Flight Simulation: Research Challenges and Flight Crew Assessments of Fidelity

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Abstract

The principal aim of simulation is to provide a platform on which environments or technology, either real or proposed, may be recreated for the purposes of training, visualisation and research. Simulators' fidelity range widely; some aim to recreate an environment or system to such a high degree that it is difficult to distinguish between the simulator and the real system, while others simply aim to recreate a small part of a system, or to present the system as a whole in a more compact and stylised fashion.. The aim of this paper is to provide an overview of the technical challenges that face the simulation field as technology and requirements change and evolve. Focusing almost exclusively upon commercial Flight and Flight Systems simulation, it will include the results of a experimental study acquiring user assessments of fidelity, involving 'Expert Users' (Captain and Flight Instructor) from a variety of international airlines and who have many hundreds of hours of experience of both the real, operational environment, as well as the simulated equivalent

Keywords: Flight Simulation, Fidelity.

1 Introduction

It could be argued that Flight Simulation is perhaps the most pervasive and successful area within the simulation arena. Within simulators flight crew can train to deal with emergency situations, can gain familiarity with new aircraft types and learn airfield specific procedures. Flight simulators vary considerably with regard to complexity, and range from fairly simple devices such as the Airbus flight-training device shown in Figure 2, to highly complex Full Flight simulators which incorporate motion and aim to present the most convincing facsimile of the real aircraft possible.

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Typically, a full flight simulator as shown in Figure 3 accurately represents a specific aircraft type by faithfully recreating the flight deck using actual aircraft avionics and instrumentation. The aerodynamic characteristics of the specific aircraft type are then mathematically modeled and used to drive the avionics, motion and visual system. In this way a simulator may create a training or research environment that is highly convincing in its representation of reality. The degree to which a simulator recreates the intended aircraft is of course highly regulated and monitored by the relevant aviation authority (FAA in America, CAA in the UK for example) and approved across 4 levels from A & B which will have a rudimentary visual and no motion, to C & D which will have a visual with highly specific visual parameters and full motion. The challenges facing future generations of simulation device may then be broken into the following four categories:

- Avionics & Instrumentation
- Motion Base
- Visual System
- Environmental

2 Avionics and Instrumentation

When considering the avionics fit within a specific aircraft type a distinction needs to be made between a high fidelity full flight simulator and other lower fidelity devices.

3 Low Fidelity

If it is not requirement to simulate an aircraft type exactly then there is clearly no need to use actual avionic devices, instead recreating the appearance of each instrument 'digitally' on a computer display. Such devices range in complexity from the FTD shown in Figure 2 which approximates the appearance and layout of a flight deck spread across multiple screens, to even simpler devices and applications which may be run on a standard personal computer or laptop with a single display, as shown in Figure 4. The great strength of such devices lies in their portability, which clearly stems from lack of actual avionics. They may be used by aircrew to train 'Anytime, Anywhere' either as a classroom aid during initial training or even for basic type familiarisation prior to progression onto a full flight simulator, and then the real aircraft. The great portability of such devices has also led to the possibility of deploying them 'in the field' within the military arena, for the purposes of mission practice and rehearsal prior to flying the sortie for real.

Figure 1. Krsko Power Plant Simulator (Courtesy of CAE).

Figure 2. Airbus A320 ‘simfinity’ Flight Training Device (Courtesy of CAE).

Figure 3. A Full Flight Simulator (courtesy of CAE).

Figure 4. Low fidelity ‘Simfinity’ training application (courtesy of CAE).

This clearly leads to increased mission success and survivability. A significant challenge for the development of these systems however lies in the nature of the recreation of the avionics display which in itself stems from the portability. In a high fidelity simulator utilising actual avionics, only the data input needs to be synthesised. Within these portable devices however the actual avionic display must also be created, clearly within limited screen space, especially with a single display device. The nature of interaction will also be synthetic and unnatural. While this is unavoidable to the greatest extent, careful application of Human Computer Interaction practices is vital. With the advent and pervasiveness of high bandwidth communication it is also possible that these devices (as well as their high fidelity counterparts) may be interconnected, either across buildings or globally, to create a virtual training scenario regardless of trainee location.

4 High Fidelity

For a high fidelity simulator that recreates a true representation of the operational flight deck the avionics fit is simply copied from the operational aircraft. This however reduces the portability of the device with the result that they are nearly always fixed in location. Obviously the advantage of this approach is a flight deck that is identical in appearance to the operational aircraft, in which a pilot may train upon more complete, complex scenarios. Indeed these devices are so convincing that a level D certified device may even be used for type conversion. The overall effect can be seen in fig 5. Since real avionic devices are used, only the data input that each requires needs to be synthesised and routed. This is a complex task which requires that the sensor device upon which each instrument relies is modeled, the data correctly formatted (ARINC for example) and sent to the device. Since this sensor data is dependant upon external factors (air temperature, pressure, airspeed etc) the external elements must also be accurately reproduced. Moreover, as technology evolves and improves new avionic devices are developed which typically rely on new types of sensor input. These must be examined and reproduced. Recent advances in avionic design have lead to some fairly exotic devices becoming available and frequently installed with operational aircraft such as Forward Looking Infrared (FLIR) and Millimetre Wave (MMW) Radar.

Figure 5. A simulated Boeing 737 flight deck with level D visual (Courtesy of Boeing).

