Flight Collision Avoidance System for Self-Separation

Peter G Higgins
Swinburne University
Hawthorn 3122, Australia
phiggins@swin.edu.au

Yakubu Ibrahim
Swinburne University
Hawthorn 3122, Australia
yibrahim@swin.edu.au

ABSTRACT
In a Free Flight Environment, pilots are delegated the authority to choose the flight paths, maintain spatial separation and consider environmental conditions with minimum intervention from Air Traffic Controllers. These factors constitute new tasks for pilots, which otherwise would be performed by Air Traffic Control. To maintain separation of aircraft, pilots are reliant on spatial awareness in controlling basic flight parameters such as speed, heading and altitude.

Author Keywords
Free Flight; Ecological Interface Design; Cockpit Display of Traffic Information (CDTI); Situation Awareness; Human Machine Interaction; Self separation

ACM Classification Keywords
H.1.2 User/Machine Systems: Human factors; H.5.2 User interfaces

INTRODUCTION
A fundamental change to the management of air traffic is seen as necessary for alleviating the rapidly increasing demands on conventional Air Traffic Control. By adopting a Free Flight Environment [1, 2, 3], pilots supported by an Airborne Separation Assurance System (ASAS) would be delegated responsibility to create their own flight paths, with minimal interference from air traffic control [4, 5]. In managing their flights, pilots need instrumentation to help them detect and resolve conflicts. To perform self-separation manoeuvres in a free flight environment, pilots need a supportive tool that clearly shows conflict geometries, and provides alternatives to overcome a loss of situation awareness of surrounding air traffic. An airborne collision avoidance display such as conflict display traffic information (CDTI) allows pilots to carry out “visual flight” manoeuvres to avoid protected zones around other air traffic [6] without relying on the current “see and avoid” technique [7].

CDTIs that have been proposed for helping pilots avoid collisions by managing safe separation between aircraft included the geometry of relative position and velocity [8, 9, 10, 11, 12]. Chakravarthy and Ghose developed the concept of a collision cone for determining whether a collision between robots is imminent [13]. The Delft University of Technology employed the cone in their CDTI, calling it a forbidden beam.

In concordance with this work, we have configured a display that has the same underlying principles of relative motion and the forbidden beam. It differs though in the expression of the vector diagram such that the higher levels of the abstraction hierarchy for an Ecological Interface Design are more likely to open to immediate perception.

RELATIVE MOTION
The current practice in Air Traffic Management is to maintain a protected zone of five nautical miles of lateral separation around aircraft. Conflict is considered to occur when this zone is violated. Aircraft on a collision course must take evasive action to avert the conflict. Evasive action depends on pilots adjusting heading and/or speed such that the motion of their aircraft (ownership) relative to the intruder does not violate the protected zone.

No instrument is currently available on aircraft for directly supporting pilots making collision-avoidance manoeuvres based on perceived relative motion. Consider a typical conflict scenario of two aircraft at the same altitude converging in a relative motion diagram shown in Figure 1, which is a Euclidean vector diagram of lateral separation of aircraft. It shows—using Newtonian relativity—the relative velocity of the ownship to the intruder within the bounds of the forbidden beam, thereby indicating that the aircraft are on a collision course. To avoid collision, the pilot must manoeuvre this vector out of the forbidden beam by changing the aircraft’s velocity (ground speed and heading).

The ownership and intruder’s vectors are represented as shown where there is no wind. The velocity of ownership ($v_{own}$) relative to the velocity of the intruder ($v_{intr}$) is given by:

\[
\begin{align*}
\vec{v}_{own} &= \vec{v}_{own/\text{int}} + \vec{v}_{\text{int}} \\
\vec{v}_{own/\text{int}} &= \vec{v}_{\text{own}} - \vec{v}_{\text{int}}
\end{align*}
\]
DESIGN WITH APPROPRIATE AFFORDANCES

In maintaining safe separation, pilots need to be able to manoeuvre their aircraft with minimal deviation from the planned flight path. That is, the aim is to manage flight paths with corrections that gently impact passengers, well before a contention arises that invokes action from TCAS (Traffic and Collision Avoidance System).

