ECOLOGICAL INTERFACE DESIGN IN AVIATION DOMAINS: WORK DOMAIN ANALYSIS OF AUTOMATED COLLISION DETECTION AND AVOIDANCE

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This paper describes Work Domain Analysis (WDA) applied to the domain of automated midair collision detection and avoidance as a first step in the design of improved ecological interfaces for automated traffic alerting displays. Three abstraction hierarchies (AH) modelling the aircraft, collision environment, and a traffic alerting system are presented, and the challenges of adapting the AH to enhanced displays will be examined. It will be shown that WDA is a feasible framework for establishing information requirements of flight and automated collision dynamics. Ecological Interface Design (EID) can then be applied to develop displays that invoke a greater trust in the automation.

INTRODUCTION

The field of Midair Collision (MAC) detection and avoidance receives significant attention in industry and academia because midair collisions are catastrophic and costly. Although rare, midair collisions do happen. Most recently, in July of 2002, a Tupolev-154 Russian airliner collided with a DHL cargo plane over South Germany at cruising altitude. Conflicting advisories were given to the Russian pilot from both air traffic control (ATC) and onboard Traffic Alerts and Collision Avoidance System (TCAS 2). Although ship-to-ship TCAS 2 resolution issued non-conflicting maneuvers to both aircraft, the Russian pilot elected to comply with ATC, leading to the collision and subsequent loss of both aircraft (Ladkin, 2002). This accident shed light on human factors issues arising from the use of TCAS 2.

The aviation industry is currently innovating towards free flight, an airspace management paradigm that gives pilots greater flexibility in flight planning. One aspect of free flight research is the Cockpit Display of Traffic Information (CDTI). Efforts addressing displays for automated collision detection include consonance and dissonance studies related to automatic alerts (Pritchett & Vandor, 2001), look ahead prediction envelopes such as T2CAS (Fulgham, 2003), 'future cone' analogies (Krishnan, Kertesz, & Wise, 2000), geometric predictor symbology (Gempler & Wickens, 1998), and displaying intent information in TCAS (Barhydt & Hansman, 1997). The introduction of formalized Work Domain Analysis to this domain may provide a new framework upon which further study can be conducted.

NOTE: The system of focus in this study is TCAS 2 (FAA, 2000), which provides automated alerts and conflict resolutions. In the remainder of the paper, 'TCAS' shall refer to the TCAS 2 implementation.

AUTOMATION IN TCAS

TCAS issues 2 types of automated alerts: A Traffic Advisory (TA) is issued if vicinity traffic poses a potential threat, alerting the pilot to their presence. A Resolution Advisory (RA) is issued when a critical threat is detected and a calculated evasive maneuver is presented to the pilot for avoiding the collision. During RA's, air traffic control (ATC) must withhold aircraft instructions until all TCAS maneuvers are completed (FAA, 2000). In the early days of TCAS, pilots were frustrated by the frequency of untrustworthy 'nuisance alerts' near airports and developed a habit of ignoring them, exhibiting the 'cry wolf' effect (Bliss, 1997). This was a known issue in the industry, and an upgraded version of TCAS software was introduced in 1993 that reduced false alarms by 80% (Klass, 1993). The FAA later mandated compliance with TCAS RA's. In countries where TCAS advisories and ATC advice have equal weighting (automated vs. human direction), there is a tendency to listen to the human decision (Mosier, Keyes, & Bernhard, 2000). Such was the case in the South Germany midair collision. When presented with equally salient information (TCAS told the pilot to 'descend', ATC told the pilot to 'climb'), the Tupolev pilot was biased against the automated aid and consequently was unable to resolve the situation.

Work Domain Analysis (WDA) and Ecological Interface Design (EID) are approaches that have been shown to improve operator performance in complex systems (Vicente, 1999) by conveying the relevant system parameters through the interface, and therefore may be able to enhance performance with the TCAS system as operators who understand the system (the pilots) should be more likely to accept its advice. The present study will reveal information requirements for creating a more informative TCAS interface, one that convinces the pilot to heed a valid TCAS advisory instead of strictly commanding them.

