International Journal of Multidisciplinary and Current Research

Original Research Article

ISSN: 2321-3124
Available at: http://ijmcr.com

Development of a Flight Collision Avoidance System for a Free Flight Environment: An Ecological Interface Design Approach

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Abstract

In a Free Flight Environment, safe –separations are delegated to the pilot by the Air Traffic Control. An adoption of a Free Flight Environment is considered vital as air traffic is predicted to double over the next two decades. Transitioning from the current Controlled Airspace to Free Flight Environment involves number of changes. A pilot role is to change to airspace and decision manager. Pilot's responsibility will change with a new set of cognitive demands with varying tasks. Tasks such as collision avoidance are constrained. Flying in a Free Flight Environment, pilot requires constrained tasks to be performed both in En-route and Terminal airspace. However, the existing Air traffic Management (ATM) cannot cater for this significant increase. To cater for the relationship between pilot, collision avoidance system and the environment, a novel ecological airborne display has been developed. The display makes full use of an aircraft relative motion and protective cone display to make these constraints visible to the pilot 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 this display.

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

1. Introduction

Air traffic is expected to increase in the next two decades [1, 3]. The future adoption of a Free Flight Environment [4] is necessary as Air Traffic Controller (ATC) will be unable to handle the workload from the forecasted doubling of air traffic. The concept of delegating self-separation to the pilots is considered [2]. Therefore, the responsibility of pilot's in the free flight environment will increase to include a new set of cognitive demands associated with separation tasks. Conventionally, pilots perform several different flying tasks. The pilot's primary task is to aviate-navigate-communicate and manage the system [6]. From a pilot's perspective, resolving conflicts is a new task. A collision avoidance system is required to support pilots perform self-separation. An airborne collision avoidance display such as conflict display traffic information (CDTI) allows pilots carry out "visual flight" manoeuvres to avoid a protected zone or obstacles at higher altitudes [7,8], besides the use of the current "see and avoid" technique [9].

Modern aircraft is now equipped with flight instruments to provide pilots with flight information about the aircraft's current status and air traffic at both low and high altitudes [10]. However, pilots still need to monitor or scan these instruments to know about changes and events as the flight progresses [62]. Pilots are usually required to scan for relevant displayed information across the cockpit. Besides picking up this information, they may have to integrate it cognitively to build situation awareness. An automated display system commonly records or displays information such as distance, direction, speed and time, usually expressed in a numerical value. This value alone may not be enough to provide pilots with information to avoid conflict. Pilots must make sense of this value. However, a system that displays operating constraints such as too close or far and/or how high or low, may provide pilots with situation awareness and aid in decision-making processes about what is important [11]. It is also possible for pilots to perceive time and distance in space while interacting with the environment [12].

Pilots interact and respond to environmental signs, signals and symbols [13]. These interactions and responses are based on perceived information through modalities such as audio, visual or tactile cues [63]. These modalities aid pilots to cope with daily tasks. Tasks such as flying to a specific or familiar location require pilots to fly within a flight boundary. Such interactions with the environment may need little or no cognitive workload, if pilots are familiar with the environment [13,14]. This familiarity provides two factors for reducing the cognitive workload:

(a) Avoidance of hazardous environment (i.e., safety).
(b) Avoidance of cognitive restructuring of problems (i.e., it reduces in solving problems).

For example, a pilot's actions to avoid obstacles his or her aircraft while flying would involve simply turning the control wheel left or right to heading to avoid the obstacle. This action can be performed naturally without due thought or consideration. In a similar way, cockpit displays are now equipped with emergent features to improve pilots' interaction and perception in emergencies [55]. The proposed display takes into account the environmental and/or aircraft performance constraints and yet shows how these constraints work as an interrelated system.

2. Previous work related to Traffic Collision Avoidance Display

A number collision avoidance approaches have 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, [15] 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 [16] relative motion for level conflict avoidance [20]; performing level turn conflict resolution [19], collision avoidance [17, 18], the effect of geometry on traffic display [22], manoeuvre constraints [23], geometry optimisation [24], conflict geometries [21], evaluation of separation display [61] and water reactor[26].While [25] first introduced the cone, several studies have adopted this approach to solve conflict resolutions problems (see [16, 19]) for detailed discussion). However, a drawback of these designs is that these studies did not into account the application of a protective cone into the collision avoidance display presented.

3. 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 ability 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 that are currently being developed or will be developed over the next decade

Let us consider a typical conflict scenario of two aircraft at the same altitude converging in a relative motion diagram shown in Figure 1. Ownership and intruder's track vectors are represented in relative motion as shown in Figure 1 under no wind conditions. The velocity of ownership ($\vec{v}_{own}$) relative to the velocity of the intruder ($\vec{v}_{\text{int}}$) is given by

$$\vec{v}_{own} = \vec{v}_{own/\text{int}} + \vec{v}_{\text{int}} \quad (3.1)$$

$$\vec{v}_{own/\text{int}} = \vec{v}_{own} - \vec{v}_{\text{int}} \quad (3.2)$$

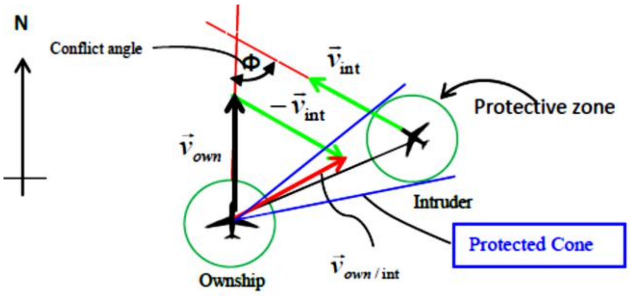

Figure 1: A typical 2D conflict scenario for lateral separation

To achieve successful conflict resolution, a protective cone and four keys of information must be incorporated, 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,
- Aircraft on a converging angle,
- Aircraft relative speeds; showing impending conflict,
- Aircraft relative positions; showing impending conflict.

The second design goal is to support pilots with a high level of information by using a protective cone (Figure 1)[19]. The purpose behind making use of the protective cone in the design (i.e., functional information) is to bridge the gap between aircraft performance and environmental constraints. For example, a car headlight affords drivers to drive at night to avoid obstacles or destinations. The third design goal is to support pilots with visual information about the flight path in accordance with aircraft ground speed vector. The ground speed vector is used to predict Ownship and Intruder intended flight path.

