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INTERFACE DESIGN TO ACTUALIZE HUMAN-MACHINE COORDINATION IN THE HIGHLY AUTOMATED COCKPIT

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Although automated systems in an advanced cockpit have contributed to the enhancement of the safety, they have also increased the system's complexity which can be a cause of inappropriate situation awareness (SA). In this paper, a supportive method for enhancing SA in the highly automated cockpit has been proposed, focusing on the following two points. One is to support in grasping the situation from a broader perspective which can contribute to the detection of SA errors and to better understanding of the system's activities. The other is mitigating additional cognitive burden by supportive information. For the achievement of both an informative cockpit and the minimum additional cognitive burden, we explore the interface design for supporting SA in terms of improving information management by assisting the detection of unexpected conditions in the early stages of risky situation.

Introduction

In recent years, various automated systems have been introduced to the aircraft's cockpit, and most normal operations have increasingly being accomplished through them. Although the advanced automation has no doubt contributed to the enhancement of the aviation safety, it can also be one of the reasons for the system's increasing complexity which leads to the difficulty of maintaining appropriate situation awareness (SA) [1]. In some of the aviation accidents involving advanced aircrafts, inadequate SA was an important cause of breakdown in the human-machine coordination [2, 3].

In this study, SA in the highly automated cockpit is assumed to be divided into the following two aspects. One is grasping the state of an automated system itself. A source of difficulty in acquiring this SA is the system's internal complexity. For example, the autopilot system has over 20 modes with complex mode combinations and automatic mode transitions. Some aviation accidents indicated that the complete understanding of an autopilot system can sometimes be difficult even for the highly trained pilot [2, 4]. The other aspect is SA from a broader perspective including situation and environmental condition. In this paper, global SA is used to mean this SA with bird's eye view. Global SA is important for greater understanding of the system's activities, the projection of future state and the result, that is "Why is the system doing that?", "What will the system do next?", "What will the result of the system's activities be?"[5] This awareness is essential for achieving the effective human-machine coordination. For example, misunderstanding of the consequences of the system's activities can cause inappropriate risk perception, which may result in the delay in taking remedial actions by pilots.

For supporting the SA concerning the autopilot system itself, our research group has proposed a method to support the pilot in detecting possible deviations in mental models by providing additional information to enhance SA for the actual state of the autopilot system. A prototype information display for supporting the SA has been developed in order to demonstrate the validity of the proposed method [6].

In the present study, an improved prototype interface for supporting more global SA based on the previous approach has been proposed. In other researches, it has also been pointed out the importance of a more global SA and various supportive interfaces have been proposed [7, 8]. Although they have the potential to the enhance pilot's SA, the negative aspect of providing additional support for practical and effective use, which may lead to increased complexity of displays or pilots' cognitive overload, should also be considered.

Therefore, for satisfying both of the achievement of an informative cockpit and the mitigation of additional cognitive burden, we explore the supportive interface design focusing on the assistance of information management in the early stages of risky situations.

Basic Models

In this chapter, we discuss models and definitions which are fundamental to the present study.

Situation Awareness Error

Some researches have indicated a strong relationship between SA and mental models, the latter of which are internal models of systems and environment [9, 10]. Endsley has explained the role of the mental model as below. "This situation model

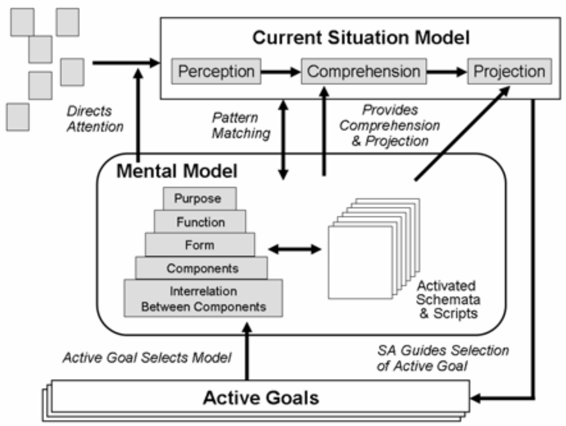


Figure 1. *Role of goals and mental models in SA [11] (M. R. Endsley, "Theoretical Underpinnings of Situation Awareness: A Critical Review", Situation Awareness Analysis and Measurement, Lawrence* Erlbaum Associates, pp.16, FIG. 1.6.)

captures not only the person's representation of the various parameters of the system, but also a representation of how they relate in terms of system form and function to create a meaningful synthesis - a gestalt comprehension of the system state" [11]. Fig. 1 shows the role of mental models in SA by Endsley. Based on the figure, the mental model affects direct attention to key features on objective system and environment for the development of SA, and this mental model is revised based on the acquired SA. It means that there is a possibility of going into a kind of error loop by the use of incorrect mental models. That is, an inadequate mental model can cause a system operator to have an erroneous SA as described in Fig. 1, and the operator might not recognize key features which might indicate the SA error because direct attention to information is controlled by the mental model updated directly or indirectly based on erroneous SA. Such a situation can be critical because it is considered to be already difficult for the operator himself to detect the SA error.

