CANADIAN FORCES COLLEGE / COLLÈGE DES FORCES CANADIENNES
JCSP 36 / PCEMI 36

MASTER OF DEFENCE STUDIES RESEARCH PROJECT

MOTION – IS THERE A REQUIREMENT IN LARGE FIXED-WING AVIATION SIMULATORS?

By Major Jason Stark

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

ABSTRACT

In a June 2008 appearance before the Senate Defence Committee, the Chief of the Air Staff stated that the Air Force was developing initiatives to resolve pilot production and absorption deficiencies, including the increased use of flight simulators.[1] Most would agree that the increased use of flight simulators can increase pilot production and, more importantly, significantly assist trained pilots in maintaining learned skills through simulator continuation training. However, few can agree on the type of flight simulator required to achieve this effective continuation training. Namely, is full motion required to achieve effective training in Canadian Forces Air Mobility fixed-wing aircraft full flight simulators? The author's opinion is no.

This analysis examines how humans process motion and applies that knowledge to the modern use of the Stewart-Gough simulator motion platform. Although pilots appear to prefer full motion in transport aircraft flight simulators, science indicates that the motion is not required. The military and civilian professional aviation communities are expending a significant amount of money on full motion platforms when there is no need. The future of flight simulators for continuation flight training requires a change in the status quo and an investment in alternative technologies, such as immersive simulators with dynamic motion seats.

---

[1] Lieutenant General Angus Watt, "Appearance before the Senate Defence Committee, 9 June 2008," as reported by David Pugliese, "Air Force Short 250 Pilots But Getting A Handle On Retention," *Defence Watch* (June 2008) [journal on-line]; available from http://communities.canada.com/ottawacitizen/blogs/ defencewatch/ archive/2008/06/13/air-force-short-250-pilots-but-getting-a-handle-on-retention.aspx; Internet; accessed 6 January 2010.

CHAPTER 1: INTRODUCTION

Almost since the invention of powered flight in 1903, simulation has been an integral part of flight training. During the ensuing 107 years, there have been drastic and remarkable improvements in the level of simulation. Aircraft cockpits are now accurately represented with all of the pertinent display panels, controls, and instrumentation. Visual display systems, with the advent of computer generated imagery (CGI), are able to recreate realistic environmental scenes. Modern aircraft simulators look, sound, feel and act almost like real aircraft. However, "almost" is the operative word. Throughout the history of aviation simulation, scientists and pilots have sought the unattainable: the absolute recreation of flight in land-based simulators. A significant bi-product of this quest has been the heated and contested debate about importance of simulator motion. Specifically, is simulator platform motion required in flight simulators?

The question does not merit a simple yes or no answer. Nor is it a matter of whether or not full aircraft motion simulation is scientifically achievable. Many solutions to complex engineering problems have been resolved with enough research and financial commitment. Mankind has visited the moon, traveled to bottom of the oceans and conquered heavier than air flight. Consequently, it is conceivable that thoroughly realistic land-based flight simulation is achievable. After sufficient investment, land-based flight simulators should eventually be able to recreate full flight motion, including sustained G force. However, the real question is whether a 100% simulation of flight is actually required for pilot training and proficiency. The best level of flight simulation currently available to aircrew is the Category D, six degrees-of-freedom, full motion simulator. Unfortunately, these simulators are very expensive, in the order of 15 to 30 million dollars depending on the included options.[2] A significant portion of that cost is associated with the level articulation required on the platform in order to simulate aircraft motion. The question is a matter of return of contribution. Is the cost associated with six degrees-of-freedom motion justified and does it provide a significant return on pilot proficiency? Is full motion required for accurate flight simulation?

The goal of this paper is to take an in-depth look at the aircraft simulator motion debate. However, this analysis is not focused on ab initio flight training where pilots obtain the initial “stick and rudder” skills required for flying. Rather, it will focus on the continuation training of qualified pilots. In today’s complex world of aviation, simulators are required to train pilots holistically. This does not mean simple “stick and rudder skills” but rather communications, crew resource management (CRM), flight management, fuel management, regulations, airspace procedures and aircraft systems. The Canadian Air Force, unlike the airline industry, will never be able to achieve zero-flight time training (ZFTT) due to the complex nature of its flight roles and nor should it try. Military pilots complete a multitude of flight profiles that are outside of the normal civilian flight envelope. Low level flight, attack, airdrop, tactical arrivals and departures at hostile airfields, and mountain flying are but a few examples of high-intensity, task-specific operations for which training in the actual aircraft will remain a requirement. However, once trained to operational status in the fixed-wing air mobility world, pilots

---

[2] Email Maj Jason Stark and Nathalie Bourque. Wednesday, 2 February 2010. Nathalie Bourque, Vice President, Public Affairs and Global Communications, (514) 734-5788, nathalie.bourque@cae.com

can complete better continuation training at lower cost by using less expensive flight simulators to create a virtual flight "environment."

