Development of a Horizontal Collision Avoidance Display to Support Pilots’ Self-Separation in a Free Flight Environment

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Abstract: In a Free Flight Environment, managing separation between aircraft is delegated to the pilot by Air Traffic Management. The future adoption of a Free Flight Environment is necessary, as Air Traffic Controllers will be unable to handle the workload from the forecasted doubling of air traffic within two decades. The responsibility of pilots will expand to include a new set of cognitive demands associated with separation tasks. In managing separation, pilots adjust speed and direction of their aircraft within specified constraint boundaries. An Ecological Interface Design approach has been used to design a novel collision avoidance display to support pilots as they visually evaluate their constraints and implement manoeuvres to avoid air conflict, as compared to conventional approaches. The novel airborne display makes full use of a relative motion and protective cone display to bring these constraints to view as flight progresses. The interactive nature of these displays enables pilots to improve situation awareness and reduce cognitive workload. This paper describes the development and evaluation of the novel collision avoidance display.

Keywords: Free Flight Environment; Ecological Interface Design; Cockpit Display of Traffic Information (CDTI); Situation Awareness; Human and Machine Interactions.

Introduction

The goal of Free Flight environment is for a pilot to manage self-separations as the flight progresses. However, the environment is predicted to introduce new systems, procedures, and tasks as compared to the current Air traffic Management (ATM). These might impose new cognitive workload. Previous tasks associated with pilots’ cognitive workload would change the nature of managing self-separation.

The volume of air traffic is expected to double in the next two decades [1, 2, 3]. The possibility of mid-air collisions and air traffic controllers’ workload will increase therefore. However, the continuous stream of aircraft to be managed can tax the ability of the most experienced air traffic controllers [4, 5]. This challenges pilots’ abilities to apply the “see and avoid” technique to avoid conflicts. The use of this technique has failed both pilots and controllers in detecting and resolving mid-air conflicts [6]. Further, pilots’ visual “see and avoid” assessment do not provide flight information the intent of other traffic. Thus, analysing conflict situations at different speed can be misleading. For example, flight dynamics of a heavy aircraft at a slow speed make it difficult for pilots to ascertain whether the aircraft is climbing or descending [6].

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Pilots should actively scan for potentially conflicting air traffic. Because the pilots “failed to look”, “looked but failed to see”, and “could not see” the incoming air traffic [7] is cited as a major cause of mid-air collisions [6]. However, not all conflict geometries are easy to detect and resolve. Therefore, for pilots to perform self-separation manoeuvres in a free flight environment, they need a supportive display that clearly shows the geometry of conflicts and provides alternate flight paths to overcome this difficulty [8].

1. Work Related to Traffic Collision Avoidance Display

Resolving collision problems has been investigated in many fields such as robotics, automobiles and the aviation domain. Several studies have proposed approaches for detecting and resolving conflict in aviation domain. However, [9] have presented an extensive review of these approaches related collision avoidance systems in aviation. The following papers have highlighted some of the flight constraints for managing safe separation: an airborne display for maintaining spatial separation [10] relative motion for level conflict avoidance [11]; performing level turn conflict resolution [12], collision avoidance [13, 14], the effect of geometry on traffic display [18], manoeuvre constraints [15], geometry optimisation [19], conflict geometries [16] and evaluation of separation display [19].

2. Development of a Collision Avoidance Display

As air traffic is predicted to increase, a new technology is being developed to replace the current ATM systems. The new technology, such as Conflict Display Traffic Information (CDTI) proposed in the literature will give pilots the ability and capability to change flight trajectory at any given time and make decisions independently [20]. In doing do, pilots will have to cope with a change in mental workload and situation awareness.

