, considerations must be taken both to the individual needs of the pilot as well as to the team as a whole. Data collected by team-members and from databases must be fused and filtered in order to create a more trustworthy picture of the environment as well as provide a better ground for decision support. Furthermore, the pilots could benefit from having the same pieces of information presented in different ways depending on, for example, the pilots’ current tasks. Whether or not to present additional team related information to the pilots must be investigated so as not to further aggravate the pilots’ working situations.

2.2 Information Updates

To provide for the creation of a more complete situational picture, it is crucial that important updates of the current situation are highlighted to the pilots. If a pilot has been assigned a new role in the team, or if a new dangerous threat has been detected, this information should be accentuated to prepare the pilot for upcoming events. According to Svenmarck [12], little time is available during the mission to plan for unanticipated events. Consequently, pilots tend to follow the original plans as far as possible, as well as returning to them when possible if digressions had to be performed. Therefore, it is crucial that a decision support system presents updated mission status information showing the pilot’s progress in relation to the original plan so as to enable him/her to compensate for possible deviations with pre-planned short term responses [12]. By guiding the pilot back to the original plan, it is probable that both the physical and mental workload of the pilot will decrease, as well as improving the probabilities for mission success.

In the Pilot’s Associate program, a dedicated module, the Mission Planner, was designed to create new routes if the former could not be followed [4]. The support system proposed a new route which could be considered superior according to its threat exposure and fuel consumption. However, the problem of mission re-planning must be extended to cover the aspects of team cooperation: if information from the different team-members is fused and a more complete situational picture can be created, additional and possible better alternative plans can be generated. Updated information regarding the current mission and threats is thus vital.

2.3 Team Cooperation

Team cooperation is often crucial for mission accomplishment and survival. Castor [11] has showed that there is a positive correlation between pilot teamwork and performance in both defensive and offensive scenarios. Together, the team can generate a more complete situational picture and jointly the pilots have additional resources to act. However, in order to cooperate, the distribution of tasks between the pilots must be clear. To make the division of tasks more transparent, the concept of roles can be used. A role within this context can be used to define the allocation of tasks within a team. Different roles have different responsibilities and in line with the progression of mission accomplishment or according to the threat situation of the team, the roles should dynamically be switched. In the scenario depicted in Section 1, one role could imply controlling the camera to gather information about the area, while another could involve being prepared to protect team-members from enemy attacks.

To fully understand how the support system could help the pilots achieve their goals, an exhaustive task analysis should be conducted. Such analysis is required to obtain an understanding of which information is needed in the current mission phase, according to the role of the pilot, as well as which alternatives the pilot should be able to select from given the current situation. The analysis could also provide information to system designers about which tasks to automate depending on the current phase of the mission, the role of the pilot and the pilot's current workload. Furthermore, in order for an efficient team work to take place, it is important that the support system generates recommendations reflecting both the individual situation of the pilot as well as the overall team situation. If possible, an individual pilot can contribute to the overall goal of the team as well as helping other team-members with their tasks, hence improving the overall mission efficiency. An introduction to task analysis can be found in [13].

We anticipate that a decision support system that supports a clearer division of tasks within the team as well as provides the pilot with individual and team related information will increase the probability of mission success and decrease the pilot's workload.

3 Team Threat Evaluation

A central part for creating team situation awareness is the evaluation of the threats in the surroundings, which relates to the perspective of combat survival in Figure 2. In the scenario described in Section 1 this implies the avoidance of being shot down by surface-based threats. However, in other scenarios, combat survival may also include avoiding or defeating hostile fighters. Generally, the best action for combat survival is to avoid entering the threat's weapon engagement zone, but this is not always possible and instead the pilot can use countermeasures to mislead enemy radars and guidance systems on hostile missiles [4]. An introduction to the use of countermeasures, such as chaffs, flares and different jamming techniques can be found in e.g. [14].

Threat is according to [15] defined as "an expression of intention to inflict evil, injury or damage." For the purpose of this paper, we also use the term *threat* for a threatening object. Threat evaluation has been studied in the context of ground based air defense, as part of the problem of threat evaluation and weapon assignment (TEWA), cf. [15, 16, 17]. In the fighter aircraft context, the problem have been studied by for instance [18, 19, 20].

