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Multiple Target Representation using a Haptically Enhanced Visual Display

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Abstract

This thesis introduces haptic interaction as a potential solution for alleviating human factors problems at the air traffic controller workstation, specifically in relation to the presentation of information on the visual radar display and associated cursor control input device.

A review of human factors principles within the air traffic control (ATC) domain is presented. The construct of workload is investigated in terms of its definition, the problems associated with it, its measurement, and the potential to alleviate workload by transferring the modality of some of the information presented to the controller. Future directions in ATC such as Free Flight and data link communications are discussed in relation to the controllers' changing role.

Visits to a Scottish ATC facility are described and discussed with emphasis on the results of questionnaires, direct controller observation, and the extent to which the findings of these visits support previously conducted research in the ATC human factors field. The outcome of these visits is a set of requirements that can be investigated by way of simulation to determine if haptic interaction has the potential to alleviate some of the identified problems in relation to targeting and visual load.

A review of previous and current multimodal research is presented, concentrating on the use of the haptic sense and it's simulation through a computer interface. Current research in relation to the ability of haptic interaction to improve targeting task performance is reviewed because of its alignment with the types of multi-target acquisition tasks performed by controllers when interacting with the radar display using the associated input device.

The progress made in building a haptically-enhanced simulation is described, and a number of suggestions for progressing this work are provided in the hope that research into the relationship between ATC human factors problems, and the suitability of multimodal enhancement of radar display/input device interaction will continue to be pursued.

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Finally, thanks must go to my partner Jeanette and daughter Lily for motivating me to finish this pursuit.

Chapter 1: Introduction

This thesis sets out the work performed to investigate whether multimodal enhancements, specifically haptic enhancements, of the air traffic controller's workstation environment could have potential benefits in alleviating human factors problems within the Air Traffic Control (ATC) domain. In particular, the suitability of haptics for improving performance of multiple target acquisition tasks, with a potential to reduce visual load, is explored.

1.1 Research Aims

The aims of this research can be stated as follows:

- To better understand the ATC environment and controller task.
- To review the existing literature in relation to the role of human factors research within ATC, identifying where problems have been found to exist within this complex system.
- To study the research field of computer haptics, specifically its use for targeting tasks, and investigate instances where haptics have been applied to the aerospace domain in general and the ATC domain in particular.
- To gather requirements from real ATC facilities and define the development of a haptically enhanced ATC simulation intended to evaluate the suitability of haptic interaction in meeting the requirements gathered
- To identify whether haptics has the potential to generally improve ATC and specifically controller interaction with the radar display and input device.

1.1.1 Thesis Question

Within the ATC domain, are there human factors problems related to the controller task, and radar display interaction that would benefit from the integration of haptics?

1.2 Thesis Structure

Chapter 2 presents the findings of a literature review relating to the human factors role within aerospace, and in particular ATC. An existing model for categorising the communication interfaces among the different components of the ATC system is reviewed in detail along with the human factors problems identified for each interface. Previous research on the construct of workload is reviewed in terms of how it relates to ATC. The future direction of the next generation of ATC systems is also discussed.

Chapter 3 reports on the findings of two visits to the Prestwick ATC facility in Ayrshire on the West Coast of Scotland. The first visit was conducted to gain invaluable understanding of the ATC domain; the second enabled direct observation of controllers and interviews in order to gather specific requirements. The chapter concludes with a discussion of how the field observations relate to the previous ATC research reviewed in chapter 2, and a small set of requirements is gathered and documented that can be used to drive the development of a haptically enhanced ATC simulation.

In Chapter 4, a review of the different sensory modes of human computer interaction is provided with particular emphasis on the field of haptics, relating to the sense of touch. One particular area of haptic research, looking at the benefits it can provide to support targeting tasks, is discussed as this is specifically of interest with respect to the controller task and the potential to reduce visual load.

Chapter 5 presents a review of the currently available ATC simulation environments and their suitability for integrating haptic interaction. Details are provided about the development of a haptically enhanced ATC simulation intended to investigate the suitability of haptics to meet any of the requirements gathered in the previous chapter. A functional specification, design for haptic effects and details of implementation work performed thus far are provided.

Chapter 6 specifies artificial laboratory tasks that can be undertaken as a preliminary step in evaluating the potential benefits of haptics before entering into the iterative implementation and evaluation of a full scale haptically enhanced ATC simulation. This chapter closes with suggestions for how various iterations of the haptically enhanced ATC simulation could be evaluated if the research was taken to this next stage.

Finally, Chapter 7 presents a summary of the work undertaken and a multitude of suggestions for future work in the hope that other researchers will follow on from the ideas introduced by this thesis.

Chapter 2: Human Factors in Air Traffic Control

2.1 Introduction

This chapter investigates the ATC domain and reviews its relationship with that of human factors. It is important to understand the failings that human factors research has highlighted in the domain, and is attempting to combat. This understanding is required before any consideration can be given to testing out whether new techniques or technologies could be employed to successfully alleviate any of the problems. Therefore, the chapter provides a deliberately broad review of the links between aerospace, ATC, and human factors in order to gain a good understanding.

The chapter starts with a discussion of the human factors role within aerospace in general, after which a succinct introduction to the Air Traffic Control (ATC) domain and the particular role of human factors in ATC is presented. The chapter continues by providing a thorough review of the SHELL model proposed by Hawkins [1] for human-machine interaction that looks at problems associated with the interfaces between humans and other components of the current ATC system. Next, the mental construct of workload is reviewed in terms of its definition, problems associated with low and high workload, how it can be measured, and whether or not the presentation of information across different modalities has the potential for workload reduction. A specific example of applying human factors principles to the ATC application area is discussed along with the future direction of ATC systems.

2.2 Air Traffic Control: An Overview

The form of today's worldwide ATC system was first born in 1958, when American Congress formed the Federal Aviation Administration (FAA) and employed 1500 new Air Traffic Controllers who would use surface based radar to track and control the flow of aircraft across America's skies. The creation of the FAA in 1958 was a reaction to a catastrophic mid-air collision of two passenger aircraft over the Grand Canyon in June 1956. Much of the equipment used in many air traffic control centres today is still based around systems put in place in the late 1950s and 1960s [2].

Today's ATC system is based around three different types of facility which handle aircraft at different stages of flight:

- Airport Traffic Control Towers (ATCTs): These are the most well known facilities within the ATC system, and the only ones which are not reliant on the use of ground-based radar to control aircraft. Controllers in ATCTs handle departing aircraft from the time they leave the departure gate, through taxiing, takeoff, until about a few miles after leaving the airport. For arrivals, ATCT controllers take control of aircraft a few miles out, through the landing phase until the aircraft stops at its arrival gate.
- Terminal Radar Control Rooms (TRACONs): These are often situated directly below the ATCT serving the same airport, and are not in any way reliant on direct visual contact with departing or arriving aircraft. TRACONs often have subdued lighting to ensure that the ground-based radar displays are legible, and are handed control of aircraft from the ATCT shortly after departure. Conversely, TRACONs hand over control of arriving aircraft to ATCTs a few miles out from landing TRACONs in almost all cases are entirely reliant on flight data strips. These strips serve as a physical memory aid which complements the radar display, and serve as a vital redundancy backup in the event of radar failure. TRACONs handle statistically, the most dangerous phases of flight; ascent and decent, within the crowded skies in close proximity to an airport. The potential for mid-air collision is greatest in this environment.
- Air Route Traffic Control Centres (ARTCCs): About 5 minutes into a flight, a TRACON controller will hand over an aircraft to an ARTCC controller. ARTCCs control aircraft during the cruise phase of flight after initial ascent and prior to the start of the descent phases. The working environment in ARTCCs is very similar to

that in TRACONs although the facilities are larger in many cases. ARTCC controllers deal with traffic flow changes due to bad weather or traffic volume.

2.3 Human Factors Problems in the Current ATC Environment

Today's ATC environment is comprised of four vital components [1]:

- Humans (for example, controllers, pilots, systems technicians, and managers)
- Hardware (for example, controller workstations, aircraft flight decks, ground radar sites)
- Software (for example, communications software, radar display tools, aircraft navigation systems)
- Environment (for example, temperature and weather)

It is the interaction between multiple instances of the human component, and the human component's interaction with the other three components (hardware, software, and the environment) that determines the operational performance of the ATC system as a whole. The interface between these ATC components was captured well in the SHEL model by Edwards [1] and later modified to the SHELL model by Hawkins [1] (to include the interactive nature of the person to person (liveware to liveware) relationship. The SHELL model is concisely summarized in the next section.

2.3.1 The SHELL Model for Human-Machine Interaction

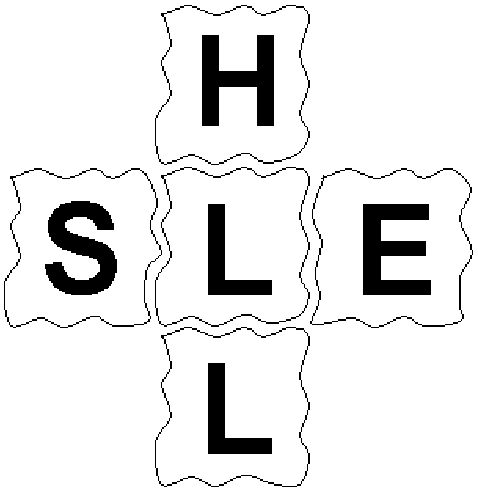


Figure 2-1: The SHELL Model (reprinted without permission from Isaac [1]).

The components of the SHELL model are defined as follows [1]:

- **S**oftware: The rules, procedures, spoken words, and such like which make up standard operating procedures, as well as computer based computer programs which enable automated systems in ATC.
- **H**ardware: The ATC suites, their configuration, controls and surfaces, displays and functional systems.
- **E**nvironment: The social and economic climate in which the controller operates as well as the natural environment.
- **L**iveware: The human beings – the controller with other controllers, flight crews, maintenance personnel, management and administration people within the system.

The SHELL model discusses the human factors issues concerned with the human participant alone (the controller), and the attributes that can affect the performance of this component.

Additionally, the following interactions between components are defined in the SHELL model [1]:

- Liveware-Liveware: The interface between the controller and other humans in the immediate environment (pilots, other controllers, supervisors, managers and engineers)
- Liveware-Software: The interface between the controller and the standard operating procedures and automated ATC software programs.
- Liveware-Hardware: The interface between the controller and the physical features within the controlling environment, especially those relating to the controller workstations.
- Liveware-Environment: The interface between the controller and those variables that may be out of the direct control of humans, namely the physical environment in which the aircraft operates.

2.3.2 Human Factors Problems attributable to the Liveware Component

This section discusses the types of human factors problems that can be attributed to the controller alone. That is, without looking at the controller's interaction with anyone or anything else, the operational performance of individual controllers can vary dramatically, as is the case with all humans (for example, in their performance, attitudes, and personalities [3]. Not only that, but any given human controller can exhibit variable performance depending on that individual's health or state of mind.

The safety limitations of human operators has been recognised for many years. Zeller [3], speaking at an international flight safety conference in 1966 provided an appropriate summary of the limitations of the human (liveware) element:

"One basic truth which must always be remembered any time a human operator is used is that regardless of how well-selected, how well trained, or how optimally used, the human is subject to limitations. If these limitations are exceeded even on a momentary basis, the potential for an accident has been created. If this potential is repeated often enough, an accident will result."

For any given individual controller, since they are after all only human, it is important to recognize that errors are unavoidable. It is the ability for these errors to be recognized (by the human in question, other humans or software) and corrective action taken that determines the safety of an operational ATC environment.

To what aspects of human performance can the majority of these liveware errors be attributed? Isaac [1] states that the auditory sense accounts for the majority of ATC incidents. For example, in many aviation incidents and accidents, problems with information transfer between pilot and controller whilst using the auditory channel have been cited as contributing factors [4]. Aspects of human performance that have been identified in relation to ATC human factors issues are [1]:

- Information Processing
- The Senses
- Situation Awareness
- Decision Making and Judgement
- Selection and Training

2.3.3 Human Factors Problems attributable to the Liveware-Liveware Interface

This section discusses the operational and social communication between the controller and other humans in the controller's work environment, for example, with other controllers, pilots, managers and engineering support staff.

The realm of communication between humans is complex and diverse, and yet effective and error-free or error-tolerant communication is vital within a safety-critical environment such as ATC. Communication falls into two distinct types:

- Verbal: spoken or written
- Non-Verbal:
    - Use of body language: for example, gestures, hand movements, facial expressions.
    - Icons and diagrams: for example, radar displays.
    - Non-speech audio: for example, auditory alarms.
    - Ordering of items: for example, flight strip order.

A single interaction exchange often uses a combination of verbal and non-verbal interaction methods. In specific situations, one of these methods may be more effective than the other, for example, one may be more susceptible to distortion or interference. In these situations, greater emphasis must be placed on the more effective method, or on an alternative method, ensuring that the message is transmitted or received without error. An example of this is where visual data link communication is available between a controller and pilot, and if the verbal communications channel is subject to interference, the data link method may be used to provide a clearance to the aircraft rather than a verbal interaction exchange. In addition to visual data link communications, research work is ongoing to evaluate the usability of data link that is communicated using speech synthesis and voice recognition [5].

Both verbal and non-verbal communication types have the potential to be affected by distortion (or barriers). For example, verbal communication is susceptible to barriers such as poor word choice, high workload, and interruption during message transfer.

In ATC, a large number of incidents are attributable to communication errors in the liveware-liveware interface [1]. The established process for pilot-controller exchanges requesting clearances is for the controller to verify the pilot's response [1]. This procedure is a confirmation that the message exchange has happened with no errors. However, in high workload situations a controller may not respond to a pilot's radio telephony (R/T) request. The pilot may incorrectly assume that because the controller has not challenged the request, it has been allowed. It can be seen that not communicating, when communication is expected, has the potential to affect safety. Could the use of additional sensory channels, other than the auditory channel that is often overloaded in high workload situations, be used to communicate acceptance of a request? This could potentially reduce the auditory bottleneck that is apparent in the current form of the ATC task.

In addition to person-person communications, the combined performance of humans communicating within groups or teams is of key importance to the ATC system. Group communication, interaction, and performance depend on many factors including leadership and followership skills. To ensure that a team of controllers are working optimally, it is important that they are skilled in communication techniques in addition to the skills and experience they have in the ATC domain.

2.3.4 Human Factors Problems attributable to the Liveware-Software Interface

The Liveware-Software interface is concerned with the interaction between the human (controller, pilot) and the software user interfaces, procedures, rules, guidelines and documentation that support ATC. In a safety critical environment like ATC, it is vital that these software and procedural systems are logically correct, actually followed during operation, and tolerant of errors [1]. In the SHELL model, the interface between humans and the physical equipment is treated as a separate interface (see Section 2.3.5). However, humans interact with software user interfaces using hardware, such as visual displays and input devices. This may indicate an over-simplification of the relationship between non-liveware interfaces defined in the SHELL model.

2.3.4.1 Software User Interfaces

Available functions of software are determined by its functional design. However, its usefulness is dependent on the quality of its user interface [4] in terms of its support for primary tasks, secondary tasks and associated actions. One of the most important aspects of the software user interface in ATC is the graphical chart display and its presentation of information. It has been found that when controllers are searching maps, the time taken to find a target is inversely proportional to the position in the periphery at which the target can be seen [1]. Perhaps the use of other sensory modalities, such as sound or touch, in combination with vision could reduce this time. The use of colour on the user interface is also important because certain colours stand out more than others, both visually and in terms of preconceived notions we have to some of them (for example, green for GO or red for STOP/ Danger). Research is also ongoing to discover if the traditional paper flight strips, used by controllers along with the radar display to provide a view of the traffic, can be successfully replaced by software-based equivalents see Section 2.4.

2.3.4.2 Procedures and Checklists

The standardisation of procedures is intended to alleviate the variances of human behaviour. It has been researched that the failure of pilots to follow standard rules and procedures is one of the main problems in aviation, and it is thought that a similar problem may be present in ATC. In some cases, procedures may differ from country to country. One recent example of this was the difference in priority of the controller's orders in relation to the Traffic Collision Avoidance System (TCAS) system in the mid-air collision of a Russian charter airliner and DHL freight-carrying airliner. The difference in procedures between Russian and European pilots has been cited as a contributing factor in this accident. In Europe, TCAS takes priority over ATC orders, but Russian pilots are trained to take account of both, and then decide themselves how to resolve the conflict [6].

2.3.5 Human Factors Problems attributable to the Liveware-Hardware Interface

Isaac [1] states that engineering principles rather than behavioural principles are typically used in designing machines for use by humans. She states that a key design criterion is the appropriate allocation of tasks either to machine or human as each has its strengths and weaknesses in terms of abilities.

Humans are more adept at activities such as sense, detection, recognition, selection, and reasoning. Machines are more suited to monitoring, processing quantitative information, performing repetitive tasks, and maintaining performance over extended time periods. An optimal system design must take into account the allocation of tasks that enables the human and machine components to work together synergistically.

This section concentrates on the design of the physical hardware used by controllers, more than the software applications that run on that hardware, and are integrated with it. One important aspect related to physical design is that humans (in this case, those employed as controllers) are all different in terms of their physical characteristics [4]. Differences exist in stature between western and oriental populations, and also people within the same population display more subtle differences. For example, seating designed for use at the workstation must be adjustable to accommodate controllers with different limb proportions.

Workspace design in facilities where no direct observation of aircraft is performed is highly variable from one ATC facility to the other. This is generally a characteristic of the layout of workstations covering different sectors. In towers, arrangement may be optimised for passing flight progress strips. Sometimes, controllers covering different airspace sectors share the same display. This has advantages in that it improves co-ordination and integration. However, the two controllers may have different needs in terms of optimising the display, which display sharing does not allow.

Where an ATCT and TRACON are located in the same building, a drop tube fed by gravity may be used to handoff flight strips from the local controller to the departure controller. In some facilities, this operation is replaced or supplemented by a Closed Circuit Television (CCTV) system that departure controllers use to watch facilities in the tower.

In some cases, individual facilities have adopted custom solutions that have been integrated into their existing systems. These tailored solutions contradict the desire to standardise systems across facilities because in many situations, trying to satisfy the requirements of different facilities is in conflict.

The Advanced Automation System (AAS) program, commissioned by the FAA and later cancelled in 1997 (because of continually changing design recommendations) specified a list of components to be integrated into a common controller workstation [4]. Despite its cancellation, the AAS program followed a process that is highly relevant to current and future controller workstation developments. :

With respect to data entry on the AAS common console, the key input devices are the keyboard, trackball, and touch screen entry panels. The keyboard and trackball use standard interfaces.

The trackball was selected as the cursor positioning device in the AAS program after a series of trade-off analysis and experimental trials, performed on trackballs of several diameters from different vendors, mice, force sticks, and direct touch [4]. A one-inch diameter ball was selected for the common console and a two and a quarter inch ball for ATC tower applications. Originally, the larger ball was embedded in the thicker shelf for an early console mock-up. During a prototype demo, the review team determined that the smaller ball enabled equal performance but had the advantage of being easier to relocate. The palm rest was found to be too high above the position of the numeric keypad. A custom design matched the profile of the keypad and flexible positioning of input devices has received good feedback.

Alternative cursor positioning devices were dismissed. A mouse was considered too fragile and had the disadvantage of having to manage the cord position (although now cordless designs are available). It was also difficult to physically locate without looking down to determine its exact position.

Although a mouse was discarded for the common console in the US, it is interesting to note that the most recently commissioned ATC facilities in the UK use a mouse rather than a trackball input device. This is a departure from previous generation ATC facilities in the UK such as those at Prestwick that use integrated trackball devices. It is unclear whether this decision was made to reduce cost, ease replacement and maintenance, or as a result of unreported human factors findings.

2.3.6 Human Factors Problems attributable to the Liveware-Environment Interface

This section discusses other environmental variables that affect controller performance.

2.3.6.1 Stress and Post Traumatic Stress Disorder

Stress can be defined as a state that is caused or associated with an event or situation that reduces work effectiveness, changes behaviour or causes health problems. The extent to which stress affects an individual depends on the type of stress factor or stressor and the type of individual.

Stressors in the ATC environment include lack of time, lack of knowledge, uncertainty, changes in procedures, constant checking of proficiency, career progression, shift work issues, and labour issues [1].

Post Traumatic Stress Disorder (PTSD) occurs when a person's functioning continues to be disrupted as a consequence of the traumatic experience. This condition can happen to individuals directly involved in an event or by those working within the same work or social environment.

2.3.6.2 Sleep, Fatigue and Shiftwork

Humans require a sufficient amount of sleep to function properly. The exact amount of sleep required varies on an individual basis. Disturbed sleep (or prolonged work) can cause fatigue. The effects of fatigue can include subjective tiredness, poor vigilance, greater tracking errors, and loss of flexibility and adaptability [1].