However, it also indicates the possibility that an operator can remedy the SA error himself by detecting the deviations of the activated mental model from the actual situation at an early stage of the event. In this study, our purpose is to support the detection of inaccuracy in the activated mental model by providing additional information with less cognitive burden.

Mental Model

According to Rasmussen's study, the mental model of a system operator consists of at least two dimensions which can be represented as hierarchies [12]. One is the functional hierarchy in line with the dimension of means-end. The other is the physical hierarchy along the dimension of parts-whole. In the real aircraft's operation, the mental model activated in a pilot's mind dynamically changes with the transition of active goals which are sometimes parallel or conflictive. Rasmussen stated that the physical and the functional hierarchy in a system operator's mental model dynamically interact with each other at appropriate representation levels in order to interpret and evaluate flooding information from the ongoing situation [12]. This operator's ability to describe the system at the various physical and functional levels can also provide a kind of redundancy for grasping situation. Even if an operator fails to realize the abnormal indication of gauge, it is possible that the operator can recognize the SA error by reasoning from the unexpected state of either a more global system or a lower levels system. In such a case, the operator recognizes the objective system at multi-levels of the mental models, which can provide redundant ways of recognition for the situation. Therefore, for supporting the redundant situation recognition, the information concerning the bird's eye view of a situation should be displayed at the same time as the existing indications.

Supporting Method

The importance of supporting global SA has been indicated, and new displays for supporting it have been proposed or already come into practical use, e.g. Vertical Situational Display (VSD). However, it is necessary to thoroughly consider the trade-off between their effectiveness and the cognitive burden in additional supportive information. In fact, according to a questionnaire survey of 10 commercial pilots in our previous research, many pilots were sensitive to increasing the amount of information on the interface, although they showed an interest in the possibility of additional supports to acquire the appropriate SA.

Therefore, the principle of our system design is to provide minimum additional cues on the interface for helping a pilot in detecting any inadequacy in the activated mental model in terms of the most important goal - safety. These additional cues can be provided as follows:

- Operators are NOT obligated to grasp the cues by excess highlighting or warning sound or other means. Operation procedure also does not require operators to do it.
- Operators are NOT obligated to respond to the appearance of cues.
- Cues do NOT have excess saliency compared with other displayed information.
- It should be intuitive and easy enough for operators to acquire the cues and to interpret their meaning.

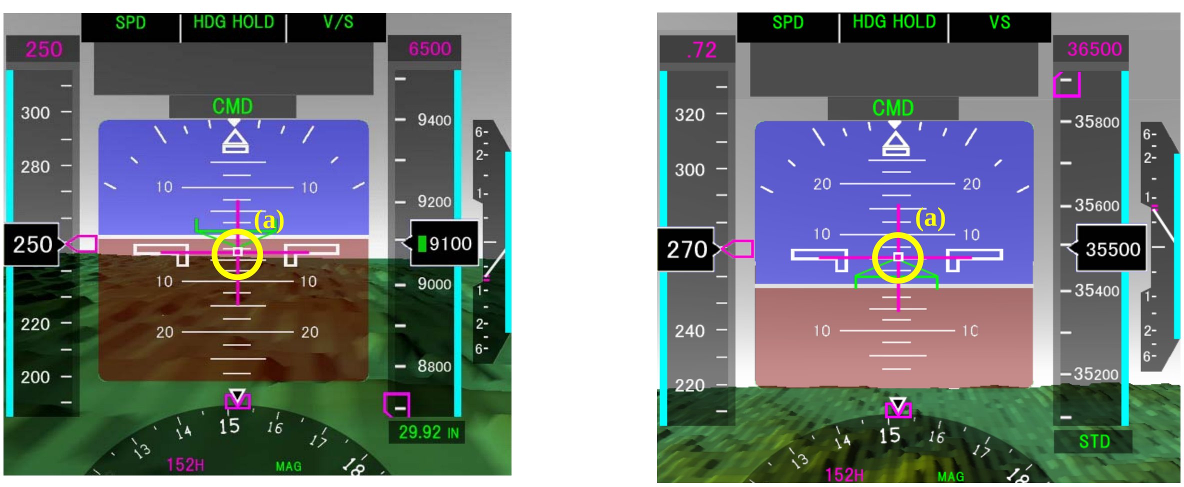
The basic concept of our method for displaying supportive information is in supporting the recognition of the deviation from expected situation in performing routine tasks in the early state of risky situation.