The instrument must warn a pilot of an impending breach of separation standards through a signal that is sufficiently salient for drawing attention to the impending situation and to support the perception of strategies for resolving the situation. To respond appropriately, the pilot must be aware of the extent of the violation of constraints on safe passage. Moreover, for goal-directed behaviour, the pilot must also perceive how to adjust heading and/or speed to alleviate the situation. For a pilot well-practised in the use of the instrument, the behaviour would be skill or rule based within Rasmussen’s SRK (Skills, Rules, Knowledge) typology [14].

\[ \vec{v}_{own} = \vec{v}_{own/\text{int}} + \vec{v}_{\text{int}} \]

In Figure 3, the forbidden beam, \( \odot \), is shaded, with its apex labelled as \( \odot \). The velocity vector for the ownership is depicted by an arrow. While its head is within the forbidden beam the aircraft are on a collision course. This display has affordances that pilots may find well-suited for operating under behaviour that is skill or rule based. They can readily see that they are on an unsafe path. By changing heading and speed, the magnitude and direction of the velocity vector can be adjusted such that the head of the arrow moves outside the forbidden beam. However, the display in Figure 3 unfortunately lacks affordances to the underlying principles of Newtonian relativity for the following reasons:

1. An ownership perspective by the pilot is lost because the pilot’s viewpoint is not at the apex of the forbidden beam
2. The intruder’s protected zone is not shown as sub-tending the forbidden beam
3. The display of the vectors for both the velocity of the intruder and relative velocity of the aircraft shown in Figure 2 are missing

**Figure 3. Delft Display with Forbidden Beam [8]**

**Work Domain Analysis**

The Newtonian principles of relativity and Euclidian vector relationships, discussed above, are abstract principles of motion relating collision avoidance activities. Representation of a system for collision avoidance can be analysed at different levels of abstraction: from the components of the physical system to the underlying abstract principles.

Work Domain Analysis (WDA) is a template, developed by Rasmussen, for analysing and modelling systems using various levels of abstraction [14]. It is a generic framework for describing goal-oriented systems, in a way that depicts their purpose and physical aspects [15, 16, 17]. It is one

**Figure 1. Euclidean vector diagram for lateral separation.**

**Figure 2. Delft vector diagram for lateral separation**

The vector diagram used by Delft in developing their display (Figure 3) is shown in Figure 2. It is based on the following vector relationship, which is a re-ordering of the relationship shown above:
of the two types of analysis incorporated in Cognitive Work Analysis (CWA). In that it describes the system in an event independent way, WDA is quite separate from Cognitive Task Analysis (CTA), which is an event dependent analysis of the activities that take place within the domain. That is, CTA represents the activities of decision agents in interaction with a system described by WDA.

WDA uses an Abstraction Hierarchy that comprehensively describes a system at each level of abstraction. The higher levels describe the reasons or purposes of the physical system described at the lower levels [18]. Rasmussen called the levels—from the most to least abstract—functional purposes, abstract functions, generalised functions, physical functions and physical form (Figure 3). Since the framework was devised in the 1980s, improved terminology has evolved that denotes the levels unequivocally. They are—in like order—functional purposes, values and priority measures, purpose-related functions, object-related processes and physical objects [19].

The uppermost level of the abstraction hierarchy expresses the functional purposes of the system. Levels are linked through “means-ends” relationships; arcs from nodes at each level link nodes at the level below, such that the lower-level nodes represent the means for obtaining the ends for the upper-linked nodes. The level of abstraction that is applicable for the description of the system and its constraints varies with activities associated with CTA, which may be skill, rule or knowledge based. The form that is appropriate for displaying data varies with the type of decision being made. The presentation and control of information between the system and human may vary with the recognition-action cycles of the cognitive tasks. The tasks associated with recognising the state of the system are linked to the abstraction hierarchy of the work domain.

To support behaviour within the SRK typology, goal-relevant constraints from the work domain should map onto salient perceptual properties of the display, at the various levels of abstraction. A display that represents concurrently the various levels of abstraction, Vicente and Rasmussen called an Ecological Interface Design (EID) [20]. Its goal is to allow activities to be performed at the level of cognitive demands that the task requires. If constraints are mapped into an interface that is based on an abstraction hierarchy, pilots’ mental models can be captured and externalised to improve situation awareness [21]. Such a configurational display, which can be directly manipulated by the user, may help novice pilots form a mental model that properly represents the system. It can act as externalised form of the user’s mental model, thereby supporting activities that would otherwise be held in working memory [22].