"The term shiftwork refers to the allocation of work schedules to allow job duties to shift between groups of workers over various times of the day. Shiftwork has arisen because many industries or workplaces require round the clock operations, either for economic reasons or, like ATC, because of the continuous services provided." [1].

A significant amount of research has been undertaken in the last decade looking at how shift patterns affect human well-being and performance. This is due to the fact that many serious accidents have cited time of day and fatigue as contributing factors. Changing an individuals' working hours affects their sleep patterns and realignment of their sleep patterns can in some cases take up to a week.

Very little research has been performed to look at the effect of shiftwork in the ATC environment, although a great deal has been performed on the flight deck and other aviation environments. However, the tasks of pilots are quite different from those of controllers so the bulk of the existing flight deck research findings cannot be transposed to the ATC domain. Pilots are subjected to high workload during take-off and landing with relatively low workload in between, whereas controllers can experience high workload situations over longer periods of time. Lower workload situations (like those experienced by pilots during level flight and controllers working quiet sectors at night) have the potential to bring on tiredness and a lack of attention. Refer to Section 2.3.7 for a review of the literature related to workload.

2.3.6.3 Safety Management

"Measures that are designed at removing, mitigating or protecting against operational hazards now play a large part in the resource allocation in organisations engaged in potentially dangerous activities." [1]

Reason in 1990 [1] proposed a model in which he stated that in every incident (excluding deliberate acts of sabotage or terrorism) there are latent human failures which remain hidden until circumstances cause them to be an active variable in the incident sequence.
An incident sequence is complex including many variables. Reason argued that each of these variables had the potential to 'pass on' both active and latent failures. He represented these failures by holes (opportunities) at each layer. A failure at any level could be kept at that level if the holes did not directly line up. If events caused any of the holes to line up then it was highly likely that the error would be passed to the next layer. In the unlikely event that all the holes lined up at a given time then there was a good chance that an incident or accident would follow [1]. Reason's systematic failure model in relation to ATC is shown in Figure 2-2 including an example of an accident trajectory that passes through a hole in each layer.

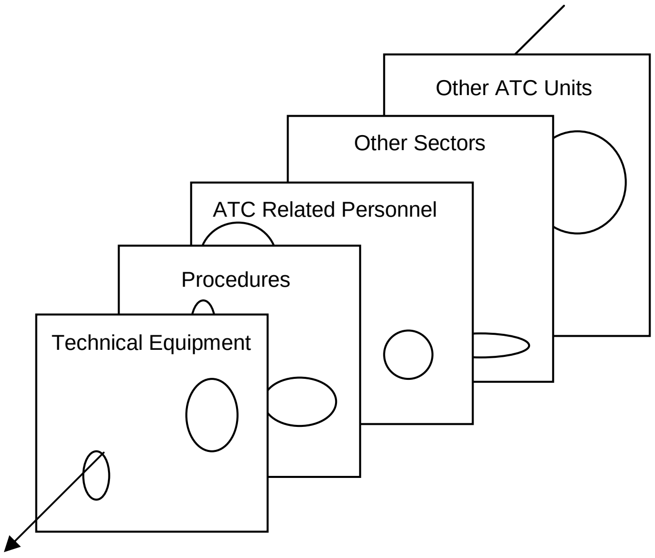


Figure 2-2: Reason's Systematic Failure Model.

Any new technology or technique proven to solve problems in a domain space has the potential to contain latent failures when integrated into an existing safety critical system.

2.3.7 Workload in ATC

It has been stated that there is no generally accepted definition of workload [4]. However, despite the lack of a generally accepted definition, the workload mental construct is the target of much work within the domain of ATC research and operations.
In 1983, Stein and Rosenberg [4] proposed the following definition of workload:

"The experience of workload is based on the amount of effort, both physical and psychological, expended in response to system demands (taskload) and also in accordance with the operator's internal standard of performance.

More concisely, it has been stated as the cost of a given task for the human operator [7] So, whereas taskload is based on the environmental conditions, workload is the human response to these conditions. Negative aspects of workload, and an increase in the chance for error, can arise when the operator is either close to performance limits (high workload), or when they are experiencing a lack of activity and boredom (low workload) [4]. In fact, FAA databases have indicated that controllers make more errors during periods of low to moderate workload [4]. Additionally, in aircrew workload research, a precursor to ATC workload research, work has been undertaken to study failure mode workload, the condition of sudden or unexpected user workload caused by the failure of some part of the aircraft system during operation [8]. Pilot workload during system failures and emergencies can be even higher than the generally accepted high workload flight stages of takeoff and final approach.

2.3.7.1 The Two Workload Extremes

The previous section introduced the notion of how low workload situations can be every bit as undesirable for the human operator as high workload situations. When coupled with shiftworking patterns, the performance effects of minimum workload in conjunction with shift working can be significant. Corradini [9] researched these combined effects, finding that low workload during a morning shift produced the most correct controller-pilot communications performance, whereas nightshift working in conjunction with low workload sectors of 1 to 2 aircraft per hour resulted in increased miscommunications (such as deviations from standard phraseology and referential ambiguity). The fact that low workload can cause problems due to the controller being under-challenged by their environment has affected, and will continue to affect the design of ATC systems and how functions are allocated. If increased automation replaces the human's role to the extent the controller or pilot experiences significant reductions in workload, this can negatively impact their situational awareness and therefore the ability to control [4]. However, Wickens [10] states that operators, when given some flexibility, usually work to achieve an optimum level of workload by seeking tasks when workload is low, and shedding them when workload is excessive. This suggests that coping strategies may prevent low workload situations from reaching potentially dangerous states.

In addition to the negative effects of low workload conditions, high workload situations are more widely identified as a cause for concern. It has been found that operators only perform a secondary task well if they are not fully loaded on the execution of the primary task [4]. The presence of a secondary, background or interruption task although contributing to workload, can be highly important to maintain the controller's situational awareness. A case in point is the research ongoing to determine the effect of digital data-link communications on the flight deck and whether the absence of party line radiotelephony (R/T) reduces or increases aircrew workload, thus contributing to flight safety [11]. Findings from this study indicate that background party line R/T does increase pilot workload, being particularly disruptive during high workload flight phases. However, party line communications are highly useful to aircrews during less busy stages of flight to maintain alertness and build situational awareness of the picture outside the aircraft [11]. Additional research by Pritchett, Midkiff, and Hansman in 1995 [12] sets out to identify the way that party line information is used, and its implications for data-link communications. The work, by means of a survey of experienced pilots, identifies elements of party line communications considered critical or important. Party line information in relation to traffic and weather situations is stated as critical, having a direct effect on flight safety. The paper concludes with the notion that information currently provided by party line R/T could instead be transferred to a data-link implementation. This transfer could be more reliable, more available, and more intuitive when compared to the unreliability of R/T party line in high workload situations. The work does not consider how the transfer of modality from audio (R/T) to visual (data-link) may affect the effectiveness of the information.

McClure in 1986 [4] identified the following attributes as contributing to controller workload:

- Number of aircraft handled
- Type and variety of aircraft handled
- Complexity of what the controller has to do (for example, turns, altitude changes)
- Amount of time working traffic at position (often referred to as fatigue)

Christien, Chaboud, and Loubieres in 2002 [13] describe a method for automating the classification of sectors according to their complexity in a non-subjective manner. The authors state that their model can be used to improve future controller workload and arrive at sector capacity predictions. The following four cluster types are defined:

- Climbing/descending traffic, low entropy. In general, these sectors contain one or two major flows near approach sectors.
- Mostly traffic at cruise level, same aircraft types, flow entropy medium. Upper en-route sectors.
- Little climbing/descending traffic, big flow entropy, lot of crossing conflicts. Upper sectors located in core area.
- High aircraft performance mix, lot of climb/descent traffic, high flow entropy and medium conflicts. Generally, these sectors are close to several airports.

Smolensky and Hitchcock in 1996 [4] stated that an increase in errors can happen with changes in workload, particularly from high to low (for example, a controller switching from an extremely busy sector to a quiet sector during his shift). They suggested that workload should be monitored continuously during task performance.

2.3.7.2 Measurement of the Workload Construct

In addition to the large body of work concerned with identifying exactly what workload is, its measurement has additionally received significant research interest. At a high level, two types of measurement have typically been used to attempt to infer workload, objective physiological measures and subjective workload measures. A discussion of work in these two areas, together with details of the use of traffic characteristics for workload prediction, is reviewed in the following sections.

Objective Physiological Measures

Physiological measures use the principal that the level of workload experience will be reflected by changes in the electrical activity and biochemistry in the human body [4]. Measurements to recognise these changes typically must be very sensitive and can require intrusive techniques. Some of the measures used have included eye blink rates, pupil diameter, eye movements, critical flicker frequency (CFF), blood pressure, respiration rates or content, electroencephalograms (EEGs), electromyography (EMG), body fluid analysis, and galvanic skin response (GSR) [3].

Orlady [3] sums up the performance of physiological measures in determining workload by stating that all attempts have so far proved unreliable, due to individual variability and a lack of correlation between the physical traits being measured and workload. Stein in 1992 [4] found no relationship between pupil size of controllers and either environmental taskload or subjective workload.

Subjective Workload Measures

Far more accessible and considered to be more successful, are subjective methods of measuring workload. Subjective measures have a history in aviation dating back to 1969 [4]. The reliability of subjective workload measures are said to be less task dependant than physiological measures[3]. Typically, this type of subjective assessment is easier and cheaper to conduct than physiological measures.

A number of subjective workload measurement methods have been developed and used to differing degrees [3]. The following list summarises some of these methods:

- Task/Time Line Analysis (TLA), used traditionally in flight crew workload measures, calculates the ratio of time required to the estimated time available, for each operating procedure and for every action of the flight crew. The Report of the Presidents Task Force on Aircraft Crew Complement in 1981 suggested the use of this method. Boeing refined the TLA method to provide more support for measuring mental workload. However, TLA is considered to have failings in measuring non-observable workload and the effects of monotony. Two experienced FAA test pilots considered TLA to be a good design tool but less useful for workload certification.

- The Cooper-Harper Scale was originally created in 1969 so that test pilots could evaluate the handling qualities of aircraft. This subjective method uses a branching, decision tree technique to evaluate aircraft flight performance [3]. A modified version was developed in 1983 that added the ability to evaluate cognitive functions such as perception, monitoring, communications, and problem solving.
- The Subjective Workload Assessment Technique (SWAT) was developed in the early 1980s by Reid, Shingledecker, and Eggemeir [4]. SWAT has been used by the US Army and US Air Force. SWAT uses the following dimensions:
    - Time load – the number of interruptions subjectively experienced by the operator.
    - Mental effort – the amount of thinking the operator considered they had to perform.
    - Psychological stress – the perceived risk, confusion and anxiety.

  SWAT has provided valid and reliable results in many use cases but there is still concern over the need for the pre-scaling activity required by participants, which is considered laborious and distracting from the main subjective evaluation being done [3].
- The NASA-Task Load Index (NASA-TLX) was refined from the ten-scale NASA bipolar scales [3], based on initial work by Hart and Hauser in 1987 [4]. NASA-TLX uses the following six subjective workload dimensions [3]:
    - Mental demand: How mentally demanding was the task?
    - Physical demand: How physically demanding was the task?
    - Temporal demand: How hurried or rushed was the pace of the task?
    - Performance: How successful were you in accomplishing what you were asked to do?
    - Effort: How hard did you have to work to accomplish your level of performance?
    - Frustration: How insecure, discouraged, irritated, and annoyed were you?

Additional subjective have been developed and used such as the Bedford Scale, developed at the Royal Aircraft Establishment in Bedford, and the Dynamic Workload Scale developed by Airbus Industrie [3].

Different techniques have been used to gather the subjective ratings. In addition to post-task sessions, studies have been conducted that ask participants to evaluate their workload at a high level during the task at set time intervals (for example, every minute). This method has been found to be non-intrusive and has the advantage of real-time evaluation at a particular point while completing the task rather than having to remember experiences in a post-task questionnaire [4]. Another technique used in the acquisition of subjective input involves workload rating by experienced controllers looking over the shoulder of the participants. This observation technique is one favoured by the ATC community and in studies has been found to correlate well with participants workload ratings. However, the potential for rating errors when using this technique alone has to be considered [7].

Workload Prediction using Traffic Characteristics

In addition to the objective measurement of workload during a task, and the subjective scaling of workload after task completion, approaches based on traffic characteristics have been used to predict workload in advance. Predictive workload assessment can be used before producing a system, or when a system is in place to schedule work/rest cycles and determine pay scales [4]. One novel approach in this area has been the use of a trained neural network with statistical measures derived from the traffic used as input for predicting controller workload [14]. The network uses kinematic variables based on the spatial distribution of the aircraft within the airspace. Findings of this work suggest that the trained neural network is able to predict controller workload with a high degree of certainty that correlates with a qualitative assessment of their workload.

Averty et al in 2002 [7], conducted a comparison study to determine the correlation between physiological, subjective, and a traffic load index (TLI) based on traffic flight data. In this study, the physiological measurement of heart rate and skin conductance were found to correlate best with the TLI method, whereas the subjective workload measures showed the worst correlation, particularly in the use of NASA-TLX. However, it is stated that a main weakness of the TLI method is computation of values by a single expert controller, rather than the mean inputs of a team of controllers. It could be that the NASA-TLX result, although poorly correlating with the physiological and TLI methods is closer to the actual workload experienced by the participants of the study.

Discussion of Workload Measures

As stated previously, subjective measures like NASA-TLX are typically considered to be more reliable, easier to facilitate, and suffer from less task variability in the measurement of workload when compared to physiological objective measures. The use of traffic characteristics has been used to predict workload in the design and evaluation of new systems. However, this type of prediction is heavily determined by taskload in the form of system demands, which frequently ignore the individual variability of individual controllers. What is clear is that, like the lack of a uniformly accepted definition of what workload constitutes, its successful measurement is still a research challenge that is still open to innovation. The measurement of workload is most definitely highly related to the task being undertaken and the environment. A method of that gives reliable results in determining workload for one task may not be reliable for another task.

2.3.7.3 Can Workload be Reduced Using a Transfer of Modality?

Research performed by Stein in 1984 and 1985 used an automated tool to predict workload based on controller activity [4]. The ATC simulation ran for one hour and during this time participants had to rate their workload every minute, observing controllers rated performance every fifteen minutes, and post-experiment questionnaires were completed specifying the workload contribution of common tasks that controllers performed during the simulation. The following activities were identified as generating the most workload:

- The number of aircraft handled.
- The number of altitude changes.
- Housekeeping (that is, maintaining order in the display).
- Using the keyboard to enter data.

It is interesting to note that visual display housekeeping is cited as a significant workload contributor. Visual load related to the ATC display environment has been the subject of additional research by Small, Hammer, and Rouse in 1997 [15]. Experiments were conducted to compare controller performance using the traditional analog radar display format against the use of a simplified digital icon radar display presentation. The study concluded that the alternative digital icon display allowed the following benefits:

- Reaction time was found to be on average over two seconds faster when subjects used the digital icon display.
- Targets on the display were located more quickly.
- Time spent focused on areas of the display without targets was less.
- Controllers preferred the simplicity of the icon display and disliked the noise of the analog display.

From this work, it can be seen that there is a potential for controller performance to improve with the use of a less complex, and less noisy display space. Although this work does not specifically consider visual load, it may be the case that a less complex radar display can reduce visual load (for example, by improvements in targeting performance), perhaps freeing up mental capacity for other activities related to the task at hand.

If a reduction in mental workload through radar display optimisation is achievable, is it possible that the distribution of the required information, across different modalities could improve performance and reduce workload that would otherwise be increased if this information were presented visually?

The work of Chih-Yuan, Nikolic, and Sarter in 2001 [16] involved a study to investigate ways of supporting timesharing and interruption management in ATC by distributing tasks across different modalities. The study involved the participation of 32 students performing a simulated ATC task under low and high workload conditions on a desktop computer. The study showed that subjects delayed starting visually notified interruption tasks significantly longer than auditory and tactile notified interruption tasks. Interruption tasks that were notified using auditory or tactile methods were found to interfere less with the visual focused ATC primary task performed during the study. When performed simultaneously with the visual ATC task, the visual interruption task gave rise to the largest number of errors. The study concluded that reduced resource competition and scanning costs, was potentially the reason that the use of different sensory channels for presentation of concurrent tasks resulted in improved time-sharing performance.

In today's ATC system the auditory channel is typically heavily used for controller/pilot and controller/controller communications. Therefore, if the study had involved a greater degree of communications simulation, it is possible that there may have been competing resources that would affect the participants' responses during those interruption tasks presented using the auditory modality. However, the result of this study looks promising in terms of the performance improvements afforded by tactile presentation, an as yet relatively underused display medium in the ATC domain.

Chan, MacLean, and McGrenere [17] investigated the use of tactile feedback to transmit background information when the user is engrossed in a cognitively intensive primary task presented visually or using the auditory modality. Promising results were achieved under high workload conditions.

2.3.8 The Importance of Looking at the ATC System as a Whole

In many ATC incidents or accidents, as discussed in Section 2.3.6.3, it is often a chain of interlinked events that causes the system to fail.

Within the current ATC system, workstation interaction is almost entirely reliant on graphical user interfaces, with the exception of a degree of auditory interaction that is used to indicate alarm conditions and pilot-controller/controller-controller radio transmissions. Advances in ATC thus far have tended to focus on applying new technology as it becomes available rather than the introduction of more intuitive and easily understandable ways to present data [4].

A key consideration when applying new technologies to problem domains is to accurately capture the issues and problem areas within the particular domain. Many information systems have been proven not to meet the needs of intended users on their completion, far too late and costly a stage in development for this to be realized. In some cases, new systems attempt to fix a problem that does not actually exist. Take for example, the many failed attempts to automate the well-established work practice involving the use of paper flight strips. Controllers use these to track and modify information about aircraft and their flight plans and are extremely sceptical of any attempts to take these artefacts out of their working system because they are proven to work [18] and provide a vital backup in the event that electronic systems fail. Often, the introduction of new technology to solve human factors problems has greater chance of acceptance if it enhances, rather than attempts to replace, existing systems [19].

Human factors problem areas that have already been recognised within the ATC system include the following [4]:

- Incorrect decision making as a result of losing situational awareness: For example, a pilot wrongly assuming that ATC had cleared his aircraft to continue descending when in fact, only a partial descent was cleared [20].
- Communication problems such as procedural deviations, inaccuracies, and non-routine transactions, and interaction between pilots, controllers, and newly introduced automated systems.
- The impact of increased automation in ATC systems. For example, the integration of new technologies which may increase usability problems or decrease user acceptance because they have not been adequately evaluated to ensure they provide the best possible solution – could an older more proven technology have provided a better more intuitive solution?. In addition, if highly reliable automated systems do fail, are the tasks that the failed system is no longer performing easily transferable to be undertaken manually?
- With the introduction of Free Flight (discussed in Section 2.6) and other future air navigation strategies, will the changing role of air traffic controllers (from manager to monitor) negatively impact their performance level? Will conflict resolution strategies prove effective?

2.4 An alternative to Paper Flight Strips: Digistrips

The traditional paper flight strip is a vital artefact of the ATC task. Paper flight strips are widely used in ATC facilities throughout the world and have been for decades. The paper flight strip provides one of two complementary views of the air traffic [18]:

- The radar screen allows the controller to track the current position of the air traffic moving along a predefined route within a particular sector.
- The collection of paper flight strips enables the controller to organise the traffic, plan strategies, and record key decisions.

The organisation of a typical paper flight strip is shown in Figure 2-3.

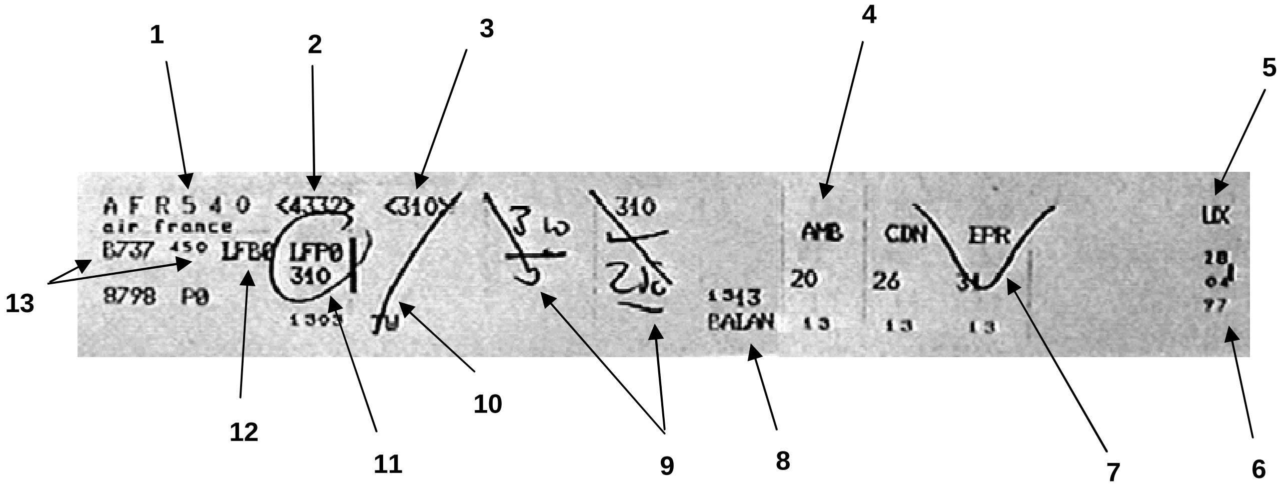


Figure 2-3: A Typical Paper Flight Strip (reprinted without permission from Mackay [18]).

