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An EID Approach to Examining TCAS 2 Automation

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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 from air traffic control (ATC) and onboard Traffic Alerts and Collision Avoidance System (TCAS) were given to the Russian pilot. The TCAS resolutions issued by both aircraft would have guaranteed safe traffic separation measures, but the Russian pilot elected to comply with ATC instead, leading to the collision and subsequent loss of both aircraft (Ladkin, 2002).

This accident has shed light on human factors issues arising from the use of TCAS. Specifically, given conflicting advice, why does the pilot choose one source over the other? Also, how can an interface better prepare pilots for automated warnings? Is there a way to convince the pilot rather than simply command them? Work Domain Analysis (WDA) and Ecological Interface Design (EID) are approaches that have been shown to improve operator performance in complex systems (Vicente, 1999). Therefore, it may be able to enhance performance of the TCAS system since operators who understand the system (the pilots) may be more likely to accept its advice.

This technical report introduces the EID approach to investigating automation within the TCAS setting. A work domain analysis (WDA) of automated collision detection and avoidance will be presented, and the application of ecological interface design (EID) methods for building an experimental TCAS display will be discussed, along with potential design ideas. It will be shown that WDA and EID can contribute to a better understanding of automation and its role in TCAS.

Note: This report focuses on the TCAS 2, version 7. The term 'TCAS' shall refer to TCAS 2 in the remainder of this report.

What is TCAS

The TCAS system evolved from the standards of the ACAS system of the 1970's, and was first implemented in 1981 by the Federal Aviation Administration. The latest implementation, TCAS 2 version 7, is internationally adopted and mandated by North American aviation authority (FAA, 2000).

TCAS operates independently of other radar and traffic management systems, ground-based or otherwise. It is responsible for detecting traffic threats, issuing Traffic Advisories (TA) and Resolution Advisories (RA) to the pilots in the case a maneuver is necessary to maintain a safe vertical distance from other aircraft.

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). Later, compliance with TCAS RA's was mandated by the FAA. In addition, ATC must withhold instructions during such events until all TCAS maneuvers are complete (FAA, 2000). 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 pilot was uncertain and consequently unable to resolve the situation.

TCAS Logic

TCAS requires transponders installed on both involved aircraft to communicate the necessary flight information for the detection of collision threats. Transponders broadcast self-identifying information as well as flight status with each other at one second increments. The TCAS transponder interrogates vicinity aircraft for information and receives their bearing, range, and altitude information. With a Mode-C transponder, pilots receive only traffic alerts in the form of Traffic Advisories (TA), which are often used for visual acquisition of traffic. Mode-S transponders on both aircraft will provide additional non-conflicting Resolution Advisories (RA).

The TCAS computer unit performs airspace surveillance, intruder tracking, ownship altitude tracking, threat detection, RA maneuver determination and selection, and generation of advisories (FAA, 2000). Using altitude and aircraft status inputs from owship, the TCAS computer determines the ownship 'protected volume'. The unit of measure for this protected volume is Tau, or time to closest point of approach (CPA). As ownship ground speed increases, it's protected volume also increases. If the CPA of traffic aircraft is within the protected volume, it is considered a threat. In the event of a potential collision, one aircraft's flight crew will be instructed to climb, while the other is instructed to descend.

Figure 2 shows the sensitivity level for alarms as ownship altitude increases (aircraft fly faster at higher altitudes). At each sensitivity level, the alarm activation activates for a different value of tau. In the case where lateral convergence of aircraft is very slow (one plane catching up to another), fixed distance thresholds (DMODs) are used to activate an alarm. Similarly, in the case where vertical convergence of aircraft is very slow (one plane climbing/descending slowly upon another), fixed altitude thresholds are used to activate an alarm. See Figure 2.