Redesigning collision avoidance display involves a deeper understanding of the relationship between collision avoidance system and the environment to make the available information visible to pilots. In order to extract valuable information from the work domain, the study adopted principles based on the Ecological Interface Design (EID) approach [27]. The approach is expected to improve pilots' performance and ascertain how situation awareness and mental workload fits into the attainment of the pilots' goals such as maintaining safe-separation in a free flight environment. The flight collision avoidance system consists of two displays: (a) a protective cone display (b) a relative motion display. There is a relationship between these two displays; however, to date the current conflict avoidance display based on EID did not adequately map the relationship between these displays to clearly show geometry of conflict and operational constraints. With well mapped constraints, a pilot might be able to instantly predict the possible future state of the system in many conflict situations. Pilots' mental models could then be captured and externalised to improve situation awareness.

4. Ecological Interface Design

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 [73]. EID is an approach based on this idea. The EID approach begins at the highest conceptual level and goes down to the detailed physical system by considering environmental constraints and not human limitations and capabilities .EID is a top-down approach that addresses pilots' cognitive interaction with the environment. An approach that addresses and supports pilots operating in a complex dynamic environment is desirable. According to Jones [56], when pilots are interacting with the environment, they will take advantage of any system that will aid them to cope with situations that do not require cognitive processes. In other words, pilots should be capable of using "natural instinct" to perceive relevant constraints provided by the environment. The EID approach is predicted to better support pilots' to improve their cognitive workload in relation to the environment, thus coping with pilot errors caused by the automated display system [48].

According to Rasmussen [13] and Vicente [27], developing an ecological interface system is a two stage process: First, the work domain is analysed. The work domain analysis (WDA) demonstrates a connection between AH and the working environment .The aims of AH are:

(a) to gain a better understanding of the environmental constraints. The environmental constraints include weather conditions, restricted airspace and air traffic

(b) to identify functional models that need to be included in the proposed system. The proposed system constraints are attributed to aircraft internal performance limitations;

(c) and to provide the means to perform a task in a way that is compatible with the ends desired.

The second process is related to Rasmussen's pilot Skills, Rules, Knowledge (SRK) behaviour [13] (see section 5 for detailed discussion).

4.1 Analysis of the Work Domain

Work Domain Analysis (WDA) is one of five phases of cognitive work analysis [28, 29]. According to Naikar, et al.[29], WDA is composed of two dimensions of the abstraction hierarchy, a five level representation and part-whole decomposition. These compositions allow pilots to develop an accurate mental model of the environment. Thus, enabling them to handle problems associated with the system more efficiently [30].

The WDA also represents the constraints of both functional properties and physical components of a complex system that enable pilots to perform a task within these constraints [27]. Previous studies have suggested the usefulness of WDA in various applications. WDA has been applied, for example, to weather information for air traffic controllers [31], training equipment for military applications [68], medical applications [32], aviation domain [36], nuclear domain, robotics, medical application [69] and oil sector [35].

With WDA as a modelling approach, environment constraints can be modelled [29]. [33] Further described the WDA as a method used to transit from theoretical studies to practical applications. [34] also suggested that WDA is the essential component of EID. The EID allows pilots to picture environmental constraints and cope with unexpected problems [28].

In this study, WDA is used as a method to identify emergent features to support the development and maintenance of appropriate pilots' mental models of flying and self-separation. The WDA under investigation consists of three separate models (a) collision avoidance system; (b) natural environment; (c) aircraft. The model of a collision avoidance system focuses on pilots' manipulation of longitudinal and lateral flight controls to provide safe passage to destinations, thus, avoiding midair collisions and maintaining minimum separation standards.

4.2 Argument for Work Domain Analysis

WDA is a theoretical framework used for analysing and modelling systems in many domains. According to these authors [29] WDA is useful for the following reasons: first, it incorporates the functional relationship between levels of abstraction hierarchy of a system. Second, it provides a template that supports researchers to represent knowledge and comprehend pilots' goals and abilities to interact with the systems in question. Third, abstraction hierarchy is a useful tool for designers using an Ecology Interface Design (EID) approach. The EID approach is used to analyse a pilot's behaviour when interacting with a system within an environment. For example, pilots' interactions between levels of abstraction hierarchy should support pilots to anticipate changes in a system likely to occur in the future. A system that supports or engages pilots actively to carry out these changes might allow them to stay ahead of any conflict situation. Fourth, a pilot's behaviour may allow them to operate between levels of the abstraction hierarchy as desired. Finally, WDA is structured for analysing a specific situation under study and not for analysis of theories or models under consideration, for example, in emergency situations. These properties make the framework a powerful model for evaluation and designing of information systems for a specific situation.

Rasmussen [70] presented and described the "how–what-why" of a system's operation. Rasmussen also pointed out because abstraction hierarchy levels are interrelated through "means-ends" relationships, knowledge of the system is enhanced. As Amelink et al., [43] suggested, if constraints are mapped into an interface that is based on an abstraction hierarchy modelling, pilots' mental models can be captured and externalised to improve situation awareness. One could argue, in particular, that an Ecology Interface Design (EID) system might hasten pilots' active learning of the system in question, thus, enhancing their experience.

4.3 Pilots' Abstraction Hierarchy of Mental Models

Five levels of Abstraction Hierarchy (AH) form the AH of pilots' Mental Models[13]. The five levels of AH are mapped to form pilots' activity needed to achieve related goals such as conflict resolution. These five levels include functional purpose, abstract function, general function, physical function and physical system (Figure 3). The AH allows pilots to move up and down these levels. These levels are supposed to answer questions pilots are likely to ask in relation to conflict resolution activities. For example, pilots would like to know how close their aircraft is to the intruder's safety zone. How much fast or slows will they have to fly in order to avoid collision? What bank angle is required for turning manoeuvres without exceeding aircraft performance limitations? What is the aircraft's maximum and minimum heading required to avoid conflicts? What is the purpose for manoeuvring, cost or safety?

