Situation Awareness Modeling and Pilot State Estimation for Tactical Cockpit Interfaces

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This paper desribes a study that assessed the feasibility of developing an adaptive pilot/vehicle interface (PVI) prototype that uses measures of pilot workload and computational situation assessment models to drive the content, format, and modality of military cockpit displays. The system architecture consists of three distinct modules: 1) an on-line situation assessor that generates a "picture" of the tactical situation; 2) a pilot state estimator module that uses physiological signals and other measures to estimate pilot workload; and 3) a PVI adaptation module, which uses the assessed situation to determine the pilot's information requirements, and the pilot state estimate to determine the most appropriate modality and format for conveying that information. The prototype display is being integrated with the Synthetic Immersion Research Environments (SIRE) simulator at the Armstrong Laboratory of Wright Patterson Air Force Base.

1. INTRODUCTION

Advances in aircraft performance and weapons capabilities have led to a dramatic increase in the tempo of air combat, reducing the pilot's available processing and decision time. Furthermore, technological advances in cockpit electronics have resulted in an explosion in the complexity and sheer quantity of information available to the pilot. The pilot has more things to deal with in the cockpit (each of which is becoming more complex to understand), and less time in which to do so (Endsley, 1993). To counter this increasingly complex environment, advanced pilot/vehicle interface concepts must make optimal use of the pilot's abilities. An effective PVI should enhance the flow of information between pilot and cockpit in such a way as to improve the pilot's *situation awareness* (SA) while alleviating workload.

To meet these objectives, we believe that three key functions are called for in an SA-enhancing PVI: 1) a means of assessing the current tactical situation; 2) a means of inferring the pilot's mental state; and 3) a methodology for combining these via an innovative PVI adaptation strategy.

The purpose of the **first function** is to use the aircraft's sensors to generate a high-level interpretation of the tactical situation facing the pilot. The air-combat task is a process in which the pilot must make dynamic decisions under high uncertainty, high time pressure, and rapid change. High pilot SA has been shown to be a key predictor of success in complex time-stressed scenarios (Endsley, 1989; Endsley, 1990; Endsley, 1993; Endsley, 1995b; Fracker, 1990; Klein, 1994Klein, 1994). Given the importance of cockpit SA, any advanced PVI should maximize it without overloading the pilot with superfluous information.

To compute an assessment of the tactical situation, a means is needed for integrating the outputs of the aircraft's various information systems and deriving a high-level abstraction of the situation. Our experience in this study and other related projects has shown that belief networks (BNs) (Pearl, 1988) provide an effective solution to this problem, and offer a natural framework for encoding complex tactical knowledge. BNs enable a designer to partition a large knowledge base into small clusters, and then specify probabilistic relationships among variables in each cluster (and between neighboring clusters). This approach facilitates construction of large, robust

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knowledge bases without explicitly specifying the relationships between all possible combinations of variables.

The purpose of the **second function** is to use physiological (and other) measures to infer the pilot’s *mental state*. Mental state refers to a set of metrics that define the pilot’s information-processing burden, mental workload, and engagement level in a set of tasks. To derive a judgment of mental state, a need exists for unobtrusive, automatic and continuous estimation of the pilot's mental workload. Wierwille and Eggemeier (1993) suggest that it is often desirable to measure multiple workload indicators, as a single method may not always provide an accurate measurement.

The use of pilot workload measures in conjunction with estimates of the current tactical situation offers considerable potential to adapt the display to enhance overall awareness. This requires the implementation of the **third function** of the envisioned system, a PVI adaptation strategy. For example, if a workload assessor determines that the pilot’s visual channel is saturated (or if his line-of-sight is directed out the window), a high-urgency display element that would nominally be presented on a visual display could be presented auditorally or via force feedback in the control stick. The PVI could also prioritize and filter visual display components to present only high-priority information for the current situation, to alleviate the pilot’s visual search. Any PVI adaptation logic should be founded on a coherent model of human capabilities, so that the pilot/vehicle system can operate as effectively as possible. If the adaptation is performed in an *ad hoc* manner that does not take into consideration human limitations and the pilot’s information needs for accurate SA, the effect may be degraded pilot performance.