The question whether the team threat evaluation should be distributed or centralized is not trivial. If the threat evaluation is performed in a single aircraft, this will cause problems for the other team-members if the communication channels fail or if the aircraft is shot down. On the other hand, if the threat evaluation is performed in all aircraft independently of each other, there is a risk that all pilots counter the most dangerous threat and no one takes care of the second most dangerous threat (which might be almost as dangerous as the most threatening one). To our knowledge, the approach used in the fighter aircraft context is that threat evaluation is performed independently in each aircraft, without consideration to the team (cf. [18, 19, 20]). We argue that the threat evaluation needs to be performed in each aircraft, but that considerations to the other aircraft in the team should be taken. There are two interesting cases that should be considered:

- If an entity is not considered threatening for the own platform, but for a team-member, the entity should be classified as a threat against the team. If the pilot has resources to counter the threat, this should be considered in order to help the team-member.

- If a member counters an entity, this should decrease the assessed threat value, since the threat has been taken care of. However, there is a risk that the member is not able to fully counter the threat. The correct action might then be to help the team-member, unless there are other threats that need to be handled.

3.1 Threat Evaluation Methods

A system that evaluates the threats in the surrounding would aid the pilots in order to achieve team situation awareness. In this subsection the challenge of designing an algorithm that can perform threat evaluation will be discussed.

Threats are usually assessed according to two criteria, *capability* and *intent* [16]. A central part of the *capability* criterion is the type of the entity, which reveals the capability of the platform, e.g. its manoeuvrability and weapons [21]. The capability also depends on the spatio-temporal relationships between the threat and the threatened object. According to [21] the *intent* of the threat is more difficult to assess, since it can often not be observed directly. Parameters that are typically used in threat assessment can be found in [17]. Liebhaber and Feher [22] and Nguyen [21] describe studies that have been performed in order to identify the parameters that experienced air personnel use to evaluate the level of threat posed by a particular aircraft.

The evaluation of threats will be based on fused sensor data and intelligence data. This data will be associated with uncertainties of different kinds. It is therefore important that the algorithms for threat evaluation are robust and able to handle uncertain and even missing data. Methods that have been suggested for threat evaluation within the literature are for instance rule-based algorithms [18, 22], Bayesian networks [17, 21] and fuzzy inference rules [23].

In the POWER project, which studied countermeasure management in a fighter aircraft, the approach was to first assign all threats a value representing the threat level and thereafter schedule appropriate countermeasures based on this value [4, 18]. Thus, the threat evaluation was accomplished without regards to own resources and possible defensive actions. The same approach is often used in the TEWA literature, cf. [16, 17].

The use of countermeasures only affects the combat survival perspective, and (in the normal case) not the perspectives of mission accomplishment or flight safety. Thus it is possible to consider the countermeasure problem separately from the other two perspectives. However, the combat survival perspective also includes how the aircraft should be manoeuvred, sensor management and, as a last resort, weapon assignment. The goal is not to maximize the combat survival (this would mean not to fly at all) but to keep a reasonable balance between the objectives of combat survival and mission accomplishment.

Consider the case when the pilot approaches a threat entity which is known to use IR-guided missiles. A common method for misleading IR-guided missiles is to release flares. If the aircraft is not equipped with flares, this entity should be considered more threatening, than in the case where there are flares available. This does not mean that the flares should be released immediately, but the fact that this is a future possible action should decrease the threat level of the entity. Depending on the mission, the pilot can choose to approach the threat or turn and re-plan the route in order to avoid it. If the mission requires that the threat is approached or if the amount of fuel left is low and an extra detour would risk the flight safety, it might be worth approaching the threat.