Such devices are employed to provide clear outside view during low visibility or hazardous conditions. Clearly within a real environment the data that is displayed from such devices is simply dependant upon sensor information – the outside environment is really there and can be measured and displayed. Within a simulator however the environment is virtual, and cannot be measured with FLIR or MMW. The low visibility image must therefore be created from the visual scene, adjusted to be displayed from the point of view of the sensor (which will be different from the pilots eye point), and displayed within the cockpit. Recent advances within visual image generator (IG) design provide for this particular example as shown in Figure 6.

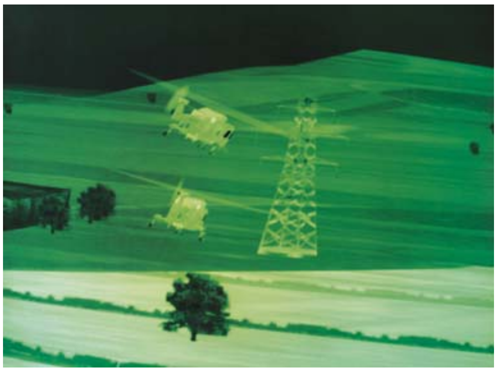

Figure 6. Simulated FLIR image (courtesy of CAE).

With the events of September the 11th still firmly in mind, another aspect of flight deck evolution focuses on security. Within a real aircraft it is clearly relatively simple to relay CCTV imagery to the flight deck to alert flight crew of any situation. This may also be fairly simply simulated by providing digital video footage as part of any appropriate training scenarios. However since we are concerned with highly accurate simulation, this must mimic absolutely the type of display expected within the operational flight deck, down to CCTV camera location (and therefore the relayed display), the location of the monitor within the cockpit and even the exact type of display device used within the real aircraft. While everything that is installed within a real aircraft can of course be replicated within a simulator, it is the speed of development and implementation of such devices that may present the most significant challenge for the flight simulation field [Bennett 2003].

5 Physiological Simulation

While the fidelity of the simulated avionics fit will clearly impact the nature, level and accuracy of the simulator overall, it is vital to consider kinesthetic aspects relevant to the human pilot in order to provide a truly convincing simulation rather than merely an expensive and highly complex machine. Kinesthesis (motion and touch), vision and hearing are the essential senses that must be simulated. Smell and taste and largely ignored, though smell may play some small role in the operation of a real aircraft. The information supplied to the auditory channel may be very representative of the real thing. Given the advent of modern digital signal processing, it is possible to reproduce noises that are indistinguishable from the real thing, indeed the fidelity of such sound is highly regulated, monitored and tested by the various regulatory bodies (FAA and CAA) during the acceptance of any simulator prior to training (and biannually thereafter). It is not practical however to accomplish near duplication of motion and visual sensations, particularly in the representation of the real, visual world [Rolfe, J.M. 1986]. It is therefore important that we should analyse the simulation of the senses provided by motion and vision to determine those features of the total environment that are important.

A starting point is to endeavor to identify what information is received by the human sensory system and then to model the manor in which this information is interpreted. What is utilized, and the way in which it is utilized is clearly task dependant. It would be highly convenient if everybody chose the same information and interpreted it in the same way for a given situation. There is however considerable evidence that the interpretation of a given set of limited information varies widely between individuals [Palmer & Petitt. 1976]. We are born with certain in-built routines in the brain that allow basic survival, but with a 'large empty space' waiting for information. The way in which this information develops depends upon the experience of each individual. While it might be hoped that the decision to become a pilot, for example, is influenced by a predisposition to view the world in a certain way, it clearly will not represent general uniformity across all elements of the piloting task, and certainly not to the relatively limited elements of the perception of motion and visual inputs and their interpretation [Rolfe, J.M. 1986]. This presents a potentially insuperable dilemma. It is possible to produce only a very limited subset of the information available in the real world, and this subset, while potentially useful to some individuals, may not be appropriate for others.

Fortunately the human being is very adaptable, and the world is full of redundant information. So if preferred information is unavailable then some other relevant though perhaps not so easily interpreted information will be selected. The limits of operation of aircraft are often determined by the reduction of information in the real world to a minimum, and the substitution of artificial aids. For example, the lighting patterns and runway markings of airfields are designed to allow aircraft to approach and land in conditions where information from the natural world is totally inadequate due to poor visibility or darkness.

The intrinsic capabilities of the human sensory system are fairly well understood, along with the adaptability of people in making use of available data cues, whether by past experience or specific training. Armed with this information, kinesthetic and visual information can be used in the creation of both motion and visual systems.

5.1 Motion Base

Motion bases are used to create the sensation of motion within a simulator. Their use is not limited flight simulation; many types of vehicle simulator employ motion bases from car and truck simulators to tank and ship simulators. Motion bases may be broken into two categories, Hydraulic and Electric. Within the realm of Level C & D full flight simulators, hydraulic motion bases are used almost exclusively. This is due to two main factors.