Automated display systems and not human issues are the driving force behind the next generation of air traffic systems [21]. [21] suggest that the literature has not yet fully identified the human factors related to NextGen flight deck activity. However, this is required to fully understand the implications of the proposed system in relation to a pilot mental workload. [21] did state two problems associated with NextGen: (a) “monitoring requirements are excessive” (b) it is “difficult to maintain situational awareness over long, boring periods of normal operations.” [22] emphasised that “Excessive use of CDTI may reduce visual traffic scan skills.” According to Funk et al., the literature has also not completely identified human factors in relation to a pilot’s capacities and limitations. Issues of “trust” of automated systems, “team work” between pilots or pilot-controller “collaboration” are also of major concern. However, the central issue of “Free Flight” concepts is how to address the question of delegation of responsibility for aircraft separation between pilots or pilot-controllers [23, 24]. In addition, “right-of-way” rules [24] have yet to be addressed. As a step forward there is need develop an interface that can present conflict information in a way to support pilots to independently a make decision in relation to self-separation.

2.1 The Design and Evaluation Goals

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. Pilot difficulties in maintaining situation awareness arise from lack of how to plan or arrange displayed information in a specified form that will aid situation awareness and decision making. This problem is an issue that increases in importance with new cockpit systems currently that are being developed or will be developed over the next decade.
We suggested that an analysis of conflict resolution information and evaluation is further needed. To do this, a protective cone and four keys of information that must be valid if pilots are to perform self-separation in a free flight environment (i.e., a pilot needs this information to avoid collision independently):

- In level flight; at the same altitude,
- Conflict angle; on a converging angle,
- Relative speeds; showing impending conflict,
- Relative positions; showing impending conflict.

Our approach to the simulation evaluation focused on comparing an Ecological Interface Design (EID) with non EID display as presented in Figure 4. The comparison is to demonstrate the usefulness of integrating and visualising the dynamics of multi elements such as relative velocity vector, ground speed vector and protected zone into the Flight Collision Avoidance System (FCAS).

2.2 A Geometric Approach

By analogy vectors are similar to airways. An airway affords pilots to fly along a specific flight path. Consequently, ATC use a vector to guide pilots to a specified flight path (e.g. turn right to heading 070, or turn left to heading 220). Pilots perceive airspace geometry in four dimensions: conflict angle, relative speed and altitude, rate of change of altitude [12] and rate of turns [11] They perform a series of actions to include configuration changes, rules or procedures to carry out flight manoeuvres to resolve detected conflicts [8,36]. An aircraft is said to be on a collision course while maintaining maintain a constant speed and heading, if no evasive action is taken to avert the conflict. Pilots usually have preconceptions about the flight environment. Pilots are trained to expect and interpret the incoming information that is consistent with their expectations. For example, if aircraft is on a collision course, pilots are expected and should see the aircraft approaching. And, they will reject any information that is in contradiction with their mental models [6].

Consider a typical conflict scenario of two aircraft at the same altitude converging in the vector diagram as shown in Figure 1. Pilots’ own aircraft (Ownship) and Intruder ground speeds are represented by velocity vectors under no wind conditions. The velocity of Ownship ($\vec{v}_{own}$) relative to Intruder ($\vec{v}_{int}$) is given by

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

![Figure 1](image-url)  
Figure 1  A top view of relative motion of two aircraft
A system that displays information such as absolute distance or speed is not enough to perform conflict avoidance tasks. However, an instrument that displays constraints such as too close to or far from an obstacle can provide pilots with situation awareness and aid in decision making processes for conflict resolution tasks [28].

Visual information obtained by pilots is relative to the environment and dynamic [29]. Pilots are not usually good at making absolute speed and distance judgments. However, they are better at judging relative distance and speed. [29] suggested the visual information is dynamic as a result of the continuously changing optic array. Therefore, there is a need to consider the optic flow field. Gibson widely used phrase 'ambient optical array' to give a representation of visual awareness. Each representation is an arrangement of light determined by the environment, thus, affords information about the object relative to observer’s movement [30].

2.3 Visual Guidance of Flying and the Protective Cone

In order to understand the purpose of a protective cone into the FCAS design, we must first define what a light beam is. A light beam by definition is a directional projection of light energy radiating from a light source. Visual information outside the light source is not important to users. For example, to artificially produce a light beam, a lamp and a parabolic reflector are used in many lighting devices such as car headlights. Car drivers driving at night are only interested in the directional projection of a light beam to guide them avoid obstacle or a destination. Similarly, an Instrument landing System (ILS) is used to provide a glide path for an aircraft approaching a landing strip with minimum visibility [31].