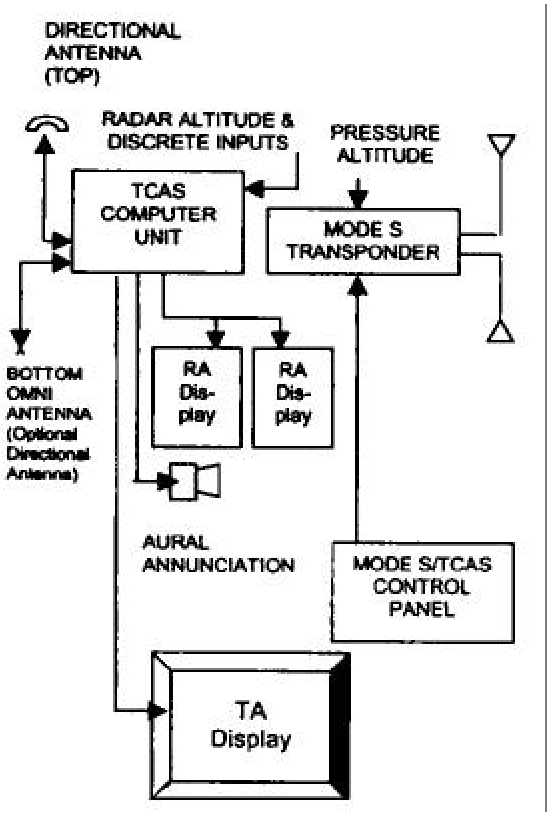


Figure 1 - TCAS schematic (FAA, 2000)

Own Altitude (feet)	SL	Tau (Seconds)		DMOD (nmi)		Altitude Threshold (feet)	
		TA	RA	TA	RA	TA	RA (ALIM)
< 1000	2	20	N/A	0.30	N/A	850	N/A
1000 - 2350	3	25	15	0.33	0.20	850	300
2350 – 5000	4	30	20	0.48	0.35	850	300
5000 – 10000	5	40	25	0.75	0.55	850	350
10000 – 20000	6	45	30	1.00	0.80	850	400
20000 – 42000	7	48	35	1.30	1.10	850	600
> 42000	7	48	35	1.30	1.10	1200	700

Figure 2 - TCAS Sensitivity Levels for Alarm Activation (FAA, 2000)

Traffic Advisories and Resolution Advisories

TCAS issues 2 types of automated alerts: A Traffic Advisory (TA) is issued if vicinity traffic poses a potential threat, and alerts the pilot to their presence. A Resolution Advisory (RA) is issued when a critical threat is detected, and an evasive maneuver is presented to the pilot for avoiding the collision.

TA's are displayed on the traffic map (see Figure 3, left photo), accompanied by aural announcement. The flight crew do not respond actively to TA's, and continue to obey ATC flight instructions. However, TA's are a positive motivator for pilots in the vicinity to confirm traffic reports and intentions with each other.

RA indicate threat traffic on the traffic map and provide critical vertical maneuver advice to avoid a disastrous incident. On the vertical speed indicator (VSI), lights will show green, yellow, and red along the vertical speed scale to indicate the climb rates that will achieve safe separation, provide potential threat, and lead to potential collision, respectively (Figure 3, right photo). Aural announcement is also produced for RA's. The pilot responds to the RA by executing a climb rate in the green colour zone. RA's typically involve one aircraft to descend while instructing the other to climb.

The symbology of TCAS alerts is described in Figure 4.

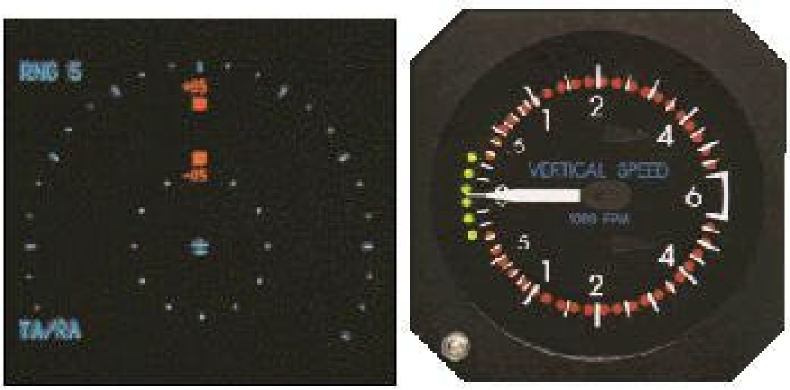


Figure 3 - TCAS Flight Displays: TA Display, and VSI/RA Display (Honeywell, 2000)