- The weight of the equipment being moved
- The fidelity of the movement required

The principal by which hydraulic motion platforms operate is quite simple. Hydraulic oil is pressurised (to approximately 1500psi) by a series of pumps and forced into hydraulic rams or jacks. If a jack is required to rise, a servo-operated valve is opened allowing oil into the cylinder, which forces the jack to extend. Conversely when the jack is required to lower, the valve is closed causing the pressure to drop and the oil is forced back out of the cylinder causing the jack to lower. While there are several different techniques by which the simulator itself may be mounted on the motion base, by far the most common within civilian & commercial aviation simulation is to support the flight deck on six individual jacks as shown in Figure 3. By varying the pressure to each jack individually the simulator can be made to move through six degrees of freedom (DoF) to provide the sensation of pitch, roll, yaw, acceleration and deceleration as well as turbulence.

Since it is impossible to compress a fluid, the use of hydraulic oil gives the ability to simulate conditions such as ‘Gear Up’ forced landings, undercarriage collapse and other violent, heavy motion events. The simulators main host computer relays data relating to the aircrafts attitude to the motion control host computer, which then controls the individual jacks to provide the sensation of authentic movement. Due to the nature of the hydraulic system, this movement can be controlled very rapidly, and while it is restricted in extent because of the limited stroke of the jacks, when coupled with a visual image that reflects the movement the results can be very convincing. A vital research area therefore is to examine the exact amount of time that is allowable between moving the motion base, and reflecting the change in attitude within the visual scene (referred to as latency) [Guo et al. 2003]. The human motor system is very sensitive to changes in pitch when coupled with a visual image, and if the detected movement is out of sync across the senses, not only will the effect appear unconvincing; it can also result in motion sickness. Typically within a full flight simulator this latency is tuned to within 100 to 120 milliseconds (ms).

Excessive latency has long been known to hinder operator adaptation to other display distortions such as static displacement offset. Latency also degrades manual performance, forcing users to slow down to preserve manipulative stability, ultimately driving them to adopt a ‘move and wait’ strategy [Sheridan and Ferrell 1963]. Operator compensation for a delay usually requires the ability to predict the future state of a tracked element.

Interest has more recently been directed toward the subjective impact of system latency relevant to virtual reality simulations. Latency as well as update rate have been considered as factors affecting the operator’s sense of presence in the environment. In a recent study, lower latencies were associated with a higher self-reported sense of presence and a statistically higher change in heart rate for users while in a stress-inducing (fear of heights), photorealistic environment involving walking around a narrow pit [Meehan et al. 2003].

System latency (time delay) and its visible consequences are fundamental virtual environment deficiencies that can hamper user perception and performance. The aim of this research is to quantify perceptual tolerance to Virtual Environment latency. In particular, the role of Virtual Environment scene content and resultant relative object motion on latency detection was examined by presenting observers in a head-tracked, stereoscopic head mounted display with environments having differing levels of complexity ranging from simple geometrical objects to a radiosity-rendered scene representing a hypothetical real world setting. Such knowledge will help elucidate latency perception mechanisms and, in turn, guide VE designers in the development of latency countermeasures. In this study, a radiosity-rendered scene of two interconnected rooms was employed. Latency discrimination observed was compared with a previous study in which only simple geometrical objects, without radiosity rendering or a ‘real-world’ setting, were used. By investigating sensitivity to latency in VEs that could represent a real-world setting in direct comparison with previous research that utilized simple objects, it can be inferred that the Just Noticeable Difference (JND) for latency discrimination by trained observers averages ~15 ms or less, independent of scene complexity and real-world meaning [Ellis et al. 1999; Adelstein et al. 2003].

In summary, results from these studies suggest that virtual environment system designers should expect observers who are not burdened with any other performance tasks to generally be able to notice differences in latency as low as ~15 ms, regardless of the relative location of objects in the scene, the ‘meaningfulness’ of the scene context in relation to the real world, or possibly even the degree of photorealism in their rendering. These results will also serve as performance guidelines to aid in the design of predictive compensation algorithms.

While hydraulic motion is currently the mainstay of professional motion platforms aimed at representing accurate motion effects, there are a number of quite significant drawbacks. Hydraulic systems are by their nature economically inefficient, they use vast quantities of power and require very large and expensive hydraulic pumps that need to be housed away from the simulator itself. They also require frequent and specialised maintenance which drives the running cost of the simulator up, and while they are not in themselves great environmental polluters, the waste oil does need to be disposed of in an environmentally safe fashion. The alternative is to replace the hydraulic system with a directly driven electrical system. Within the area of simulated motion, this is perhaps the most significant challenge. The problem with electric motion bases so far has proved to be twofold, weight and motion authenticity. Any simulator that uses systems and instrumentation taken from the real world, either from an aircraft, a ship or a tank will have a significant weight. When this is coupled with the superstructure that actually makes up the simulator, which has to be built to withstand quite significant load forces, the platform that needs to be manipulated can weigh several tons. Electric motion bases may use either linear motors, direct driven screw jacks or a ‘Gas Spring’ created by replacing the hydraulic oil with compressed gas to create the hydrostatic pressure required to move the platform [Denne 2003]. The most significant problem with all three of these approaches has so far been the weight that they can support, although this is rapidly becoming less of a problem as technology improves. American motion base manufacturer, Moog incorporated, has a system in development that it is claimed can manipulate a platform weighing up to 32 tons, more than enough support even the heaviest simulator [Moog Incorporated, 2003]. The second problem facing the use of electric motion bases is that of motion fidelity. The nature of hydraulics provides a system that is ideally suited for the accurate creation of simulated motion, however recreating this within an electric base is challenging. Linear motor and screw jack approaches may provide the most suitable overall results, while gas springs may be better for certain effects such as turbulence. It is unclear however whether a gas spring will be able to provide suitable motion for heavy events such as forced landings. Since gas is highly compressible, the weight of the simulator would need to be counteracted exactly, at exactly the right time during the heavy event. If it were not then the weight of the simulator itself would compress the gas in the cylinder causing a 'Bounce' rather than a convincing hard stop. The move to electric motion bases is however very compelling due to socio-economic demands. A direct driven electric motion base is less expensive to run and doesn't require the same degree of specialised maintenance and care as its hydraulic counterpart, which will reduce the running cost of the simulator considerably. They are also far more environmentally friendly with virtually no possibility of causing pollution, and have no waste products that require careful disposal.