4.1.1Functional Purpose

The uppermost level of the abstraction hierarchy is the functional purpose of the system. The purpose of the proposed system is to provide the safe passage to a destination. This level presents a deeper understanding of the system. The functional purpose of a free flight environment is to allow pilots to choose the desired flight path and provide safe passage to a destination as the flight progresses. This level states the objective behind the design of the system. For example, the goal of pilots in a free flight environment is to maintain minimum separation standards, and avoid air traffic or obstacles within the aircraft flight envelope. Safe flight can be achieved through four factors that can influence and control the pilots' goal [37]These factors include (a) the "significance" of the goal i.e., purpose and importance, (b) 'expectancy', the selection of a specific goal determined by the desirability of the outcome i.e., shorter versus longer distance to destination, (c) prediction of aircraft future states (i.e., a change in flight path) enables pilots to instantly predict the possible future state of the system in many conflict situations and (d) the "effort". The use of pilots' physical or cognitive processes requires to manoeuvre the aircraft. However, the concept of "worth" is also essential. The possibility of what the pilot does should have a value e.g. to choose to fly in front of or behind the aircraft is an important consideration for avoidance collision avoidance.

4.1.2 Abstract Function

Abstract function defines the principles or laws that govern how the system should work to achieve the functional purposes. This level defined the independent variables that pilots need to control to achieve the functional purposes. 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. The laws that govern conflict zones are defined and controlled by minimum separation standards. For example, pilots' ability to violate minimum separation standards in a free flight environment depends on traffic density as a function of dynamic constraints, aircraft performance limitations, conflict geometry, and cognitive workload. The understanding of aircraft performance limitations is critical to all aspects of flying aircraft, especially for obstacle clearance. Accidents such as midair collisions may have occurred due to lack of information on the relative velocity and position of obstacles that were not adequately displayed to the pilots. For example, turning a flight to avoid obstacles can be constrained by bank angle and distance. These constraints address the pilot's ability to instantly change flight path and intercept the original flight route in timely manner. However, the cost of flight path displacement depends on distance and original planned route to destination.

Another factor regarding aircraft performance limitation is speed. Deceleration is susceptible to an increase in minimum separation standards and a decrease in fuel consumption. On the other hand, acceleration is responsive to estimates of time arrival. Because acceleration ($\underset{\sim}{a}$) is defined as the instantaneous change in velocity ($\underset{\sim}{v}$) as a function of time, the equation is often rewritten as:

$$\underset{\sim}{a} = \frac{d\underset{\sim}{V}}{dt} \tag{1.4}$$

The velocity vector is expressed as

$$\underset{\sim}{V} = \underset{\sim}{u} i_k + v \underset{\sim}{j_k} \tag{4.2}$$

The expression (5.1) for V, airborne aircraft acceleration can be written as

$$\underset{\sim}{a} = \dot{u}\,\underset{\sim}{i_k} + \dot{v}\underset{\sim}{j_k} \qquad (4.3)$$

where $\dot{u}\,\underset{\sim}{i_k}$ is the tangential and $\dot{v}\,\underset{\sim}{j_k}$ is the radial acceleration.

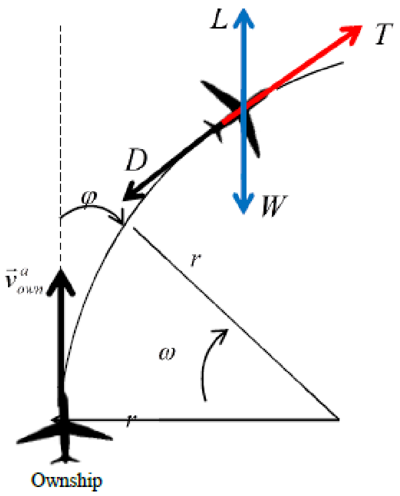

Figure 2: Top view of a turning flight in a horizontal plane

The tangential acceleration ($\underset{\sim}{a}$) of the airborne aircraft can be written as the derivative of two functions,

$$\underset{\sim}{a} = \frac{d\,\underset{\sim}{\omega_t}}{dt} \times \underset{\sim}{r}(t) + \underset{\sim}{\omega_t} \times \frac{d\,\underset{\sim}{r}}{dt} \qquad (4.4)$$

where $\frac{d\,\underset{\sim}{\omega_t}}{dt} \times \underset{\sim}{r}$ and $\underset{\sim}{\omega} \times \frac{d\,\underset{\sim}{r}}{dt}$ are the tangential and radial acceleration respectively , $\underset{\sim}{\hat{u}}$ is the unit normal vector for the aircraft trajectory and $\underset{\sim}{r}$ is its instantaneous radius of curvature.

Substituting equation (5.2) into (5.3), the following expression is obtained

$$\underset{\sim}{a} = \frac{v^2}{R}\underset{\sim}{\hat{u}} + \underset{\sim}{\omega_t} \times \frac{d\,\underset{\sim}{r}}{dt} \qquad (4.5)$$

Figure 2 is used to derive aircraft's dynamic equation of motion, is represented by

$$\sum F = m\underset{\sim}{a} \qquad (4.6)$$

The equation (4.6) governs the law of aircraft dynamics .The equation allows us to sum up all the aerodynamic forces acting on the aircraft in turning a flight can be re-written as:

$$L + T + W + D = m\underset{\sim}{a} \qquad (4.7)$$

where L is lift, T is thrust, W is the weight, D is the drag, $\boldsymbol{\varphi}$ *is the heading change, and a is the acceleration of the aircraft.*

From equation (4.1), the aircraft is experiencing acceleration during turning manoeuvres. However, the aircraft change velocity in relation to the acceleration is associated with drag related issues. Aircraft performance is less efficient under this circumstance. This circumstance may result in flight operations that are not effective in relation to time, effort or fuel expenses to destinations [48].

4.1.3 General Functions

Above the physical functional level, is the general function describing physical processes. The physical processes enable pilots to perform tasks at the abstract function level. The purpose-related function described the functions, responsibilities and processes that influence the constraints at the abstract function level. The purpose of aircraft is to fly passengers to the destination safely. Therefore, to achieve this objective, it is often necessary for pilots to alter the aircraft heading as the flight progress. In this study, only aircraft heading and speed changes at constant altitude and coordinated turns in a horizontal manoeuvre were considered.

A heading change is a basic aircraft manoeuvre to avoid conflict [38]. Turning manoeuvres are directed at changing the flight paths as effectively as possible for lateral separation. At this level, airspace dynamics for conflict avoidance can be described as either a continuous environment or a discrete environment. A discrete environment is considered to be discrete in that the environment changes its behaviour and pilots' decision-making process occurred at a discrete time. For example, a pilot operating in this environment uses coded messages such as "climb and maintain FL150 or reduce speed" at a specific time during flights. Discrete decisions are usually issued by the ATC to enforce safe- separation standards.

