AUTOMATION GUIDELINES FOR INTRODUCING SURVIVABILITY ANALYSIS IN FUTURE FIGHTER AIRCRAFT

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Abstract

Pilots of fighter aircraft are often exposed to the risk of being hit by enemy fire from ground-based threats. It has been argued that the pilots could be aided by a tactical support system that automatically assesses the danger posed by such threats and analyzes the survivability of the mission. It has also been argued that the automation design of such system must be properly adapted according to the pilots' needs. In this paper, empirical results are presented regarding the characteristics of an operator-centered survivability support system in the fighter aircraft domain, where both the development of the system and its automation design are discussed. The results indicate a strong potential for the survivability model and the automation guidelines within the fighter aircraft domain, but also a need for further refinements of the model and the guidelines to reflect the specific characteristics of the domain.

1 Introduction

During flight, fighter pilots need to analyze large amounts of data in order to make correct decisions. Not only do the pilots need to concentrate on flying the aircraft safely, they also need to perform actions to accomplish the goals of the mission as well as to survive potential battles. It has been argued that automatic support systems are able to aid the pilots balance these objectives through automating carefully selected tasks [2]. For example, in threatening situations where the pilots concentrate on avoiding enemy fire while at the same time strive to perform tasks to accomplish the goal of the mission, automatic support systems could aid the pilots fly the aircraft safely.

The automatic support system being investigated here is the one discussed in [3], which is believed to aid fighter pilots survive the mission by evaluating the risk of flying the intended route. By collecting and fusing information from different sensors, databases and team members, a coherent picture of the threat situation can be generated. Based on this information, the survivability system can calculate the probability of flying a specified route without getting hit. This might aid the pilots to better assess the threatening situation as well as plan their actions to increase their chances of surviving the mission. However, it is here assumed that the survivability calculations presented in [3] need to be investigated further in order to identify the important characteristics of the threats that should be included in the calculations. Furthermore, the need of realism in the survivability calculations depends on the functionality the support system should offer to the user. It is therefore important to analyze different survivability analysis support functions.

To aid developers of automated systems design with the human operators in mind, several guidelines have been proposed that stress the importance of a good operator-automation relationship. These guidelines form an attempt to diminish the known negative consequences of automation, such as skill degradation and complacent behavior (see for example [4]), while at the same time ameliorating the positive ones (such as enhanced situation awareness and decreased workload, see for example [5]). However, a need for adapting these guidelines to suit the fighter aircraft domain has been raised to make them useful for developers of automatic fighter aircraft support systems (see for instance [1]).

The purpose of this paper is twofold – to investigate the need for further developments of the survivability support system presented in [3] as well as to discuss how it should be designed in terms of its automation design. The rest of this paper is structured as follows: Section 2 describes the survivability model and presents suggested improvements to the model based on discussions with domain experts. Section 3 presents the automation guidelines identified from literature as well as the results from a survey performed together with domain experts where the importance of these guidelines in relation to the specific domain was discussed. Section 4 presents a discussion regarding the automation guidelines for introducing survivability analysis in future fighter aircraft whereas Sections 5 and 6 present our conclusions and suggestions for future work.

2 Development of the Survivability Model

The survivability calculations require a model that describes how the threats affect the pilot's chances to fly the route without getting hit by enemy fire. An initial survivability model was suggested in [3], but it is anticipated that this model needs to be developed further to be useful in a tactical support system. In order to understand how the model can be improved, discussions have been conducted with domain experts with expertise of operational analysis, ground-based air defense, survivability and tactical support for fighter aircraft. Inspired by these discussions and information found in literature, suggestions of how the model can be enhanced have been identified. This section first describes ground-based air defense systems and presents the initial model suggested in [3]. Suggestions for refining the model are thereafter presented and the use of the model in a tactical support system is discussed.

2.1 Ground-Based Air Defense Systems

The threats described in the model are ground-based air defense systems. The task for the ground-based air defense is to protect defended assets such as airfields, harbors, critical infrastructure and troops. The air defense system consists of sensors, weapon units and command and control (C2) stations. The sensor information is distributed within the system and information from all sensors as well as other information sources is fused into a situational picture that is presented to the C2 operators. The sensors are often surveillance radar and weapon control radar, but other kinds of sensors can be used as well. The weapon units can be anti-aircraft-artillery (AAA) or surface-to-air missiles (SAM).