1. Flight name and number.
2. Radar ID number
3. Requested flight level approved
4. Beacon name and the time that this aircraft is scheduled to pass over it.
5. Sector that this flight strip was printed for.
6. Date printed
7. Annotation indicating that pilot is authorized to fly a direct route from BALAN beacon to EPR beacon.
8. Beacon name and scheduled leaving time.
9. Flight level change from FL310 descending to FL250.
10. Indication that the controller has authorized the approved level and the pilot has agreed.
11. Arrival airport/requested flight level.
12. Departure airport.
13. Aircraft type and speed.

A key function of a flight strip is that it can be annotated. As there are variations in the way people take notes, then there are differences in the way controllers annotate on a flight strip. Even though there are guidelines as to how annotations should be made, there is still potential for error caused by one controller misinterpreting annotations made by another controller.

There is significant research being undertaken to look at how the traditional flight strip model can be enhanced, transformed to an electronic implementation, or even scrapped completely.

So, can the traditional paper flight strip be enhanced so that inherent issues such as annotation misinterpretation could be alleviated? Would users of paper want some other tool entirely which performs the same function, would they want another tool which looks at the tasks which paper flight strips support and come up with a lateral solution that bears no resemblance to the current paper flight strips usage model?

ATC Researchers at the Centre D'etudes De La Navigation Aerienne (CENA) in France have been investigating the use of an alternative to paper flight strips [21]. These electronic versions of paper flight strips are termed DigiStrips. The main features of DigiStrips are as follows:

- The user can move graphic objects (electronic strips) by using a "Drag and Drop" operation directly on the touch screen.
- Using combinations of gesture recognition and menus, the user can enter input information.
- Two instances of DigiStrips can be employed allowing radar and planning controllers to interact.

Figure 2-4 shows an example of a DigiStrip and the placement of a DigiStrip by a user. A handwritten font is used for annotations. Animation is used to indicate events such as the arrival of a new strip and the insertion of a strip among existing strips [22].

Figure 2-4: A Typical DigiStrip and Example of Manipulation Using Touch Display (reprinted without permission from CENA [21]).

Digistrips have been integrated into the Toccata controller workstation research project [23] of which there are a number of working demonstrations in France. The aim of the Toccata program is to gather related research projects to understand interaction issues in controller workstation design [24]. Two key benefits over paper flight strips that DigiStrip researchers have cited are enhanced information sharing and user feedback.

In addition, Digistrips are said to afford the same benefits as traditional paper strips, and enable the transition of existing skills into the new environment.

A significant amount of research has been performed in investigating the automation of paper flight strips. Paper strips are regarded as highly important to preserve the controllers situational awareness [4] and it is thought that the act of physically manipulating the strip (for example, while annotating it) positively impacts situational awareness. This physical act would be lost if a system such as DigiStrips replaced paper versions. However, qualitative feedback in a research setting has been positive [24]. Whether or not the acceptance would be as positive if the system was extensively evaluated in an official ATC system is unclear. The approach used by DigiStrips is to attempt to replace a well-established artefact that has proven to be effective. Other human factors research approaches, related to the introduction of new technologies within ATC, include the enhancement rather than replacement of existing interaction objects. Another alternative is to take a top down approach, looking at the ATC domain as a whole and to completely redesign the way controllers perform the ATC task, so that for example, there is no longer a need for paper or electronic equivalents of flight strips. This sounds like an attractive research proposition but is fraught with danger because of the difficulty in fully understanding the complex and dynamically changing ATC domain.

2.5 Pitfalls of Human Factors Research in ATC

Human Factors research in ATC must be targeted towards attributes of the system which needs to be improved. In some cases the existing method used to perform a task is already close to optimal, using existing computer systems or manual procedures. Applying new computer-assisted approaches may not offer significant performance improvements and in some cases may create different, and often more dangerous human factors issues. An example of this is increased automation that can in some cases cause an operator to mistrust the information that the computer is reporting. This is a phenomenon that has been cited as a contributing factor in some aircraft incidents and accidents, particularly in modern glass cockpit flight decks. Is the reported failure a computer defect or a true alarm condition? In some cases, automating an existing manual process “just for the sake of it” may not be the optimal solution. Computer assistance may enable significant benefits by using a completely new approach.

To ensure the greatest chance that its intended users will accept any new tool or technology, it is vital that users are involved throughout the requirements, design, implementation, and evaluation phases. Often, the system designers’ picture of the requirements that a solution must satisfy is vastly different from the solution that is actually required.

2.6 From Active to Passive: The Future Role of Controllers and Related Safety Concerns

Challenging times are afoot for the ATC system. Many bespoke computer systems exist in different ATC establishments throughout the world, but the infrastructure has to integrate as a whole to maintain safety and efficiency. A significant body of work is in progress to move towards a new ATC model termed as Free Flight [25]. In Free Flight airspace, it is envisioned that flight crews will have the authority to make real-time decisions about route alterations, for example changing altitude to avoid turbulence [4]. The controller is expected to act in more of a monitoring role. Potential cost savings are significant since aircraft can take more direct routes negating the need for pre-defined air corridors. In addition, free flight should be able to allow for significantly increased capacity over the fixed air corridor model. However, the transition to this model must be achieved while still maintaining the same degree of safety initially, and with improved safety levels long-term as flight capacity requirements increase. The issue of how aircraft move between Free Flight airspace and traditionally managed airspace is receiving research attention [26]. Responsibility rules for pilot and controller have to be precisely defined for the free flight model to work seamlessly.

Another concern is the affect that the changing role required by the controller will have on performance and situational awareness. Many ATC incidents and accidents happen during quiet periods, or within sectors with very little traffic. If the controller monitoring free flight airspace is taking less of an active role, this has the potential to increase the level of inactivity experienced by the controller [1].

2.7 Conclusion

This chapter has provided a review of the ATC domain and the role of human factors in striving to identify and propose solutions for recognised problems. The various interacting components of the ATC system have been reviewed in detail drawing extensively on the work from Isaac [1] regarding the factors that affect human performance, and specifically in this case, controller performance. The previous research concerned with workload has been reviewed in detail, including its definition, problems associated with it, and its measurement. “Display housekeeping” was identified as a significant generating factor of workload for controllers, and in response to this, the question is asked as to whether transferring some controller activities across to a different sensory channel, could reduce the problems associated with competing resources and thus improve controller performance. The answer to this question is significant for the subject matter presented in this thesis.

Chapter 3: Visits to ATC Facilities

This chapter provides details of two visits conducted to the En-route ATC facility at Prestwick in Ayrshire. The first visit provided an opportunity to be immersed in the ATC domain within an en-route facility, and gather results from an initial questionnaire. The second visit was more highly targeted at radar display and input device use, so as to understand the interactions performed and appreciate the controller task. A discussion of these visits is included, describing any limitations of the field study design and details of how the findings relate to previous research. The final section in this chapter discusses and defines requirements gathered as a result of these visits, in relation to human factors problems and suggested enhancements of the systems at the Prestwick facility.

3.1 First Visit to Scottish and Oceanic Control Centre (SOACC)

On Friday 15th February 2002, a visit was conducted to the National Air Traffic Services (NATS) Scottish and Oceanic Area Control Centre (SOACC) at Prestwick, Ayrshire. An Aeronautical Engineering student set up the visit and the author was invited along. Since the other student was the main organiser of the visit, the author was constrained in the amount of time available to gather specific information. Hence, this first visit was intended to provide an introduction to an en-route ATC facility and answer some basic questions about the ATC environment. The visit host was involved in ATC Operations Support and was also an active controller.

The rationale for the visit was as follows:

- To perform an initial visit to a real ATC environment so as to gain a better understanding and appreciation of the controller's workplace.
- To get an overview of the numerous IT systems that are used in a typical ATC environment, specifically the interfaces and tasks performed using these systems.
- To ask interviewees ten questions that capture initial domain knowledge.
- To determine the possibility of having access to real controllers for the purposes of conducting future empirical studies as part of this research.

3.1.1 Overview of the SOACC Facility

This section provides an overview of the two control centres at Prestwick, the Scottish Area Control Centre (SACC) and the Oceanic Area Control Centre (OACC).

3.1.1.1 Scottish Area Control Centre

The SACC controls aircraft in the Scottish Flight Information Region (FIR). The Scottish FIR is Europe's largest, stretching to the north of a line between Carlisle and Newcastle, to near the Faroe Islands including Northern Ireland and the surrounding seas.

Each control suite at the SACC can house a planning controller and an executive or radar controller, with support from a flight progress board assistant. A flight planning board displays the flight progress strips and there is a radar position with two radar displays [27].

3.1.1.2 Oceanic Area Control Centre

The OACC supports aircraft flying over the Eastern part of the North Atlantic from the South of Iceland to North of the Azores. Controllers communicate with pilots and other controllers using high frequency radio to gather position reports and pilot estimates. Radar cannot be used for safe aircraft separation over the Eastern Atlantic because it only has a maximum range of about 200 miles.

The North Atlantic air traffic is busiest at certain times due to passenger demands, and airport noise restrictions. Westbound traffic is busiest in the late morning and afternoon, while eastbound traffic is busiest during the night and early morning. In addition to the above constraints, the situation is compounded due to the fact that jet aircraft typically need to cruise within a specific flight level range for optimum use of fuel. These factors ensure that the airspace is congested during busy periods. Therefore, an organised track structure is created every 12 hours, allowing aircraft to be handled in an expeditious manner. Aircraft are constrained in air corridors within this track system. The OACC is responsible for the day track system and the Gander Centre in Canada provides the night track system.

Once an aircraft has entered oceanic airspace, the pilot makes position reports at every ten degrees of longitude. The traffic information displays used by the controllers are automatically updated by flight data processing system (FDPS), which receives the pilot reports. The FDPS alerts the controller if a report is overdue, or if the situation is abnormal, and calculates the next position of the aircraft based on its previously reported position. In addition, the controller receives a warning if the minimum separation between any two flights is approaching [27].

3.1.1.3 Military Control

Military controllers are based at the SOACC facility, providing services to civil and military aircraft operating outside controlled airspace in the Scottish Flight Information Region (FIR). The military controllers work closely with civilian controllers to ensure the safe movement of traffic.

3.1.2 Introductory Phase Observations

During the introductory phase of the visit, the student who had organised the visit asked the visit host a number of questions. Since a number of the questions, and the subsequent responses were applicable to the research described in this thesis, these responses have been summarised in the following list:

- It was stated that for controllers to have a comfortable workload, they handled a maximum of about five to six planes at any one time. A higher number than this would indicate excessive workload.
- Regarding the transition to the Free Flight model, the roles and responsibilities of controllers and pilots had to be very clearly defined to ensure that the new model would work correctly. Once the roles and responsibilities are worked out, the correct system tools need to be put in place to support the users (pilots and controllers). The visit host considered flight data processing tools as a key factor, stating that most modern airliners already had this capability on board. The major investment would be required in ATC centres and older, or smaller aircraft.

- A large map of the area that was controlled by the Scottish Area Control Centre (SACC) was hanging on a wall in the visit host's office. The map showed pre-defined air corridors used between the different Scottish airports. The visit host mentioned two areas of the centre's control jurisdiction specifically. The airspace above the North Sea in the East coast adjacent to Fife is used heavily for military training purposes. It is also an area used by commercial airlines as well so this airspace requires particular attention to resolve potential separation conflicts between civil and military aircraft.
- The visit host additionally discussed the upper airspace over Scotland commenting that the operations there were effectively employing a "controlled" Free Flight model. They are not actively controlled, but passively monitored. Very little interaction is required between pilot and controller in this en-route airspace.

3.1.3 SACC Control Room Layout

During the first visit, a tour of the two operations rooms was provided, initially the SACC room. Figure 3-1 illustrates an approximation of the control room layout.

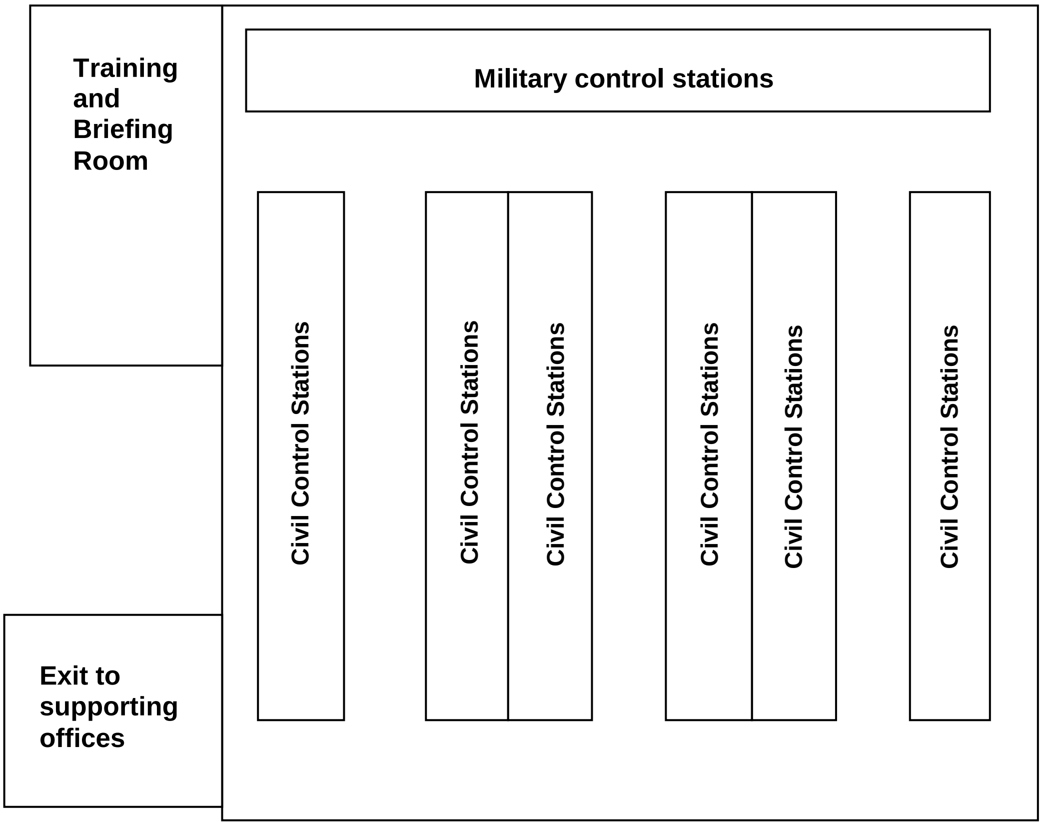


Figure 3-1: Approximate Layout of the SACC Operations Room.

The first attribute about the environment that was noticeable was the subdued artificial lighting in the room. This is to ensure that the lighting is optimal for the radar displays, making them easy to read and reducing the extent of reflections. A number of different airspace sectors were demonstrated, highlighting the differences between them. For example, some involve the task of controlling mostly non-jet traffic. Other sectors are relatively quiet; some sectors are busy at certain times of day or during different seasons.

The display systems used are standard PCs with display monitors behind a plastic screen. The curvature of the CRT display could clearly be seen behind the flat front screen. Each of the targets on the display is shown in green until the cursor is moved with a trackball over one of the targets (at which time the target icon changes to a white colour). It was stated that the resolution of the new display is not quite as high as that of the legacy system that was used previously. It was noticed that a standard 102-key keyboard was not used. Instead two separate banks of colour-coded keys were positioned vertically and horizontally adjacent to the radar display and system information display.

The next room visited was the Training and Briefing room. Controllers are required to use the facilities in this room at the start of each shift, logging onto this system to find out about any advisories or changes to procedure. Their time looking at such information is logged and recorded in case of any incidents.

The visit host also provided a short tour of the Oceanic Control Centre (OCC). The environment in the OCC uses brighter lighting and the systems being used are around twenty years old. The majority of traffic monitored by this centre operated using pre-planned flight routes with very little interaction between pilot and controller. The routes are planned approximately twelve hours in advance.

The visit was considered to be extremely beneficial in providing a high level introduction to a typical ATC environment.

3.1.4 Questionnaire Results

Prior to the initial visit to the Prestwick ATC facility, a set of ten questions was defined. The aim of this questionnaire was to gather more information about the ATC operation at Prestwick, specifically in the following areas:

- Human factors activities
- Thoughts on future ATC programs
- The use of sensory modes

Table 3-1 shows the ten questions asked along with the responses provided. Due to time constraints during the visit, only one participant was involved in this questionnaire, the visit host.

No.	Question	Response
1.	How much emphasis is placed in human factors during the design and ongoing maintenance of operational computer systems?	All new systems are subjected to some Human Factors investigation. This work is normally undertaken by our research department in Bournemouth. Very little emphasis is placed on Human Factors in maintenance.
2.	Do you see these systems changing significantly as new air traffic management techniques are introduced?	Systems will have to change to accommodate new air traffic management (ATM) technologies. We will need better tools to be able to accommodate such concepts as Free Flight.
3.	Are controllers actively involved in the design of new systems or enhancements to current systems, specifically in the way that they interact with them?	Usually we have an engineering led solution to a problem. Controllers are consulted and used as guinea pigs to test functionality/man-machine interface, etc.
4.	How closely is National Air Traffic Services (NATS) aligned with the FAAs Free Flight program? Will NATS develop systems to support free flight in the future?	Pass. Probably not as we tend to follow EuroControl policy.

No.	Question	Response
5.	What do you see as possible issues or particular challenges with the introduction of free flight?	We do not have the ATC tools or airspace to accommodate Free Flight. A difficult decision will have to be made as to who is responsible for the separation of aircraft conducting Free Flight.
6.	Are the computer systems used by controllers continuously enhanced during their lifecycle or are they purely maintained once they enter service?	They are enhanced where possible/practicable.
7.	Is the controller's interaction with computer systems essentially visual, using display terminals?	At SOACC yes. The new systems at Swanwick are more interactive.
8.	What role does the controller's sense of hearing take? Is it used for communication with other controllers on site and for communication using radio transmissions or are auditory alarms of some kind used as opposed to purely visual alarms?	Very little is used of auditory warning systems. We rely on visual alarms on the displays.
9.	To your knowledge, has haptic interaction (related to touch) ever been used in computer systems on this site? For example, a force feedback mouse providing vibrations to indicate some condition? Do you think haptic interaction could be useful in improving the user interface of one or more ATM computer systems?	Not used. Haptic interaction could be useful for future systems. Preventing illegal inputs, providing warnings.
10.	What types of statistical data is recorded at this facility, and what is it used for? What aspects of statistical data are you particularly interested in?	We record statistics for investigation of demand, supply and incident/safety investigation. Data is mainly: How many aircraft? How long did we control them?

Table 3-1: Questionnaire and Responses from First Prestwick Visit.

3.1.5 First Visit Discussion

This section provides a critique of the design of the first ATC visit, and a discussion of the extent to which observations made during this visit support previous research.

3.1.5.1 Visit Design Critique

It is important to appreciate the limitations of this initial study. Although an interview and questionnaire was conducted, it was an unstructured, purely qualitative one based on a single participant's responses. It is not intended to form the basis of a valid user requirements study, but rather provide a first taste of a typical ATC environment.

In order to perform a valid contextual evaluation, a robust evaluation design would have to be constructed using ethnographic principles and techniques, and a far greater number of controllers would have to be involved. In addition, the study would have to be performed at more than one ARTCC facility, as each facility will be somewhat different in terms of environment, technology, and traffic requirements. In addition, the study would have to use at least some level of indirect participant observation to overcome the Hawthorne effect which is an undesirable outcome of direct observation techniques [28].

Despite its limitations, this visit was extremely worthwhile in gaining valuable initial insight into a typical en-route ATC environment and an introduction to the types of information systems used by controllers. The host of the visit was very helpful and supportive of further more focused visits.