On the other hand, continuous environment can be considered as free flight. The environment will continue to change its behaviour and pilots' decision-making processed at countless points in time. There are no specific instructions for pilots from ATC under this flight environment. These instructions such as change in speed or heading and/or application of certain operational procedures to avoid obstacles can be applied at any time of flight. At this a level, pilot's responsibility is to maintain separation standards at all times. However, under this environment, pilots might be constrained by aircraft system dynamics from achieving this objective.

4.1.4 Physical Functions

The physical function specifies the individual parts from which a composite system is made. These individual parts include weather conditions, obstacles and /or air traffic density. Physical functions describe possibilities, characteristics, and properties of the system. This level provides pilots with necessary information about these parts that is sufficient to perform flying activity. This activity includes 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 protective 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.

4.1.5 Physical Form

At the lower level of the hierarchy is detailed information about the physical system and how the functional purpose of the system can be achieved. The physical system enables pilots to interact with the system at the physical functional level. This level specifies the physical location of the speed and heading indicator. Under the free flight environment, ADB-S will display aircraft relative positions, ground speed of ownership and intruder on the CDTI. The physical presence and appearance of ownership, obstacles and intruder are included at this level. However, the proposed EID uses a graphic representation of relative motion to display conflict geometry (i.e. conflict resolution envelope), thus, indicating aircraft relative positions and relative velocity vector.

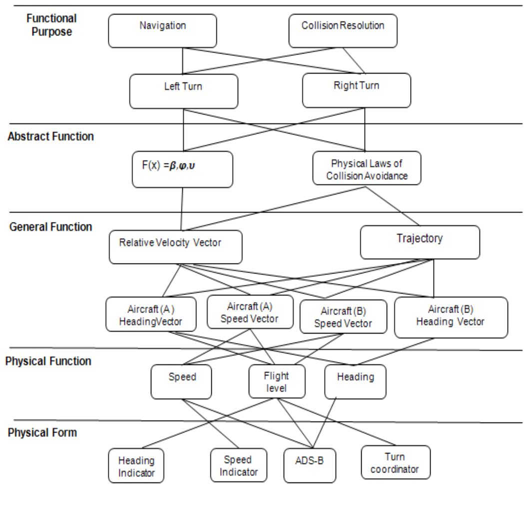

Figure 3: Abstraction Hierarchy of Flight Collision Avoidance display

5. Hierarchy of Pilot Cognitive Control Model

The framework of Rasmussen [13] provides the abstraction hierarchy of pilots' cognitive control to develop a system that supports pilots' task for collision avoidance. The framework guides designers to assign roles to an automated display system that supports, for example, "conflict alert" or "advisory" information to Pilots. According to Xiao and Seagull [39], as much as pilots prefer to use an automatic mode of behaviour (SBB), they often perform different tasks at three levels of behaviour. The following subsections will discuss briefly pilots' cognitive models as related to the three levels of behaviour.

5.1 Supporting Skill-Based Behaviour (SBB)

Pilots' skill based behaviour involves largely physical actions with no conscious control or without monitoring of conscious attention. At this level, the display should be designed to capture pilots' interaction between the perceived information and the action performed. Thus, pilots should be able to manipulate the controls of a display directly, requiring less physical, and/ or cognitive effort to accomplish or understand the task. SBB should support some, if not all the information needed at the level of Knowledge Based Behaviour (KBB). Pilots' familiarity with environment requires minimal cognitive resources to interact [65]. However, the environment can also be distinctly acquired in several ways. For example, a pilot may consciously pay attention to individual parts of tasks being performed until his/her behaviour is smooth and "pre-programmed". Once the skill is acquired, pilots may find it difficult to pass this skill on to team members or articulate it. Skill-based behaviour may also need some feedback from the environment; in much the same way that, for example, driving a car still needs drivers to obey road signs. However, under high cognitive load, pilot situation awareness and may change, warning cues (i.e., visually or auditory) may go unchecked. Thus, pilots may fail to apply an appropriate step to correct a particular abnormal operation of the system.

Another example of skill-based behaviour is when pilots perform repetitive tasks such as performing a checklist in the cockpit. If the checklist is repeated many times, it is possible for pilots to perceive the present task as already completed, when in fact, that it was previously performed and completed on the same type of aircraft with the same configuration. This activity can affect pilots' decision making by the brain planting "false memories."

5.2 Supporting Rule-based behaviour (RBB)

Pilots' rule-based behaviour (i.e., procedural behaviour) describes performance related to routines with less-conscious and standardised behaviour patterns. This type of pilots' behaviour involves practise, sometimes automatic behaviour with a well-established set of rules or procedures to check a system's progress. For example, a checklist placed in the cockpit encourages rule-based behaviour. If expert pilots look at a familiar check list, they can assume what the checklist is all about without actually performing tasks. Further, pilots' rule-based behaviour use states conditions such as "When, If…… Then" for selecting an ***appropriate action*** based on sets of signals, rules or procedures. These sets of rules and procedures can also be formed from pilots' past experience when operating a specific type of aircraft system that requires application of a specific set of rules or procedures. These sets of rules or procedures are systems constraints. RBB is also suitable for automated system applications as well, where all possible sets of rules or procedures are examined. However, from a pilot's perceptive it is practically impossible to examine all possible solutions under emergency situations. In emergency situations, Pilots' may be prevented from interacting with the system due to lack of knowledge of the system's current state, thus, keeping the pilots "out-of- the loop''[40]. Therefore, an EID approach might be able to support pilots' to resolve this problem by providing a visual representation of the problem, for example, highlighting the relationships between perceptual cues and constraints.

5.3 Supporting Knowledge-based Behaviour (KBB)

Pilots' knowledge based behaviour (KBB) involves complex problem solving. This behaviour allows pilots to identify, and interpret and ascertain system status in normal or abnormal situations. The activity of pilots at this level involves planning, adjusting, creating and implementing new solutions to an unexpected problem. It is the highest cognitive level of pilot's and is applied to novel situations. Pilots' interaction within the environment is consciously controlled. With knowledge-based behaviour (KBB), pilots' mental models represent deeper internal structures of the environment. Mental models are built based on the acquisition and analysis of information from the environment to formulate goals and plans to handle the current events. Knowledge-based behaviour in work domains is outward representations that reflect mental models and is independent of the abstract cognitive process performed by pilots.