The decision to engage a hostile aircraft or helicopter is usually taken by the operator at the C2 station. Depending on, for instance, the type of conflict and the rules of engagement, different criteria must be fulfilled before a hostile aircraft can be engaged, such as that the aircraft has not been identified as "friendly" by the IFF (Identifying Friend or Foe) system or that it is flying within an area where it is not supposed to fly. The decision regarding which weapon unit that should engage the hostile aircraft is taken based on, for instance, which weapon unit that has the best opportunities to hit the aircraft. The air defense system also needs to protect itself, since it is an interesting target for the hostile air force. This is accomplished by a combination of camouflage, delimited emission and re-location of the units.

2.2 Initial Survivability Model

An initial survivability model was suggested in [3] and is illustrated in Figure 1. The model has two states, "unharmed" and "hit", and the survivability describes the probability of being in state "unharmed". The model also includes a transition intensity $\lambda(t)$ between the states. The intensity λ depends on, for instance, the geometry between the aircraft and the threat and therefore varies along the route. In the initial model suggested in [3], the threats are represented with a threat area and a constant intensity λ inside the threat area. The model is further described in [6].

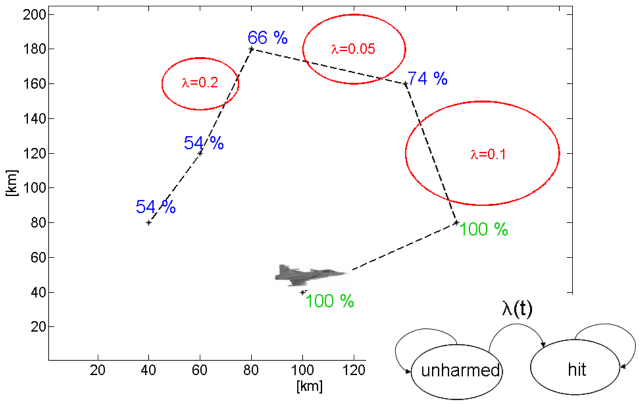

Figure 1 – The survivability for each waypoint along the route is depicted. The intensity λ between the two states depends on whether the aircraft is inside or outside any threat area.

2.3 Suggestions for Improvements

Inspired by the discussions with the domain experts, the following suggestions for improving the model have been identified:

- The threats should not be considered as independent units, since sensor information is distributed within the unit and the decision of engaging a hostile aircraft is taken by the C2 operator.
- The model should describe both the risk of getting hit and the risk that the aircraft has been detected and tracked by the air defense system.
- The altitude of the aircraft should be taken into account, since the ranges of weapons and sensors differ with altitude.

These suggestions for refining the model can be incorporated into the survivability model by adding additional states to the model and by describing the threats in 3D, as described below.

2.3.1 States in the Model

The information from the sensors is communicated between the units and the information is fused into a situational picture. The decision regarding which aircraft to engage and which weapon units that should be used are made at the C2 center, from which the orders are distributed to the affected weapon units. From the fighter aircraft's point of view, the air defense system can therefore be considered as a single system with different states describing the threat's knowledge and interest of the aircraft. We suggest that the model should include the states and transitions depicted in Figure 2.

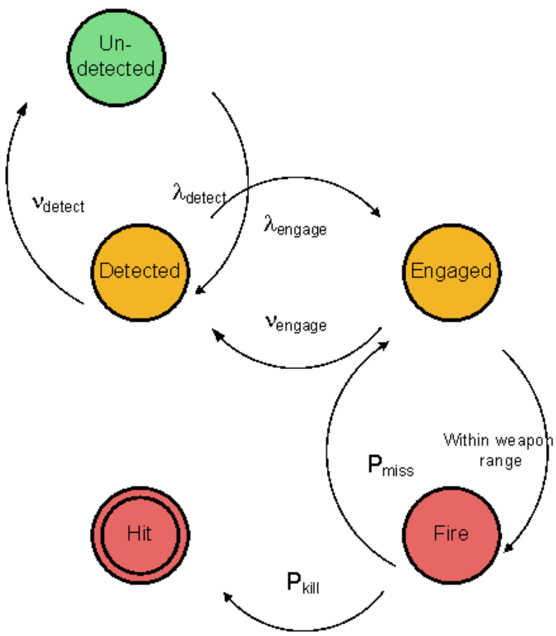

Figure 2 – The states in the model describe the relation between the aircraft and the air defense system.