3.1.5.2 Visit Observations in Relation to Previous Research

This section discusses the correlation between the findings of this first visit to Prestwick and the literature review performed in Chapter 2.

In Section 3.1.2, the visit host stated that controllers at Prestwick were considered to have "comfortable" workload when they handled a maximum of five to six planes simultaneously. This seems on the surface to be a simplistic reference to workload when considered against the multitude of measurement techniques and workload dimensions reviewed previously (see Section 2.3.7.2. However, the stated "comfortable" workload measure is likely to be based on a large amount of past experience and research in relation to the specific types of sectors and traffic characteristics at the Prestwick facility. In addition, there appears to be a high degree of apprehension about the introduction of the Free Flight model (see Section 2.6). This apprehension is perhaps related to controllers having to relinquish an as yet undetermined degree of control. Flight data processing (data-link) is also seen as a key factor. The previously reviewed research discusses the need to ensure that the required information currently communicated using other means (for example R/T) is provided in the transition to data-link. For example, certain aspects of party line communications need to be maintained for flight crews (see 2.3.7.1). In addition, the delay time before a controller acts on a data-link communicated interruption task needs to be investigated. Since the modality of data-link is essentially visual, it seems reasonable to suspect that data-link will increase visual load while reducing auditory load, a redistribution of workload across the controller-pilot interface (see Section 2.3.7.3).

In Section 3.1.3, it is stated that some sectors at Prestwick require controllers to handle mixed jet and turboprop aircraft, with differing performance characteristics. As discussed in Section 2.3.7.1, this is a factor that contributes to controller workload. Differing performance characteristics need to be considered during the management of traffic. In addition to many other en-route facilities, Prestwick has a mixture of light and heavy traffic sectors and this would indicate a combination of low and high workload situations for controllers. Particular vigilance needs to be employed in low workload sectors during night shifts (see Section 2.3.6.2).

If the Free Flight model is introduced across transatlantic routes (see Section 2.6), it will be interesting to see how the role of the OACC at Prestwick is affected. The pre-planned flight routes may no longer be required, potentially requiring dramatic changes in the role of controllers in this centre.

The SACC at Prestwick uses a tailored controller workstation suite design. This supports the finding discussed in Section 2.3.5 that workspace design is highly variable in facilities where there is no direct observation of traffic.

In response to Question 5 (see Section 3.1.4), the participant stated that "a difficult decision will have to be made as to who is responsible for the separation of aircraft conducting Free Flight." This supports the comments made in Section 2.6 in terms of the changing role of the controller and the increased potential for low workload situations, compounded by shiftworking effects (for example, fatigue). In response to Question 7, it was stated that the new controller workstations at Swanwick use a more interactive visual display when compared with the visual displays used at Prestwick. This may suggest the potential for increased visual load, due to the larger amount of information displayed visually on the systems at Swanwick. Question 9, which asked generally about the use of haptic interaction, received a favourable response. It is interesting to note that the two examples provided by the participant are interruption conditions. Haptics has proved to be useful for interruption tasks in an experimental study referred to previously (see Section 2.3.7.3).

3.2 Second Visit to Scottish and Oceanic Control Centre (SOACC)

On Wednesday 18th December 2002, a follow-up visit to the SOACC at Prestwick was conducted. The Operations Support department again hosted the visit.

The rationale for this second visit was as follows:

- To gain an overview of UK airspace and the different ATC facilities that are part of the ATC network.
- To observe controllers on active duty and focus on the following attributes of their work:
  - Overview of controller workstation layout.
  - How the trackball is used with the radar display.
  - Speed of aircraft trace movement on the radar display.
  - How the audio modality is used.
  - Mood and stress level of controllers in the control room and on active duty.
- To observe trainee or fully trained controllers in a training environment with a view to learning the following:
  - Ask about the tasks they perform during their work. This interactivity may not be possible while observing controllers in an operational environment.
  - Understand how they are trained. That is, in terms of procedures and the ATC simulations used.
  - If circumstances permit, ask why tasks are done in a specific way.
- To conduct two or more semi-structured interviews with controllers (at least one of which was previously observed).
- To identify any human factors problems or enhancements related to controllers' interaction with the controller workstation, specifically those problems and enhancements associated with radar display and input device use in the SACC facility.
- If any human factors issues or enhancements are identified, document a set of requirements that captures these issues or enhancements. A haptic enhancement of the radar display and associated cursor control device will be developed to test whether or not haptic interaction techniques could prove a useful solution for those requirements identified.

- In addition, although not part of the original rationale, an opportunity arose to meet with the systems engineering department and receive a demonstration of using a non-active controller workstation.

3.2.1 Overview of UK Airspace and ATC Facilities

United Kingdom airspace is divided into two flight information regions (FIR), London and Scottish. Within these regions there is controlled and uncontrolled airspace. The United Kingdom is also responsible, by international agreement, for the airspace over the Eastern part of the North Atlantic [29]. The Scottish FIR contains upper (above Flight Level 255) and lower level (below Flight Level 255) sectors some of which share the same name.

- The upper level sectors are Hebrides, Moray, Central, Forth High, South West, and Dean Cross.
- The lower level sectors are Hebrides, Moray, Forth Low, West Coast. Antrim, Terminal Control Area (TMA) Out, and TMA In.

3.2.2 Observation of a Controller on Active Duty

After an escort from the visit host to the operations room, the shift manager provided a headset to use, and then introduced an active controller on duty, who was controlling the upper level Hebrides sector. The notes taken while observing the controller at work are provided in the next sections, with emphasis on the specific aims of the observation.

3.2.2.1 Overview of Controller Workstation Layout

Figure 3-2: SACC Control Suite with Planning and Radar Controller Positions.

Figure 3-2 shows one of the twelve civil control suites at Prestwick's SACC facility. Typically, a Planning Controller and Executive Radar Controller occupy the two positions at each suite. However, in some cases (for example, when the traffic at a given sector is relatively quiet) a single controller will combine the role of both planning and radar controller.

On the radar display, the colours used are green and white, with a black background. The cursor on the radar display is white in colour. All other elements on the display are various intensities of green to emulate traditional radar displays. The displays currently in use are capable of supporting colour presentation, but the decision was taken to try to make the radar display as close to the original displays as possible so only green and white has been used. Figure 3-3 shows the visual and textual elements on the radar display at the SACC.

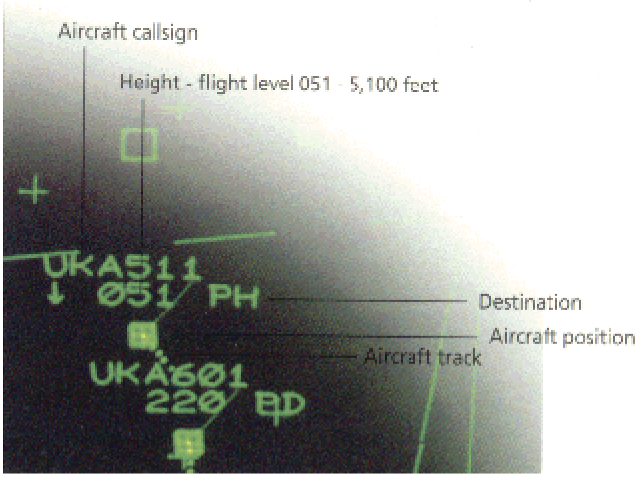


Figure 3-3: Radar Display Elements at the SACC (reprinted without permission from NATS [29]).

A flight strip board is positioned between the two controller workstations that make up a suite. The flight strips incorporate borders that indicate the direction of travel; either orange for Eastbound flights, or blue for Westbound flights.

The headsets used by controllers for audio interaction are connected to a connector on the front of the control suite.

3.2.3 How the Trackball is used with the Radar Display

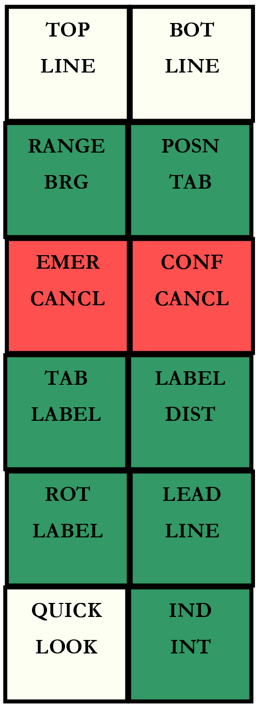
Prior to this second visit to the SACC, a number of questions were submitted to an Operations Support person with regards to trackball use. The intent was to understand the tasks that the trackball is used for prior to the visit so that more could be gained whilst actually observing controllers using the trackball during active controller duty.

These questions and answers are summarised in Table 3-2.

Question	Response
What kinds of tasks are trackballs used for?	• Rotating the label to resolve label overlap. Label overlap occurs on the radar display when multiple aircraft targets are in close proximity geographically. • Tabulating the label for the same reason usually when holding. Tabulating the label changes the format of the textual information so that stands out more on the radar display in comparison to other targets. • Quick look at traffic which is filtered out. In many instances more than one sector can occupy the same geographical space, but they are distinguished by flight level ranges, (and named as either low or high). A controller managing the high level sector would typically filter out traffic below the minimum flight level defined for the sector being controlled, because the controller is not responsible for that traffic and it just adds clutter to the controllers display. • Calculating range and bearing.
How frequently is the trackball used by controllers on active duty?	Controllers might use the trackball twenty to thirty times an hour during busy periods.
How frequently do users use the trackball to move the cursor to different aircraft targets on the radar display, and is this an important task for them?	The cursor is used in all instances either to a map position or an aircraft, or both in the case of range and bearing. This is very important functionality.
When a specific aircraft is selected on the radar display using the trackball, is further information available on that aircraft which is not included in the aircraft's associated data label?	Not on the system at SACC
Does the trackball work with only the radar display or does it control cursor movement on the other displays as well (for example, those that provide weather reports)?	The trackball only works on the radar display.

Table 3-2: Questions and Responses relating to Trackball Use in the SACC.

The trackball is used in conjunction with an adjacent keypad (see Figure 3-4) that changes individual aircraft display functions.



TOP LINE	BOT LINE
RANGE BRG	POSN TAB
EMER CANCL	CONF CANCL
TAB LABEL	LABEL DIST
ROT LABEL	LEAD LINE
QUICK LOOK	IND INT

Figure 3-4: Keypad associated with the Trackball.

The function of each key can be summarised as follows:

- TOP LINE: Moves auxiliary information to the top area of the display.
- BOT LINE: Moves auxiliary information to the bottom area of the display.
- RANGE BRG: Enables the range/bearing predict mode. A line is projected from the aircraft target to the cursor position with continually changing textual information about the range and bearing between the two points.
- POSN TAB: Shows the position table.
- EMER CANCL: Cancels an emergency alert. This has a higher priority that the adjacent CONFL CANCL key.
- CONFL CANCL: Cancels a conflict alert. A conflict alert is indicated on the radar display by flashing targets that have a higher brightness setting than other parts of the display.

- TAB LABEL: Changes the aircraft label to a table format.
- LABEL DIST: Changes the distance between the target and the associated data block.
- ROT LABEL: Rotates the data label (block) of the selected aircraft (target).
- LEAD LINE: Toggles the lead line that is displayed in front of the target making it easier to see the direction of travel.
- QUICK LOOK: Toggles the data block for a filtered-out (by altitude) target so that the details of an aircraft outside a controller's control parameters can be viewed momentarily.
- IND INT: Function of this key is not known.

3.2.4 Aircraft Trace Movement on the Radar Display

The speed of trace movement across the radar display is obviously mapped to the aircraft's speed. Therefore, turboprop aircraft will tend to move more slowly across the display while in cruise when compared to jet aircraft in the same stage of flight. However, as an approximate guideline, a jet aircraft flying at 450 knots in an hour (7.5 knots a minute) will travel 1.5 cm on the radar display in 1 minute.

3.2.5 How the Audio Modality is used

Controllers wear stereo headphones while on active duty. The left audio channel is used for communication between pilots and controllers. This communication uses very high frequency (VHF) and ultra high frequency (UHF) radio telephony (R/T). The right audio channel is used for standard telephone conversations with controllers at the same facility or other facilities, and with support staff.

During observation, it was noted that the audio modality was heavily used during the one hour period. This use mainly involved R/T communications with pilots of the aircraft being controlled.

3.2.6 Mood and Stress Level of Controllers on Active Duty

There was no obvious sign of high stress levels in the SACC room. However, it would be necessary to design and conduct interviews and/or experiments to ascertain scientifically the stress level of controllers on active duty. Certainly, the controller observed appeared calm and composed throughout the one-hour observation period.

3.2.7 Further Observation of Active Controller

The controller explained that the sector he was controlling was high-level airspace where aircraft tend to fly from North West down to the South-East of Scotland and in the reverse direction over Scotland leaving the sector. Aircraft flying through this sector do not land in Scotland but instead fly through Scottish airspace at a high level on their route towards another destination. The controller explained that he was combining the role of the active controller and the planning controller because he was not controlling a particularly busy sector.

3.2.8 Plan to Observe Controllers in a Training Environment

Unfortunately, this objective could not be met because no training was scheduled for the day of the visit. However, an Operations Support person was asked to provide details of the training that ATC students receive. Initial training lasts 2.5 years and includes:

- Air law
- Navigation
- Practical observation
- Airfield control simulations
- Real air traffic control experience for 10 weeks
- Approach and area control
- Approach control, basic and radar
- Area radar and procedural
- Continuous assessment throughout career

3.2.9 Semi-structured Interviews with Controllers

Two semi-structured interviews with controllers were conducted during the visit. The real names of these controllers have been omitted to protect their identity. The purpose of these interviews was to gather information about each controller's background, the control tasks they perform, how they interact with the workstation, and future communications. It was hoped that the responses to many of these questions would help to identify any human factors issues. The questions and responses are presented in the following sections by category.

3.2.9.1 Questions relating to user profiling

Question 1: How many years experience do you have as a controller?	
Response: Controller 1	Response: Controller 2
27 years	30 years

Question 2: What is your background and education?	
Response: Controller 1	Response: Controller 2
I started as an administrative assistant and then trained for 3 years at Prestwick. Been here ever since.	As from early teens, had an interest in aviation and navigation.

Question 3: Can you comment on any experience you have had in other ATC facilities?	
Response: Controller 1	Response: Controller 2
Worked in Scottish Oceanic centre previously, purely procedural environment – no real-time radar.	Airfield control, West Drayton (very busy approach/area control), Tiree (own boss), Stornoway, Arrived at Prestwick in 1988 and has been there ever since.

3.2.9.2 Questions relating to controller tasks

<table>
<tr><th colspan="2">Question 4: Please describe the tasks you do in a typical workday?</th></tr>
<tr><td>Response: Controller 1</td><td>Response: Controller 2</td></tr>
<tr><td>Typically stay in same sector that you are rostered for. Controller 1 also works as a competency checker for other controllers – he is an on-the-job training instructor.
The participant was asked about multi-tasking and Controller 1 stated that he sees overall aircraft separation as one task as opposed to lots of little tasks – that is, he sees the overall picture.</td><td>20% of time 4 days a month I work as an active controller. This involves getting aircraft from A to B helping them to achieve their desired flight profile. My other role is Operations Support and changes to operating manuals.</td></tr>
</table>

<table>
<tr><th colspan="2">Question 5: What aspects of your job do you consider to be most difficult?</th></tr>
<tr><td>Response: Controller 1</td><td>Response: Controller 2</td></tr>
<tr><td>The degree of difficulty depends on the sector in which you are working.
• The radar controller looks at the radar to ensure that aircraft don't meet.
• The planning controller ensures that the flight progress strips are appropriately sequenced.
Controller 1 explained that on the shift in which I was observing him at work, he was performing the role of both radar and planning controller at the same time.</td><td>Keeping an overall picture of what's happening and staying ahead with moves.
Remaining alert, need to have spare capacity but have to be monitoring oneself. Need to know when to ask for help.</td></tr>
</table>

Question 6: Which tasks or aspects of your job do you find most enjoyable?	
Response: Controller 1	Response: Controller 2
Controlling, doing radar. Don't want to do management and Controller 1 commented that nearly every controller in the room had the same viewpoint. It was like a big videogame but of course the stakes are much higher. However, he rarely thinks about the human aspect consciously, however it is always at the back of his mind and occasionally he does think about it directly especially if an incident occurs. Controller 1 considers the statement "safe orderly expeditious movement of aircraft" to be a very valid definition of the ATC job.	Formulating a plan for a complex ATC situation, which works out the way you'd planned it.

3.2.9.3 Questions relating to Controller Workstation Interaction

Question 7: Comment on the way you use the trackball with the radar display?	
Response: Controller 1	Response: Controller 2
• Label overlap – rotating • Label distancing – changing the distance between the target and data block • Range and bearing – using predict tool/line	No response provided.

<table>
<tr><th colspan="2">Question 8: Are there any things that frustrate you when using the trackball to interact with the radar display?</th></tr>
<tr><td>Response: Controller 1</td><td>Response: Controller 2</td></tr>
<tr><td>Difficult to pick out aircraft when in close proximity geographically.</td><td>Can't always find the cursor as may be hiding off screen.
Cursor doesn't always pick up targets immediately.</td></tr>
</table>

<table>
<tr><th colspan="2">Question 9: Can you think of any additional information that you would like to have when using the radar display and trackball, which is not currently available with the present system?</th></tr>
<tr><td>Response: Controller 1</td><td>Response: Controller 2</td></tr>
<tr><td>map colours – danger areas, not all active at one time. Different colours, different levels, danger areas which are active.</td><td>Ground speed (Swanwick has this) this would involve a third line on the data block which could lead to visual overload.</td></tr>
</table>

<table>
<tr><th colspan="2">Question 10: What is your opinion of increased automation in your working environment; for example electronic alternatives to paper flight strips?</th></tr>
<tr><td>Response: Controller 1</td><td>Response: Controller 2</td></tr>
<tr><td>No response provided.</td><td>Not against increased automation, but must be designed with the user in mind – Swanwick is a case in point with the font size problem. No apparent recognition of user work (human factors). These recommendations need to be given sufficient weight and this is not always the case – ergonomic considerations are important.</td></tr>
</table>

3.2.9.4 Questions relating to Controller-Controller/Controller-Pilot Interaction and Communication

Question 11: How do you see controller-pilot interaction changing in the future with increased use of data-link communications rather than speech?	
Response: Controller 1	Response: Controller 2
No response provided.	Data-link doesn't have the constant feedback – anytime away from the radar display is not a benefit Free flight – constraint of military, good idea but is still a long way off.

3.2.10 Demonstration of Inactive Controller Workstation

The Operation's Support staff arranged a short period of time for a visit to the Engineering Services Group in order to use a non-operational controller workstation, with identical trackball, associated keypad and visual display hardware to those used by controllers. The radar display was showing real-time aircraft data in one of the same Scottish FIR sectors controlled by an active controller. This proved to be a valuable activity as it was interesting to try out both cursor movement using the trackball, and appreciate the interaction between the trackball and the keypad (see Figure 3-4). It was unfortunate that more time was not available during the visit to use the non-operational workstation.

3.2.11 Visit Observations in Relation to Previous Research

This section discusses the correlation between the findings of this second visit to Prestwick and the literature review performed in Chapter 2.

In Section 3.2.2.1, it is stated that when traffic in a sector is relatively quiet, a single controller may occupy both positions at a controller workstation suite. This may indicate the use of a standard procedure, a decision by the shift manager, or some other decision-making process to alleviate a potential low workload situation, by giving the controller more work to do. The problems associated with low workload situations are discussed in Section2.3.7.1.

In the responses to the pre-visit questionnaire, it is evident that the trackball is used heavily (along with the related keypad) for configuring functions that alleviate visual load on the radar display. For example, rotating or tabulating the target label during a label overlap condition. This supports previous research, which indicates that maintaining order in the display is a controller activity that generates a significant workload contribution. A transfer of modality may be helpful in reducing workload associated with visual display configuration (see Section 2.3.7.3).

In Section 3.2.5, it is stated that both audio channels are used heavily. This finding supports the statement in Section 2.3.7.3 that a transfer of modality to the auditory channel for some tasks in today's ATC model may not be useful due to competing resources generating higher workload. Of course, the effectiveness of the auditory channel may need to be re-evaluated if the continued introduction of data-link communications reduces the extent of R/T communications.

In Section 3.2.9.2, the response to Question 4 from Controller 1 indicated that he occupies an additional role as a competency checker for other controllers. It is unknown whether this activity involves some degree of "over the shoulder" workload rating as discussed in Section 2.3.7.2). Controller 2 cited the need to remain alert, and being able to maintain spare mental capacity as being among the most difficult aspects of the controller role. The need for spare mental capacity has been highlighted in previous research (see Section 2.3.7.1, suggesting that operators only perform a secondary task, or interruption, well if they are not fully loaded on the execution of the primary task.