In contrast to Rule-Based Behaviour, pilots' behaviour often changes based on their current situation. Stored sets of procedures and rules have no longer apply, however, they can still access these set of information when needed. If a novel situation is presented, a new plan must be developed to solve the problem. In most cases, solutions to these new plans are based on "trial and error" [13].These new plans are prone to human error. However, expert pilots will tend to avoid knowledge-based behaviour, due to high cognitive workload in trying to analyse novel events. For example, when coping with complex problems such as unexpected engine failure, pilots tend to shut down the failed engine without proper diagnostics, thus, applying RBB [66]..

6. Modelling the Flight Collision Avoidance Display

This section outlines a model for an en route flight collision avoidance display from pilots' perspectives. The research outlines the following aspects of the model:

(a) Design Goals
(b) Work Domain Boundary
(c) Information Acquisition
(d) Abstraction Hierarchy of Mental Models

The proposed model for designing the new display defines the environmental constraints as the airspace. The airspace boundary constraint is limited to pairwise conflict (Figure 1).

6.1 Design Goals

The section has already been discussed in section 3

6.2 Work Domain Boundary

The first assumption for modelling of a flight collision avoidance system (FCAS) is to decide the system's boundary (30,29].[29] suggested the boundary of the analysis must be first defined based on the system's objective, such as problems needed to be solved. A system boundary for avoiding collision is determined by pilots' perceptions, thoughts, or appropriate actions within the environment in which a conflict situation is said to exist. In deciding for collision avoiding system, boundary conditions has to be identify for both pilots' tactics and strategy are essential [41], if the design is to be successful as shown in Table 1. According to [30] there are some key decision issues the analyst must into an account before analysing a system's boundary. For example, some of the key issues need to be addressed are the purposes of the system for which the system exists within the environment and pilots' role in the environment over which rules or controlled is exercised.

Table 1: A system boundary for Conflict Resolution

Pilots' Tactical Conflict Resolution *State information*		**Pilots' Strategy Conflict Resolution** *Intent information*
1	**Conflict awareness**	**Situation** - What is the current situation? A pairwise conflict? Evaluate the current situation.
2	**Decisions** to avoid conflict situations	**Path-** a possible flight path to achieve goals/objectives (i.e., conflict resolutions).
3	**Detailed manoeuvres** to achieve objectives set by strategy	**Plan** - What properties necessary and sufficient to achieve conflict resolution? Flight envelope (more or less bank angle, speed, altitude etc.)

According to Erzberger and Paielli [5], pilots need to perform tactical manoeuvres during critical situations because of the limited time available. Tactical manoeuvres address conflicts in a time frame of around three minutes into the future [41]. Pilots under such circumstances are required to apply procedural manoeuvres needed for avoiding collision within this time frame. These procedures include changing aircraft heading, altitude or speed crucial to avoid collision [42]. However, in contrast to tactical manoeuvres, strategic manoeuvres addresses planning and implementation of conflict resolution. The time frame is between three to twenty minutes into the future [41].

6.3 Information Acquisition

This section outlines information acquisition of an abstraction hierarchy. The obtained information supports pilots in relations to at the abstraction hierarchy representations [59]. According to [44] procedures for obtaining this information involved data collection of interviews, surveys and publications. These data can be used to develop a work domain model as shown in Table 2. However, as [44, 45] pointed out, for a novel system under development, concept papers should be the main source of information.

Table 2: Information Acquisition for a Work Domain Model

Abstraction levels	**Methods of acquiring information**	**SMEs Examined**
Functional Purpose	Concept papers	Researchers, Senior academics, Captains, flight navigators ,Air Traffic Controllers
Abstract Function	Textbooks, Engineering documents (requirements and specifications)	Flight Instructors
General Function	Flight Textbooks , Feasibility studies	Captains, flight navigators ,Air Traffic Controllers
Physical Function	Flight training manuals,	Technical manuals, research reports,
Physical Form	Feasibility studies	Questionnaire, Interview, survey

7. Work Domain Model for Collision Avoidance System

According to [30] the work domain model is the basis on which EID is grounded. The model allows pilots to develop accurate mental models of how the system works. Further, the mental model guides pilots in solving midair collision problems efficiently. WDA focuses on three separate domains: (a) physical processes of flight; (b) the natural environment; (c) an AH. The AH are combined to complete a work domain model. The AH should allow pilots to interact at the physical level. According to [27] the levels of abstraction hierarchy are classified into physical and functional information .The systematic confirmation of the model requires the use of criteria governed by scenario mapping [33]. Pilots flying activities that are used to evaluate the model at the physical level as discussed in section 3

7.1 Requirements for Work Domain Model

The first stage of modelling the collision avoidance system is to address requirements for the uppermost level of abstraction hierarchy. These requirements should relate to the system's description as closely as possible. The basic conflict tasks are required to address THE system's functional requirements. Table 3 shows the proposed novel collision avoidance system. The reportable attributes of the system which actually express measurements, must be validated.

Table 3: Technical Functions of aircraft

Collision avoidance information requirements for FCAS	
1. The Heading indicator	Basic Instruments
2. The True Airspeed Indicator	
3. The Altimeter Indicator – flight level	
4. Vertical speed indicator	
5. The Turn Coordinator Indicator	
6. Resolution displays: advised, caution and danger. 7. Vertical speed range 8. Relative positions	**TCAS** (Traffic Collision Avoidance System)
9. The ability of aircraft to control direction laterally	**FCAS**
10. The ability of aircraft to control relative velocity	
11. The ability of aircraft to control speed	

Table 4: Requirements for Free Flight information

1. The Aviation Safety Regulations -5nm of protected zone horizontally is centred around both Ownship and Intruder
2. Obstacles – weather cells, intruders and terrain (mountain-wave)
3. Congested Air Traffic
4. Navigational Mass
5. Horizontal Separation capability
6. Vertical Separation capability
7. Flight level as a function of speed

Table 5: Free flight and Collision avoidance information requirements

1	Standard Separation as a function of speed and flight level
2	Safety - protected zone (5nm) air traffic, flight path, speed and visibility
3	Tracking– relative speed and directional control
4	Performance Cost- deviation from flight path, speed & visibility
5	Conflict Geometry (Conflict Cone) -relative velocity, speed vector bearing, distance to loss of separations (LOS)
6	Return to flight plan route

Table 4 shows standard contents for avoiding collision commonly used by the current collision avoidance system. The information provided by the current system indicates that pilots may have to scan for other relevant instruments across the cockpit (i.e., from Table 3 item 1-5) to update their mental models, thus creating situation awareness. Though this may not endanger flight progress, it increases pilot cognitive workload and reduces situational awareness, however. While these instruments or displays may still provide essential flight information that is spread over different locations in the cockpit, these are regarded as a working memory [47]. A study by Endsley [46] suggested that integrating relevant information into one manageable display will minimise a pilot's cockpit scanning, thus, providing better situation awareness.