When the air defense system is not aware of the aircraft, the state is "undetected". The air defense system thereafter detects and tracks the aircraft (state "detected"). In state "engaged" the air defense system tracks the aircraft accurately enough to guide a weapon toward the aircraft. Furthermore, the aircraft has also been identified as hostile and the commander has decided that the aircraft should be engaged. However, if the aircraft is outside any weapon range, it cannot be hit. The criteria for when the air defense system should engage an aircraft depends on for instance the rules of engagement and may therefore differ between missions and countries. Four intensities are used for modeling the transitions between the three states, λ_{detect}, λ_{engage}, ν_{detect} and ν_{engage}. When the aircraft flies inside the range of a weapon and is in state "engage", a weapon will be fired (state "fire"), which will either hit the aircraft with probability P_{kill} or miss the aircraft with P_{miss}=1-P_{kill}.

2.3.2 Threat Description

If the survivability model should be extended to include the states depicted in Figure 2, it is necessary to associate all points along the route with the transition intensities λ_{detect}, λ_{engage}, ν_{detect} and ν_{engage}. Furthermore, it is also desirable to have a 3D-model that takes the altitude of the aircraft into account. Figure 3 illustrates what the model could look like, where the large blue areas illustrate the area where the aircraft might get detected by the air defense system and the red areas illustrate the areas with weapon systems.

The model requires information regarding the location of the threat's sensors and weapons. The aircraft can usually detect the energy emitted by the air defense system's sensors, but it is difficult to know where the weapon units are located. The topography can give some indication of where the sensors and weapons are located, since they are typically located where their ranges are good and where some protection can be given by the terrain. On the other hand, the air defense relocates its units for protection, meaning that information regarding their position from previous missions in the area can be out of date.

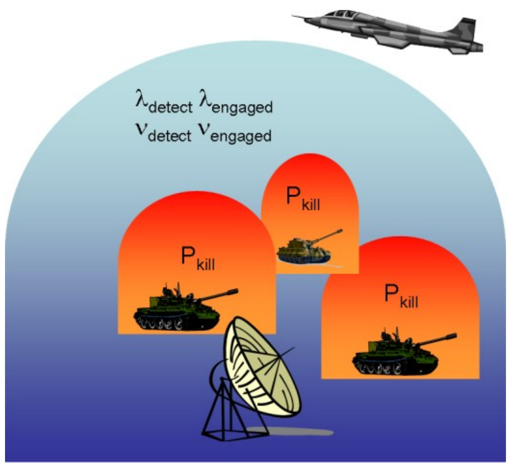

Figure 3 – When the aircraft is inside the sensor range (blue volume) it risks to get detected and when it is within weapon range (red volume) it risks to get hit.

Ball [7] refers to survivability as a function of several conditional probabilities that describe that there are threats in the area and that these threats detect, track, approach, hit and kill the aircraft. Similar models have also been presented in [8] and [9]. The refined survivability model presented here resembles these models, but describes not only the risk of getting hit but also the risk of being detected.

2.4 Tactical Support Functionalities

The aim of the survivability model is to be part of a tactical support system that can aid the pilot perform the mission without getting hit by enemy fire. This section suggests a number of functionalities that can be developed based on the survivability model and discusses how the model could be complemented in order to achieve this.

2.4.1 Pre-Planning

Before the mission, the pilots plan how they should perform their mission based on the information available regarding the goals of the mission, the terrain, enemies, weather etc. The survivability model could be a useful tool for evaluating the routes that the pilots plan to fly. Since a lot of the information regarding the threats is uncertain, it would also be interesting to test different conditions during the pre-planning phase, to investigate the stability of the plan. If the expected outcome of the plan drastically changes with small changes in the preconditions, it might be desirable to come up with another plan that is more stable.

2.4.2 Presentation and Re-Planning

Even though the pilots are likely to plan the route to minimize the risk of being hit, new threats can appear during flight and the pilot might want to fly another route to increase the survivability. The survivability calculations can therefore be presented or warnings can be generated when the survivability is deemed to be too low to make the pilot aware of this.

It would also be desirable if the tactical support system could re-plan the route when the survivability is low, for instance by suggesting a new route to fly to the next waypoint. Andersson [10] has recently investigated fighter pilots' opinions regarding mission planning support and has suggested an algorithm for calculating a new route around an obstacle to the next waypoint. Route planning has been studied for both manned and unmanned aircraft, with the aim of minimizing either the risk of becoming detected, cf. [11, 12] or getting hit, cf. [8, 9]. These algorithms can serve as inspiration for the design of a re-planning functionality in a survivability support system.