WORK DOMAIN ANALYSIS

WDA describes an abstraction hierarchy (AH) of five layers, from functional purpose to physical form, in order to produce a high-level overview of system interactions. Vertical interpretation between layers of the abstraction results in a means-end ("how-why") understanding of the system components. The approach of WDA was proposed by Rasumussen (1986), and has been successfully applied to complex systems such as nuclear power plant control (Rasmussen, 1985), operating room patient monitoring (Hajdukiewicz, Doyle, Vicente, & Burns, 1998), and shipboard command and control (Burns, Bryant, & Chalmers, 2000). In the aviation domain, WDA has been performed on the aircraft engineering system (Dinadis & Vicente, 1999), and the entire aircraft as a single work domain (Moradi-Nadimian, Griffiths, & Burns, 2002). This study presents a novel application of WDA to the aviation domain that highlights aircraft flight dynamics and the threat environment in which a collision occurs, all of which interact with components of an automated warning system. Although the system of focus is TCAS, the flexibility of WDA allows this model to be adapted to any automated collision warning system being developed for aviation.

General Model

The domain of collision detection and avoidance was separated into three entities: Aircraft, Environment, and TCAS. The Aircraft entity models the flight dynamics (not the aircraft as a physical entity) of each aircraft that is involved in the potential collision. In our example, ownship and intruder ship are modeled separately to illustrate a two-ship encounter. The Environment entity describes the airspace in which the aircraft are interacting, and the TCAS entity describes the automated warning system. Each entity was further broken down into five layers of abstraction. It should be noted that the flight and environment parameters in the AH are derived solely from the current available TCAS dataset (FAA, 2000). This ensures that the new EID interface is consistent with TCAS in the context of data capture, only differing in its approach to information representation.

Functional purpose. This is the overall goal or purpose of the entity. The primary purpose of any aircraft is to safely transport passengers from a source to a destination. This is accomplished by maintaining minimum separation from vicinity aircraft in order to avoid collision, and travel along ATC prescribed flight plans, also to avoid collision with other aircraft. The purpose of the onboard TCAS system (one instance of TCAS exists for every instance of Aircraft entity) is to protect ownship by detecting and issuing advisories to the flight crew. The purpose of the Environment can be set to none since the environment cannot and does not carry out a plan, but it was decided here to establish an entropic behaviour to personify the randomness of the environment.

Abstract Function. These are the underlying principles that are necessary for the system to actually work. The principles of aerodynamics, mass, and energy balances are modelled as a requirement for flight. For TCAS, the concept of a ‘protected volume’ is necessary to determine the existence of potentially colliding flight paths. This protected volume is measured in seconds to closest point of approach with intruder aircraft. It is variable in size and grows as the closure rate of aircraft increases. The physical laws of collision avoidance represent the algorithms that TCAS uses to detect and resolve collisions. Finally, the Environment must conform to the physical laws allowing flight and collision avoidance. Also, there must be a conservation of traffic density; aircraft do not suddenly appear or disappear from the sky.

Generalized Function. In the case of Aircraft, the general phases of flight are modelled: Takeoff, Climb, Cruise, Maneuver, Approach, Landing, and Taxi. In the case of TCAS, ownship and intruder tracking functions combine with surveillance and threat detection activities, from which a determination of TA or RA may be necessary. In the event of a critical threat, the output of TCAS functionality is a planned avoidance maneuver to issue to the pilot. Finally, the Environment functions are closure or separation of the involved aircraft.

Physical Function. This layer describes physical parts needed to accomplish the General Functions. For Aircraft, the engines, control surfaces, autopilot and flight deck controls work together to orchestrate any one of the Generalized functions. Note that autopilot and flight deck controls are not mutually exclusive physical functions. Autopilot is a subset of flight deck functionality, and can be disengaged at any time. The TCAS computer unit, along with the necessary sensors and transponders, provide threat detection functionality. Finally, the Environment contains a physical flight path (or set of flight paths) leading to or avoiding collisions. Also, current flight paths and predicted flight paths are expressed as physical functions.

Physical Form. The Aircraft entity consists of detailed flight parameters measured for instrumentation: indicated airspeed, heading, position, attitude, and pressure altitude. These flight status parameters reveal the location of the aircraft and are indicative of flight performance. For TCAS, its appearance and location are both integrated into the Primary Flight Display, while its fundamental output data are the ranges of vertical speed that are safe, cautious, or dangerous with respect to the collision situation. When an RA is calculated, a climb or descent command is issued based on a comparison with the current vertical speed of the aircraft. Finally, in the Environment, the most fundamental data elements relevant for collision detection and avoidance are time to contact, lateral and vertical separation, closure rate, and the closest point of approach of the involved aircraft. Figures 1 through 3 illustrate the three AH’s.