**FLIGHT COLLISION AVOIDANCE SYSTEM**

The functional purpose of the Flight Collision Avoidance System (FCAS) is to assist pilots to manage the safe separation from other air traffic as the flight progresses. The level of functional purposes in the abstraction hierarchy pertains to the purpose and constraints affecting the system’s operation. These processes are influenced by external constraints that are based on standard rules, laws or tests for achieving the main objective or purposes of the system. A goal of pilots operating in a free flight environment is not to violate separation constraints with other aircraft. Therefore, the functional purposes of a FCAS that supports activities associated with this goal are depicted at the top level of the abstraction hierarchy shown in Figure 4 as:

- Detect potential violation of separation
- Provide resolution guidance

A display based on EID allows pilots to access information at the level of abstraction they require when making decisions. Typical questions may be: How close is their aircraft to the intruder’s protected zone? How much faster or slower should they fly to avoid collision without changing heading? What change in heading, while maintaining speed, should they fly to avert conflict? These questions concern relative relationships between aircraft, which are derived from information from physical sensors. That is, their observation is at the level of purpose-related functions.

The principles and performance metrics that direct the processes underlying the system’s progression towards its functional purposes is at the level of values and priority measures. The laws governing conflict zones are defined and controlled by minimum separation standards, while performance is judged by suitable metrics—concerning, perhaps, increase in flight path, flight time or fuel burnt—and observation of inviolable constraints, such as not transgressing the boundaries of the protective zones.

Below the level of values and priority measures is the level of purpose-related functions. This level is in terms of the functions, responsibilities and processes that influence the constraints at the level above. It provides pilots with necessary information for performing flying activities such as lateral manoeuvres to avoid obstacles. Pilots are required to manoeuvre their aircraft outside the intruder’s protective boundary, i.e., not violating minimum separation standards. Fundamental physical quantities of aircraft are relative positions, velocity and protected zone. There are key elements of conflict geometry. The ability of pilots to change aircraft direction is constrained by aircraft manoeuvrability. An aircraft’s manoeuvring capability for lateral control is also constrained by the minimum separation standard and wind speed. However, understanding these constraints provides pilots with the mechanism to control and maintain the desired flight path.
At the second lowest level of the hierarchy is detailed information about the physical system in terms of object-related processes: the means for achieving the functional purpose of the system. It enables pilots to interact with the system at the physical functional level. The lowest level specifies the actual physical objects for the functions described by the object-related processes: for example, the physical object for obtaining the function of airspeed is depicted in Figure 4 with a generic label of airspeed sensor. In its simplest form, this instrument displays indicated airspeed, which is not true airspeed as it is uncorrected for changes in temperature and altitude. In the FCAS, ground velocity is derived from a combination of sources including GPS and the on-board inertial navigation system.

**Formation of the FCAS display**

The display for the FCAS was developed as shown in Figure 5 by starting with the Euclidean vector diagram for lateral separation (Figure 1). It is a presentation of the FCAS at the level of purpose-related functions in the abstraction hierarchy (Figure 4). The circle around each aircraft shows the constraint boundary of five nautical miles for the protective zone that must not be violated. The vector labelled “e”, depicting the velocity of the ownship relative to the intruder, when inside the forbidden beam signifies that the aircraft are on a course for which separation will be violated. That is, a view of the FCAS at the level of value and priority measures is accessed via the protected zone, the forbidden beam and vector relationships.
As aircraft move closer, the white line labelled “f” denotes loss of separation. Accompanying the loss of separation, the angle of the forbidden beam increasing, thereby adding salience to the signalling of its rate of loss.

The image of a miniature aircraft is centred on the navigational compass. The arc labelled “j” at the top of the display represents the bank angle range. This guides the pilot to not violate physical parameters of flight (which would be included in a separate abstraction hierarchy with flight as the functional purpose).

**EXPERIMENTAL TEST OF FCAS DISPLAYS**

Under simulated flight conditions, two collision avoidance displays—one FCAS based on EID (Figure 6) and the other not (Figure 7)—were studied under experimental conditions. The twenty one participants recruited were either aviation students or professional pilots, of which 81% were between 18 and 40 years old and the others were older than 50 years. Divided into experimental (13) and control (8) groups, they used the EID and non EID displays, respectively. The experiment lasted approximately an hour.

The experiment was conducted on a standard desktop computer and colour monitor (using 1024 x 768 XGA with a graphics card) with the inclusion of a Saitek Pro Flight System. The simulator software and the interface for the yoke and throttle were written in C++ language and MATLAB script. The software enabled pilots to avoid obstacles by tracking, navigating, maintaining or deviating from the intended flight path. The algorithm was a level-aircraft conflict resolution of flying a twin-engine aircraft under no wind conditions [9]. Aircraft dynamics were not modelled.

Participants were asked to perform tasks under simulated Instrumental Flight Rules. Each experimental run consisted of three conflict scenarios—head on, port and starboard approaches—in which a conflict occurs. Both the ordering of the scenarios and the heading for each scenario were randomly assigned. The ownship was allowed to manoeuvre to avoid conflict, while the intruder maintained a constant heading that was randomly assigned.