2.4.3 Jamming

One way of increasing the survivability is to try to delude the threat's sensors so that the air defense cannot track the aircraft with enough accuracy to fire a weapon against the aircraft. Jamming makes it more difficult for the threat's sensor system to detect the aircraft meaning that the threat's detection distance could be decreased and that the time before the threat system is able to track the aircraft should be increased. In the model described above, this can be represented by decreasing the area where the aircraft can be detected and/or modify the transmission intensity between the states "undetected", "detected" and "engaged". However, the domain experts pointed out that the effects of jamming are difficult to model.

Literature regarding jamming and other countermeasures is sparse, but a few reports exist. Randleff [13] describes how the lethality of the aircraft is reduced when jamming is applied, where the reduction depends on the angle and distance between the aircraft and the threat. Kang et al. [14] describe an autonomous decision-making process for the selection of countermeasures, where the probability that the countermeasures will be successful is taken into account. However, a deeper investigation regarding jamming models is needed if the survivability model should be enhanced to include this.

2.4.4 Information Acquisition

Information regarding the environment and other aircraft, ships etc. is important for the pilots' situation awareness. However, active sensors such as radar and laser emit energy that can be detected by the threat's sensor systems. Thus, the information acquisition process may reveal the position of the own aircraft and thereby decrease the survivability. It is therefore desirable to minimize the emission of energy, but still be able to collect the important information. The design of functionality for information acquisition could utilize a model of how the emission of energy affects the threat's ability to detect the aircraft. When fighter pilots operate together in teams, information can be transmitted between the aircraft on a data link. Cooperation between the aircraft regarding information acquisition could imply that the aircraft share the task of gathering information so that the exposure of each aircraft is minimized.

3 Operator-Centered Automation

The introduction of automated functions, such as those suggested for the survivability support system described in the previous section, is often motivated by the anticipated positive effects upon operator performance and situation awareness. However, negative effects of automation have also been reported, such as skill degradation and complacent behavior (see for instance [4]). Thus, it has been acknowledged that the automated functions must be developed with the human operator in mind. Several approaches have been suggested for designing operator-centered automated systems such as the adaptive aiding, the mixed-initiative, the team-player and the human-centered automation approaches (see for instance [15-18]). These approaches have slightly different focuses, but all stress the importance of designing cooperative automation that works in collaboration with the human operator to reach stated objectives. As such, it is possible to keep the operators active and involved in the action and decision loop, to inform them of what is happening and how the automation works – a foundation that enables the operators to trust and use the automation appropriately.

Several guidelines have been proposed to aid developers of automated systems design with the intended operators in mind. However, these are described in general terms and might be difficult to apply when designing support systems for fighter pilots due to the specific characteristics of the fighter aircraft domain (such as the often high workload, stress and the possible fatal consequences of automation faults or making a wrong decision [19]). The following sections present a set of such automation guidelines identified from literature and from empirical studies with fighter pilots (see [20]). The views of seven developers of aircraft support systems upon the importance of these guidelines within the fighter aircraft domain and the usage of such guidelines are presented.

3.1 Automation Guidelines

Several automation guidelines concerning the physical design of the automation, how to achieve system transparency as well as how the automated systems can support enhanced team cooperation have been suggested. A set of such automation guidelines for system transparency and team cooperation has been identified from literature studies (see Table 1). The first guideline advocates the presentation of the raw data used by the system for generating recommendations and results. This might aid the operators to understand how the system works and why. The second guideline concerns the importance of indicating the reliability of the results and recommendations generated by the support system so that the operators are able to act and decide thereafter as well as receive a better understanding of the situation. The third guideline highlights the importance of only automating functions that will aid the operators, i.e. that the automation has a purpose, while the fourth guideline advocates that the operators should receive some form of education regarding the underlying logic behind the system. The fifth guideline stresses the importance of explicitly presenting automation failures if they occur, for example if the automated functions do not have enough data to generate recommendations. In the same spirit, the sixth guideline stresses the importance of providing relevant feedback to the operators so that the operators know what the system is doing. Also associated is the seventh guideline, which stresses the significance of collaborative automation in which the strengths of the operators and the automation are exploited. Furthermore, as highlighted by the eighth guideline, the designers of automated functions should consider different automation levels so that a good collaboration between the automation and the operator can be achieved. Finally, the last two guidelines suggest that operators as a team can be aided by automated functions if these provide support for enhancing the information and decision distribution within a team, as well as support the creation and maintenance of the operators' individual and common situational pictures (see [1] for more information about these guidelines).