The response of both controllers to Question 6 (see Section 3.2.9.2) demonstrates the level of satisfaction that controllers have in performing the ATC role as it is currently defined. This highlights the concerns of many that controllers may feel under-challenged if the role transitions, with the introduction of concepts such as Free Flight, from one of control to one of monitoring (see Section 2.6).

In Section 3.2.9.3, Controller 1 indicated that trackball use is associated with the display housekeeping activity, as identified by another controller during the first Prestwick visit (see Section 3.1.5.2). As stated previously, from research that has been conducted, display housekeeping is a significant contributor to increases in controller workload. It is interesting to note that in response to Question 9, both controllers requested the provision of additional information, which if implemented visually on the display could have the potential to increase visual load. If this additional information was implemented in a way which could be toggled, this would indicate that controllers are not opposed to the addition of yet more work in terms of display housekeeping activity.

3.2.12 Requirements Gathered from this Visit

As stated at the start of Section 3.2, the final objective of this second visit to the Prestwick SACC facility was to arrive at a set of requirements, and investigate whether a haptic enhancement of the radar display and associated cursor control device could prove to be a suitable solution for meeting any of these requirements, and thus alleviate any identified human factors issues.

It should be noted that any requirements drawn from this visit to Prestwick, or the earlier visit, are only valid for this ATC facility. The systems used by different facilities are diverse, as are the types of ATC tasks performed by controllers. However, the requirements listed below may certainly be relevant to other ATC facilities in the United Kingdom, and perhaps worldwide.

3.2.12.1 Discussion of Findings

Where there is the potential for increased visual load, haptics can be considered as an alternative interaction style to reduce this. For example, in the responses shown in Table 3-2, it was stated that aircraft visual labels are rotated to resolve overlapping. The transfer of modality of this visual task could be investigated to identify whether or not haptics could help alleviate this.

The Predict (Range Bearing) tool is frequently used by controllers at Prestwick for trajectory planning (see Section 3.2.3). It is worth investigating whether or not haptics could be used to enhance the abilities of this tool beyond what is currently achieved visually.

Question 8 asked controllers to identify things that frustrate them when using the trackball to interact with the radar display. Two key reservations were identified from controller responses to this question. When aircraft are in close spatial proximity, it was stated that it could be difficult to differentiate them visually, and thus make it difficult to select the desired target using the trackball. An example of when this issue can occur is when multiple aircraft are in a landing approach holding pattern separated vertically by distances of 1000 feet. These aircraft can continually overlap while maintaining the holding pattern so a means other than visual identification would be useful in distinguishing them.

Another response to question 8 from the other interviewee suggested that targeting problems exist with the radar display when using the trackball. At Prestwick, the active trace and associated data block changes colour to white from green when the cursor is positioned on it. It was stated that the cursor does not identify a "hover over" state as quickly as desired. It is not known whether this is a targeting problem or a software fault with the Prestwick system. However, if it is a targeting problem, haptic enhancement may be able to help.

Question 9 asked respondents to identify additional information that could be provided by the system. Controller 1 highlighted the issue of danger areas, for example where military training is taking place. Controllers are notified about which danger areas are active on a particular day. However, there is no indication on the radar display as to which danger areas within a sector are currently active. Visually, danger areas could be identified using differing colours. However, this causes alternate problems as the colours may make it harder to see aircraft traces. It is worth investigating whether haptics could be used to indicate these areas.

The Swanwick systems have a visual data block that indicates ground speed for each aircraft. However, this requires a larger data block, increasing the contribution to visual load in busy sectors. Could an indication of ground speed be represented by haptics?

In question 11, reservations were raised about the increased use of data-link communications between data-link equipped ATC facilities and aircraft. The constant feedback between pilots and controllers is not as active with data-link communications as it is with R/T. In addition, every time the controller has to look away from the radar display, the potential exists for safety to be compromised. It is worth investigating whether haptic interaction would be suitable to notify the controller about the availability of new supplementary information (for example, a new incoming data-link message) without the need to interrupt the controller's visual focus.

The requirements discussed in this section are now summarised in Table 3-3.

Req. No.	**Requirement**
1.	Reduce visual load associated with aircraft label overlap.
2.	Provide supplementary feedback and/or information when using the Predict tool.
3.	Solve or improve the issue of being able to differentiate targeting of aircraft that are in close geographic (spatial) proximity.
4.	Improve controller performance when attempting to lock on to a specific aircraft target using the cursor.
5.	Improve the identification of danger areas within a sector.
6.	Provide ground speed indication without the need for a third line of information in the aircraft's associated visual data block.
7.	Reduce the amount of time the controller is required to move visual focus away from the radar display to view supplementary information.

Table 3-3: Summary of Requirements.

3.3 Conclusion

The work documented in this chapter was important in order to gain insight into the air traffic control environment. An array of investigative requirements were performed to increase understanding of the domain space and to try to identify any issues that controllers at Prestwick related to the users' interaction with the radar display at the controller workstation. Although, the findings of these visits are valid only for the SACC facility, some of the information gathered can be considered to be relevant to the ATC task as a whole. Many of the observations made during these visits supported the previous ATC research reviewed in Chapter 2. The seven requirements discussed and defined in Section 3.2.12 are now used to drive the development of a haptically enhanced ATC simulation that can be evaluated by controllers to determine whether haptic interaction effects could provide a viable solution.

Chapter 4: Review of Haptic and Audio Interaction Research

4.1 Introduction

This chapter describes the research fields of haptic and audio interaction, reviewing the work of researchers in this field to date. With respect to audio interaction, speech and non-speech sounds are discussed along with the application in which they have been used in the aerospace domain. Particular attention is devoted to the use of haptics to improve performance in targeting tasks. Targeting is a vital aspect of controller interaction with the radar display while managing air traffic. Improvements in targeting performance have the potential to reduce controller workload, for example, when performing "display housekeeping" activities.

4.2 The Different Modes of Interaction

While research into non-visual interaction with computers is becoming more widespread, the primary interaction style used today still essentially involves visual interaction through computer display technology. This is the case, despite the fact that hardware and software technology is increasingly more capable of supporting cognition through multi-modal interaction with the computer using complementary senses working in synergy. For example, to alleviate the problems of competing resources with increases in visual load, the senses of touch and hearing can be employed, with the potential to improve the users' performance. The problem is how to most effectively integrate the sensory hardware so as to provide an effective multimodal interaction environment for the user. In addition, it is important to identify the tasks to which non-visual representations are most suited. For some types of tasks, graphical sight-based representations are tremendously powerful and very little may be gained by modelling these tasks using a different modality. The key to successfully employing non-visual modalities is in identifying the application domains and specific design variables to which they are most suited.

4.2.1 Visual Interfaces

The visual interface is traditionally the primary interface for interacting with computers. However, it is important to recognise that the form of the visual interface has changed dramatically over the last two decades. Command-driven user interfaces have been almost exclusively replaced by graphical user interfaces. The primary interaction style used in many graphical user interfaces is direct manipulation [30]. Shneiderman [31] presents a definition of direct manipulation interfaces, along with their associated benefits and drawbacks when compared to command-driven interfaces (see
Figure 4-1).

Definition of Direct Manipulation

- Visual representation (metaphor) of the “world of action”
    - Objects and Actions are shown
    - Analogical reasoning is tapped
- Rapid, incremental, and reversible actions
- Replacement of typing with pointing and selecting
- Immediate visibility of results and actions

Advantages

- Control-display compatibility
- Less syntax reduces error rates
- Errors are more preventable
- Faster learning and higher retention
- Encourages exploration

Disadvantages

- Increased system resources, possibly
- Some actions may be cumbersome

Figure 4-1: Definition, Benefits, and Drawbacks of Direct Manipulation.

With the changing physical attributes of display technology depending on the type of computer device being used (standard computer monitor, laptop display, Personal Digital Assistant (PDA), mobile phone display, or embedded display), the potential for increases in visual load is apparent. Information needs become ever more complex while computer portability requirements become more vital as we interact “on the move”. The products of information visualization research can be used to filter out data that is not important to the user's task, allowing the information of interest to be highlighted even in the confines of a limited display space [32]. Another course of action to reduce visual load caused by dependency on one modality, is to transfer suitable interactions currently performed visually, over to alternative auditory or tactile modalities.

4.2.2 Auditory Display

Traditionally, sound in computer interfaces has been used to convey feedback to the user or alert them to a system event [28], for example, a beep to indicate an attempt by the user to perform an invalid operation. However, a large body of research is looking at the use of more complex speech and non-speech sounds to provide richer non-visual interaction to the user.

4.2.2.1 Speech Sounds in Interfaces

Auditory human/machine interfaces that use speech as an input or output mechanism are making use of language syntax and semantics that have already been learned by the user [33].

Speech input systems include:

- Discrete-word recognition devices, which recognize individual words spoken by either a specific person (speaker-dependant) or any person (speaker-independent), working with 90-98% reliability for 20-200 word vocabularies [31].
- Continuous-speech recognition devices, which are less common, strive to recognize single words within a group of words connected together, rather than recognizing words individually. These have the potential to enable much faster input and be more natural to use [28]. The difficulty with the development of these systems is in the understanding of lexical, syntactic, and semantic ambiguities which are inherent in all languages [34].
- Speech store and forward systems, which enable the storage and forwarding of spoken messages. Examples of these systems include stored messages for weather and financial information, voicemail systems, and portable voice recording devices.

Speech output (also know as speech generation or synthesis) has been used in such applications as telephone directory enquires, industrial or aerospace warning systems, and vending machines. There are two basic methods for speech generation:

- Concatenation, where digital recordings of real human speech are stored, *and*
- Synthesis-by-rule, where rules that relate to both phonemics and sentence/phrase structure are used to synthesize speech.

4.2.2.2 Non-speech Sounds in Interfaces

In addition to research looking at the use of speech in user interfaces, non-speech audio is a significant area of study. The research in this field may be categorized into three primary areas [33]:

- Sonification,
- Audification, *and*
- Auditory Interfaces.

Scalletti defines sonification as:
"*a mapping of numerically represented relations in some domain under study to relations in an acoustic domain for the purposes of interpreting, understanding, or communicating relations in the domain under study.*" [33]

Kramer resonates with Scalletti's definition of sonification, with the caveat that he makes a distinction between *"data-controlled sound (sonification) and data samples played back directly as sound."* [33], which he refers to as audification "*A direct translation of a data waveform to the audible domain for purposes of monitoring and comprehension will be referred to as audification.*"

The following list provides examples of sonification applications. Some of these existed before the sonification term was devised [35]:

- Geiger counter
- Sonar
- Auditory thermometer
- Medical and cockpit auditory displays
- Software that enables blind chemists to examine infrared spectrographic data via auditory presentation
- The mapping of data-dependent auditory signals to ongoing processes in dynamic monitoring tasks such as anaesthesiology workstations

Examples of audification research projects include [33]:

- Tonal acoustic simulation of rotor-stator interaction inside a jet turbine
- Auditory monitoring and analysis of seismic data

The research area of auditory interfaces is looking at both the addition of auditory cues to complement existing visual interfaces, and the development of auditory-only interfaces as described by Mynatt, which can be used, for example, to provide access to a traditional graphical user interface for people who are blind [33].

Examples of some of the research work in auditory interfaces is provided in the following list:

- Gaver's *Auditory Icons*, which he describes as being "…*like sound effects for computers*" are self-labelling sounds which have a direct mapping to the data that they are intended to represent [36]. They can be used to provide valuable information about computer system events without the need to use any of the visual display space.
- Spatialized audio can be employed to allow more auditory information to be displayed to the user in the same presentation space and sounds can be mapped to different positions around the user's head. A head tracker allows the reference point to be determined so that the relative position from where the sound is intended to originate can be preserved.
- Alarms are used in many safety critical environments such as hospitals, nuclear power stations and aircraft [37], where an already rich visual interaction environment may cause vital time critical information to be missed.
- Earcons, which were first devised by Blatner, Sumikawa, and Greenberg, are tones or sequences of tones (motives) that can be used to provide information to the user about a computer object, operation or interaction. Unlike auditory icons, earcons are not self-labelling sounds with an intuitive link to what they are intended to represent. Instead, the mapping has to be learnt by the user [38].

4.2.3 Applications of Audio Interaction in Aerospace

The following list provides some examples of using speech and non-speech interaction within the aerospace domain:

- The use of R/T to facilitate voice interactions between pilots and controllers, pilots and pilots, controllers and local controllers/controllers in other facilities.
- Various auditory warning systems on aircraft flight decks [3]:
    - Ground Proximity Warning Systems (GPWS) and Enhanced Ground Proximity Warning Systems (EGPWS) use alarms and automated speech ("Pull Up, Pull Up") to indicate terrain obstructions directly below the aircraft and, in the case of EGPWS, rising terrain in front of an aircraft.
    - Traffic Alert and Collision Avoidance Systems (TCAS) provide information intended to prevent aircraft mid-air collisions. These systems use a visual display in conjunction with automated speech alarms (such as "Traffic, Traffic" and "Clear of Conflict") to indicate when another aircraft is within vertical separation limits.
    - Wind Shear Advisory Systems (WSAS) alert pilots when the aircraft is in close proximity to wind shear. These are severe air disturbances that are particularly dangerous to aircraft during takeoff and landing approaches. An auditory alarm sounds when the initial stages of a wind shear threat are detected.

Currently, the bulk of basic communications transmitted and received between humans in the ATC system is undertaken using R/T. However, the use of R/T is not without its problems as discussed in Section 2.3.3. Data link systems are a relatively new medium for pilots and controllers to communicate, indirectly via computers. Data link's primary purpose is to ensure that clearances, and certain other information, are received and promptly seen and understood [3]. If data link usage becomes widespread, then the question must be raised as to whether the spare capacity on the R/T channel could be used for communicating other useful information that may currently be transmitted and received visually.

4.2.4 Haptic Interfaces

The term haptic relates to the sense of touch. Computer haptic devices take advantage of the user's sense of touch (or force on the body) to provide feedback during interaction with a computer user interface [28].

McGee [39] performed significant work to propose a definition of terms concerned with touch as presented in Table 4-1.

Term	**Definition**
Haptic	Relating to the sense of touch.
Proprioceptive	Relating to sensory information about the state of the body (including cutaneous, kinesthetic, and vestibular sensations).
Vestibular	Pertaining to the perception of head position, acceleration, and deceleration.
Kinesthetic	Meaning the feeling of motion. Relating to sensations originating in muscles, tendons and joints.
Cutaneous	Pertaining to the skin itself or the skin as a sense organ. Includes sensation of pressure, temperature, and pain.
Tactile	Pertaining to the cutaneous sense but more specifically the sensation of pressure rather than temperature or pain.
Force Feedback	Relating to the mechanical production of information sensed by the human kinesthetic system.

Table 4-1: Haptic Definitions [39].

Immersion [40] define the categories of two different types of devices that are capable of providing computer haptic feedback as follows:

- **Full Force Feedback Devices** use motors to exert forces on parts of the body (for example, the hand). These forces may inhibit or exaggerate movement of the body part in a specific direction.
- **Tactile Feedback Devices** use vibration to recreate high-fidelity touch sensations of texture, periodicity, enclosure, and such like. However, they generally do not move or inhibit the movement of either the device or the hand holding it, in the same way that force feedback devices do.

Haptic interfaces have thus far been researched in a number of application domains including computer user interfaces for visually impaired people [41], collaborative virtual environments, and human and veterinary medicine to name but a few [42].

The following list presents a summary of the advantages of haptic interfaces in terms of attributes and applications to which they are particularly suited:

- **Non-intrusive enhancement to visual display space:** In the same way that auditory display can be considered to augment visual displays without interfering [Kramer 1994], the same can be said of haptic effects, allowing interaction to be spread across different sensory modes and thus reducing the potential for information overload in a single modality [42].
- **Target acquisition performance can be improved:** For example, a significant amount of research has been performed proving that thoughtfully designed haptic enhancements to traditional GUIs can significantly improve performance in cursor pointing tasks [43]. Organisations such as Immersion are already producing software (called Immersion Touchware) which provides a haptic enhancement to the Windows desktop.
- **Replacement for the Visual Interface:** Haptics can be used individually, or in conjunction with auditory display to enable visually impaired users to enjoy rich interaction with computers [42].
- **Enhanced realism in virtual environments:** For example, users can feel shape outlines or textures, rather than purely see them.
- **Increase in perceived quality/excitement of user interface:** An enhancement to the visual interface that transmits a certain "wow-factor" to the user.

4.2.5 Review of Haptic Targeting Research

A significant amount of research has been dedicated to investigating the potential for haptic interaction to improve targeting performance. One of the key operations performed by controllers using the input device to interact with the radar display is targeting, whereby the cursor is moved to a specific location on the display, prior to performing actions on the selected target. For this reason, it is important that the current targeting research in the field of haptic interaction is investigated to determine what aspects of this work are relevant to ATC targeting tasks. This section reviews and discusses this haptic targeting research.

Firstly, it is important to mention the targeting work performed in 1954 by Paul Fitts [44]. In the field of ergonomics, Fitts published a principle of human movement that is very much still relevant to the user interfaces of today. Fitts discovered a formal relationship that models speed/accuracy tradeoffs in rapid, aimed movement (not drawing or writing). This can be stated as [45]:

The time to acquire a target is a function of the distance to and size of the target.

Fitts' Law indicates that the most quickly accessed targets on any computer display are the four corners of the screen, because of their pinning action [45]. Fitts' Law is used extensively in haptic interaction research for calculating index of performance measures [46]

Haptic feedback has been shown to improve user performance and satisfaction in single target operations within graphical user interfaces [47]. This performance benefit can be achieved by applying a force that attracts the cursor to the target. However, in multiple target situations (for example, on a desktop menu with numerous options), attracting the cursor to every target using the same attraction effect has the potential to irritate and distract the user. Oakley et al. [47] argue that target prediction techniques, like those used in other haptic targeting experiments [48] can have inherent problems (for example, difficulty of accurate prediction for some tasks, processing cost). An alternative method was tested and proved to be effective which involved defining the targets to which attraction effects were applied by determining the user's most likely menu interaction.

With respect to the two categories of haptic devices, tactile and force feedback, Akamatsu [46] conducted research with a desktop mouse to compare performance in targeting tasks when applying either no feedback, tactile, force feedback, or combined force feedback and tactile effects. The two feedback conditions using tactile effects (tactile, tactile and force feedback were found to offer better speed and accuracy performance than no feedback, or force feedback effects [46].

In other work by Akamatsu, MacKenzie, and Hasbrouc [49] a mouse employing tactile feedback effects was found to allow a wider area of the target to be used, and enable targets to be selected more quickly when compared to the other sensory feedback conditions normal, auditory, use of visual colour, and combined. Although the combined sensory feedback condition was close in terms of performance to the tactile condition, it is thought that this is because the user has a tendency to use the most effective feedback and filter out others.

Oakley et al. [50] propose guidelines for the design of haptic interaction widgets [50]. These guidelines are based on findings from two separate studies, in conjunction with previous work in the field. The guidelines presented can be summarised as follows:

- **Guiding Strategy:** Haptic feedback should concentrate on improving user performance by reducing the number of errors made, rather than by attempting to decrease task completion times.
- **Choice of haptic augmentation:** Haptic effects with walled areas or attractive basins typically provide better performance improvements. However, the shape of the effect is important, as diagonal motion (for example, at the corners of a square) is more difficult than vertical or horizontal motion.
- **Relationship between force strength and widget size:** The maximum strength used for any widget, or set of widgets, should be dependent on the size of the widget and the density of the arrangement that it is presented in.
- **Range of useful force magnitudes:** This guideline states a force range that haptic targets should be within, 0.25 N to 0.8 N. However, in multi-target environments these strengths may need to be continually adjusted to exploit widget behaviour and present dynamic responses to slow or rapid movement. A system for use outside of a research environment should always allow the user to adjust the maximum force strength.

- **Exploit patterns of user behaviour:** The haptic effect on any given target should capitalise on patterns of motion afforded by that target.
- **Exploit widget behaviour:** Haptic feedback can be designed to aid the completion of an action that has started. This guideline could be applied to any haptic object that has more than one explicit state.
- **Dynamic response to slow movement:** Force should vary according to speed with slow movement requiring low forces. This is particularly important in situations where there is a high population of closely spaced widgets.
- **Dynamic response to rapid movement:** Low forces should be used on targets that are not the users final destination. Like the previous guideline, this is important in situations where there is a high population of closely spaced widgets.

From existing research, it can be concluded that tactile feedback is a promising approach for improving targeting performance when used to enhance a graphical display featuring multiple targets. Additionally, it can be seen that the design of haptic objects requires careful consideration, especially in densely packed multiple target environments like that of a busy ATC sector.