Thus, instead of first evaluating the threat and thereafter deciding upon appropriate actions, available defensive actions should be considered already in the threat evaluation process. In many cases when the threat level is low, the considered action should not be executed, because this would hinder the mission. However, in the cases where the probability of combat survival would be too low unless actions are taken, appropriate actions for decreasing the threat level (i.e. counter the threat or re-plan the route) have already been calculated and can be suggested to the pilot. This approach is similar to the approach suggested by Roy, where the threat evaluation is divided into two parts: *Inherent Threat Assessment* and *Actual Risk Assessment* [15]. In the *Inherent Threat Assessment* the threats are evaluated without regards to own resources, while the *Actual Risk Assessment* takes into account the defensive actions that could be performed to eliminate or decrease the threat. In the example previously discussed in this subsection, it is not certain that the threat is going to launch any missiles. However, if it does, the pilot is prepared to use flares to mislead it.

We believe that a threat evaluation algorithm that takes available resources into account and considers the threat situation for all members in the team, could increase the survivability and increase chances of mission success.

4 Situational Adapting System

As described in the sections above, the pilot needs to consider different perspectives of the situational picture in order to both survive and accomplish his/her mission. We suggest that a situational adapting system would aid the pilot, see Figure 4.

Figure 4: A situational adapting system would aid the pilot to handle the three different perspectives: Flight Safety, Combat Survival and Mission Accomplishment.

A situational adapting system is a system that is able to respond to changes in the environment, as given by the situation analysis (see the OODA-loop depicted in Figure 1). The adaptivity of the system can be manifested in terms of changes in the user interfaces as well as the presentation of recommendations of suitable actions, adapted to different types of information, tasks, missions and roles. Situational adapting systems have been studied in the context of adaptive aiding, cf. [12]. One example of such system from the aircraft domain is the ground collision warning system which helps the pilot avoid terrain collisions by, for example, de-cluttering the displays from task-irrelevant data [12]. In literature regarding adaptive aiding, typical functions provided by an adapting system are information management and task allocation, or a combination thereof [24].

An adapting support system could help the pilot balance the different perspectives of the situational picture in order to both survive and accomplish his/her mission. When collaborating in a team, the situational adapting system should serve as a basis for distributed collaboration between individual pilots, managing adaptation of communication, information sharing and division of tasks in relation to changes in environment or mission objectives. Work within information fusion on autonomous collaboration (cf. [25, 26]) could contribute to the realization of such system.

By adapting the presentation of information as well as generating recommendations reflecting the current situation of the team and individual pilot, the probability for mission success and combat survival should be improved. The support system should present important past and current information as well as probable future events in order for the pilot to plan their actions. The following subsections present how a support system could aid the pilot through situational adapting displays and recommendations.

4.1 Situational Adapting Displays

As reflected upon in Section 2, central information in relation to the pilots' tasks and roles must be highlighted in order to make it easier for the pilots to understand the current situation. To ensure that the most relevant information is adequately presented to the pilot, the situational adapting display should be grounded in the role of the pilot and the specific task-at-hand, taking into account both the pilot's current activities and the explicitly represented knowledge derived from the task analysis (e.g. mission objectives, roles in the team and tasks connected to specific phases of the mission) [27]. One approach for addressing this challenge is to move from fixed display designs to adapting designs that present information reflecting the developing situation [28]. The idea of adapting displays is not at all new, though debates are concerned with analyzing whether the displays should be adaptive or adaptable [28]. Adaptive displays adjust mainly automatically, whereas adaptable displays allow operators to alter the presentation according to their needs and preferences [28]. In the military aviation domain, an example of a situational adaptive function is the ground collision warning system that de-clutters the display of irrelevant data. A situational adaptable function, on the other hand, is achieved through pilot-active choices of the displays' menu system. Adaptive designs have the advantage of not interrupting the operator in his/her work, though a loss of situation awareness and a feeling of ”losing control” might be resulting consequences when distancing the operator from the system functions. On the other hand, it might be difficult for an operator to identify the need for adaptation. To balance between the flexibility, predictability and workload, a hybrid solution between adaptive and adaptable designs might be the best solution. We anticipate that future adaptive and adaptable functions are able to adjust which information to present according to the pilots' current roles as well as let the pilots make more fine-grained adjustments of which information to present.