8. Analytic and Intuitive Decision to Collision Avoidance Tasks

In this section, a brief discussion of decision making is provided. However, the study is informed by the following discussions related to pilots' decision making. In general, Naturalistic Decision Making [49,50] has shown how expert pilots cope with the constraints of time and information. There are, analytical and intuitive approaches are discussed briefly.

To fly an aircraft, pilots process a vast amount of information. The information they process may be simple or complex, clear or distorted, complete or incomplete with gaps that need to be filled. All of the above mentioned issues may have an effect on pilots' decision making. Decision making is of fundamental importance to pilot activities [72]. Pilots monitor and control the aircraft, and interact with other automated display systems. In doing so, they decide what information is critical for a safe flight. Cognitive processes affect these decisions. Limitations on processing this information affect the fidelity of pilots' mental models. Mental models are vulnerable to both problem complexity and conflicting information. These are crucial when pilots make critical decisions. However, in a free flight environment, pilots have multiple goals as the flight progresses. The goal activates a suitable mental model to extract specific information from the environment. In the environment where pilots are required to choose a flight path and maintain self – separation with minimum intervention from ATC this is a new task.

8.1 Decision Ladder Model (Analytical Approach)

The decision ladder developed by Rasmussen et al. [28] is one of the core components of Cognitive Task Analysis (CWA). The decision ladder is a "map" that can represent a pilot's path to decision-making processes. As suggested by Rasmussen and Goodstein [51], pilot's decision making behaviour can be mapped onto the decision ladder's template. Further, the decision ladder captures pilots' states of knowledge and information-processing activities necessary to reach a decision. The process of mapping of cognitive strategies onto the decision ladder provides a structure that shows what knowledge and information pilots uses during decision making. Figure 2 below shows the decision-ladder for a pilot's decision to avoid a potential midair collision. The Figure illustrates the process of mapping pilots' mental strategy onto the decision ladder.

This analytical approach tries to base the decision on the structure of the problem on the relationship between option and results. The decision ladder acts on an abstraction – decomposition matrix (work domain). On the other hand, the work domain analysis highlights the environmental constraints and information necessary to map a pilot's decision making to the decision ladder.

As Wickens et al., [64] pointed out, with the nature of pilots' behaviour it is impossible to design a decision system to support their decision making in all air traffic scenarios. However, according to Rasmussen et al. [28], pilots use common sense rule (or simple rules) intended to increase the likelihood of solving the problem, for example, avoiding aircraft on a collision course. Thus, the application of a simple rule may reduce the pilot cognitive workload by rejecting information they consider not important.

This information may include for example, weather seals, fuel, desired flight path, restricted airspace and separation recovery in time. Rasmussen et al. [28], pointed out that to maintain situation awareness, the current alerting systems are designed to indicate two or more levels by using different colours or auditory commands. Contrary to this approach, the proposed new automated display system should be able to continue to present the evolution of conflicts over time. Thus, the pilot is informed whether his or her actions are effective in solving the problem in real time.

According to Rasmussen et al.,[28] pilots perceive information from the environment to determine the conflict situation. If the conflict situation is familiar, pilots will simply apply already an acceptable set of procedures (i.e., skill based behaviour) to avoid collision. However, if the information presented to the pilots is unclear or ambiguous, further clarification is needed. The task or procedures are then changed. For example, regarding rule based behaviour (RBB), if tasks or procedure is how to avoid collisions are not clear; pilots will have to examine the state of the environment for more information or alternative routes for safe passage to destinations based on a set of rules. In a situation where no skills or rules knowledge exists, pilots will have to perform mental simulation (KBB) of the current situation to examine what other possible options are available with respect to their goals or objectives. This process is repeated until the set objectives or goals are achieved (i.e., safe passage to a destination). Pilots' final execution to avoid obstacles is at a low level. At this level, the execution is performed by considering basic parameters such as the bank angle, relative speed and heading.

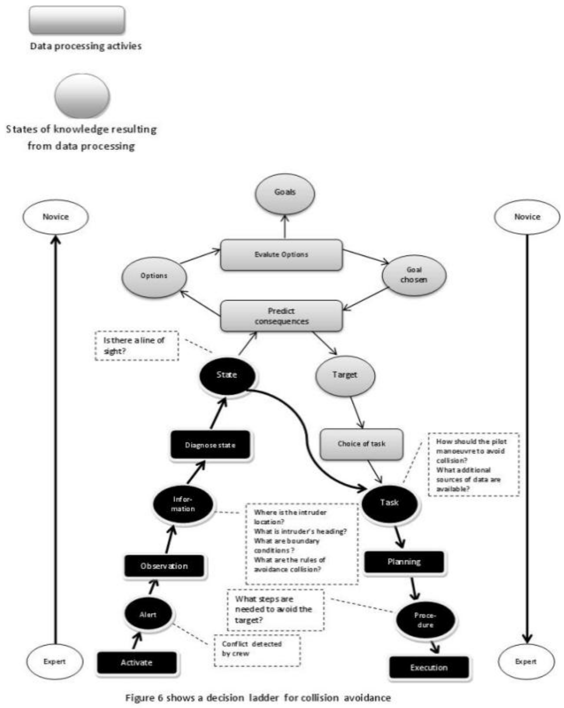

Figure 4: Ecological interface for the flight collision avoidance display

8.2 Ecological Decision Making (Intuitive Approach)

As discussed in section 7.1, the decision ladder is a generic model for mapping any pilots' tasks that may be involved in decision making [51]. The decision ladder shows what knowledge and information is needed by pilots during the decision-making process. Pilots' decision making is a cognitive process. The process directs a pilot's behaviour in acquiring, analysing, implementing and executing a choice of actions. However, pilots may not able to acquire, analyse, evaluate and implement all relevant courses of action. Their cognitive capabilities are limited. Thus, the decision making process must be simplified. In reality, where a specific decision making model is required, the simplification of the decision making process may be effective and efficient, as compared to a generic model. For example, according to a study conducted by Klein [67] and Rasmussen [70] , expert pilots tend to shunt across the decision ladder to reduce cognitive activity, while novice adopts a sequential approach.