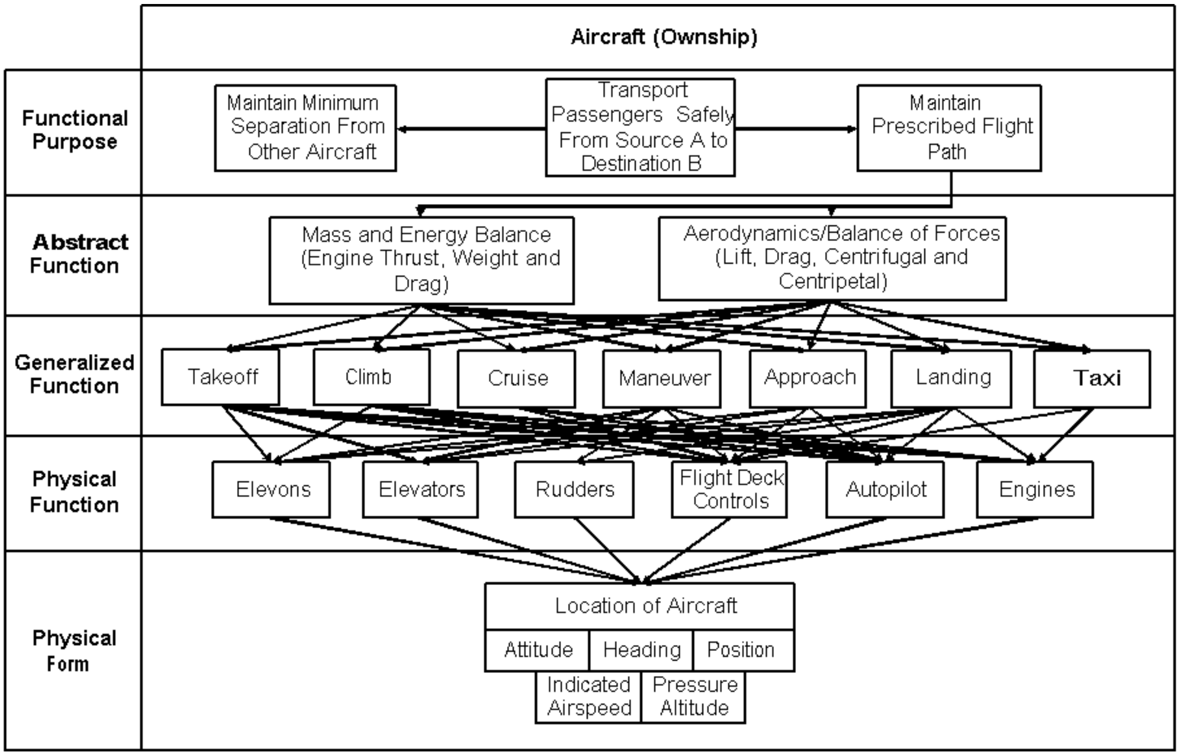

Figure 1. Abstraction Hierarchy of ownship.

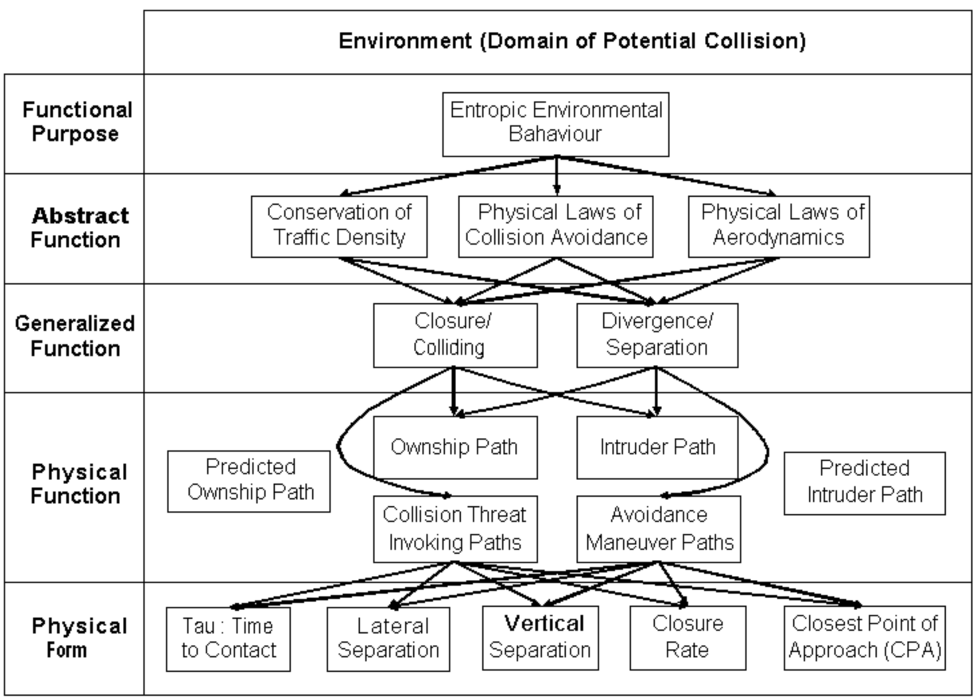

Figure 2. Abstraction Hierarchy of collision threat environment.