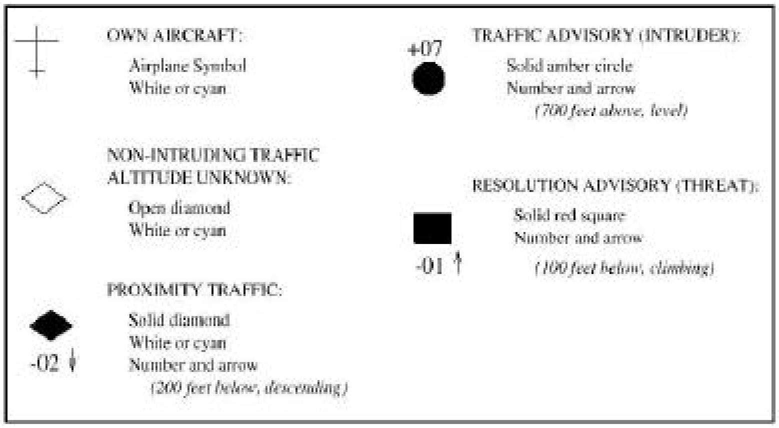


Figure 4 – TCAS Symbology(Leveson, 1999)

Flight Crew and ATC Interaction

According to North American air safety regulations, the flight crew must exercise all measures necessary to insure flight safety. In the case of RA's, the flight crew is expected to execute all RA's, with the understanding that they are overriding ATC flight instructions (FAA, 2000). Additionally, it is the flight crew's responsibility to inform ATC of the RA incidents, and confirm execution of the maneuvers. ATC is required to release responsibility of the aircraft's route in the event of an RA, reinstating control after the RA maneuver is executed. However, should an RA be advised to flight crew and they fail to inform ATC, the system exhibits communication breakdown (Mellone, 1993). ATC may continue to issue instructions, sometimes conflicting with TCAS recommendations. This was the case in the July 2002 midair collision.

The EID Approach

Work Domain Analysis (WDA) and Ecological Interface Design (EID) methods help interface designers focus on revealing the system or process as much as possible to the user, in a matter that is contextually relevant, conceptually coherent, and perceptually efficient. The end result is a flexible interface that can be tailored easily for experts to beginner users alike, helping them to fulfill monitoring, operating, and maintenance tasks. WDA and EID begin from the system level approach, as opposed to the user-task level, typically found in task and cognitive design methodologies. The question here is "What data should be extracted and how should it be presented to help the user make the best decisions?" instead of "What does the user perform best, and how can we make the interface meet their performance level?".

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 in 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.

The Abstraction Hierarchy

EID relies on a developed hierarchal model of the system or process, from which critical informational requirements can be extracted. 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. At the top are the overall system goals, with a progression downwards to the most basic specification of system components. In order, these layers are: Functional Purpose, Abstract Function, Generalized Function, Physical Function, and Physical Form. Horizontal interpretation within individual layers conveys a part-whole ("contains-within") understanding. The part-whole abstraction has not yet been finalized at time of writing of this report.

Applying EID to Collision Avoidance and Detection Domain

The Three Entities

The domain of collision detection and avoidance was separated into three entities: Aircraft, Environment, and TCAS. The Aircraft entity models the flight dynamics of any and all aircraft that are involved in the potential collision, not the aircraft as a physical entity. In our example, ownship and intruder ship are modeled 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 broken down into their respective five layers of abstraction. Figures 5 through 7 illustrate the three entity AH's.

Layer Descriptions

The first layer is 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, again 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.

The second layer is 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 variable in size, and grows as the speed of the 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.

The third layer of the AH is 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.

The Physical Function 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.

In the last layer of the AH, 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.

The EID analysis revealed information requirements for creating a more informative TCAS interface, an interface that convinces the pilot of the automated TCAS advisory.