4.2.6 Applications of Haptic Interaction in Aerospace

Within the Aerospace domain, the most widely recognised application of using an electronic device to supply feedback to the user is in the flight deck stick shaker. Stick shakers are used to notify the pilot in advance of an imminent stall condition [51]. When such a condition occurs, the stick shaker device uses an electric motor to vibrate the control column, wheel, or stick (depending on the aircraft type) that it is attached to. The pilot receives a clear stall indication that is unlike any other alarm condition in the cockpit. The shaking action is intended to simulate aircraft pre-stall buffeting which is a natural effect of the airframe in this situation. In many aircraft designs, the intensity of the natural pre-stall buffeting effect is not high enough to make the condition obvious to the flight crew. The stick shaker leaves the flight crew in no doubt that a stall condition is imminent.

While the stick shaker is a successful application of haptic interaction within the aerospace domain, there is also a significant amount of additional haptic research ongoing. Some of these activities are summarised in the following list:

- Haptic Simulator for aeronautics maintenance operations [52]: This work proposes a method to simulate forces and torques with a 3 Degrees of Freedom (3-DOF) haptic interface for manipulating virtual objects. The intention is for haptic interfaces to enable a shorter development time of aeronautical prototype products by taking into consideration assembly and maintenance constraints. Forty participants from Airbus France qualitatively evaluated prototypes and feedback was favourable. The work states that a quantitative analysis is planned using typical maintenance scenarios to evaluate differences in performance with and without the use of haptics.
- 3D stereoscopic visualization in ATC using tracked and haptic devices [53]: This work looks at alternate devices to support flight trajectory 3D visualization and interaction. The paper discusses the use of two tracking devices (tracked wand, tracked glove) for interacting with physical objects (for example, terrain, aircraft, airports) and conceptual objects (airspace, sectors, and trajectories) in a virtual environment. It is stated that the next device to be evaluated is a haptic device but the outcome of this research (if conducted) is not known at this stage.
- Use of tactile torso displays in aircraft cockpits [54]: Tactile torso displays convey information by applying vibrations to various areas of the torso. 3D spatial information is presented intuitively because the vibration points are mapped to body coordinates. These displays have been researched to determine how well they support, among other things:
    - Tactile directional threat display
    - Resistance to high G load conditions of tactile displays over purely visual displays
    - Detection of position drift in helicopter hover operations when night vision goggles are being used by the pilot
    - Countermeasure for pilot spatial disorientation
- The use of haptics to present information to controllers in support of multiple task timesharing, and notification of interruption task events. This work was discussed previously in Section 2.3.7.3.

4.2.7 Combining the Modalities

The successful combination of interaction using two or more of the sensory modalities has vast potential to improve the interactions between humans and computers. It is for this reason that a significant amount of research is ongoing in the field of multimodal interaction. A key consideration is to combine interaction techniques so that they complement and work synergistically with one another, enabling the user's experience to be more pleasurable and productive (rather than frustrating and inefficient). An appreciation of the strengths and weaknesses of each modality's capabilities is an important design criterion during the development of a multimodal user interface.

In this age of ubiquitous computing, for context aware systems, the ability to dynamically change the multimodal characteristics of a user interface in real time to improve the user interaction experience in any given computing environment (for example, desktop PC, laptop, PD, embedded device) is an interesting research problem that is receiving significant attention [55]. For example, when interacting with a user interface where a significant amount of background noise is evident, the multimodal balance of the interface could lean towards visual and haptic feedback. On the other hand, when the user is operating in a quiet solitary environment, a greater degree of auditory feedback could be employed by the user interface.

Within the domain of ATC, the sensory modes of sight and sound are combined. The sense of touch is of course used when interacting with hardware or manipulating paper flight progress strips. However, computer generated haptics have not, as yet, been integrated with other modalities in official ATC systems.

4.3 Conclusion

This chapter has reviewed the research fields of haptic and audio interaction. Haptic interaction in particular is of key importance for the work presented in this thesis. Promising research suggests that the use of haptic effects, when designed appropriately has the potential to improve user performance, specifically in error reduction, when performing target acquisition tasks, even in an environment populated by many multiple targets. Could these performance benefits in terms of multi-target acquisition be important for providing a solution to human factors problems associated with controllers' use of the radar display and associated input mechanisms at the controller workstation? The remainder of this thesis conducts a requirements study, and documents the design and evaluation of a haptically enhanced simulation intended to investigate the suitability of haptics in this target-rich domain.

Chapter 5: Development of ATC Simulation

5.1 Introduction

This chapter describes the development of a haptically enhanced ATC simulation. Firstly, a functional specification is provided to outline the structure of the functional modules that will collectively make up the ATC simulation. Following this, a software tool investigation is discussed along with details of the iterative simulation design process. Finally, this chapter closes with a report on the progress that was made during the implementation of the simulation.

The purpose of building this simulation was to provide a mechanism for testing whether or not haptic interaction would be a suitable solution for each of the requirements discussed in the previous chapter, and summarized in Table 3-3. The intention was to use an evolutionary prototyping approach to the development of these simulations. Only a small part of this evolution was realized during the time available. However, Section 7.3 discusses proposals for how this work could be significantly extended to make a more worthwhile contribution to this field of research.

5.2 Functional Specification

This section provides a summary of each of the discrete functional modules that make up the haptically enhanced ATC simulation. The modules specified, if followed by an appropriate design and implementation, would provide a way to test the suitability of haptics for supporting the requirements stated in Table 3-3. Within the following sections that describe each module, a reference is provided to the requirement(s) that the module is intended to support.

5.2.1 Radar Display Module

This module will provide the simulated visual radar display used by all other modules. This module will consist of the following elements:

- Sector boundaries
- Aircraft targets and associated data labels
- Aircraft Tracks (indicating direction of travel)
- Cursor position indicators
- Simulated dynamic air traffic

In addition to the radar display, this module will provide a simulation of the trackball-associated keypad that is used by SACC controllers at Prestwick (see Figure 3-4).

5.2.2 Simulated Traffic Module

This module will provide the simulated dynamic air traffic objects. Specific properties of each object, such as position, direction of travel, air speed, flight level, origin airport, and destination airport will be reflected visually in the Radar Display Module.

5.2.3 Haptic Targeting Module

This module will produce haptic effects for use with the Radar Display Module to determine whether haptics would alleviate problems associated with:

- Data label overlap (Requirement 1)
- Identification of targets that are in close spatial proximity, or even in the same spatial position (while at different flight levels) (Requirement 3)
- Successfully locking the cursor onto aircraft targets to enable access to supplementary information. (Requirement 4)

5.2.4 Haptic Predict Tool Module

This module will combine with the Radar Display Module to provide a haptic version of the predict tool used by controllers at Prestwick (Requirement 2). This tool allows controllers to determine whether or not a suggested heading and flight level will result in any conflicts. It will be possible to switch off the haptic components of this module so that performance with and without haptics can be compared.

5.2.5 Danger Area Identification Module

This module will overlay the Radar Display Module with haptic information identifying specific areas within sectors that are designated as danger areas due to the presence of military aircraft or other non-civilian traffic in the area (Requirement 5).

5.2.6 Ground Speed Indication Module

This module will use haptics to provide low-resolution information that indicates the ground speed of the currently selected aircraft target (Requirement 6). In some ATC facilities, this information is provided as an additional row in the aircraft's data label, however this information is not available visually on the radar displays at Prestwick.

5.2.7 Haptic Supplementary Information Module

This module will test ways in which haptics can be used to provide non-essential supplementary information, thus reducing the need for controllers to move their visual focus away from the radar display (Requirement 7).

5.3 Software Tool Investigation

An investigation was undertaken to identify the available software tools capable of building ATC simulations and additionally tools that support haptic interaction with provision of appropriate force feedback devices.

5.3.1 Investigation of Existing ATC Simulation Resources

In order to reduce the significant development investment required to generate a visual ATC simulation from scratch, it is desirable to make use of an existing simulation environment. A vital consideration for the purposes of this research is that the simulation environment must support the easy integration of haptic effects. This section discusses the search to find a suitable, and freely available open source ATC simulation tool.

Large ATC research facilities and commercial organisations such as NASA and the FAA have access to extremely powerful air traffic control simulation environments that enable the evaluation of new procedures and research innovations with ultra realistic simulated traffic and sectors [4]. In addition, Virtual Reality environments are being investigated for ATC simulation use [56]. However, virtually no open source small-scale simulation environments could be sourced for the ATC domain that can be used with standalone personal computers. In fact, only one organisation in particular, OpenATC.org [57], provide freely usable ATC software tools that have the potential to support the integration of haptic interaction effects.

OpenATC.org is “a consortium created to stimulate Air Traffic Control research and development by providing as easy way to share resources.” The resources available from OpenATC.org include the following:

- AudioLAN: A voice communication system over Internet Protocol (IP) for ATC.
- SkyLabel: A java program demonstrating anti-overlapping of aircraft labels on modern ATC displays.
- Fugue: A lightweight simulation and demonstration environment for ATC tools, based on the Ivy software bus. This lightweight simulation and demonstration environment is intended to allow smaller labs or private individuals to have access

to a simplified version of the realistic sophisticated simulation environments available to large ATC research facilities. To date, organisations such as CENA, Eurocontrol, and the University of Toulouse have built applications using Fugue. The Fugue environment simulates air traffic and radar, flight plan management, and pilot interactions with controllers.

- ZINC: This graphical toolkit can be used to develop ATC radar images and graphical interface components. The toolkit supports structured graphics and additionally provides functions from OpenGL, such as advanced gradient colour and transparency operations. Zinc has been used by CENA for developing a number of applications including Digistrips (see Section 2.4). An airport advanced radar display created using Zinc is shown in Figure 5-1.

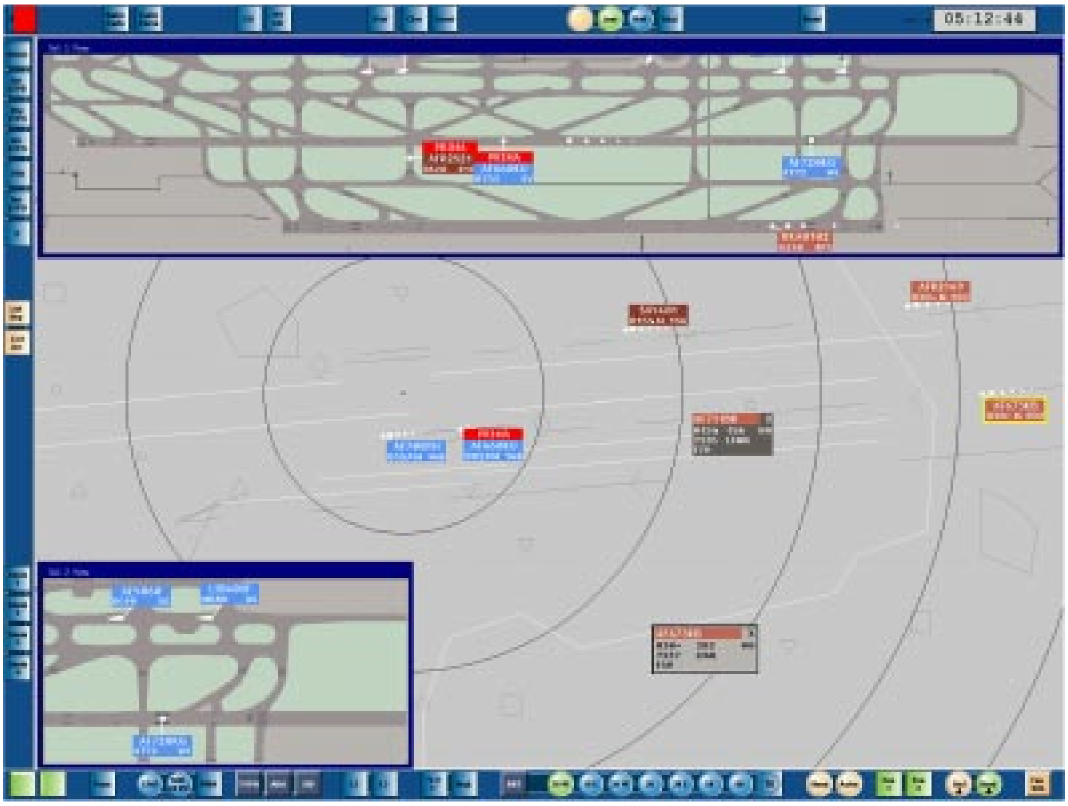


Figure 5-1: Airport Advanced Radar Display (reprinted without permission from [58])

5.3.2 ATC Simulation Tool Selection

Initially, it was decided for the purposes of this research to use software tool resources available from the OpenATC.org consortium

The visual aspects of the simulation would be supported by a combination of the following resources:

- Fugue, for providing simulated air traffic.
- Zinc for building the Radar Display Module, along with visual controls for initiating haptic effects associated with the other functional modules.

At the time of this investigation, both of these tools were available only for differing flavours of UNIX and Linux operating systems. No Windows operating system support was provided, which was to prove a major barrier to the research, as discussed in Section 5.3.2.2.

5.3.2.1 Haptic Simulation Resources

The requirements used to drive the development of the haptically enhanced ATC simulation were gathered from the Prestwick ATC facility. Since this facility uses an integrated trackball for cursor control, it was decided to use a haptic trackball as the input device. The only commercially available force feedback trackball at the time of this investigation was the Kensington Orbit 3D Trackball with Immersion Corporation's TouchSense Technology (see Figure 5-2). Therefore, this device was selected for use in building the simulation.

Figure 5-2: Kensington Orbit 3D Trackball (reprinted without permission from [59])

The Orbit 3D, and Immersion's haptic interaction software TouchSense, is supported under various versions of Microsoft Windows. No support is provided for UNIX or Linux operating systems.

Immersion provides a graphical development environment, called Immersion Studio, for creating and editing haptic effects. The parameters of these effects are then stored in a library resource file (with a .ifr file extension) that can be referenced from a Visual C++ or Visual Basic application.

5.3.2.2 Issues with Operating System Support

During this tool investigation and selection, it became apparent that the small numbers of ATC simulation tools available were intended for UNIX or Linux operation systems, whereas the haptic interaction software tools were designed for Windows operating systems. Open source drivers can be found for some haptic devices but these have little or no support as individuals typically develop the drivers.

If the aim of this research was to develop a purely visual ATC simulation, it is considered that the Fugue and Zinc tools running on the Linux platform would have made a good choice of development environment. However, the primary aim, of this research was to investigate whether or not multimodal interaction involving haptics would be a suitable solution to meet any of the requirements identified previously. Therefore, the decision was reached to initially build a low-fidelity visual interface using the standard graphics libraries that are included within Microsoft Visual C++ and use Immersion Studio to create haptic effects presented using Immersion's TouchWare and TouchSense technology. The intention was to continue to seek an ATC simulation tool that could be used to improve on the visual implementation while the haptic effects were being developed. This would potentially involve a further search for commercially available tools to determine their support for haptics, or even the development of the visual simulation environment from scratch. Either of these could prove costly in terms of resources, and time constraints prevented this further investigation.

5.4 Simulation Design Process

The design model used for development of the simulation is based on an iterative design process as encouraged by the User Centred Design approach to application development [28]. This involves using a rapid prototyping technique to allow subsequent versions of the simulation to be built and evaluated throughout the development cycle, each containing increasing functionality or enabling testing of alternative haptic interaction effects.

The Artillery method [34] emphasises the belief that is almost impossible to achieve a correct implementation of an interactive system at the first attempt. It is stated that the initial prototype provides a reference point from which to reanalyse and redesign.

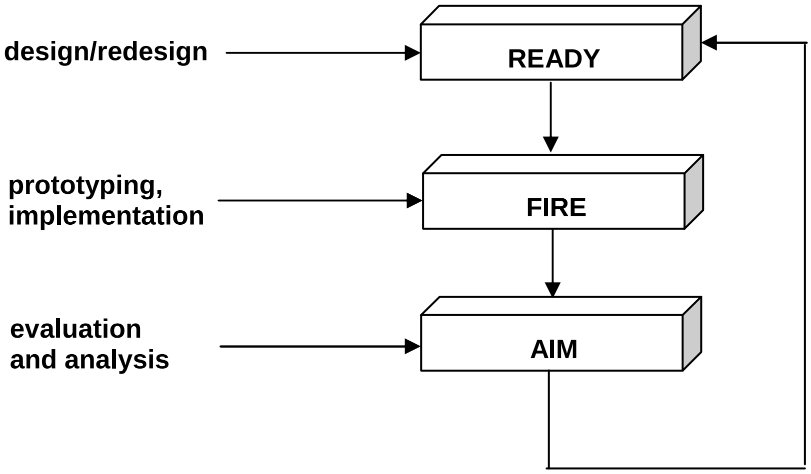


Figure 5-3: The Artillery approach to rapid prototyping [34].

If time had permitted, the intention was to cycle through the iterative process multiple times, with each successive prototype adding a new functional module to evaluate whether or not it could successfully meet the requirements gathered from the second Prestwick visit. In addition, new iterations would provide revised implementations of other modules based on evaluation feedback received. Details of the proposed evaluation activities are discussed in Chapter 6.

5.5 Haptic Effect Design

At the point when development of the haptically enhanced ATC simulation was halted, one trial haptic effect had been implemented (see Section 5.6.3.2). This was a simple elliptical wall (boundary effect) round each aircraft target.

In determining the haptic effect design for the haptically enhanced ATC simulation, the haptic design guidelines proposed by Oakley et al. [50] (discussed in Section 4.2.5) need to be considered in determining the design rationale for those requirements specifically related to targeting tasks. As a result, these guidelines are summarised in Table 5-1 with comments provided about how these relate in terms of generic design conventions for the haptically enhanced ATC simulation [50].

Haptic Design Guidelines	**Conventions for use with Haptically Enhanced ATC Simulation**
Haptic feedback should concentrate on improving user performance by reducing the number of errors made, rather than by attempting to decrease task completion times.	Error reduction is a useful goal in the ATC domain given its safety critical nature.
Haptic effects with walled areas or attractive basins typically provide better performance improvements, with the shape of the effect being an important design consideration.	Boundary effects will be used as much as possible, although different effects, such as pulses may be required to convey supplementary information. Elliptical shapes will be employed rather than squares or rectangles to avoid the negative aspects of "escaping" from corners.
The maximum strength used for any widget, or set of widgets, should be dependent on the size of the widget and the density of the arrangement that it is presented in.	Interaction strength will be variable depending on whether a sector being controlled is busy or quiet. Sectors which occupy a larger spatial area, with typically larger areas between targets will require stronger forces, while smaller sectors that are highly populated will require softer forces as they should be sufficient to help targeting tasks.
The maximum range of useful force magnitudes should be within 0.25 N to 0.8 N, with the understanding that these strengths may need to be continually adjusted in multi-target environments.	Force magnitudes will require to be continually adjusted given the multi-target nature of the ATC task.

The haptic effect on any given target should capitalise on patterns of motion afforded by that target.	Visual areas such as sector boundaries, or aircraft tracks will exert strong forces along their length, but very little force if the user wants to move the cursor off the line.
Haptic feedback can be designed to aid the completion of an action that has started.	Haptic effects will be designed to change depending on the state of the target (for example, when the cursor has been moved to the target and it is currently selected.)
Force should vary according to speed with slow movement requiring low forces. This is particularly important in situations where there is a high population of closely spaced widgets.	A busy ATC sector is a good example of an environment where there may be a high population of closely spaced targets. Therefore, this guideline is extremely applicable.
Low forces should be used on targets that are not the users final destination. Like the previous guideline, this is important in situations where there is a high population of closely spaced widgets.	A busy ATC sector is a good example of an environment where there may be a high population of closely spaced targets. Therefore, this guideline is extremely applicable.

Table 5-1: Haptic Design Guidelines [50] and Conventions for Use in the Haptically Enhanced ATC Simulation.

Table 5-2 now presents a proposal for the design of the other haptic effects, with respect to each of the requirements listed in Table 3-3. It should be noted that in some cases, more detailed requirements gathering activities would need to be conducted with controllers, or operations support staff at the SACC facility and this is stated where appropriate.