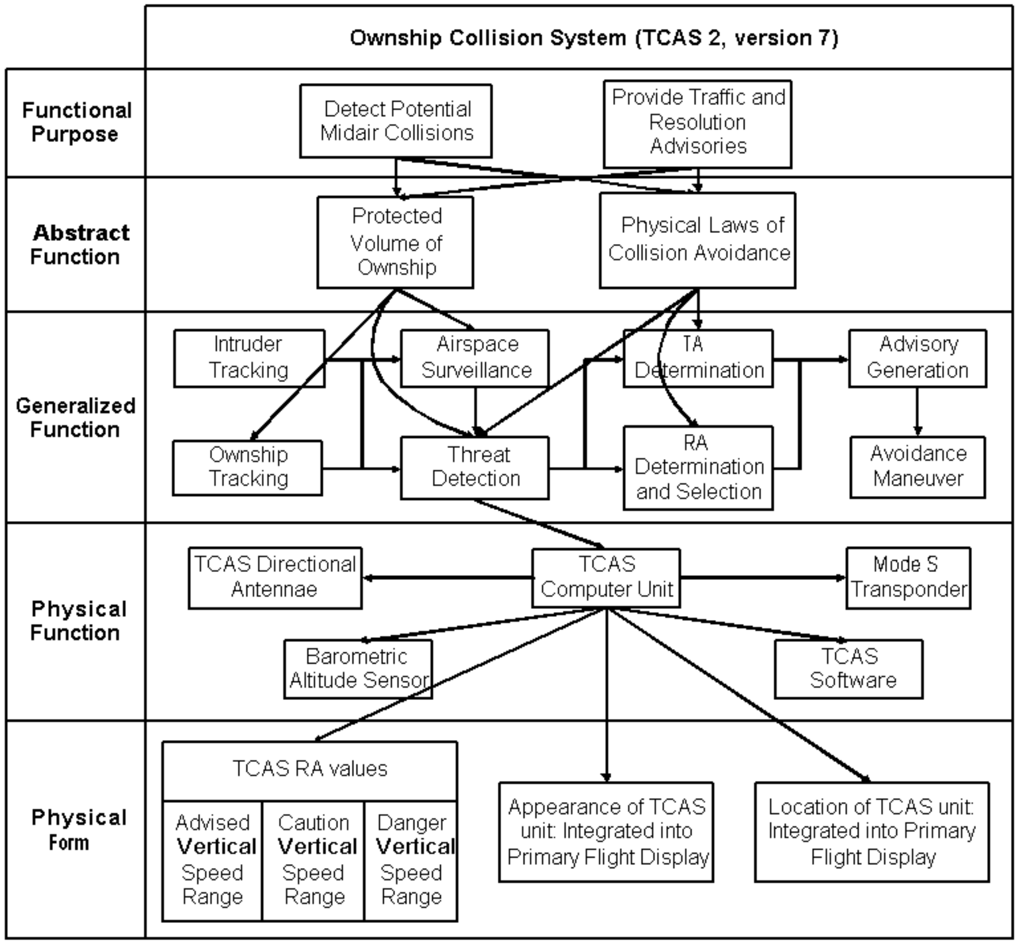

Figure 3. Abstraction Hierarchy of TCAS system onboard ownship.

DISCUSSION

The current TCAS display acts as a status display and a command display (Wickens & Hollands, 2000). Bearing, vertical rate, and relative altitude of nearby aircraft are shown on a traffic map. This information helps the pilot visually acquire the aircraft to maintain separation and perform in-trail climb and descent (Klass, 1996). If ownship is within 50 seconds of a loss of separation (LOS) with surrounding aircraft,a TA is issued in the form of verbal warning: "Traffic. Traffic", and the intruder icon color will change to yellow on the display. If ownship is within 25 seconds of LOS, the intruder icon turns red in colour and an RA is issued verbally and on the vertical speed indicator (VSI), indicating the required range of climb/descent rate to avoid the LOS.

The WDA performed in this study revealed additional information requirements beyond those of the current TCAS display that may increase its reliability. The EID-derived elements such as traffic history trends, traffic path prediction, explicit display of time-to-contact, and closure rate envelopes are viable candidates for further TCAS display research. With further application of EID methodology, enhanced TCAS displays will allow progressive monitoring of a collision threat, potentially reducing the likelihood of TCAS automation disuse (Parasuraman & Riley, 1997).