2. FUNCTIONAL DESIGN OF ADAPTIVE PILOT/VEHICLE INTERFACE

Figure 1 shows a block diagram of our adaptive PVI architecture, shown within the context of an overall pilot/vehicle system. This study focused on developing a framework for the adaptive interface concept, and creating a limited-scope prototype that demonstrates each key component.

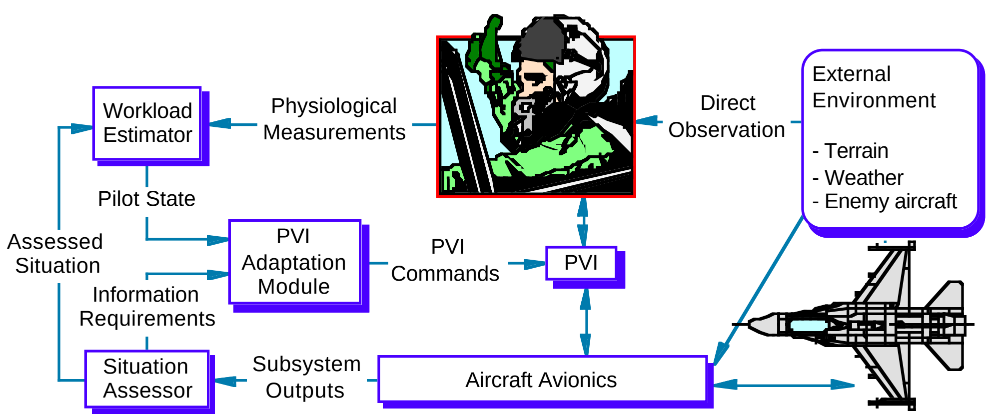

Figure 1. Overall Architecture of Adaptive Pilot/Vehicle Interface

The overall architecture consists of the three distinct but tightly coupled modules described in section 1: 1) an on-line situation assessor; 2) a pilot state estimator; and 3) the PVI adaptation module. The pilot interacts with the aircraft using a number of modalities. Graphical displays may be in the form of head-down displays, head-up displays, or helmet-mounted displays. The PVI provides auditory alerts in the form of tones or synthesized speech, using localized 3-D or non-localized audio as appropriate. Speech recognition may make it possible for the pilot to command system modes and content verbally. The pilot operates the aircraft via manual control inputs, and he may receive tactile feedback from the controls via (for example) a control loading system.

2.1 Situation Assessor

The situation assessor block uses the outputs generated by the aircraft avionics to compute the assessed situation **S***, which is a vector defining the occurrence probabilities of key situational features. A situation thus defines an aggregated set of states, events and sub-situations that call for some course of action by the pilot. We developed a BN model that quantifies the *threat* posed by a radar contact (described as *high*, *medium*, *low*, or *none*). This assessment supports the pilot's decision to attack, avoid, or defend against the detected contact. This network was developed via knowledge engineering with a domain expert, and it expresses threat potential in terms of the type of contact (*fighter*, *bomber*, etc.), its position with respect to the own aircraft, its behavior, etc.

2.2 Pilot State Estimator

The adaptive PVI's second key driver is the pilot's mental state. By pilot state we mean a set of metrics that define the pilot's information-processing burden, mental workload, and his engagement level in a set of tasks. To incorporate a judgment of pilot state into a PVI management strategy properly, a need exists for unobtrusive, automatic and continuous estimation of pilot workload. We explored the feasibility of using BNs for modeling pilot workload, with an initial focus on physiological workload. Physiological measures have a number of attributes that make them attractive, particularly in conjunction with performance-based metrics (Kramer, 1991).