5.2 G-loading

One very desirable feature that may be demanded of a motion base is that of simulating the G forces that a pilot may be exposed to. While not so significant for the majority of civilian simulation, within military fast jet simulation this would be highly desirable. Simulating the full range of G loading effects in a realistic manor would be a huge challenge for simulation due to the way in which it is caused. Acceleration or deceleration in a given direction is detected by the human motion system and interpreted as a change in speed. If this motion is across the vertical plane of the body then blood is forced into or out of the brain leading to the possibility of grey or blackout for the pilot - blackout normally occurring at around 8 – 9 G for a fit, experienced military pilot [Greene et al. 1992]. While a blackout will cause the pilot to loose consciousness, and therefore control of the aircraft, a grey out will at the very least cause an inability to concentrate and therefore operate the aircraft in a safe efficient manor until the load is reduced. Within an actual military fast jet the pilot is equipped with a special 'G-Suit' that helps to counteract some of the effects of high G loads. These suits comprise of compartments within the legs that inflate when high G loads are detected, restricting the flow of blood, thus helping to maintain an adequate supply to the brain. Under prolonged and increasing loads however the supply of oxygenated blood will still decrease, leading to an inadequate supply resulting in grey, and then blackout. As the G load begins to increase leading to the first stages of a grey out, peripheral vision begins to fail and vision starts to become 'fuzzy'. As this increases in intensity, vision may be totally lost until the pilot experiences a complete blackout, ultimately resulting in unconsciousness. Several approaches are already used within military fast jet & helicopter simulation that attempt to reproduce some of the effects of high G loading. The pilot may wear a G-suit for example that inflates when a high G maneuver is entered. This provides a physical cue informing the pilot of the calculated load factor the he and the aircraft are currently being subjected to. As this load continues or increases, the avionics and simulated visual scene may be dimmed and defocused giving the impression of a grey out. This may continue until they have been dimmed to a point where they are no longer visible at all, giving the impression of a blackout. In this way it is possible to simulate certain effects associated with high G loading. There are however other significant effects that cannot be simulated in such a fashion. At a load of 5G for example the pilot will feel as if he weighs 5 times more than he normally does, and will almost certainly be experiencing additional grey out effects such as a mild inability to focus on operational tasks and may be finding it difficult to interpret information being relayed via the avionic displays due to the lack of oxygen. If these effects could also be simulated, then the overall training value for fast jet simulation would increase dramatically (though clearly rendering a pilot unconscious would be undesirable). This would be a significant challenge indeed since the only way to simulate the full spectrum of high G loading effects is to reproduce the motion and velocities involved, and while certain approaches have been taken in the past the Vertical Motion Simulator (VMS) at NASA Ames Research Centre in California (Figure 7) is the only one which is operational, and this is used for research rather than operational training [Nasa Ames 2003]. Indeed the shear cost, complexity and size of systems such as the VMS may make them economically unviable for mass training, and are only likely to be developed should it become a requirement within the specification of future simulators.

Figure 7. The NASA VMS system

6 Visual System

Perhaps the most rapidly advancing aspect of simulation is that of the visual representation of the environment as recreated by the visual system. Once again the visual system can be broken into two distinct and equally important parts, each one dependant upon the demands and abilities of the other.

- The image generator (IG)
- The display system

The IG generates the image from its database, dependant upon the aircraft position, attitude and the specified environmental conditions for the scenario, while the display system is responsible for reproducing this data in a visible form to the aircrew.

6.1 Image Generation

The inclusion of image generation devices is relatively new within the field of simulation, and has only become possible with the advances in microcomputer technology. Early IG devises were only capable of calculating the relative position of light points for displaying runways for example, which resulted in the limitation of only being able to run 'Night time' scenarios within the simulator. Clearly computer technology has improved exponentially since the inception of these early systems, and has been capable of depicting terrain, other air traffic, ground vehicles and ground buildings for many years in the form of shaded polygons. Early versions of this form of IG technology were only capable of displaying a few hundred polygons per channel, and could only employ 'flat shading' algorithms to give them substance. With the advent of increased CPU speed, memory bandwidth and the development of texture memory however, this flat shading was replaced with texture mapped surfaces that not only appear to have substance but also the appearance of realistic surfaces, frequently created from photographs of the specific object that requires simulated display. Modern IG's are capable of calculating and rendering many tens of thousands of polygons per channel in real time, and with the development of increased texture handling subsystems within the dedicated Graphics Processing Units (GPU's) can render some truly impressive images as demonstrated in Figure 7. Until recently IG's have been custom designed and built by a small handful of companies such as CAE, Evans & Sutherland, MacDonnell Douglas and Silicon Graphics, each containing custom built boards housed in large cabinets each about the size of a domestic fridge freezer. The displayed image typically has a horizontal field of view of 180 to 220 degrees in a commercial flight simulator and up to 360 degrees in other systems such as Air Traffic Control.