Implementation

Based on the discussion in previous chapters, we have proposed a prototype of the improved Primary Flight Display (PFD) for the enhancement of SA. Fig. 2 and Fig. 3 show some examples of the display. The basic structure of the display is the same as the existing PFD because pilots are highly accustomed to the existing form. Some incremental information has been added in the proposed display.

Firstly, the graphical information of the terrain is added to the proposed display. The topographic data comes from a database of existing Enhanced Ground Proximity Warning System (EGPWS). The graphical information is adjusted such that the center pointer of the aircraft symbol indicates the flight path (inside the circle (a) of Fig. 2 (1)(2)). It means that the aircraft will fly on in the direction of the center pointer. The indication can enhance the awareness for the physical relationship between the terrain, and the current position and flight path of an aircraft. As the terrain display are based on the flight path and the range of visibility is also limited to about 40km (enough to indicate terrain information for the next few minutes), the saliency of the terrain display naturally declines when the information is considered to be less important, for example, when the aircraft is climbing or cruising at the high enough altitude as described in Fig.2(2).

Compared to other terrain displays previously proposed, the saliency of the terrain indication of this display is appreciably low. Most part of it is overlaid by other indicators, giving them the priority. The reason is that, as the first aim of the terrain indication is to support the detection of possible error in the activated mental model which is used for projecting future situation, minimum information may be enough to accomplish the aim. In the context of this study, the error in the activated mental model signifies the "existence" of causes of danger which may result in a crash along the flight path which pilots do not expect, caused by some factors such as the erroneous setting of the autopilot pilot system which leads to unexpected sudden descent, or by the pilot's misunderstanding of the terrain feature. Therefore, the indication is enough to represent the relationship between the flight path and the existence of causes of a crash. There is no need for the display of detailed land features. In other words, it provides only some key features of the information of the aircraft's flight path with connection to the physical terrain information, which can describe the deviation from the pilot's expected situation more intuitively than the existing indications. This kind of global situation display can contribute to the detection of the possible deviation of



(1) descending at 9100feet

(2) climbing at 35500feet

Figure 2. *Examples of the proposed display*

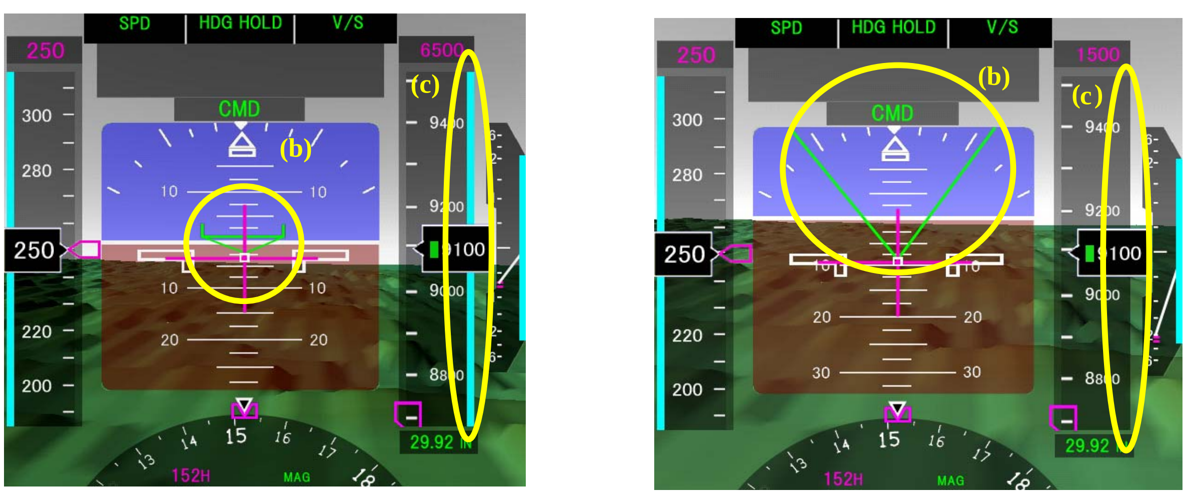
the pilot's mental model from the actual situation. This, in turn, is useful for evaluating whether the aircraft will be safe or not in the foreseeable future.