The general strategy of experimental research in this domain is to demonstrate correlation between measures in one category and another. We implemented a BN model of physiological workload, and developed the network's quantitative relations using correlation results from the literature. The network expresses overall pilot physiological workload as either *high*, *medium*, or *low*. Workload is estimated using physiological measurements such as heart rate, heart rate variability, blink rate, blink duration, respiration rate, and EEG measures.

2.3 Pilot/Vehicle Interface Adaptation Module

The final key component of our system architecture is the PVI adaptation module, which drives interface content, format, and modality. One of the objectives of this study was to develop a systematic approach and formal means of implementing adaptive interfaces.

The development of adaptive interfaces is in many ways analogous to the development of automated systems: the designer must decide how far to go with automation. To formalize this problem, Sheridan (1992) developed a scale quantifying the *degree of automation.* Each level of the scale assumes some previous ones (when ANDed) or imposes more restrictive constraints (when ORed). Each successive level precludes human intervention to a greater extent, and introduces additional opportunities for machine error (motivating careful consideration of what to automate). Inspired by Sheridan's scale, we developed a preliminary taxonomy of the *degrees of adaptation* of a human/machine interface (HMI), shown in Table 1. Each level corresponds to an increasing degree of computer-based control of the HMI and underlying systems. This taxonomy is intended to have a scope of application that is broader than the military cockpit environment.

Table 1
Scale of Levels of Interface Adaptation

Level	Type of Adaptation
1	No interface adaptation; the human controls all aspects of interface operation
2	The computer adapts graphical symbology, and
3	Augments the display by modality, and
4	Manages interface mode and configuration, and
5	Automates specific operator tasks

At **level 1**, no interface adaptation takes place (a "conventional" HMI). At **level 2**, the computer adapts graphical symbology in a manner that corresponds to situational features. The intent is to drive graphical interface content in a manner that intuitively supports SA. At **level 3**, the computer augments graphical displays with multi-modal elements (e.g., auditory or haptic displays). At **level 4**, the computer takes on the tasks of configuring display modes and settings. Finally, at **level 5**, the computer offloads specific operator tasks and carries them out itself.

For our prototype, we developed a single aircraft-specific example of each adaptation level:

1: Basic air-to-air radar display, and
2: Adaptation of graphical symbology to show BN-derived threat potential, and
3: Augmentation of radar symbology with audio warnings and alerts, and
4: Computer-based management of radar display mode and configuration, and
5: Computer-based alleviation of pilot tasks during missile evasion maneuvers

Figure 2 presents a snapshot of the integrated display (implemented in a flight simulator on an SGI workstation). The italicized annotations show the meaning of various symbology elements. At the instant shown, a high-threat incoming missile is approximately 7 miles away, while the aircraft that fired it is veering to its left. Simultaneously, a medium threat fighter radar (indicated by the “F” within the arrow) has been detected at a range greater than 20 miles (the current display setting).

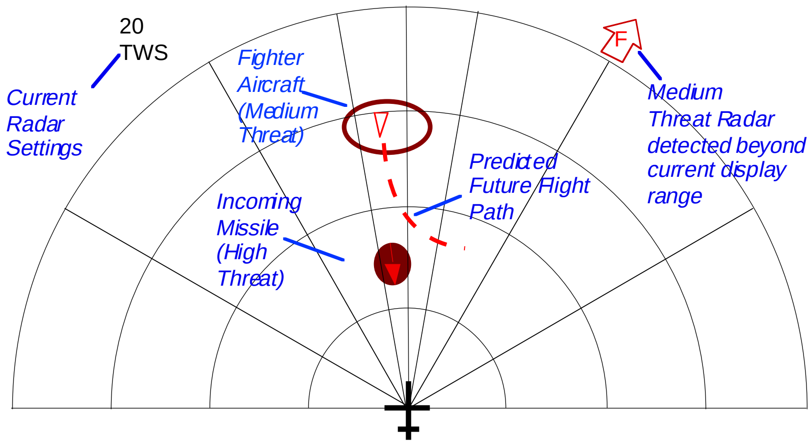

Figure 2. Prototype Radar Display.

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