Figure 8. Image from a CAE Tropos IG (Courtesy of CAE).

These images are displayed by 'tiling' segments of typically 60 degrees together. Each 60 degree segment being rendered by an individual IG channel, and data shared across channels by a high bandwidth backplane. With the development of high performance PC's and high speed networks, one area of research and development in this field is looking into basing the entire IG around a network of high speed PC's, with each individual PC rendering an individual channel of the visual scene – the so called 'PC IG', with the clear goal of a vast reduction in cost per channel since commercially available (COTS) products may be used. Another approach takes a similar line but maintains the very high speed available through a shared backplane, presenting a single unit with one point of interface and control. In such systems (such as the CAE Tropos shown in Figure 7) each channel is rendered by a series of commercially available GPU's. The use of commercially available GPU's allows other non simulation specific research and development to be taken advantage of, effectively reducing the cost per channel and allowing advancements to be made at a greatly increased rate. With polygon counts now up to between 80,000 and 160,000 (peak) per channel, it is arguable that the demand for greater polygon counts is reducing. While the progression of pixel and polygon capacity will clearly continue in future generations of IG, the key benefits from the increase in power will come in the form of improved processing. For example the inclusion of Phong shading will allow for specular lighting on water surfaces and runway contaminants such as ice, something that has not been possible until now due to limited pixel and vertex shader performance. Anisotropic texture filtering and layered fog are already included in the most modern systems, and these greatly improve the realism of adverse weather conditions. By looking at research being conducted globally into the human visual and cognitive systems, it is challenging to create an image generation system of high perceptual simulation fidelity by examining the relative importance of rendering aspects such as specular highlights and diffuse inter-reflection as well as simulating cognitive models of spatial perception and tailoring the abilities of the IG to match. This is an important research area for the future [Mania & Robinson 2002; Mania et al. 2003; McNamara 2001; Mania & Chalmers 2001; Mania 2001].

A goal of Virtual Environment (VE) systems is to provide users with appropriate sensory stimulation so that they act and react in similar ways in the virtual world as they would in the natural world. The research community is challenged to investigate the factors that make virtual reality technologies effective (simulation of spaces and humans). Realising the goals of virtual reality systems and harnessing them to successful applications could be accomplished by employing robust fidelity metrics based on human-centred experimentation.

What makes a simulation 'feel real' to a human observer? Can we use what is known about human visual system and human cognition to help us produce more realistic synthetic images? Can our perception of the real world (space and people) around us 'survive' the transition to a graphics environment or to a virtual human? How can we use the attributes of the human visual system and human cognition to design computer graphics simulation systems in a way that a sense of 'being there' is communicated? Are there perceptual commonalities among applications; or are practical applications so independent that we cannot generalise findings from one application to another? These are significant questions for the research community to tackle.

It is increasingly important to provide quantitative data on the fidelity of rendered images. This can be done either by developing computational metrics which aim to predict the degree of fidelity of an image, or to carry out psychophysical investigations into the degree of similarity between the original and rendered images. Psychophysics comprises a collection of methods used to conduct non-invasive experiments on humans, the purpose of which is to study mappings between events in an environment and levels of sensory responses to those events. The term *visual fidelity* refers to the degree to which visual features in the Virtual Environment conform to visual features in the real environment. *Interface or interaction fidelity* refers to the degree to which the simulator technology (visual and motor) is perceived by a trainee to duplicate the operational equipment and the actual task situation. It is not computationally feasible to immerse a person into an interactive artificial environment which exactly mimics the panoply and complexity of sensory experiences associated with a "real" scene. For a start, it is technologically challenging to control all of the sensory modalities to render the exactly equivalent sensory array as that produced by real world interaction. When visual (or interaction) fidelity is increased, the system responsiveness decreases resulting in reduced frame rate and added visual/tracking latency. It is argued that training in a VE with maximum fidelity would result in positive transfer equivalent to real-world training since the two environments would be impossible to differentiate. Robust metrics are essential in order to assess the fidelity of VE implementations comprising of computer graphics imagery, display technologies and 3D interaction metaphors across a range of application fields.A small study investigating subjective assessments of fidelity by aircrew using flight simulators will be reported in this paper.

7 Display System

A level C or D flight simulator places some specific demands upon the display device with the result that only cathode ray tube (CRT) devices are suitable. While other technologies such as LCD, DLP and Plasma offer enhanced visual quality, none of these devices are capable of one vital requirement of a level C or D display – Calligraphic light points. A Calligraphic light point is a high intensity point created by focusing an electron beam at an electron sensitive raster. By varying the time the beam is focused, it is possible to vary the intensity of the light point. Non calligraphic displays (including standard CRT) function by dividing the horizontal and vertical screen elements (the pixels) by the required refresh rate to determine the amount of time that each pixel may remain illuminated each frame, for example at a resolution of 1024 – 768 at a refresh rate of 72Hz (quite a common combination) we have

1024 X 768 = 78642 pixels
1 second = 1000Ms (milliseconds)
1000Ms ÷ 72 = 13.8Ms per frame
13.8Ms = 13800 µs (Microseconds)
13800µs ÷ 78642 pixels = 0.175 µs per pixel