Table 1 - Automation guidelines concerned with automation transparency and enhanced teamwork.

1	Provide access to raw data [21].
2	Provide means to indicate to the user that data is missing, incomplete, unreliable or invalid [21].
3	Make clear to the user the purpose of the automation [21].
4	Reveal the rules and algorithms used by the automation and, if possible, keep the algorithms simple [21].
5	Show the source of automation failure [21].
6	Provide relevant feedback [21].
7	If possible, make the automation cooperative rather than replacing the operator [22].
8	Carefully design the automation with appropriate automation levels in mind [23].
9	Provide automatic support to enhance information and decision distribution within a team [20].
10	Provide automatic support that updates the individual and team situational pictures [20].

However, how these guidelines can be incorporated into the fighter aircraft system development process has not been investigated. Thus, the following section presents the results from a survey performed together with aircraft system developers who were asked to express their views upon the identified guidelines.

3.2 Ranking of Automation Guidelines

Seven aircraft system developers working at a fighter aircraft industry participated in the study and were asked to express their views upon the ten automation guidelines listed in Table 1. They were asked to rank the different guidelines according to their perceived importance when developing the proposed support system described in Section 2. The ranking was performed using a 10 point scale, where the guideline receiving 10 points was considered the most important and the one receiving 1 point the least important. The results from the study can be found in Table 2 below.

Table 2 - Ranking of guidelines.

Guideline 3	61 points
Guideline 7	57 points
Guideline 6	49 points
Guideline 2	47 points
Guideline 10	38 points
Guideline 8	34 points
Guideline 9	31 points
Guidelines 4 and 5	25 points
Guideline 1	18 points

According to this ranking, the guideline highlighting the importance of the pilots understanding the role of the automated functions received the highest points by the participants. One of the participants argued that the most important thing is that the automated function implemented will aid the pilot and be useful for him/her, i.e. that the function meets a need and has a purpose. Furthermore, the function should also strive to unburden the pilot, i.e. to decrease his/her workload.

Another guideline that received a high score was the seventh guideline, promoting the implementation of collaborative automation. In the same spirit, the sixth and second guidelines also received high scores, i.e. that the automation must provide relevant feedback to the pilots as well as give an indication of the reliability of the results generated by the automated functions. These guidelines were given high scores due to the importance of a good pilot-automation relationship for appropriate usage and trust.

The least important guideline in relation to the proposed support system was the guideline advocating the possibility to provide access to the raw data used by the automation. One of the participants argued that the raw data could be made available upon request during flight, but that the standard display visualizations should not include this data due to the risk of pilot information overload. One of the developers claimed that if the pilots must have access to the raw data to be able to trust the automated system, there seems to be a general problem with the system design not being transparent enough.

3.3 Improvements and Usage of Automation Guidelines

The developers participating in the study argued that the automation guidelines could be used as a checklist during the task analysis phase of the design process. They claimed that the guidelines could be useful when designing so as to aid developers focus on the most important things first and to make a first screen of what to implement or not. Yet, they also argued that the guidelines must be further described and adapted to the fighter aircraft domain. The meaning of the different guidelines as well as their consequences for the design must be evaluated and documented. For example, during brainstorming sessions, the meaning of relevant feedback in relation to the suggested support system could be discussed.

One of the participants in the study argued that "*one should think about the aircraft as an extender of the pilot. A human being is like a bad sensor, who makes poor decisions and is weak. Thus, we need to design a system that compensates for these shortcomings. This should be done in a way that feels natural*". To make this automation "natural" it is important to involve the pilots early in the design process so as to investigate their needs and interaction preferences with the support systems. The developers argued that since many pilots are sceptical when it comes to automation of tactical functions, it is important to involve them when designing so that they start to think about how they want the system to aid them, while at the same time feel that they are the ones in control. To be in control and understand what happens, the developers further argued that it should be possible for the pilots to modify the raw data used by the support systems to see which parameters that affect the calculations performed. As such, the pilots would be able to validate the decisions and recommendations generated by the support systems.