Req. No.	Requirement	Proposed Haptic Design
1.	Reduce visual load associated with aircraft label overlap.	Abbreviate or hide certain information on the label until the target has been selected. Since target selection performance is expected to improve with the use of suitable haptic effects, the user should be able to select the desired target with a lesser chance of error. Therefore aircraft label display will be more dynamic based on the target selected and therefore reducing label overlap.
2.	Provide supplementary feedback and/or	The predict tool was discussed during the second visit to the SACC facility (see Section 3.2.3) The

	information when using the Predict tool.	cursor is used to drag a line from an aircraft target to a cursor position with continually changing textual information about range and bearing. A more detailed definition of the available functions and main usage scenarios would have to be gathered by further requirements definition work before the exact nature of suitable effect design could be decided upon. Simply applying a walled effect to the prediction line would be of no use as the line will be continually dragged to different locations, and a walled effect would only make this more difficult.
3.	Solve or improve the issue of being able to differentiate targeting of aircraft that are in close geographic (spatial) proximity.	Since the use of walled or attractive basin effects has been shown to improve targeting, these types of effects would be applied in this case. Since this requirement is concerned with many targets in close spatial proximity, the interaction strength used will be low.
4.	Improve controller performance when attempting to lock on to a specific aircraft target using the cursor.	This is a key multiple targeting task scenario. It is expected that using elliptical walled haptic effects, while taking into account the other design guidelines indicated in Table 5-1 should give positive findings.
5.	Improve the identification of danger areas within a sector.	It is proposed that danger areas within a sector should be indicated when the cursor is moved over them by a maximum strength compound effect featuring a walled effect along the danger areas perimeter and a pulsing effect. This should make the danger area immediately obvious to the user. The user should be able to turn off this effect if required.
6.	Provide ground speed indication without the need for a third line of information in the aircraft's associated visual data block.	Use a predefined tactile pulse designation to provide a low-resolution indication of air speed. Long pulses indicate 100 knots, Short pulses indicate 50 knots. Therefore, an airspeed of 450 knots on a selected target would be indicated by 4 long pulses and 1 short pulse. Further requirements work would be needed to determine if this resolution is sufficient.

7.	Reduce the amount of time the controller is required to move visual focus away from the radar display to view supplementary information.	It is proposed that a series of haptic codes should be defined, each using a different effect to indicate a supplementary information category. The purpose of this code would be to alert the controller that supplementary information of the indicated type is now available. Therefore, the haptic effect behaviour is akin to a non-urgent alarm condition. This would prevent the controller from having to shift their visual focus away from the radar display periodically to check secondary displays for any supplementary information. Further requirements work is needed to identify the types of supplementary information that should be supported.

Table 5-2: Proposed Haptic Effect Design in Relation to Requirements.

It should be noted that this design, if implemented, would form the first of many haptic design iterations, so the proposal for haptic effects presented in Table 5-2 should be considered as a starting point for any researcher intending to expand this work.

5.6 Implementation

This section describes various aspects of the implementation of the ATC simulation. It should be noted that for the purposes of this work, the term implementation is concerned with only the coding of the simulation, not the issues concerned with the transference of ownership of a system from its developers to the clients, which is the real crux of the implementation phase of any systems development.

5.6.1 The Zinc Toolkit

As mentioned previously, the Zinc toolkit was not available for the Windows operating system until well into the simulation development process. The intention was to take the low-fidelity radar display module implementation constructed using Visual C++ graphics libraries and transition it to a graphically rich implementation using Zinc. However, time constraints did not allow this phase of development to be undertaken and therefore no time was available to become proficient or even sample the Zinc toolkit. It is still believed that if the Windows versions of Zinc and Fugue could be successfully integrated with Immersion haptic effects, this combination would be an ideal vehicle for building testable iterations of the haptically enhanced ATC simulation.

5.6.2 The Visual C++ Implementation

Visual C++ 6.0 was selected to build the low fidelity prototype. This section provides a brief description of the Visual C++ environment.

Microsoft Visual C++ 6.0 is one component of the Visual Studio 6.0 suite of development tools. Visual C++ is a hybrid tool integrating a C++ compiler with a suite of visual Windows programming tools and a vast selection of automated application development tools. As well as the significant number of programming components that are provided as standard with Visual C++ and Visual Studio [60], additional components can be sourced from third parties to extend its programming power. The Immersion Foundation Classes (IFC) library is one example of such add-ons.

Although a newer version of Visual Studio was available at the time of selection, namely Visual Studio.NET, version 6.0 was selected because the Immersion libraries were specifically developed to integrate with Visual C++ 6.0. In addition, a significant number of researchers in the university department had experience in developing haptic interfaces within Visual C++ 6, but not in Visual C++.NET. It was considered important to have colleagues to ask for advice.

5.6.3 Immersion TouchWare and Immersion Studio

This section introduces the Immersion Corporation's haptic software products and discusses aspects of how these are integrated with Visual C++.

5.6.3.1 Introduction to Immersion and its Software Tools

Immersion, founded in 1993, is a technology company in the field of haptic hardware and software. It creates tactile feedback products that can be integrated into products by their industry partners (for example, Logitech, BMW, Siemens, and Boeing).

Immersion provide the following software products for use with the Microsoft Windows operating system:

- Immersion TouchWare: This software is comprised of two separate applications:
    - TouchWare Desktop integrates haptic effects with the Windows user interface, and web browser.
    - TouchWare Business integrates haptic effects with Microsoft Office applications such as Word and Excel.
- Immersion Studio: This is a graphical environment for creating haptic effects that can be saved in a resource file and referenced by applications developed with Microsoft Visual Studio. Version 4.1.0 of Immersion Studio was used during development of the simulation. At the time, this software tool was available free of charge. However, in order to download newer versions, a license must be purchased. Figure 5-4 provides a high level description of the main components of the Immersion Studio environment.

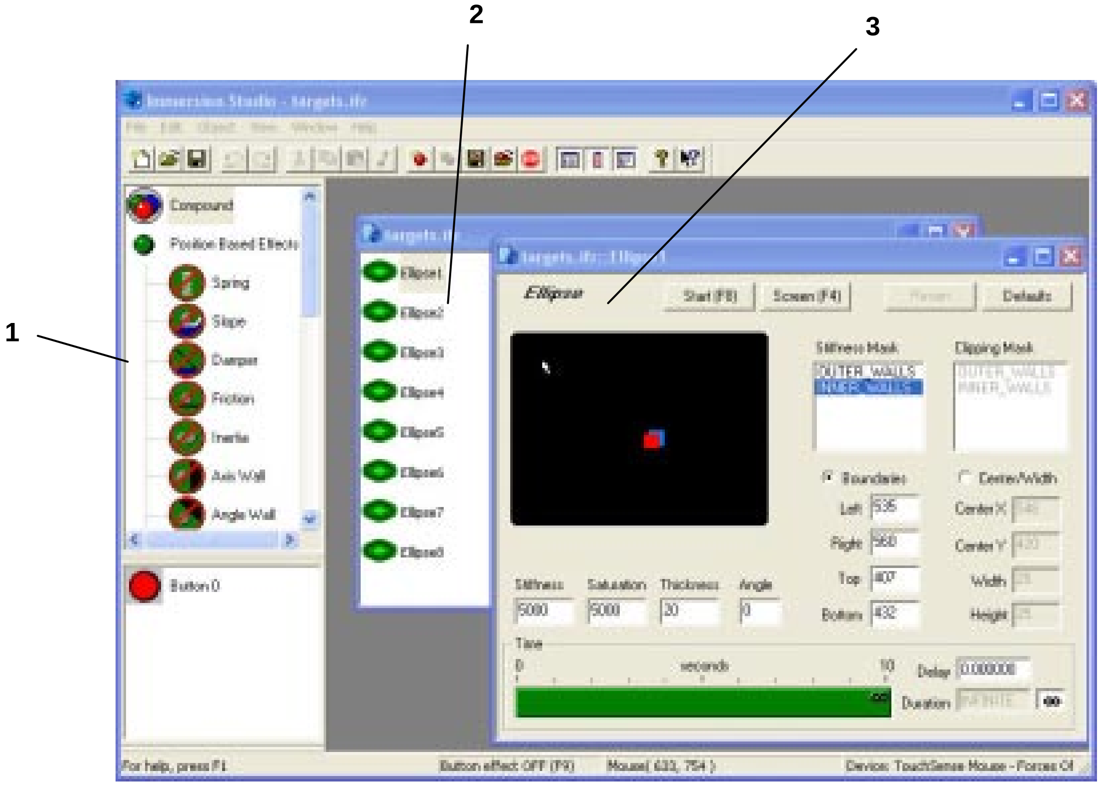


Figure 5-4: The Immersion Studio haptic effects development environment.

1. Templates window: This is a list of all the basic force effects available. In this case, the initial Position Based Effects shown are not selectable because the Orbit3D tactile feedback device does not support these types of effects.
2. Project window: Shows all of the effects defined in the currently opened document, in this case targets.ifr. Effects are added to the project using drag and drop operations.
3. Effect Properties window: Enables you to define the tactile variables, the position and duration of the selected effect.

Input devices that support Immersion's haptic interaction software provide a statement citing that they use TouchSense Technology licensed from Immersion Corporation.

In addition to the previously mentioned Kensington Orbit 3D Trackball (see Section 5.3.2.1), Figure 5-5 shows examples of other input devices that use TouchSense Technology.

Figure 5-5: Input Devices that use Immersion TouchSense Technology.

1. Logitech iFeel Mouse
2. Logitech iFeel MouseMan
3. Belkin Nostromo n30 Game Mouse
4. Logitech WingMan Force Feedback Mouse
5. HP Force Feedback Web Mouse

5.6.3.2 Using Immersion Resources within Visual C++

The process involved in adding haptic effects to the Visual C++ application using Immersion Studio and Immersion Foundation Classes (IFC) involves the following high level steps:

1. Create the required DirectX or TouchSense haptic effects using the Immersion Studio visual environment, saving the effects in an Immersion Force Resource (.ifr) file.
2. Modify the Visual C++ code to include the IFC header file and link to the necessary libraries. This adds the Immersion header files to the Visual C++ application as external dependencies.
3. Declare a CImmMouse object pointer and initialise it.
4. Include code to open the .ifr file from within the application, initialise and start the defined effects.
5. Clean up (delete) the haptic device and effects when the application is closing.

The effects can be modified in Immersion Studio, the .ifr file re-saved, and then the application can be executed again without the need to recompile.

To make the haptic coding task easier, sections of the source code were reused from one of the tutorial applications provided by Immersion as part of the IFC installation.

Figure 5-6 shows an early iteration of the ATC simulation screen including haptic effects. The following functionality and objectives were integrated into this implementation:

- A static image, initially created using the Zinc toolkit and available from the Zinc web pages [58] was loaded into the application as a bitmap and used as a starting point to show a radar-type display featuring eight aircraft targets and associated data labels.
- The coding uses a Document/View architecture for separation of data (document) and the way in which the user interacts with that data (view).
- An ellipse was drawn round each of the aircraft targets within the bitmap using the graphic-object classes provided in Microsoft Foundation Class Library (MFC). By doing this, the coordinate positions of the targets could be determined for applying haptic boundary effects to the same co-ordinates. Since the pen colour chosen is red/white, these visual boundaries can be easily seen over the aircraft targets (see Figure 5-6). These visual boundaries could later be removed since they had served their purpose of identifying the screen areas to which haptic effects needed to be applied.
- Using Immersion Studio, a separate ellipse boundary effect was defined for each aircraft target using identical coordinates to those defined for the visual boundaries. Due to time constraints, only one haptic effect was referenced in this iteration of the simulation. However, additional effects were defined. Refer to Section 5.5 for details about the design of other effects that would have been included in future iterations to test their suitability for meeting the previously identified requirements.

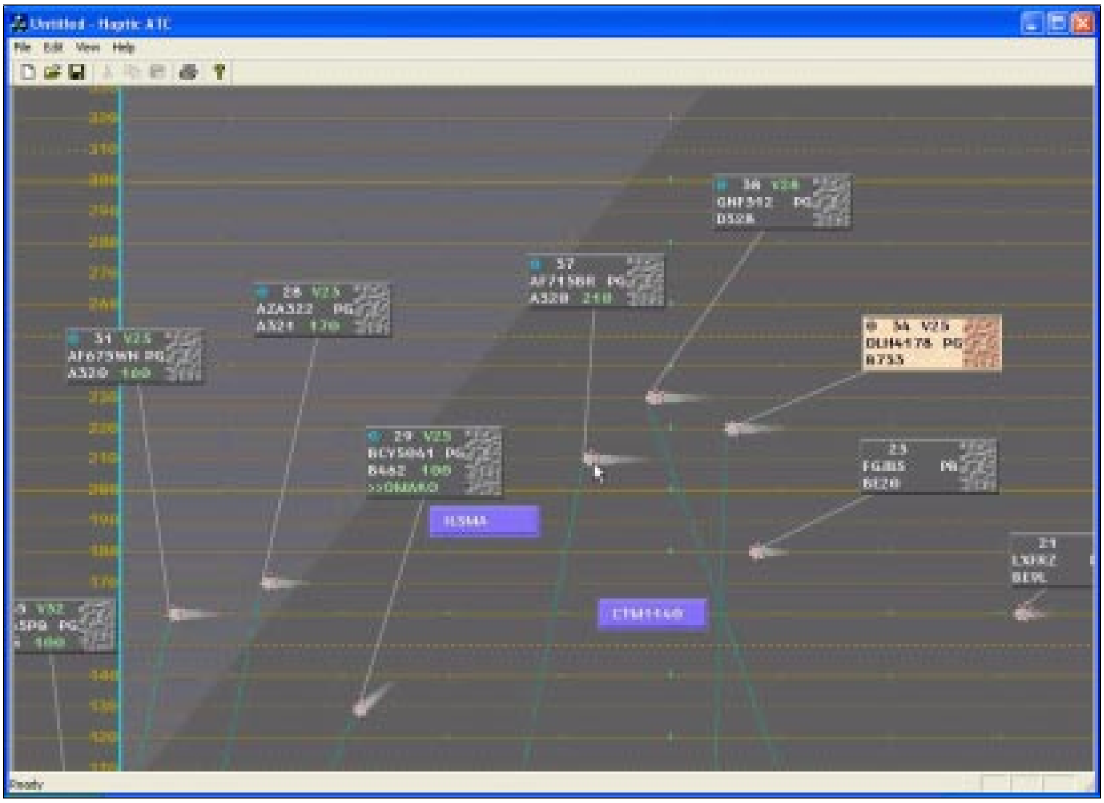


Figure 5-6: An early iteration of the ATC Simulation with tactile aircraft targets.

5.7 The Extent of Progress Made Thus Far

At the point where implementation of the ATC simulation had to be halted because of time constraints, work was still ongoing to create the first testable release and this was never completed. However, a significant amount of work was performed to get the implementation to this stage, including having to learn many aspects of Visual C++ programming (such as Document/View concepts and some of the MFC graphic object classes). Further haptic effects were created but there was no time available to add these to the simulation. In addition, work was ongoing to transition the radar display module from static targets to moving tactile targets. The one haptic effect that was integrated into the simulation was a boundary effect round each of the aircraft targets. It was noted that having this effect present made it easier to determine when the cursor was exactly positioned over the screen coordinates that the target occupied.

Section 7.3 suggests the further implementation activities which could have been performed if there had been enough time to continue development of the simulation.

5.8 Conclusion

This chapter has documented the functional specification, tool investigation, design process, and implementation details of a haptically enhanced ATC simulation. The purpose of building this simulation is to evaluate the suitability of haptics, particularly in multi-target tasks, and determine if suitably designed haptic interactions could provide solutions to meet the previously identified requirements in Section 3.2.12.

Chapter 6: Evaluation

6.1 Introduction

This chapter provides a specification for artificial laboratory tasks that would form a preliminary step in evaluating the potential benefits of haptics. If the evaluation of these tasks proves that haptics can provide useful performance benefits, this supports continuation of the iterative work to fully develop and evaluate the haptically-enhanced ATC simulation. To this end, the remainder of this chapter discusses and describes the types of evaluation activities that might be performed to ascertain whether or not the haptically enhanced ATC simulation could satisfy each of the requirements identified in Chapter 4.

6.2 Specification of Preliminary Laboratory Tasks

This section provides a specification for two experiments aimed at evaluating the potential benefits of haptics in supporting specific tasks. This work would form a preliminary evaluation step before the full development and evaluation of the ATC simulation. The design of these experiments is influenced by the work of Cockburn and Brewster [61].

6.2.1 Targeting Task Experiment

Purpose

To determine whether the use of tactile effects in a high target population environment improves targeting performance. This preliminary experiment relates in general sense to all requirements documented in Section Table 3-3 that require the user to navigate to targets on the radar display (for example, Requirement 4).

Method

The user interface for this experiment involves a full screen display space with 10 elliptical targets moving randomly in straight-line trajectories across the display space. The targets move at a rate equivalent to that of a jet aircraft moving across a radar display space (approximately 1.5 cm per minute). A target enters the display space at a random point and follows a straight-line path until the perimeter is reached, at which time the target is deleted and replaced by a new target. There are always 10 targets on the display space at any one time. When a target on the display turns from the default light grey colour to green, the participant must acquire the target as quickly as they can. After the target acquisition has been completed, the target returns to its default light grey colour and another target is highlighted.

Participants

15 to 20 participants will be required, comprising of graduate and undergraduate students of mixed gender and age. Participants will use their right hand to control the trackball device and the experiment will take approximately 30 minutes per participant.

Equipment and Software Requirements

A Kensington Orbit 3D tactile Trackball positioned on a standard mouse mat will be used as the input device for both conditions (with tactile enhancement and without). A laptop running the Windows XP operating system and supporting a screen resolution of 1024x768 will be used.

A Rapid Application Development tool, such as Visual C#.NET will be used to create the software environment and the tactile sensations will be supported using Immersion Studio, Immersion Foundation Classes (IFC) and Immersion TouchSense (which the Orbit 3D supports). All user actions will be logged and the task time will be the time between the cursor leaving one target and clicking on the next highlighted one. Cockburn and Brewster [61] employed the use of a low-level, broadband noise to block out the sound of motor noises from the Logitech IFeel Mouse input device and the same approach will need to be used here due to the similar noise generated by the Orbit 3D Trackball.

In the non-tactile condition, the participant receives visual over-target feedback, with the target turning from the default light grey colour, or the highlighted green colour, to white when the cursor enters its boundary. In the tactile condition, a walled boundary effect with a high force vibration magnitude is generated when the cursor is positioned over the final destination (highlighted) target. All other targets on the display exhibit a walled boundary effect with a low force vibration magnitude, since these other targets are not the participant's final destination at that time.

Experimental Design

The time to acquire target, and time over target prior to selection, will be recorded for both the visual feedback only condition, and tactile feedback condition.

Procedure

Participants will be asked to complete a short questionnaire enquiring about background, age, and previous haptic experience, along with a set of instructions related to the study. Participants will then be allowed a short practice session prior to each experimental condition so that the participant is not having to enter the task completely uninitiated.

Each condition will last for 5 minutes, in which time the participant will continue acquiring targets. Participants will be allowed a 5-minute break before commencing the tasks within the second condition. The ordering of the two conditions (tactile and non-tactile) will be randomised.

6.2.2 Haptic Communication Experiment

Purpose

To determine whether information conveyed using tactile pulse effects, can be correctly interpreted by users in a high target population environment. This experiment relates in a general sense to Requirements 6 and 7 (see Table 3-3 and Table 5-2).

Method

The user interface from the previously defined experiment is reused here (see Section 6.2.1). However, since the purpose of this experiment is concerned with evaluating the potential of haptics to convey supplemental information, only the non-tactile targeting condition is used from the previous experiment's interface. The participant must acquire targets in the same manner as before, that is, when the target turns to green. However, in this case the participant's task after they navigate and select the target is to interpret the tactile pulses presented to them. After the user inputs their perception of the pulse stream, another target is highlighted and the experiment continues.

Participants

The participant requirements will be identical to the previous experiment (see Section 6.2.1).

Equipment and Software Requirements

A Kensington Orbit 3D tactile Trackball positioned on a standard mouse mat will be used as the input device. A laptop running the Windows XP operating system and supporting a screen resolution of 1024x768 will be used.

The same software development environment used for the previous experiment will be employed here (see Section 6.2.1). All user actions and responses will be logged and the task time will be the time between the cursor leaving one target and clicking on the next highlighted one. Broadband noise will again be used to block out the sound of motor noises from the Orbit 3D Trackball.

The participant receives visual over-target feedback, with the target turning from the default light grey colour, or the highlighted green colour, to white when the cursor enters its boundary. When the user clicks the Orbit 3D Trackball's left button within the target boundary, a number of long and then short pulses are presented using tactile vibrations. When the pulse stream has completed, the participant is required to indicate the number of long and short pulses that they encountered in a dialog box. When finished, the user selects to close the dialog box, the next target is highlighted, and the experiment continues.

Experimental Design

The user responses to the number of long and short pulses they experienced will be recorded for each target acquired during the experiment. In addition, the time into the experiment will be recorded for each target acquired, to be able to gauge any differences in performance between the early part of the experiment and the final stages. For completeness, the time to acquire target, and time over target prior to selection, will be recorded, but may not be used in interpreting the results.