Within a standard raster scan device then at a resolution of 1024 – 768 and a refresh rate of 72Hz each pixel can only be focused on for 175 Nanoseconds. There is no flexibility within this so individual pixel intensity cannot be varied. The colour may be varied by controlling the amount of red, green and blue, but the intensity may not. A level C or D display explicitly requires high intensity light points that accurately reproduce the appearance of real world lights (such as runway or navigation lights). To achieve this, the background image (runway, buildings, mountains etc) is displayed in a conventional raster scan, typically at 60Hz for day and 40Hz for night. This raster scanning is interlaced, which means that all of the odd numbered lines are drawn, followed by the even. This 60Hz refresh rate is however simply the time it takes to draw the raster – 60 times a second or once every 16 Ms. However, in calligraphic displays the actual time it takes to draw each frame may be as little as 2 Ms, effectively leaving 14 Ms per frame 'free'. This free time is divided by two due to the interlaced nature of the display, which gives 7 Ms at the end of each raster scan. During this 7 Ms period, before starting the next raster scan, the electron beam can be focused at any individual pixel or group of pixels to form a very bright light point, the intensity of which is governed by the time the beam is focused before moving on to the next light point or starting the next raster scan. Calligraphic CRT displays are large cumbersome devices that require HT voltages and complex deflection. The net result of which is a display that has considerable weight. This is undesirable since they need to be mounted upon the motion base, and even at a horizontal field of view of 180 degrees, three such displays are required. In addition to this the nature of the high intensity light points (coupled with a level D requirement to display the raster at 6 foot lamberts) leads to quite rapid CRT tube degradation resulting in time consuming and expensive replacement. Of major interest to the development and evolution of simulation devices is developing a suitable replacement for the calligraphic CRT in order to reduce weight on the motion platform (and therefore aid the deployment of electric bases), reduce cost of tube replacement and increase the overall fidelity of the visual system. While it is possible that LCD or plasma displays may be developed to function in a similar way in order to produce calligraphic points, neither technology is capable of generating the required intensity. Three chip digital light processing (DLP) projectors such as those used in high fidelity cinema may be a candidate, however these devices are also extremely complex and expensive. The most likely replacement will come from the current and ongoing development of laser projectors. These devices create the image in the normal raster scan fashion, but replace the individual RGB CRTs with individual red, green and blue lasers. Since they are capable of scan times in excess of CRT, refresh rate could be increased leading to enhanced visual scene clarity, an increase in resolution when driven by more capable next generation IGs, and increased light points per frame. Given the possibility of increased resolution and rapid scan times offered by laser projectors, it should also be possible to scan the entire 180 – 220 degree field of view (FoV) with a single projector, removing the need for multiple projector heads. This would remove the current need for vastly time consuming and complex edge blending and colour matching across the boundaries between CRT projected images within the FoV. Moreover since these devices don't reply on X & Y electron deflection much of the complexity of CRT will be replaced with a single laser generation source which may lead to increased reliability. This laser source may be placed up to 30M away from the projection head with the result that it can be mounted off-board, further reducing the weight on the motion platform. Research and development of next generation IG and projector systems is rapidly being pursued representing a fundamental step within the evolution of next generation, high fidelity simulators.

8 Environmental Simulation

Environmental simulation refers to the simulation of all aspects external to the aircraft, from weather conditions and terrain to other air traffic and air traffic control. With advances in our understanding of the weather and the resulting development of more sophisticated weather radar and detection devices, it is vital that the simulation keeps pace. Simulating sensor data and driving avionic display accordingly has already been discussed; however of equal importance is how weather conditions are visually represented and displayed. With increasingly clear, accurate weather radar being installed within aircraft for example various weather effects can be viewed with greater efficiency. This must be represented within the simulated external view. If the weather radar shows a cloud formation of a specific shape and size then this must be accurately represented within the visual system. Other weather effects play a subtler role and must also be accurately simulated for enhanced training value. A temperature inversion for example, under certain conditions indicates an extremely hazardous condition known as Wind Shear [Thom 2002]. Modern aircraft, and therefore their simulated equivalents, carry sophisticated computers dedicated to the detection and warning of wind shear, however it is highly desirable to simulate the subtle visual conditions associated with this phenomenon to provide the most believable simulation possible. This is only now becoming possible with the enhanced capabilities of modern IG / GPU technology and is shown in Figure 9.

The ability to render and display such phenomenon is of course only part of the problem. Such accurate effects take a considerable amount of time to model, which again leads to increased cost and a less than desirable flexibility. Modeling tools must be developed that enable these conditions to be created efficiently to reduce the workload of the modeler and enable more rapid and flexible model development.

Figure 9. Cloud layer indicating a possible inversion (courtesy of CAE).

The modeling of terrain can also be accomplished in a highly accurate way by developing tools that allow satellite data to be used to automatically generate terrain models, based around actual geo-specific information. This will lead to the most accurate possible depiction of airfield and route specific terrain that will again enhance the training value of the simulator.