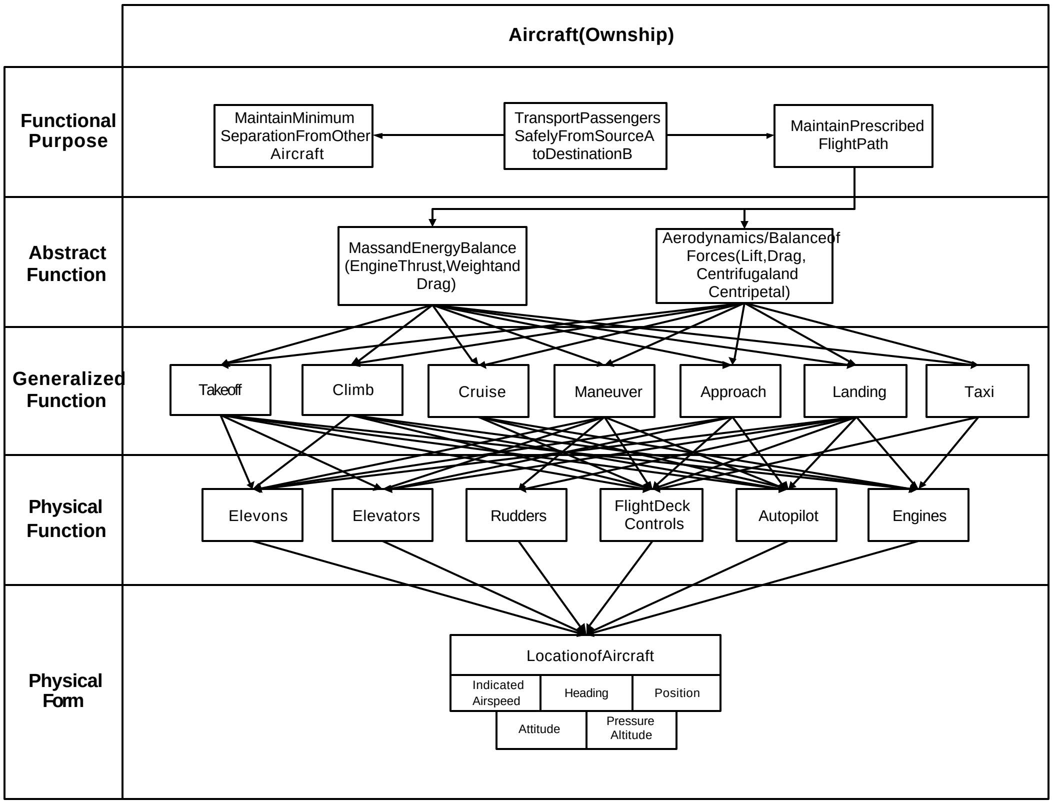


Figure 5 – Aircraft (Ownship) Entity - Abstraction Hierarchy

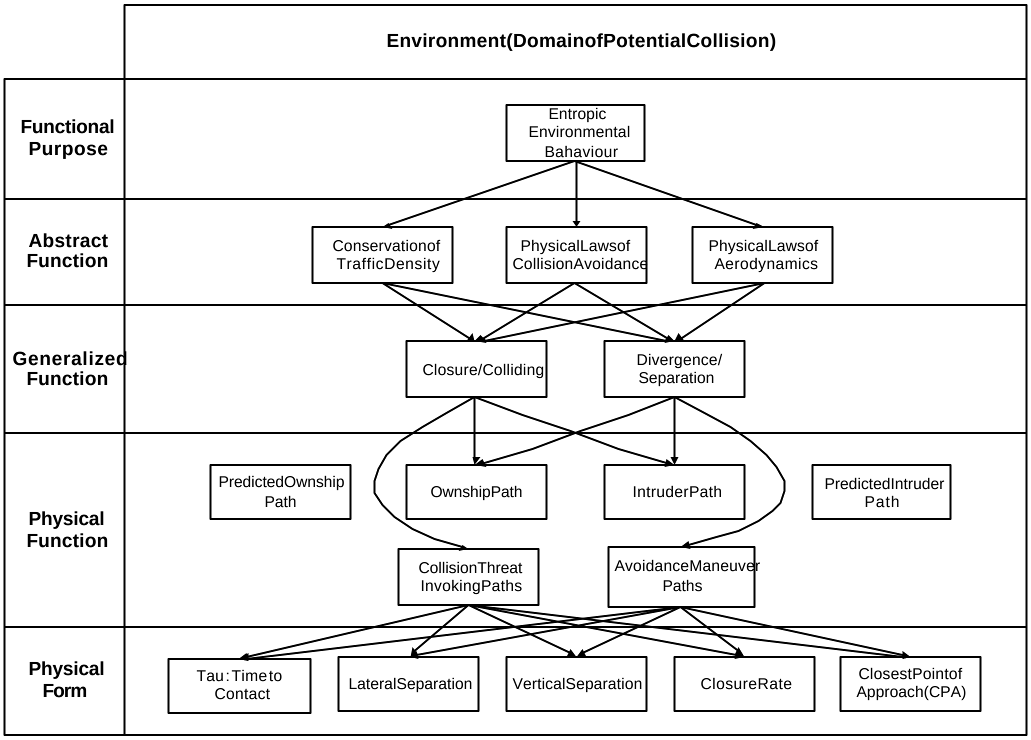


Figure 6 - Environment Entity- Abstraction Hierarchy

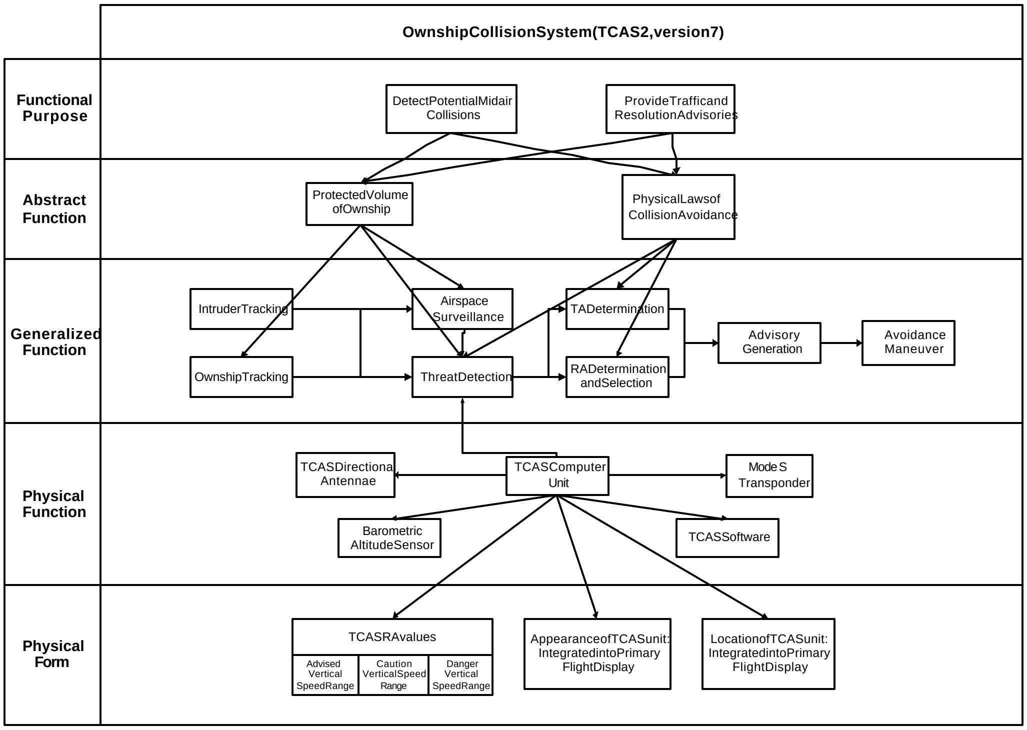


Figure 7 – TCAS Entity - Abstraction Hierarchy

Literature Review

Traffic Displays - CDTI

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). The CDTI is a consolidated platform responsible for displaying a variety of information, including weather, terrain, traffic, and flight plans to name a few. Research efforts addressing CDTI with respect to 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 traffic intent information in TCAS (Barhydt & Hansman, 1997).

Cockpit Automation

Although there are many studies of automation in the cockpit, two common observations across studies are highlighted here:

> **Crew reliance on automation**, studied by Mosier (2000). She discovered that when other data are made to be equally salient with automated information (such as ATC vs. TCAS), pilots do not exhibit a systematic preference for automated information. They seem to trust traditional indicators over automated information. Other factors, such as the perceived validity of conflicting information (the perceived reliability of the automation is evaluated), also impact whether or not automated cues were trusted. Pilots seem to assume high validity when information comes from fellow crewmembers, and less validity when the reporting human is an air traffic controller. In other words, with human advice, those physically closer to the situation are trusted more.
>
> **Automation overtrust versus undertrust**, studied by Wickens (1994). Wickens determined that overtrust may result from a failure to initially calibrate a level of less than perfect automation. If one believes initially that the automation may be perfect, then minimal monitoring or 'second guessing' will be result. Mistrust occurs once trust is lost in automation because it fails to perform as expected. This trust becomes hard to restore. Sources of mistrust include the failure to understand (poor mental model), automation failure, and perceived automation failure.

For the current study, both CDTI and automation issues will be considered for the design of an EID-based interface that automates the task of detection collision and avoidance.