Participants were instructed to fly a specific flight route by an ATC command shown in the upper right corner of the display. They continued to fly the prescribed flight route and airspeed with minimum deviation as commanded by ATC. Each scenario began with a different flight course. Participants observed the development of conflict scenario for seventy seconds. There was one or two other aircraft, which could pose a threat to the ownship protected zone. The FCAS display provides participants with basic information about others aircraft relative positions, velocity vector, altitude and airspeed of a nearby aircraft. The forbidden beam appeared when the intruder position was 21 nautical miles relative to the ownship position. Participants were required to start manoeuvring only on a TCAS-like audio warning of a threat. A standard rate of turn (three degrees per second) was used for a heading change. A rate of change in aircraft heading was a function of bank angle. Both the control and experimental FCAS incorporated the
Post-trial questionnaire

To evaluate the system's usability, participants undertook a post-trial questionnaire that used a five-point Likert scale for the questions shown in Table 1. The results in Figure 8 show that for all questions, the users of the EID display responded more favourably than those using the non EID version. The results for the questions (Q2, Q4 and Q6), which relate directly to the primary purpose of the FCAS, indicate that while users found the EID display somewhat more useful than the non EID version for locating intruders and avoiding conflict, the EID form of the FCAS was perceived to be much more useful for following a desired flight path.

<table>
<thead>
<tr>
<th>Question</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Q1</td>
<td>The response of the yoke and throttle was too sensitive for me to track the path I wanted to follow.</td>
</tr>
<tr>
<td>Q2</td>
<td>How useful was the system for understanding the location of the Intruder relative to the Ownship?</td>
</tr>
<tr>
<td>Q3</td>
<td>How useful was the system for understanding the direction of travel of the Intruder?</td>
</tr>
<tr>
<td>Q4</td>
<td>How useful was the system for avoiding conflict?</td>
</tr>
<tr>
<td>Q5</td>
<td>How useful was the system for avoiding stall when manoeuvring the aircraft?</td>
</tr>
<tr>
<td>Q6</td>
<td>How useful was the system for providing sufficient information for following a desired flight path?</td>
</tr>
<tr>
<td>Q7</td>
<td>Please rate your overall opinion of the system.</td>
</tr>
</tbody>
</table>

Table 1: Post-trial questionnaire

Correlation analyses were conducted on the responses to the questions, to determine how well the dependent variable correlates with the participants’ ratings. Results of the analyses are plotted in Figure 9 and Figure 10. Participant pilots are shown as nodes; arcs represent the correlation between paired pilots. Correlation coefficients of 0.7, 0.8 and 0.9 are shown as light blue continuous lines, black dashed lines and black continuous lines, respectively.

Figure 8: Mean ratings on seven subjective preferences questions for experimental and control group.

Figure 9: Spider-web visualization of the correlation matrix for the experimental group.

The patently obvious difference between pairing for the two displays reflects a difference in responses to the questions. The common pattern of responses by users of the EID display is not matched by the users of the non EID version. These results indicate—prima facie—that pilots using the non EID FCAS had very mixed assessments of the display. A “positive” conclusion that is tempting is to conclude that a design of an FCAS based on EID principles is superior. However, a scientifically sceptical view is that the display used as a control is that of a “straw man.” The problem that the researchers encountered was that flight collision avoidance systems used by pilots for maintaining spatial separation are not currently available. Therefore, they had
to develop a non EID display that represents all information for the separation task in a “conventional” way.

Figure 10: Spider-web visualization of the correlation matrix for the control group.

CONCLUSION

The design of the flight collision avoidance system (FCAS) was based on the principles of Ecological Interface Design (EID), with the objective of making constraints and principles of relative motion visible to pilots. The FCAS with EID has two major elements associated with purpose-related functions and measures of values and priority:

(a) A forbidden beam display

(b) A relative motion display

Previous developed experimental collision avoidance systems based on EID inadequately map the relationship between these components, as they do not clearly show the geometry of conflict and operational constraints. With well-mapped constraints, pilots may be able to enhance their mental models of collision avoidance and then make use of the mental model that is externalised in the FCAS to improve situation awareness.

While experimental results are inconclusive, they show that there were significance differences in the behaviour of the users of EID and non EID displays. It seems that what is important in collision avoiding system’s design for a free flight environment is that they should support pilots in guiding them in such a way that their performance is consistent and safety is not compromised.

REFERENCES