Perhaps the most important aspect of environmental simulation relates to accurate representation of other air traffic, and a complete air traffic control system. While Traffic Collision Avoidance System (TCAS) has been simulated for a reasonable amount of time, these systems only provide fairly limited and specific scenarios, which require the simulator pilot to take action as directed by the TCAS computer. These scenarios are selected by the flight instructor for relevant procedural practice; however they typically fail to take into account air traffic that is not in direct conflict. In reality airspace is extremely crowded, especially within an airfield control boundary, and is divided into sectors, each being controlled by a specific air traffic controller on an individual frequency while an aircraft is on route, an approach controller when approaching a terminal airfield, a ground controller while taxiing for parking or takeoff, and a departure controller when leaving a airfield. TCAS alone does not account for this vast quantity of air traffic or airspace complexity, and simply warns the pilot of any conflict and may offer avoiding action. Should Air Traffic Control (ATC) be required, it is normally the flight instructor that assumes the various roles at the appropriate times. This is less than ideal since

- It is the same instructor; all sector controllers sound the same.
- The instructor workload is increased which may detract form his observation of the trainee.
- Sector frequency changes may not be accurate
- There is no accurate display of other air traffic, either visually on any installed radar.

One possible solution to this is to interconnect ATC and full flight simulators and run combined scenarios, indeed this approach has been used by Deutsche Flugsicherung (DFS), the German aviation authority. In their system 4 Boeing 747 simulators are connected via a serial data stream to a Raytheon ATC simulator. While this system may overcome some of the shortcomings of the purely instructor lead approach, it too has many disadvantages such as

- One type of training has to take priority, either ATC or Flight.
- It requires very meticulous scenario and exercise planning.
- It is vastly expensive in terms of both set up and ongoing running costs.
- May be of limited use since it is not particularly flexible (if one pilot makes an error for example the whole exercise may need to be restarted for all trainees)

With ever increasing computer power leading to the ability to run applications with greater complexity however, one proposed solution is to digitally recreate the various controller's voices and command set, and use voice recognition (Vrec) to interpret pilot requests. This could lead to the virtual recreation of real airspaces and place more accurate demands on the trainee pilot, as well as allowing for increased familiarity with specific routes. Sector handover or approach requests for example would have to be handled correctly, and more demanding situations could be set up and represented on all relevant devices (visual display, radar etc).

At the same time instructor workload would be reduced allowing for greater monitoring of pilot activity. A real airspace is a highly dynamic environment; it is highly desirable to recreate this within the simulated aircraft. Research and development of such integrated ATC environments (such as CAE's GATES system) is ongoing and represents a significant challenge. With increased IG capacity and visual clarity, coupled with enhanced avionics and computer power, simulating the ATC environment itself, while challenging, should be possible within a reasonably short time frame. The integration of Vrec however will require significant work to be done on existing systems. Voice recognition systems have been used for the past few years in such things as word processing with some moderate degree of success. However these systems are nowhere near as demanding as those required for Flight / ATC integration. For example all voice types (male, female, high pitched and low pitched) must be equally as acceptable to the system without significant time spent 'Coaching' the system on individual voices. Previous attempts to integrate Vrec within simulation have used industry specific engines (such as SAPI 4 & 5) that are derived from more generic products such as word processing, and require high levels of coaching in order to build a dictionary of individual words and phrases based upon the waveform of each users individual voice [Bennett, T. 2003]. In order to reduce the coaching time required, one very recent test bed for a USAF system used a 'lookup table' of possible responses, whereby if the exact phrase couldn't matched the best 'guess' based on the input waveform was used. This approach worked with some degree of success, however the rate of 'incorrect guesses' was considered too high, and the system still required substantial amounts of coaching averaging approximately 20 – 25 minutes per student [Tomlinson 2003]

An additional and very significant difference between Vrec in an office or ATC environment and a simulated flight deck is background noise. In an office or ATC simulator, background noise is minimal. Within an aircraft the noise levels can be significant, especially within a helicopter where background noise can be extreme. This background noise is of course also present within the full flight simulator, and can reach levels of approximately 55 – 65 dBA. (up to 106 dBA in a Blackhawk helicopter for example). Existing Vrec technology is incapable of 100% recognition rates even with a background noise level of less than 20 dBA as may be found in a small office. Ways must be found therefore to not only increase the fidelity of recognition, but also to compensate for background noise. Within a simulator the noise is of course artificially introduced into the flight deck, the waveform and volume are therefore known in advance. One possible solution therefore maybe to send the waveform of this sound to the Vrec system along a separate channel to the incoming voice communication, and then employ a filter to remove it from the actual communication channel prior to interpreting the voice command. The integration of a fully automated ATC environment is a very significant challenge, and a vital direction for future development [Bennet 2003].

9 Qualitative Assessments of Fidelity

9.1 Simulation of physics

Computer graphics algorithms have for long dealt with simulation of physics: simulation of the geometry of a real-world space, simulation of the light propagation in a real environment and simulation of motor actions with appropriate tracking. Perception principles have subsequently been incorporated into rendering algorithms in order to save rendering computation, mainly following the generic idea of 'do not render what we can not see' . However, with VE simulator technologies trying to simulate real-world task situations, the research community is challenged to produce a much more complex system. We do not necessarily require accurate simulation of physics to induce reality. Much less detail is often adequate.
Recent research results have been produced where:

- Fidelity metrics for VE simulations based on task performance in real world and VEs' task situations have been complemented by investigations of cognitive processes or awareness states while completing tasks [Mania et al. 2003]
- Simulations of how human perceive spaces from a cognitive point of view rather than just simulation of physics [Mania & Robinson 2002].