A heading change is a basic aircraft manoeuvre to avoid conflict [27]. Turning manoeuvres are directed at making a change in flight path as effective as possible for lateral separation, for example Figure 2 shows a typical conflict scenario and head change manoeuvre to avoid conflict. To perform a heading change manoeuvre pilots are required to rotate the relative velocity vector in a clockwise or anticlockwise direction so that the relative velocity vector is aligned with one of the protective cone’s rays.

![Figure 2. A typical 2D Conflict Resolution Scenario for lateral separation](image-url)
where, $\psi_{own}^*$ is the new Ownship heading, protective Cone* is the new position of the protective Cone for a clockwise manoeuvre (i.e., in front of the Intruder), $\vec{V}_{\text{own/int}}^*$ is the new value of relative velocity vector and $\vec{V}_{\text{int}}^*$ is the new Ownship heading relative to Intruder and $M_d$ is the miss- distance.

For pilots to effectively guide their collision avoidance activity, they need to know how far the Intruder is from Ownship, which way to turn to avoid collision and how are they approaching. However, to guide pilots to perform self-separation, FCAS makes use of a protective cone. The protection cone is formed by two lines tangential to the protective zone centred on both the Ownship and Intruder as shown in Figure 2. While [32] first introduced the cone, several studies have adopted this approach to solve conflict resolutions problems (see [10, 12]) for detailed discussion). However, these studies did not incorporate a protective cone into the collision avoidance display presented.

In geometry measurements, the protected cone is defined as an angle ($\phi$) subtended by two rays tangential to Intruder’s airspace protective zone (see Figure 3). The protected cone will expand as the distance to the Intruder becomes less than the minimum separation standards. As a result, pilots can perceive rapid expansion of the protected cone as conflict becomes imminent. The perceived cues can also activate time – to- collision ($\tau$). Thus, ($\tau$) represents the observation time the Intruder is approaching the Ownship.

According to [33] there are two approaches pilots can visually obtain time -to -contact information from the environment. The first approach is in line with the ecological optic array (i.e., directly from the changing optic array). With this approach time-to, collision is specified by the relative rate of expansion of the retinal image over time. Pilots need only to watch how Intruder is approaching with little or no interpretation. The second is a cognitive approach derived from low order information as expressed in equation 2.3

$$\tau = \frac{d}{V_{\text{own}} - V_{\text{us}}} \quad 2.3$$

where $\tau$ is the predicted time to reached loss of separation($V_{t_i}^R - V_{t_j}^R$), $\vec{V}_{\text{own}}^*$ and $\vec{V}_{\text{us}}^*$ is the Ownship and Intruder groundspeed respectively, $d$ (Ownship – A) distance to first loss of separation along the relative velocity vector(see Figure 3). The rate of expansion of the protective cone which relies on distance change information is derived from the following equation:

$$\varphi = \sin^{-1} \left( \frac{S_{\text{min}}}{S_o} \right) \quad 2.4$$

$$\varphi = \sin^{-1} \left( \frac{S_{\text{min}}}{\tau \ast (V_{\text{own}} - V_{\text{int}})} \right) \quad 2.5$$

$$\varphi = \sin^{-1} \left( \frac{S_{\text{min}}}{\tau \ast V_R} \right) \quad 2.6$$

where $\varphi$ is the rate of expansion of the protective cone and $S_{\text{min}}$ is the minimum separation standard, $S_o$ is line of sight (Ownship – Intruder).
3. Ecological Centred Design Approach

This section outlines briefly the importance of the ecological interface design approach which is the approach adopted in this research project. In 1950, [30] laid the foundation for the ecological design approach. The approach is based on direct-action perception. According to [30], both perception and action are connected through the physical world. Individual perception affords access to certain forms of action that the individual chooses to perform. [34] explored the application of Gibson’s theory of direct perception to designing a complex system, proposing a model that was based on perception and action. This model has been used to develop an ecological interface design, for example, ecological interface design for the condenser [35].