Current Study - TCAS Implemention

Technical Implementation

The chosen software platform for developing and testing of the TCAS design is Microsoft Flight Simulator 2002 (FS2002) because this simulation game has a reputation for accuracy among flight enthusiasts and pilots and Microsoft provides software development kits (SDKs) for the creation of 3rd party applications. Peter Dowson has created a tool called FSUIPC tool interfaces with FS2002 and exposes flight system data to be read and written to using the FSUIPC protocols (Dowson, 2003). For a TCAS implementation, the datasets required for calculating collision avoidance detection and avoidance include ownship flight data and A.I. (Artificial Intelligence) Traffic data. With the ability to process positional relationship between ownship and traffic over time, collision detection and avoidance algorithms can be implemented.

An external TCAS display was created using Visual Basic, which takes FSUIPC data and plots them in a radar-type interface. See Appendix for VB source code. This display matches closely to existing TCAS symbology, and is the foundation for enhanced displays to be used in the experimental design stage of the thesis.

Data Architecture

Applications interfacing to FSUIPC can obtain A.I. traffic in FS2002 via an 'offset area' located at E000 to FFFF inclusive, a portion of FSUIPC allocated memory. This data area is read-only and contains the following dataset for up to 96 generated A.I. traffic:

Variable	Explanation
DWORD	Reference ID: '0' if no traffic
Lat	Latitude (degrees)
Lon	Longitude (degrees)
Alt	Altitude (feet)
Hdg	Heading (degrees)
Gs	Ground speed (knots)
Vs	Vertical speed (ft/min)
IdATC	ATC Tail number of traffic
Com1	The COM1 frequency of traffic

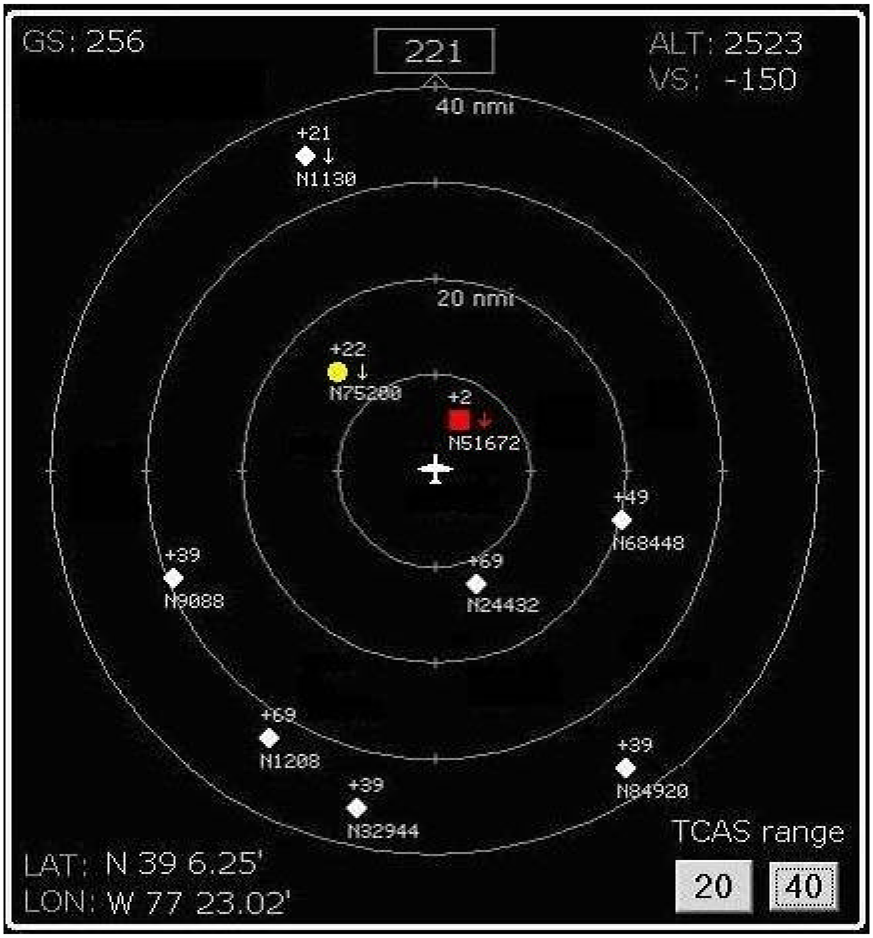
Table 1 - FSUIPC A.I. Traffic Dataset

A data type called Aircraft was created to track each aircraft, including ownship. With exception of Com1 and DWORD, the remaining variables were used to derive relative bearing and distance from ownship. All these variables are kept in a history trend of 10 capture frames, and will be used to interpolate future aircraft position, projected flight paths, and assist in TA and RA determination.