We can therefore pose the following research question:
Could we interrogate cognitive systems which are activated by being in a scene of a specific context to see if the same systems respond similarly to a VE version of the scene? And how could we match the capabilities of the VE system (related to visual and interaction fidelity) to the requirements of the human perceptual and motor systems?

A high fidelity system which is not necessarily produced by slavish simulation of physics, could be produced by non-linear informative distortions of reality since it is often the information uptake that matters. Due to limitations of displays, tracking and computer graphics algorithms, simulation of physics will often result in systems that do not simulate behaviour, cognition or perception processes as operating in the real-world. Therefore, the challenge is to induce reality with 'magic' meaning inducing a sense of 'reality' by building systems which include non-linear distortions of the physics taking into account not only the human cognitive and perceptual systems but how these will be transferred to the components of the VE system concerned, e.g. displays, tracking, computer graphics algorithms. How we scientifically define a system's attribute to 'feel real' when it is far from simulating physics due to, for instance, limitations of computational power, is a challenge for the research community.

9.2 Experimental study

A number of flight crew who are familiar with operational aircraft as well as the simulated equivalent were asked to participate in a investigation about fidelity perception in a simulator, as expert users. The flight crew which gave qualitative survey input, immediately after exposure to a commercial flight simulator, represented a number of international airlines, and were all qualified, operational Airbus A320 or Boeing 757 and 767 pilots. This survey was very brief and in no way exhaustive, concentrating on certain key areas of simulation such as

- Flight deck fidelity
- Accuracy of motion
- Visual scene image quality

Considering Flight deck fidelity on both the 757 / 767 and A320 simulators that the crew are exposed to, all crew without exception stated that the flight deck is a 100% accurate representation of the aircraft they fly operationally right down to the Captain & F/O seating (and even the floor carpet in the case of the A320). This is perhaps not surprising since within the full flight simulator, the flight deck is deliberately recreated from the original in terms of size and appearance, and all avionics systems present are actual aircraft systems.

When considering motion the majority of crew were happy with most of the motion effects such as clear air turbulence, while take off and landing were considered adequate but not truly representative of a real aircraft. One instructor stated that forced landings 'Just didn't feel right' but still had the desired effects.
Take off and landing motion discrepancies between the real and simulated aircraft are due almost entirely to the nature of the motion base. G Load cannot be simulated (even the relatively minor G force associated with commercial flight) and the sensation of speed relies upon an illusion created by deliberately tilting the motion base back whilst keeping the visual appearing level – causing the sensation of acceleration. With the limited stroke of about 60 inches that these and the majority of motion bases have, it is difficult to envisage a way of improving this, and it is still deemed acceptable by the crew.

Forced landings 'Don't feel right' is a very subjective term since (it is hoped) most aircrew will never experience the situation for real, which was indeed the case with the instructor who made the statement. All forms of motion are checked and 'tweaked' frequently to maintain parameters agreed with the various regulatory bodies, but this comment highlights concerns over the suitability of 'Gas Spring' systems as a hydraulic replacement. The instructors concern was that the motion of the forced landing (a single undercarriage collapse at touch down in this case) was not violent enough. If the hydraulic base was unable to reproduce the violence then it is unlikely that a gas spring system will be. Linear motor and screw jack systems may well be able to replicate hydraulic systems in terms of fidelity but there will always be structural limitations as well as safety concerns that will limit what can be done with simulated motion.

With regard to the visual systems it should be pointed out that the two simulators are from two different generations with the A320 being certified at level D (built in 2001) and the 757 / 767 certified at level C (built in 1991). The airbus employs a CAE Maxvue plus IG coupled with a 180 degree display, while the 757

/ 767 uses an MacDonnell Douglas Vital 7 IG coupled to an off set 220 degree display. Within both simulators all crew stated that the fidelity of the systems was such that it was adequate for the type of training that they perform, though not surprisingly the 757 / 767 was criticised for poor texture, weather and ambient lighting effects. The maxvue system has since been superseded by the Tropos system which has greatly enhanced polygon limits and texture handling abilities which will resolve many of the limitations of the existing system within the A320, such as limited airfield buildings and inaccurate water effects. The main complaint for both systems was stated as being 'visible blend zones' causing the appearance of vertical 'pillars' within the visual scene. This is caused by the nature of the display and highlights the limitation of current CRT technology. The blend zone is the region within the image where one 60 degree segment ends and is matched with the next. It is notoriously difficult to get these blend zones exact, and even more difficult to make them stay matched since the different projector setting will drift over time by varying amounts. Various systems to remove some of this effect exist using both opto-mechanical and digital systems to automatically balance and adjust the colour within the blend zone, but these generally only succeed in reducing the size of the visible boundary. The only real solution would be to generate the image using a single projector; this is currently being researched.

Generally, flight simulation succeeds in its goal of producing highly convincing and accurate systems for training and research. However in the highly dynamic world of aviation it is vital that simulation keeps up to date with advancements in flight technology. Additionally, it is vital that new 'Simulation Specific' technology that is not employed within operational aircraft such as IG's, Visual display devices, motion bases and Vrec systems, are developed to provide perceptual fidelity enhancement for future generations of flight simulators. Perceptual fidelity is not necessarily the same as physical simulation. Identifying ways to 'induce' reality rather than simulating the physics of reality is the greatest but also most fascinating research challenge of all.

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