CONCLUSION

This paper presented a WDA of the automated collision detection and avoidance domain in aviation as a first step towards EID enhancement of the pilot-automation interaction of TCAS. A five-layer abstraction hierarchy was constructed for the three separate entities of the domain: Aircraft (flight dynamics), TCAS, and the collision threat environment. The resulting layers revealed information requirements that may be candidates for future TCAS display research. The next phase of this research effort is to duplicate TCAS 2 functionality on Microsoft Flight Simulator 2002 Professional. A set of EID-based enhancements will be implemented and tested to measure their impact on pilot trust in TCAS automation.

It is possible that an altered TCAS display will change pilot perceptions of its reliability. From a cognitive workload standpoint, pilot performance on overall cockpit activities may also be affected. Further investigation is recommended to determine if the costs to cockpit performance is worth the increased reliability of the TCAS automation.

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REFERENCES

Barhydt, R., & Hansman, R. J. (1997). Experimental studies of intent information on cockpit traffic displays. *9 th International Symposium on Aviation Psychology*.

Bliss, J-P. (1997). Alarm reaction patterns by pilots as a function of reaction modality. *International Journal of Aviation Psychology*. Vol. 7 (l), l-14.

Burns, C.M., Bryant, D.J., & Chalmers, B.A. (2000). A work domain model to support shipboard command and control. *Proceedings of IEEE Transactions on Systems, Man and Cybernetics*. 2228 – 2233.

Dinadis N., & Vicente, K.J. (1999). Designing functional visualizations for aircraft systems status displays. *International Journal of Aviation Psychology*. Vol. 9 (3), 241-269.

FAA (2000). Introduction to TCAS II Version 7. *U.S. Dept. of Transport. Federal Aviation Administration*. Nov. 2000.

Fulgham, D.A. (2003). New collision warning system undergoes flight testing. *Aviation Week & Space Technology*. Vol. 158 (3). 51.

Gempler, K.S., & Wickens, C.D. (1998). Display of predictor reliability on a cockpit display of traffic information. (*Technical Report ARL-98-6/ROCKWELL-98-1*). Savoy, IL: University of Illinois, Institute of Aviation, Aviation Research Lab.

Hajdukiewicz, J.R., Doyle, D.J., Vicente, K.J., & Burns, C.M. (1998). A work domain analysis of patient monitoring in the operating room. *Proceedings of HFES 42nd Annual Meeting*. 1038-1042.

Klass, P.J. (1993). New TCAS software cuts conflict alerts. *Aviation Week & Space Technology*. Vol. 139 (12). 44.

Klass, P.J. (1996). In-trail TCAS descent approved by FAA. *Aviation Week & Space Technology*. Vol. 145 (23). p 32.

Krishnan, K., Kertesz, S., & Wise, J.A. (2000). Putting four dimensions in "perspective" for the pilot. *Proceedings of HFES 44th Annual Meeting*. 3-81 – 3-84.

Ladkin, P.B. (2002). ACAS and the South German midair. (*Technical Note RVS-Occ-02-02*). Bielefeld, Germany: Universität Bielefeld, Networks and Distributed Systems Research Group.

Moradi-Nadimian, R., Griffiths, S., & Burns, C.M. (2002). Ecological interface design in aviation domains: work domain analysis and instrumentation availability of the harvard aircraft. *Proceedings of HFES 46th Annual Meeting*; 116-120.

Mosier, K.L., Keyes, J., & Bernhard, R. (2000). Dealing with conflicting information – will crews rely on automation? *Proceedings of the Fifth Austrailian Aviation Psychology Symposium.*

Parasuraman, R., & Riley, V. (1997). Humans and automation: use, misuse, disuse, abuse. *Human Factors*, 39,230-253.

Pritchett A.R., & Vandor, B. (2001). Designing Situation Displays to Promote Confrormance to Automatic Alerts. Proceedings of HFES 45th Annual Meeting. 311-315.

Rasmussen, J. (1985). The role of hierarchical knowledge representation in decision-making and system management. *IEEE Transactions on Systems, Man and Cybernetics*, 15(2), 234-243.

Rasmussen, J. (1986). Information processing and human-machine interaction: an approach to cognitive engineering. New York: North-Holland.

Vicente, K.J. (1999). *Cognitive work analysis: towards healthy computer-based work*. Mahwah, NJ: Lawrence Erlbaum Associates.

Wickens, D.D., & Hollands, J.G. (2000). *Engineering psychology and human performance. (3rd. ed.)*. New Jersey: Prentice-Hall Inc.