Challenges with adapting display designs include that the adapting system has to recognize the need for adaption and, furthermore, to make operators aware of the changes in the situational picture. For example, in the scenario depicted in Section 1, it is vital that the pilots are made aware of current and future role assignments, and how the role-switching will affect the displays, the information presented and the functions available. Another challenge is to inform the operator of display changes, without adding to the already existing problem of data overload [28].

4.2 Situational Adapting Recommendations

In order for the pilot to plan his/her future actions, the pilot must be able to predict how different actions could affect the situation, considering both mission accomplishment and combat survivability. An action that could increase the probability of mission success may at the same time decrease the probability of survivability. Most decision support systems for fighter aircraft presented in literature only consider one of the three perspectives of mission accomplishment, combat survival and flight safety. For instance, Sundqvist [29] presents a system for aircraft collision avoidance (flight safety) and Enevoldsen [30] presents a decision support system for avoiding missiles (combat survival). These are examples of systems that only suggest recommendations when the situation is too critical for the pilots to consider all three perspectives.

However, in many other situations it is possible to take all three perspectives into account, for instance when the detection of a threat can be handled either by a small deviation from the mission route or by the use of countermeasures, as in the scenario described in Section 1. A study of a decision support system that takes both mission accomplishment and combat survival into consideration is performed by da Costa [19], who studied sensor management and weapon allocation. Even though this system only considers a single aircraft, the system becomes quite complex. This complexity is likely to increase when there is a team of fighters that must collaborate. There is a risk that designing a system that tries to find the best action in all situations would be too complex. Instead, we believe that a more suitable approach would be a system that shows the impact on mission and survivability of typical actions (e.g. ”turn left”, ”turn on radar”, ”release chaffs”). Inspiration may come from work within information fusion on supporting tactical decision making using 'threat maps' and planning in the threat map space [31].

The actions evaluated and presented as typical actions should depend on the mission, the pilot's role, the threat evaluation and available resources. Furthermore, the number of actions that are presented and how they are displayed may depend on the situation. In time critical situations, the pilot should not have to consider many possible actions, though in less time critical situations, more possible actions can be displayed. Fundamental is the understanding of automation, i.e., when and to what degree should the system provide recommendations only and when and to what degree could the pilot delegate decisions to the system. This implies that workload distribution, allocation of responsibilities between pilot and system and trust are important issues [32]. Research within information fusion on personalized and context-aware decision support systems [33] could guide the development of a situational adapting system as described above.

5 Conclusions

During a flight mission a fighter pilot must consider the three different perspectives of the situational picture: flight safety, combat survival and mission accomplishment. Since the probability of mission success increases if several pilots collaborate, a pilot should not only consider his/her own situational picture, but the situational picture of the whole team. In the domain specific literature, the usual approach is to study a single fighter aircraft with one pilot, but we argue that studying a team of fighters and the collaboration between them has the potential to increase the probability for both mission success and survival.

Within the domain of decision support and situation awareness for collaboration between fighter pilots, we have identified three areas where more research is needed:

- **Team situation awareness:** In order for a team of pilots to collaborate effectively, they must be aware of each others' situational pictures, which may be expressed in terms of team situation awareness. We argue that this can be achieved through the development of additional information presentation techniques that take pilot roles and mission phases into account. We suggest that this would enable a clearer division of tasks within the team.

- **Team threat evaluation:** When evaluating threats, we argue that consideration has to be taken to entities threatening all members in the team. Furthermore, the process of threat evaluation must be able to handle uncertain and even missing data, as well as take available resources and possible defensive actions into account.

- **A situational adapting system:** A situational adapting system supporting the pilot's need to balance between the perspectives of mission accomplishment, combat survival and flight safety should be developed. Such system should adapt the information to present, generate recommendations on which route to take etc. depending on the current situation.

5.1 Future Work

To address the challenges described above, we anticipate that interviews with experienced pilots are required to understand which information is needed in a few, specified scenarios. Furthermore, different presentation techniques should be tested to analyse how to best provide for team situation awareness. Threat evaluation algorithms that take team cooperation and resources into account should be developed and tested. These concepts and ideas could be implemented in a prototype for evaluation together with fighter pilots.

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