Pilots use their basic instinct to acquire information directly from their natural environment without further mental stimulations. How does perception form a pilot that he or she cannot avoid a collision? According to [26], a theory that addresses this question must consider indirect and direct perception. First, on indirect-perception, pilots need to perform mental stimulation when interacting with the environment and storing the meaning of events in the long-term memory. Direct-perception, on the other hand, does not need pilots to perform mental stimulation when interacting with the environment. Thus, current events have an inherent meaning. Jones further argued that the meaning of avoiding obstacles is not internally constructed and stored; however, it is an essential part of human and environment interaction as a system.

According to [36] an ecological interface design can be used to make constraints visible that support both direct perception of affordances and controlled by cognitive levels of human behaviour (i.e., skills, rules and knowledge behaviour). [34] define the interrelationships between affordances and five levels of abstraction hierarchy. The five levels of abstraction hierarchy include physical form, physical functions, general functions, abstract function and functional purposes of the system. These five levels are articulated based on generic questions such as “What”, which relates to declarative knowledge. For example, declarative knowledge is in the form of a physical system such as aircraft. "How" relates to procedural knowledge of flying an aircraft. “Why” relates to meta-knowledge, the purpose of flying the aircraft. However, a pilot can “slide” up or down the levels of abstraction hierarchy to cope with the complexities and unexpected events in the natural environment.
4. Methods

4.1 Participants and Procedures

To examine the research issues, we developed two collision avoidance displays as presented in Figure 1. Twenty one (21) participants were recruited from the Swinburne University and Aviation Community in Melbourne via advertisements on campuses. Participants were students and professional pilots. The participants’ ages ranges between 22 and 75 years old and categorised into experimental (13) and control (8) group. In appreciation for time and valuable contribution to research, participants received an incentive in form of $30 iTunes gift card. The experiment lasted approximately an hour.

The evaluation 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 was written in C++ language and MATLAB. The software enables pilots to avoid obstacles by tracking, navigating, maintaining or deviating from the intended flight path. The algorithm is a level-aircraft conflict resolution of flying a twin-engine aircraft in no wind conditions [12]. Aircraft Dynamics was not modelled.

The scenarios are modelled based on two aircraft currently en route maintaining constant altitude, speed and heading, however, conflicts exist. In this study participants were asked to fly simulated Instrumental Flight Rules tasks. The two experimental test runs consisted of three (3) blocks of three minutes each was administered to the participants within which a conflict will occur. In each scenario, heading ranging between 133 and 037 were randomly assigned to Ownship at FL130, and speed of 356kts. The Ownship is allowed to manoeuvre to avoid conflict. The intruder is to maintain constant heading ranging between 220 and 337 were randomly at FL130 and speed of 300kts. We made a set of assumptions and built a full free flight scenario to make data available for conflict detection and resolutions.

In this study, we assume that:

**Scenario 1 Head on approach:** A level left or right turn conducted at the current airspeed and a roll angle of > 0 or < 0 was required to escape a collision.

**Scenario 2 Port approach:** A level left or right turn conducted at the current airspeed and a roll angle of > 0 or < 0 was required to escape a collision.

**Scenario 3 Starboard approach:** A level left or right turn conducted at the current airspeed and a roll angle of > 0 was required to escape a collision.
4.2 Pilot Evaluation of System’s Usability

A questionnaire was used to evaluate the system’s usability as presented in Table 1. Seven (7) post-questionnaires were presented to the participants. Participants rated their opinion by placing an “X” at the desired point on the systems utility scale. The scale was a continuous rating Likert scale ranging from 1 to 5.