4. Discussion

The automation guidelines are valuable in the development process of a survivability analysis system that can support fighter pilots before and during the mission. The survey results indicate that the third guideline is important, which states that the purpose of the automation should be clear to the user. Section 2.4 discussed a number of tactical support functions that a survivability analysis system could offer, such as support for re-planning the route or support for jamming. Jamming is an example of functionality where the third guideline is important for the automation design. It is difficult to model the effects of jamming and it is therefore important that the users understand the limitations of the model so as to understand how to use the function and trust it appropriately. An alternative approach could be to design automation support for jamming, without the need of explicitly modeling the effects of the jamming, as is done in the self-protection electronic warfare manager prototype described in [24]. This system uses tables for deciding which countermeasure technique that should be applied against which threat type. If this approach is suitable needs to be investigated further.

Another guideline that received a high score in the survey was the seventh guideline, stating that the automation should be cooperative. This guideline is important in the design of a re-planning function, which can suggest a new route for the pilot to fly in order to avoid threats. The automation design could let the pilot decide when new routes should be suggested and the support system could also give the pilot the opportunity to modify or reject the route suggested by the system. The automation could also offer support according to the pilots' preferences, for instance to minimize the risk of detection, to save fuel, to accomplish the mission, to survive etc. Aust [25] describes experiments where pilots used an automated planner and the experiments showed that the pilots sometimes refined the route suggested by the system. Nevertheless, the experiments showed that the automated planner decreased the pilots' workload and increased the survivability compared to planning the route manually.

Guidelines 2 and 10 are important for instance when designing support functions for information acquisition. One of the goals of information acquisition is to reduce the uncertainty in the situational picture to enhance the pilots' situation awareness. However, information regarding the situational picture will often be uncertain and it is important that the pilot is aware of this uncertainty. Thus, as the second guideline suggests, providing the pilots with an indication of the quality of the recommendations posed and the decisions made by the automated functions might enhance their situation awareness as well as highlight the need for an improved information acquisition process when necessary. Furthermore, if the pilots in a team can cooperate and share the information acquisition tasks, more information might be collected in a more efficient way.

5. Conclusions

The implementation of survivability analysis in a fighter aircraft requires that the survivability can be modeled. The development of such a model is an iterative process. The investigations in this paper started with the initial survivability model suggested in [3] and identified ideas for how to refine the model. The inspiration for the enhancements came from discussions with domain experts as well as information found in literature. The refined survivability model suggested in this paper considers the air defense system as a single threat consisting of different subsystems. The model describes both the risk that the aircraft gets detected as well as the risk that it gets hit by enemy fire. The discussions with the domain experts revealed that it is difficult to model jamming and that simple models are preferable. Furthermore, the automation should be designed so that the pilots understand the limitations of such models.

Regarding the automation guidelines for system transparency and team collaboration, the results from the survey performed indicate that the aircraft system developers found it important to implement automated functions that work in collaboration with the pilots, that these functions have a clear purpose as well as that the reliability of the results generated by the automated functions are explicitly presented to the pilots. This implies that extensive studies and evaluations together with fighter pilots would be useful when further investigating how the proposed support system should be designed from an operator-centred automation perspective. Furthermore, by following these guidelines, the aircraft system developers further argued that they would be aided by prioritizing what to implement as well as to have the automation design, from an operator's point of view, in mind during the design process.

Before applying the automation guidelines during the development process of a survivability analysis system it is clear that further developments are needed. The guidelines appear to be too general and need refinement and adaptation to the domain. They also need to be more clearly connected to the development process of the underlying model, since its design may constrain the possibility to adhere to the guidelines. Nevertheless, as shown in the development of the survivability model presented here, they could be used to gain valuable insights when developing the underlying model and the survivability analysis support functionalities.

6. Future Work

A deeper investigation of the identified automation guidelines should be performed. Such investigation should be conducted together with aircraft system developers so as to describe the guidelines in more detail as well as elaborate upon their consequences for the design of future fighter aircraft support systems. To formulate the guidelines as questions in a checklist, as suggested by one of the participants in the study performed, could further improve the guidelines and make them usable for developers within the domain.

An implementation of the proposed support system, which mirrors the characteristics of the survivability model and the identified automation guidelines, could be used as a foundation for extensive pilot tests. Such evaluations could investigate if the survivability support system meets the needs of the pilots. During such evaluations, different strategies for making the proposed support system as transparent as possible so as to foster an appropriate operator-automation trust could further be investigated.

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Copyright Statement

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