Secondly, the consequence of the activities of autopilot system is also shown in the proposed display as described inside the circle (b) in Fig. 3(1). Although the autopilot system originally consists of lower level functions or their combinations, such as maintaining the vertical speed or maintaining the heading, the proposed display represents the future situation by describing the function of the autopilot system at a more global level with connection to the physical terrain model. For a clearer indication, if the system detects a possible crash, the symbol is indicated as shown inside the circle (b) in Fig. 3(2), which is different from that in a safe situation. This indication of the intention of the autopilot system can support the pilot's more global SA. That is, the pilot can understand the situation not only at the level of "What is the system doing?", but also at the level of "What is the outcome of the system's action?" by the indication. Furthermore, if the system detects a possible crash, a blue bar which is presented on the altitude indicator turns invisible (inside the ellipse (c) of Fig. 3(1) and Fig. 3(2)). The blue bar indicates a result of safety assessment by the system, and disappearance of the indication from the display can inform the pilot about the system's abandonment of responsibility for safety when detecting a possible erroneous direction based on the system's situation assessment.

These indications described above cannot provide detailed information like the precise distance or remaining time to the possible crash. However, the proposed display can be expected to indicate possible dangers in its earlier phase by supporting the recognition of the deviation from the pilot's expected situation. In other words, the aim of the proposed display is to promote the acquisition of necessary information by the pilots in an earlier time frame, which can allow the efficient use of more supportive information like VSD.

In addition, we have explored the use of the framework of the proposed display which provides information of a more global situation for a greater understanding of the system's direction or intention especially in the critical situation. We have designed an enhanced display for TCAS based on the framework of the proposed display. Symbols of other aircraft subject to the TCAS advisory are overlaid in the proposed display described in Fig. 4. In that case, the pilot is informed of an aircraft which is coming close to the center pointer, a significant cause of danger because the center pointer indicates the flight path. The indication can support a pilot in recognizing the transition of the degree of danger intuitively. Therefore, the pilot can decide whether he/she should follow the TCAS advisory or not earlier. It can contribute to the proper understanding of the appropriateness of the TCAS advisory, and to the avoidance of erroneous decision under severe time pressure.

The proposed display can clearly indicate the possible danger of an expected crash in the early stages of the accident. The function can provide pilots with more



(1) normal descent

(2) abnormal descent into the terrain

Figure 3. *Examples of the proposed display*

The aircraft is descending using the autopilot system. In Fig. 3(2), the aircraft has a possibility of crashing into the terrain because the pilot erroneously directs too low a target altitude to the autopilot system.

opportunities to recover from errors. It can help to prevent certain types of CFIT accidents such as the accident of Air Inter Flight 148 at Strasbourg in 1992, the accident of Korean Air Flight 801 at Guam in 1997, because one of the important causes of these accidents is that pilots could not recognize the situation that the aircraft was heading to the terrain erroneously. Although the evaluation of the prototype display is still ongoing, we believe that the proposed method is effective for realizing a higher level of safety in the highly automated system.

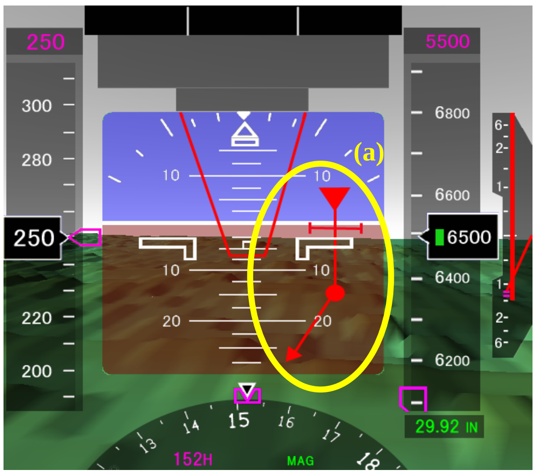


Figure 4. *Examples of the proposed TCAS display*

The symbol inside the ellipse (a) indicates the relative altitude, the position, the lateral and vertical direction of the closing aircraft.

Conclusion

We have developed the prototype interface for providing supportive information to the pilots. It aims at providing cue information for detecting possible deviation of mental model from the real situation. The great cue has been taken not to increase the cognitive burden in providing additional information in the already congested PFD. The importance point of the proposed interface point of the proposed interface concept is that it can increase the possibilities that pilot can recognize the existence of the risky situation in its early stage. Authors believe that the validity of the proposed interface concept will be validated by the experimental evaluations.

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