Procedure

Participants will be asked to complete a short questionnaire enquiring about background, age, and previous haptic experience, along with a set of instructions related to the study. Participants will then be allowed a short practice session so that the participant is not having to enter the task completely uninitiated.

The experiment will last for 10 minutes, in which time the participant will continue acquiring targets, receiving tactile pulses relevant to each target, and indicating a response as to how many long and short pulses they experienced.

6.3 The Evaluation Design Rationale

In the event that the preliminary experiments defined in Section 6.2 prove that haptics has potential benefits for improving targeting performance and alleviating visual load, this section discusses the evaluation design that would be used for evaluating the full-scale haptically enhanced ATC simulation.

Key attributes that need to be taken into account when evaluating any kind of interactive system include [31]:

- Stage of design (early, middle, late)
- Novelty of project (well defined versus exploratory)
- Number of expected users
- Criticality of the interface
- Time available
- Experience of the design and evaluation team

To relate these attributes to the haptically enhanced ATC simulation:

- Different types of evaluation activities would be required at different stages of the project. During the early stages of design, testing would most likely involve a large degree of qualitative evaluation and very little quantitative evaluation. This balance would probably change with later stages of design as quantitative measures would be required to effectively compare performance differences with and without haptic effects being present. Activities at a later stage would additionally involve more complex usage scenarios that cover acceptance testing for multiple requirements rather than individual requirements.

- Initially, the ATC simulation is exploratory, but as the development process progresses through multiple redesign/implement/evaluate iterations, and the suitability of haptic interaction in meeting requirements is determined, the project would gradually become more defined, necessitating different evaluation methods.
- The number of expected users would vary depending on the scope of the project, but if the scope did not expand beyond the Prestwick facility, the number of potential users would be in the hundreds if any positive findings of this research were to make their way into real controller working positions. Therefore, to evaluate the system with all users would be time consuming but potentially necessary given individual differences in controller performance and the safety-critical aspects of the application domain.
- The ATC domain is extremely safety critical and this fact would have an important impact on the level of evaluation performed if any positive findings of this project were integrated into real ATC systems. Having said that, user interface problems still occur with ATC systems, even after a high level of user testing. The Swanwick control centre has been the target of criticisms regarding font legibility, and a number of minor incidents have occurred due to incorrect interpretation of aircraft data labels [62].
- Time constraints meant that no evaluation could be performed prior to the completion of this thesis. However, it is envisaged that at least one to two weeks worth of evaluation activities would be required for each iteration, with the time required increasing as the prototypes became more well-defined.
- The lack of experience of the design and evaluation team would obviously mean that it would take longer to design and perform evaluations, and would increase the chance that an evaluation would be ineffective due to poor experimental design. To reduce the potential of this happening, advice could potentially be sought from experts in evaluation of ATC simulations.

For a given iteration, the intention would be to perform pilot evaluation studies using undergraduate students as participants. After any problems with the evaluation design had been identified and corrected, real controllers would be asked to participate, and in fact permission was already received from controllers at the Prestwick facility to take part in evaluations of the simulation. It is important to ensure that real controllers are involved in evaluation activities even at early stages for a number of reasons:

- Controllers have a thorough understanding of the existing workstation interface and ATC tasks.
- Involving controllers in participatory design increases the likelihood of a successful implementation and user acceptance [31].
- Controllers are trained (or selected) to have a very high level of peripheral awareness, allowing them to conduct a main task and at the same time keep track of one or more secondary tasks [19]. It is extremely unlikely that all members of a set of undergraduate students selected at random would have the same peripheral awareness skills. However, students would be a valuable resource for conducting pilot studies to identify any flaws in an experimental design prior to conducting experiments with real controllers.

When asking evaluation participants to compare two systems (in this case, a haptically enhanced ATC simulation to an ATC simulation without haptics) either a between-subjects or within-subjects design can be used [30]. A within-subjects design would have been employed for evaluating the ATC simulation for the following reasons:

- Individual performance differences of participants are automatically controlled because each participant tests both systems.
- Fewer participants are required. This is particularly important given the difficulty of access to real controllers.

A number of quantitative and qualitative measures would have to be tested on the available functional modules at each iteration, including:

- Speed of task performance (for example, time to correctly move the cursor to the specified aircraft target)
- Rate of errors made while performing task (for example, incorrectly interpreting the data provided by the predict tool).
- Subjective workload assessments to determine measures such as effort, frustration, mental and physical demands. NASA Task Load Index (TLX) could be used for this purpose [63].
- Subjective user satisfaction (gathered by means of a survey or talk aloud protocol).

When conducting any kind of evaluation experiment in which the participants are aware they are the subjects of such an experiment, there is the potential for the Hawthorne Effect to occur, whereby a significant performance improvement occurs due to the positive effect on the participants of knowing that they are being studied [64]. The Hawthorne effect has been controlled in many types of experiments (for instance, in medicine) by the use of double and triple blind trials, and additionally by analysing post-experiment interviews to ascertain how participants' interpret the experiment.

6.4 Validity of the Evaluation Environment

This section discusses the issues that must be considered in relation to the suitability of the testing environment.

The intention was to facilitate experiments by installing the haptically enhanced ATC simulation onto a laptop computer with the Kensington Orbit 3D trackball as the input device. However, it should be noted that the use of a commercially available laptop and input device in a classroom or office environment, is vastly different from using an integrated controller workstation, with the stresses and dynamically changing environment associated with active duty within an ATC facility.

One of the major difficulties is in attempting to simulate a real traffic situation. Normally, to evaluate a system's suitability for performing the tasks it is required to support, realistic use cases, or user scenarios have to be defined. However, the nature of the ATC task makes this very difficult given the high level of unpredictability and un-repeatability that is a feature of the domain space.

In order to simulate air traffic for the haptically enhanced ATC simulation, the intention was to use the Fugue simulation tool. Although this is a lightweight simulation tool which is no match for those ATC simulators owned by large aviation research centres, it has been used with some success by other research organisations such as CENA and EuroControl [57]. However, the long-term suitability of Fugue remains unproven for use in developing and evaluating the haptically enhanced ATC simulation.

In large technical centres, for example the FAA Technical Center in New Jersey, facilities exist for simulating real-time dynamic air traffic either in tower control scenarios or on a visual radar display. Training of controllers, and experimentation (and evaluation) of new systems and procedures are the main purposes of these simulations. Air traffic simulation has been said to be the best vehicle for human factors research in ATC [4].

6.5 Difficulties of Identifying Potential Limitations of the ATC Simulation

If the ATC simulation had been developed and evaluated to a high level, but the outcome of the research turned out to be negative, it is important to recognise that any lack of suitability of haptic interaction to satisfy the documented requirements may not be a general finding about haptic interaction, but instead could be a failing of this particular simulation. A potential way to prove or disprove this would be for other experienced researchers to independently design and evaluate a haptically enhanced ATC simulation intended to meet the same requirements. If the independently developed simulation was shown to successfully meet any of the requirements that this ATC simulation could not meet, this would indicate some failing in the design and/or implementation of this simulation. However, if both simulations provide very similar or identical positive or negative outcomes for each of the requirements, this strengthens the case to prove that this haptically enhanced ATC simulation has been developed to a good standard.

6.6 Conclusion

This chapter has provided a specification of artificial lab tasks that should be performed as a preliminary step in evaluating the suitability of haptics for targeting and information presentation tasks. These preliminary steps are vital in determining the suitability of haptics to support the previously identified requirements presented in Table 3-3. In the hope that these preliminary experiments do prove that haptics are beneficial, the chapter has suggested an evaluation design rationale for the development of a full scale haptically enhanced ATC simulation.

Chapter 7: Conclusions and Future Work

The purpose of this final chapter is to summarise the work documented in this thesis and provide suggestions for future work that could be performed to build on the development that has been done thus far. In closing, a conclusion provides final words on the work undertaken.

7.1 Summary

This thesis has investigated the contribution of human factors to the ATC domain. In particular, various human factors problems associated with the interaction of human, software, hardware, and environmental components of the ATC system have been summarised. A particular emphasis in the literature review was placed on previous and ongoing research in the field of workload, its definition and effects, measurement, and whether transferring any aspects of the controller task to a different modality may reduce it. The future systems for ATC are currently under development and concerns related to the changing role of pilot and controller in relation to these new systems have been highlighted.

Two visits were conducted to the NATS en-route facility at Prestwick in Ayrshire, the first of these to enable a relative novice to the domain of ATC to gain a better understanding, and the second to observe controllers in action and identify human factors problems specifically related to controller interaction with the radar display and associated input device. A set of seven requirements worthy of investigation was identified, specific to the usage model at the Prestwick facility.

The work continued by reviewing research performed thus far in relation to haptic and audio interaction, with a review of specific applications and ongoing research within the aerospace domain. In particular, haptic research in relation to targeting performance was discussed and the work of researchers in suggesting haptic design guidelines was presented. Targeting is a key component of controllers' interaction with the workstation.

Work commenced on the iterative development of a haptically enhanced ATC simulation to attempt to prove or disprove the suitability of haptics in alleviating the identified problems, with particular emphasis on those problems relating to targeting tasks and the reduction of visual load. A discussion of the ATC simulation's proposed haptic effect design is presented in Section 5.5 and aligned with the haptic effect design guidelines proposed by the work of Oakley et al. [50]

Unfortunately, due to time constraints, the simulation was not progressed beyond its initial development. However, the specification of two artificial lab tasks is provided which form a preliminary step to determine the suitability of haptics for improving targeting performance and reducing visual load by transferring some aspects of information presentation away from the visual display. In the event that the results of these preliminary experiments prove that haptics does have potential benefits, proposals are provided for an ongoing evaluation strategy. In addition, specific suggestions for continuing this research are presented in Section 7.3.

7.2 Limitations of this Work

It is important to recognise that there are significant limitations in the research documented in this thesis. The requirements gathered to drive the development of the simulation were extracted from two visits to a single ATC facility and so the results cannot be generalised. In addition, a single controller was subject to direct observation and only two controllers were participants in semi-structured interviews. This population cannot be considered a big enough sample size to ensure validity.

However, many interesting points are raised by the work herein and are considered to be worthy of serious investigation for future research projects. It is clear that there are human factors problems in all aspects of the ATC environment, some of which will be solved by the new systems that are under development as part of a worldwide mass modernisation of the ATC system. However, with new systems and interaction styles, different human factors problems are surely likely to arise, and research will continue to identify and suggest solutions for these as yet identified time bombs. Perhaps the application of haptic interaction could be the key to at least one of these future failings in an industry that must continue to place safety at least as important as profit.

7.3 Suggestions for Future Work

This section presents suggestions for future work on two fronts:

- Progressing the development of the existing research while maintaining the same scope.
- Expanding the scope of this research either in terms of requirements gathering or investigating whether an increased level of multimodal interaction could be integrated into the next generation of ATC systems.

7.3.1.1 Progressing the Development of the Existing Research Scope

A significant level of work is required to take the ATC simulation to its initial testable iteration, and subsequent iterations. In particular, the radar display module needs to present a realistic visual model of traffic in a format that is familiar to real controllers. The current radar display module implementation, coded using the Visual C++ graphics libraries, is obviously incomplete and is too low fidelity to release to participants for evaluation. To prevent having to develop a realistic visual model from scratch, it is preferable to use an existing software toolkit to build the radar display, such as the Zinc tool already proposed. Although Zinc appears to be a promising tool for this purpose, now that it has been expanded to operate on the Windows platform, it is equally possible that additional ATC simulation tools may have become available since the development of the simulation halted.

If the preliminary experiments specified in 6.2 prove that haptics may be beneficial in the ATC environment, then the tools required to build a high-fidelity prototype of the radar display module need to be carefully considered. It is hoped that the Fugue environment can be used to implement the Simulated Traffic Module. At this point, it will be necessary to consider a number of attributes related to the simulation design [4]:

- How large a system area should be represented?
- How many controllers or controller teams are needed to operate and evaluate it?
- How many runs will be needed?

- How many unique traffic samples will be needed?
- How many practice sessions will be necessary before the evaluation starts?

It is believed that this simulation would require a vertical prototyping approach, with the development of each iteration adding another column of the full functionality of the system. For example, the first testable iteration would include the following modules (see Section 5.2):

- Radar Display Module
- Simulated Traffic Module
- Haptic Targeting Module

This release would be evaluated by students in a pilot study and then by real controllers at Prestwick. As a result of the evaluation the design and implementation of these modules would be revised, and then re-tested as part of the evaluation performed on the next iteration. However, the next iteration would also include the first implementation of another haptic module (for example, the Haptic Predict Module). The richness of the iterations would develop in this way until the point was reached where all haptic modules were implemented and a more thorough combined usage experiment could take place, with participants using the full suite of modules that together make up the ATC simulation.

Suggestions for haptic effect design in relation to each of the functional modules are presented in Section 5.2. However, it is important to note that because the development of this simulation is an exploratory activity and the design model used is user-centred and iterative, it would be important to implement and evaluate alternative types of haptic effects within each module if a specific effect design was found not to be suitable.

7.3.2 Expanding the scope of this research

After the two Prestwick visits were conducted, it would have been extremely valuable if additional visits could be conducted to a number of other ATC facilities in the UK to observe and interview controllers and researchers (in the case of the Air Traffic Management Development Centre at Bournemouth). Additional visits would provide further insight and data into the ATC domain, and identify the differences in workstation interaction (particularly radar display and input device use) at the different facilities. It would be interesting to identify whether a set of requirements common to all facilities and types of ATC role could be identified. If the initial study at Prestwick proved successful in meeting any of the requirements, potentially the ATC simulation development and evaluation could be expanded to take in other facilities if permission was given for controllers at these facilities to take part in evaluation experiments.

Thus far, very little consideration has been given during the design of this simulation as to how it would break down if a software failure occurred. This is of prime importance given the safety critical nature of the ATC domain. If haptics proved successful in alleviating any human factors problems within ATC, the system would have to be able to survive during a failure of the haptic component. In this sense, a haptic enhancement to the visual interaction object, would be more likely to break down gracefully than a haptic replacement for a visual object. This is deserving of significant research.

In Chapter 3, an introduction to speech and non-speech audio was provided along with sample applications within the aerospace domain. It would be interesting to extend the scope of this research so as to compare the suitability of non-speech audio effects and haptic effects in meeting any of the documented requirements. If data-link communications continue to replace R/T communications between pilots and ATC centres, this would free up space on the audio channel. Audio interaction has the benefit that the user does not have to be touching an input device in order for the interaction effect to be transmitted to the user. The combination of haptic and audio interaction effect would also be worthy of attention. The Immersion Studio environment already supports the creation of combined audio and haptic compound effects so any combined effect design could be implemented using the currently selected haptic interaction tool.

In many ATC facilities, touch-screen units are being employed. Another interesting research direction would be to investigate enhancing these displays with haptic effects to reinforce the selection made. For example, each software button could employ different haptic effects depending on their function.

If this research was progressed and haptics or non-speech audio was found to have a positive outcome in alleviating one or more human factors problems within the ATC domain, and the research was shown to be valid in a research setting, this would be a significant finding. However, there is significant gap between validity in a research setting and validity in the field. In order to validate whether or not a haptically enhanced radar display would be suitable in a real ATC system, the findings of this research would need to be taken on by ATC systems designers to test whether the same findings were valid in an actual ATC integrated system. This would be a significant and difficult achievement.

7.4 Conclusion

In conclusion, this thesis set out to achieve the following:

- Review the identified human factors problems within the ATC domain
- Investigate for those problems related specifically to controller workstation interaction whether or not the use of multimodal interaction, and in particular haptics, could prove to be a worthwhile research direction for alleviating any of these problems.

A small-scale requirements gathering activity was completed to identify issues at one specific facility and a proposal for the development of a haptically enhanced ATC simulation intended to evaluate multimodal suitability was presented herein. The initial target for evaluation was targeting performance and, in due course, additional development was intended to evaluate the remaining requirements.

This thesis is significant in that it applies the research area of haptics to the domain of ATC. This combination has received very little research attention to date. Unfortunately, time constraints prevented the research progressing to the level hoped. However, a significant body of further work is proposed and it is hoped that this work will influence others within the ATC and multimodal research communities.

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Appendix A: Questionnaire Used During First Prestwick Visit

This appendix contains a copy of the questionnaire handed to the ATC Operations Manager during the first visit to the Prestwick ATC facility on Friday 25th February 2002.

Human Factors Questionnaire

1. How much emphasis is placed in human factors during the design and ongoing maintenance of operational computer systems?

2. Do you see these systems changing significantly as new air traffic management techniques are introduced?

3. Are controllers actively involved in the design of new systems or enhancements to current systems, specifically in the way that they interact with them?

4. How closely is NATS aligned with the FAAs Free Flight program? Will NATS develop systems to support free flight in the future?

5. What do you see as possible issues or particular challenges with the introduction of free flight?

6. Are the computer systems used by controllers continuously enhanced during their lifecycle or are they purely maintained once they enter service?

7. Is the controller’s interaction with computer systems essentially visual, using display terminals?

8. What role does the controller’s sense of hearing take? Is it used for communication with other controllers on site and for communication using radio transmissions or are auditory alarms of some kind used as opposed to purely visual alarms?

9. To your knowledge, has haptic interaction (related to touch) ever been used in computer systems on this site? For example, a force feedback mouse providing vibrations to indicate some condition? Do you think haptic interaction could be useful in improving the user interface of one or more ATM computer systems?

10. What types of statistical data is recorded at this facility, and what is it used for? What aspects of statistical data are you particularly interested in?

Appendix B: Agenda and Interview Questions Used During Second Prestwick Visit

This appendix contains a copy of the proposed agenda and the questions used to interview controllers during the second visit to the Prestwick ATC facility on Wednesday 18th December 2002.

Visit to SCOACC – Wednesday 18th December 2002

Proposed Agenda

1. Introduction, confirm restrictions and introductory questions.
    - Overview of Scottish airspace and the different facilities which exist.
    - Briefly describe my research to John, what stage am I at.
    - Contact names for other facilities (e.g. Bournemouth, Swanwick)

2. Observe controller(s) at work for 1 hour
    - View how the trackball is used with the radar display
    - Appreciate the speed of aircraft trace movement on the radar display for purposes of building simulation.
    - How relaxed controllers are when going about their work
    - Controller/controller and controller/pilot communication.
    - Differences in controller behaviour under different workload conditions.

3. If possible, observe trainee or fully trained controllers in a training environment with a view to learning the following:
    - Ask about the tasks they perform during their work. This interactivity may not be possible while observing controllers in an operational environment.
    - Understand how they are trained. That is, in terms of procedures and the ATC simulations used.
    - If circumstances permit, ask why tasks are done in a specific way.

4. Conduct two or more unstructured interviews with controllers (at least one of which was previously observed).

5. Final questions/comments and end of visit.

1. Introduction, confirm restrictions and introductory questions

- Overview of Scottish airspace and the different facilities which exist.
- Briefly describe my research to visit host, what stage I am at.
- Find out contact names for other facilities (e.g. Bournemouth, Swanwick).

2. Observe controller(s) at work for 1 hour

- View how the trackball is used with the radar display.
- Appreciate the speed of aircraft trace movement on the radar display for purposes of building simulation.
- How relaxed controllers are when going about their work.
- Controller/controller and controller/pilot communication.
- Differences in controller behaviour under different workload conditions.

3. If possible, observe trainee or fully trained controllers in a training environment with a view to learning the following:

- Ask about the tasks they perform during their work. This interactivity may not be possible while observing controllers in an operational environment.
- Understand how they are trained. That is, in terms of procedures and the ATC simulations used.
- If circumstances permit, during observation ask why tasks are done in a specific way.

4. Conduct two or more unstructured interviews with controllers (at least one of which was previously observed)

Questions relating to User Profiling:

- How many years experience do you have as a controller?
- What is your background and education?
- Can you comment on any experience you have had in other ATC facilities?

Questions relating to Controller Tasks:

- Please describe the tasks you do in a typical work day?
- Which tasks or aspects of your job do you consider to be the most difficult?
- Which tasks do you do most frequently?
- Which tasks or aspects of your job do you find most enjoyable?

Questions relating to Controller-Controller/ Controller-Pilot Interaction and Communication:

How do you see controller-pilot interaction changing in the future with increased use of data-link communications rather than speech?

Questions relating to Controller Workstation Interaction:

- Comment on the way you use the trackball with the radar display?
- Are there any things that frustrate you when using the trackball to interact with the radar display?
- Can you think of any additional information which you would like to have when using the radar display and trackball, which is not currently available with the present system?
- What is your opinion of increased automation in your working environment; for example electronic online alternatives to paper flight strips?

Real-time Questions during the Visit:

This space is provided to add any additional questions that arise during the visit.

Final questions/comments and end of visit