A typical high-risk environment such airspace needs pilots to diagnosis conflict situations according to standardised procedures and account for aircraft performance limitations. Therefore, it is procedural decision making. The procedural process includes go/no go decisions as well. For example, selecting a flight path may involve some of aspect of air safety. A pilot's primary safety concerns depend on which route to fly to avoid obstacles. "Bounded rationality" is the fundamental process responsible for this action according to Reason [14]. This action is based on a simple rule of reality. However, these simple rules should lead to *appropriate actions* and be adapted to a specific environment to be ecologically valid [52]. Pilots' *appropriate actions* in this context are to avoid environment constraints. For example, a simple rule of turning left or right to change the aircraft heading is usually used to avoid collision. Therefore, the intuitive approach may not be based on their understanding of the task at hand, however, but similar to other conflict scenarios for which the same appropriate behaviour is familiar. However, if the task is complex and difficult to understand an intuitive approach may be the only option available to pilots (i.e., switching off a faulty system, shutting down the engine that has just malfunctioned). As discussed in chapter 3, these rules are based on the evaluation of mental models rather than formal logical conclusions[54]. According to Todd and Gigerenzer [53], ecologically rational decision making is "making good decisions with mental mechanisms whose internal structure can exploit the external information structures available in the environment".

In a similar manner to the adaptation of the flight route selection heuristic, the reconsideration of the flight route choice (i.e., pilots' second decision) may result from pilots' experience carried over from the previous flight (i.e., rule based behaviour)[53]. To evaluate the future trajectory, pilots need to operate at level of knowledge based behaviour. The acquired knowledge at the level enable pilots to predict the future trajectory of aircraft that is possible in the particular conflict scenario, for example.

9. Mapping Conflict Information to Display

Flight information is obtained from different instruments across the cockpit [47]to enable pilots to develop situation awareness [55]. This requires pilots' focal attention to "effectively" scan and extract information from these instruments across the cockpit. Air accidents reported over the past years occurred either because the pilots diverted their attention away from the ongoing task or a system failed to draw their attention. Thus, an important piece of information is likely to be missed [71]. If a piece of information that is relevant to resolve conflicts, such as miss distance is salient enough, pilots are likely to have been drift further away from the intended target compared to pilots with a system with accurate information. However, pilot must perceive information in such a way that it does not conflict with their mental models. The accuracy depends on the interpretation of digital versus analogue signals. A digital signal representation is accurate, but needs pilots to have a mental "picture" of information being presented. The combination of these two kinds of signals is essential in acquiring situation awareness. A significant challenge is to develop a display that enables pilots to correlate pieces of dynamic information at glance. The proposed display should address this issue by using two-dimensional graphic representation to display flight constraints and performance (see chapter 4 for discussion).

9.1 The Domain Invariants and Constraints

A similar study was conducted by Lau and Jamieson [73]. The authors mapped domain features of invariance based on work domain analysis. The system analysis and findings of the work domain analysis are shown in Table 6.

Table6: Some of selected features of domain invariants based on work domain analysis

Process Description	Geometric Invariants	Levels of Abstraction Hierarchy	Geometric Forms
Protected cone to provide collision avoidance	The protected zone should be the same	Physical Form	Figure 6d
	Heading and bank angle indicator are related to one another	Abstract functions	Figure 6k
	The relative velocity tip must lie inside the cone at a given conflict	Physical Form	Figure 6e
	The relative velocity tip must be inside the cone at a given conflict	General/ Physical Form	Figure 6e
	Ownship and Intruder vectors should denote a triangulation operation.	General/ Physical Form	Figure 6b, Figure 6g
	The circle represent 5nm of protected zone limits should be centred around Ownship and Intruder	Abstract functions/ Physical Form	Figure 6d
	Ownship and Intruder's speed vectors set the conditions of the resolution process.	Abstract functions	Figure 6b, Figure 6g

9.2 Graphic Representations of Conflict Information

Table 8: Function and conceptual benefit of the graphic forms in the ecological interface

Graphic Form	Description and Function	Conceptual Benefits
Figure 6c	The white line depicts the intruder's vector (i.e., velocity and heading)	○ Provides an interpretation and leads to only one conclusion: illustrate future changes in vector (SBB), rather than numerical computation and mental simulation (KBB) ○ Illustrates the extent of a vector with a line (SBB), rather than a mental simulation of numerical values (KBB)
Figure 6l	An image of aircraft miniature is centred around the navigational compass.	Provides an unambiguous aircraft's heading indicator(SBB)
Figure 6b	The dark red vertical line depicts Ownship's vector. A change of the line length indicates speed change and wind vector	Provides an interpretation and leading to only one conclusion: increase or decrease in length (SBB), rather than numerical computation (KBB)
Figure 6a	The cone-shaped zone is formed by two blue lines tangential to the Intruder's protective zone limits	○ Illustrates an interpretation and leads to only one conclusion(SBB)
	The angle of connecting the two blue lines expands perceptually to illustrate the rate of change for the LOSs	○ Illustrates the expansion of the protective cone (SBB)
Figure 6f	The white line connecting the Ownship and Intruder is depicting the Loss of Separation(LOS)	○ Illustrate robustness of the system in maintaining separation (SBB) ○ Illustrate deviation of the actual flight path spatially (SBB) rather than numerical computation(KBB)
Figure 6d	The circle represents 5nm of protected zone limits centred around Ownship and Intruder	Provide appropriate constraints for heading and bank angle indicators (SBB).
Figure 6d	The yellow diamond depicts air conflict	Provide an indication of a conflict between the two aircraft in conflict (SBB)
Figure 6j	The curved green line represents the bank angle. This should be the same under the normal bank angle range. Yellow is caution and red is the limit	Illustrates normal or abnormal operations entire set of
Figure 6e	The velocity vector of Ownship relative to intruder is given by the red vector .The objective is to move the tip of the relative velocity out of the protective cone to obtain a new relative velocity required to avoid the risk of collision	Provides two possible solutions to avoid conflict by at least aligning the relative velocity vector tangential to the intruder protective zone by rotating the relative velocity clockwise or anticlockwise (RBB) rather than using mental simulation (KBB)