Interface Implementation

The TCAS interface created thus far is shown in Figure 8. It is conceivable that it can replace the TCAS portion of the primary flight display entirely, since it's functionality will ultimately be identical to that of TCAS. In order to reduce screen clutter, abbreviations were used as headings of flight information. Additionally, the current heading of ownship is displayed at top center of the TCAS radar, providing intuitive heading indication. Measurement units were also omitted since there is strong pilot familiarity with these flight parameters, and display redundancy of such data exists across the flight deck displays.

One element still lacking is the VSI advisory output, which shows the necessary vertical speed range in the case of an RA. This will be incorporated as part of the experimental display design process.



GS: 256

ALT: 2523
VS: -150

LAT: N 39 6.25'
LON: W 77 23.02'

Figure 8 - TCAS screenshot

Future Direction

Consistent with past EID approaches to interfaces design, the TCAS environment was treated as a system process, with the inputs, outputs, processes, and entity relationships as uncovered by the abstraction hierarchy. Already, WDA has unveiled informational requirements previously not considered in previous airborne traffic displays.

One departure from traditional TCAS displays will be the multi-panel approach. Because TCAS is embedded with a wealth of automated reasoning (detection, avoidance, and resolution decision algorithms), it would be advantageous for the flight crew to access this information. Since the current traffic map shows current state data only, the flight crew cannot rely on it for traffic tracking or intuitive flight path projections. In other words, TCAS may be left to do all the 'thinking', while the flight crew are at the mercy of ATC instructions and the sudden alerting of TCAS.

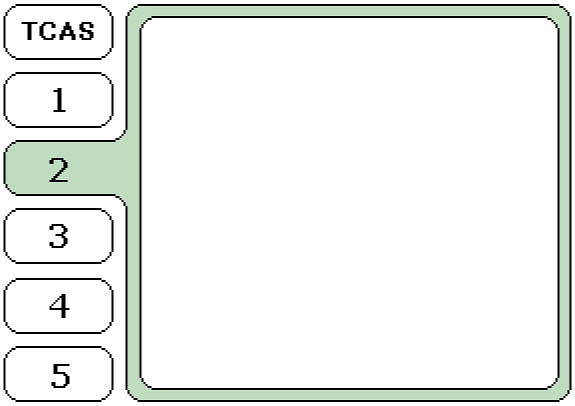


Figure 9 - An example of multi-display TCAS

In addition to exposing more of the TCAS system parameters to the flight deck though an EID enhanced display, three paradigms of traffic mapping are considered below. Using these scenarios, an experimental setup will be designed to observe the performance effects of automated TCAS decision making on pilot reactions.

Threat Tracking

Traffic may be classified based on threat probability and urgency, showing a history of their flight paths. Pilots will be alerted according to regular TCAS protocol, and they will be able to access a 'history' display to determine how and why TCAS is issuing the alerts. Since an RA alert generally evolves from a TA alert, flight crew analysis of TA occurrences will lead to expected RA alerts, where commands can be executed efficiently and safely.

Threat Projection

Traffic flight paths may also be interpolated into the future, providing a visual representation of potential collision paths so that with minimal increase of mental workload, flight crew can anticipate TA's before they happen.

Time-to-Contact Map

The unit of measure for the radar map could be scaled to Tau as opposed to distance. This way, spacing of traffic from ownship on the traffic map is directly proportional to its threat potential.

Conclusions

This technical report has summarized the progression of the thesis effort thus far, illustrating the WDA method applied to the collision avoidance and detection domain, and discussing some of the challenges and considerations for design an EID-based TCAS interface. The next step is to complete the full replication of TCAS functionality in Visual Basic, and the A.I. Traffic will be coded so that a conflicting aircraft will perform their respective RA's when the TCAS algorithm determines it.

Next, a number of EID interfaces will be proposed, implemented, and a viable experimental setup will be designed to measure the performance of pilot interaction with automated alerts in the TCAS environment.

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