<table>
<thead>
<tr>
<th>POST-TRIAL QUESTIONNAIRE</th>
<th>Answers Scale</th>
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<tbody>
<tr>
<td>1 The response of the yoke and throttle was too sensitive for me to track the path I wanted to follow</td>
<td>1[Fully Disagree] to 5 [Fully Agree]</td>
</tr>
<tr>
<td>2 How useful was the system for understanding the location of the Intruder relative to the Ownship?</td>
<td>1[Extremely Unuseful] to 5 [Extremely useful]</td>
</tr>
<tr>
<td>3 How useful was the system for understanding the direction of travel of the Intruder?</td>
<td>1[Extremely Unuseful] to 5 [Extremely useful]</td>
</tr>
<tr>
<td>4 How useful was the system for avoiding conflict?</td>
<td>1[Extremely Unuseful] to 5 [Extremely useful]</td>
</tr>
<tr>
<td>5 How useful was the system for avoiding stall when manoeuvring the aircraft?</td>
<td>1[Extremely Unuseful] to 5 [Extremely useful]</td>
</tr>
<tr>
<td>6 How useful was the system for providing sufficient information for following a desired flight path?</td>
<td>1[Extremely Unuseful] to 5 [Extremely useful]</td>
</tr>
<tr>
<td>7 Please rate your <strong>overall opinion</strong> of the system.</td>
<td>1[Extremely Unuseful] to 5 [Extremely useful]</td>
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5. Results and Discussion

The preliminary results offered a view of the system’s usability of the proposed FCAS in contrast to a conventional display as shown in Figure 4. The data analysis was focused on comparing the mean difference between experimental and control group. A t-test procedure was adopted using SPSS software to compare the mean difference.

5.1 System’s Usability

Seven (7) post-questionnaires were presented to the participants. Participants rated their opinion by placing an “X” at the desired point on the systems utility scale. However, the overall score was used to the analysis. The analysis revealed that there was a statistically significant difference in the system’s usability scores between experimental and control groups. The experimental group was more engaging ($M = 4.13$, $SD = .43$) than the control group ($M = 3.62$, $SD = .87$), a statistically significant difference, $M = .086, t(19) = 1.811, p = .086, d = 0.59$. The results are graphically displayed in Figure 5.

![Figure 5: Pilot System’s Usability Mean Scores](image-url)
The need to update the current system to enable ground-based controllers and pilots cope with high air traffic demand is important. The aviation community hopes this new concept would alleviate airport congestions in a free flight environment. Once the updated system becomes operational, pilots and controllers simultaneously can share the same information regarding aircraft positions, altitudes and directions. Pilots would receive continually updated information of aircraft positions with an accurate “picture” of a Free Environment, fly below minimum standard than is currently applied, thus increasing the capacity in the space leading to greater risk Mid-air Collision. The availability of conflict resolution and tracking information would enable both pilots and controller to avoid mid-air collisions.

The results from this evaluation have identified the characteristics of Free Environment that create pilots difficulty to manage self-separation and understand how to improve airborne conflict resolution display that would work in a real world environment. Thus, it may be interesting to evaluate pilot performance at different levels of behaviour using airborne resolution displays that are consistent or inconsistent with their abilities and strategies to avoid collision. It might possible that pilots’ ability and strategies are consistent with their cognitive representations of problem-solving skills which could lead to their best performance. On the other hand, the inconsistencies of problem-solving skills that reflect pilots’ choice and expectations might improve performance, but may not support acceptances of the FCAS.

6. Conclusions

The goal of a free flight concept is to ensure that pilots have the freedom and responsibility to maintain separations as compared to the current ATM. The free flight concept is predicted to introduce new devices, procedures and tasks. The FCAS presented here relies mainly on displaying flight information such as bank angle, relative speed and ground speed in the form of geometric representations of vectors. The proposed display expresses pilots’ simple vector representation that replaces complex data needed to be processed when interacting with systems such as Flight Management Systems. An instant feedback is predicted. This enables a noticeable amount of time for pilots to build situation awareness, reduce mental workload and keep the pilots “in the loop”. A display that prevents pilots from having a total control of the current and future states of the aircraft is a recipe for poor situation awareness [25]. As pilots have the freedom to choose a flight path, ATC would not need to restrict the pilot to fly within designated flight route as the flight progresses.

This research will further examine pilots’ ability to identify geometric features and factors in a free flight environment that contributes to pilots’ situation awareness [25]. This would help guide the developing of conflict display traffic information to compensate for pilots’ resolution weaknesses consistent with pilot expectations and choices.

References:


[29] Lee D N, 1976 “A theory of visual control of braking based on information about time-to-collision” Perception 5 437-459