The flight collision avoidance design consists of invariant geometric representation as shown in Table 6 with relevant information for collision avoidance. The Table describes the anticipated benefits of visualisation constraints captured in the work domain analysis as guided by the skill, rule and knowledge behaviour. The results indicated that affordances could be structured as a means-ends hierarchy, and thereby function as a mechanism for pilots to cope with complexity and dynamic environments (Table 8). The new system is capable of handling both top-down and bottom up approaches. The top down approach represents deeper information of the system at a higher level (i.e., decision-making process, functional purpose, goals). A bottom–up approach detailing how to achieve the functional purpose of the system is presented.

The selected domain invariants and flight parameters are mapped onto the final ecological interface design as shown in Figure 5.

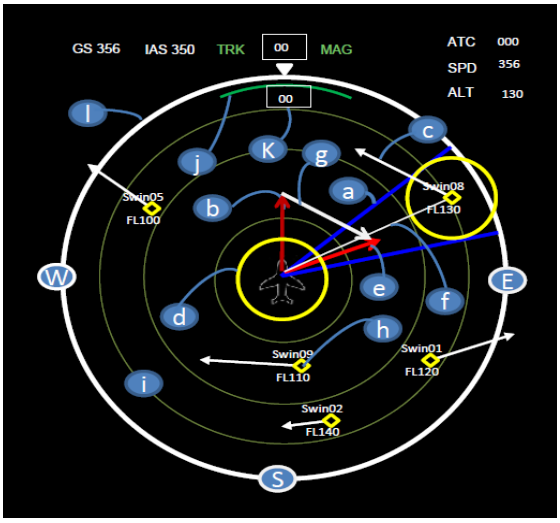

Figure 5: Flight Collision Avoidance Display description

10. Results and Analysis

The section examine pilot preferences manoeuvre. The study developed two collision avoidance displays as presented in Figure 6.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.

(a) FCAS- EID display

(b) Non EID display

Figure 6: Collision Avoidance Display formats

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 [19]. 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. In this study, we assume that:

Scenario 1 Head on approach: an Intruder is approaching opposite to the Ownship. A level left or right turn is required by the Ownship at the current airspeed to escape a collision.

Scenario 2 Port approach (in the 4th quadrant): the Intruder is approaching from the left hand side of the screen. A level left or right turn is required by the Ownship at the current airspeed to escape a collision.

Scenario 3 Starboard approach (1st quadrant).: the Intruder is approaching from the right hand side of the screen. A level left or right turn is required by the Ownship at the current airspeed to escape a collision.

10.1 Preference manoeuvre findings

The pilot will need to determine an appropriate manoeuvre required to avoid air traffic in a free flight environment. The possible solution to avoid conflict is to make sure the relative velocity is outside the protected cone (see Figure 6e). This is done either by rotating the yoke system clockwise or anticlockwise and/or using the throttle lever to change speed. Under the free flight environment pilots have the freedom to choose their flight path to avoid collision. However, this freedom is constrained by the environmental factors such as Intruder and aircraft performance. To achieve this objective, pilots are allowed to change system's configuration to accommodate flight constrains [57].

Pilots' avoidance manoeuvres are reflected in Figure 7. For example, nearly all pilots' in the experimental group avoid a collision by flying behind the Intruder (e.g. due to safety) as compared with the control group. The possible explanation of these consistencies is that pilots in this group consider protective cone's information as a directive from ATC to perform collision resolution as defined by the protective cone. However, the results for control group suggest that converging angle may have imposed some right-of-way ambiguities [60]. The possible explanation of these ambiguities may be as results of pilots' set personalised techniques for how they would prefer to avoid collision [58] when aircraft are converging course as compared to the experimental group. These findings have safety implications in relation to how a pilot may behaviour in a free flight when unsupervised or without making geometry constraints visible while avoiding collision. Clearly, the study revealed the benefits of using the protective cone.

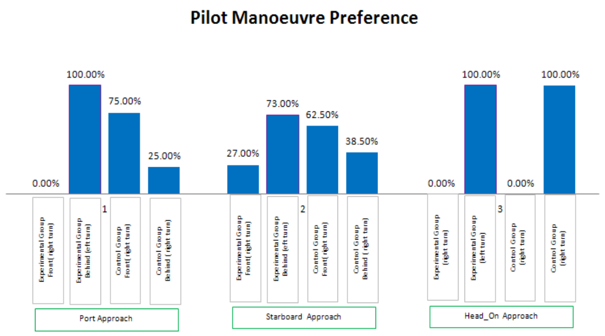

Figure 7: Pilot preferences for Control _Group and Experimental _Group

Conclusions

The paper has provided the background knowledge and methods to design a useful collision avoidance system. A system that improves situation awareness and reduces cognitive workload and cope with errors in conflict situations is important [75]. The proposed flight collision avoidance system is based on the principles of EID approach. Work domain was for flight collision avoidance system analysed. The objective of this analysis is to make environmental constraints visible to pilots. The visibility of these constraints should reduce pilot cognitive workload and errors. Thus, the approach will improve pilots' performance and ascertain how situation awareness and mental workload fits into the attainment of the pilots' goals such as maintaining safe-separation in a free flight environment. The flight collision avoidance system consists of two displays: (a) a protective cone display (b) a relative motion display. There is a relationship between these two displays; however, to date the current ecological interface design displays for conflict avoidance display did not adequately map the relationship between these components to clearly show geometry of conflict and operational constraints. With well mapped constraints, a pilot might be able to instantly predict the possible future state of the system in many conflict situations. Pilots' mental models are captured and externalised to improve situation awareness.

The results from the experimented indicated that affordances could be structured as a means-ends hierarchy, and thereby function as a mechanism for pilots to cope with complexity and dynamic environments. The FCAS is seems to handle top-down approaches. The top down approach represents deeper information of the system at a higher level (i.e., protective cone). 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.

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