THE COMPLEX AVIATION ENVIRONMENT

As aviation has evolved, so has the complexity of the aviation environment. In the world of professional and military aviation, there is no longer such a thing as "basic" flight. Modern aircraft are extremely complex machines that require pilots to have a commensurate level of complex management skills. The number critical emergencies requiring an immediate reaction from the pilot of a CC-130E/H Hercules aircraft is twenty-two whereas the number of critical emergencies in the C-17 Globemaster III is only four.[3] However, this is does not mean that the C17 is a less complex aircraft. Rather, where the CC-130E/H flight crew checklist has a list of 61 possible malfunctions, the C17 flight crew checklist has over five hundred listed possible malfunctions.[4] This is indicative of the complex nature of modern aircraft. Aircraft and the world of aviation are changing. Often, the task of piloting an aircraft from point A to point B is now referred to as "managing the flight" vice flying the aircraft.[5]

The airspace in which modern pilots operate their aircraft has also increased in complexity due to increased air traffic density. To regulate the traffic, and avoid mid-air

---

[3] Canadian Air Division, *C-12-130-00/MB-005, CC130 Hercules Flight Crew Checklist Change 2000-02-18* (Ottawa: Department of National Defence, 1998) and United States Air Force, *1C-17A-1: C-17 Flight Manual Change 4* (Wright Patterson Air Force Base: Department of Defense, 2006).

[4] Ibid.

[5] Mathew W. Blake, "The NASA Advanced Concepts Flight Simulator: AIAA Paper 96-3518," in *AIAA Meeting Papers on Disc* (San Diego, CA: AAIA Flight Simulation Technologies Conference, 29-31 July 1996), 385.

collisions, intricate rules and procedures have been imposed. Nonetheless, even with the current technology and regulations, the air traffic control (ATC) environment is rapidly approaching maximum capacity. Ground based and satellite navigational systems are poised to increase traffic density further by allowing aircraft to complete more efficient direct routings between destinations.[6] The expected increases in technological capabilities and traffic density will require pilots to grasp more complicated rules of flight while the margin of error continues to decrease.

The modern aviation environment combines complex aircraft systems with an equally complex ATC framework. Often, aside from take-off and landing, standard long-haul air mobility missions are flown through the use of on-board computers and automation that are managed by the aircrew. The risks and hazards associated with system failures resulting in catastrophic emergencies have been significantly reduced due to the increased mean time between failures (MTBF) of modern aircraft.[7] Although aircrews need to train for the catastrophic failures that could result in loss of life and equipment, it is imperative that they are also trained to deal with the new emergencies and failures that are a result of the new human-machine interface hazards. These new hazards are at the core of continuation pilot training and need to be the focus of aviation simulators.

---

[6] Ibid., 385.

[7] Boeing Aviation Safety, *Statistical Summary of Commercial Jet Airplane Accidents* (Seattle, WA: Aviation Safety Boeing Commercial Airplanes, July 2009), Slide 23; available from http://www.boeing.com/news/techissues; Internet; accessed 17 February 2010.

THE APPLICATION OF AVIATION SIMULATION

Aircraft simulators fulfill three vital functions in the aviation community. First, flight simulators are a critical component of pilot training. It is safe to assume that there are no professional military or civilian pilots who have not logged hours in an appropriate simulator. If not used in ab initio flight training, it is a foregone conclusion that simulators are used in the continuation training of qualified pilots. Secondly, simulators have found a niche roll in the acquisition and testing of both pre-production and established aircraft fleets. Finally, simulators are the platform of choice for aviation research. Although this paper is predominantly focused on pilot training, it is important to note that all three applications play important roles in aviation.

Training simulators offer the opportunity to depart from reality in such a way that more cost-effective and applicable training can be achieved. Simulators allow aircrew to fly without burning fuel, conduct engine and flight control failures with no threat of injury, and change the time of day and geography instantaneously to achieve specific training objectives. Simulators even permit crews to pause the flight in order to discuss a course of action or anticipated aircraft response.[8] Training simulators grant pilot instructors the ability to control all of these external factors. This in turn allows the instructor to increase and decrease pilot workloads as applicable allowing the students to concentrate on the current lesson. It is this ability to control “reality” that makes simulators an invaluable tool in pilot training. Simulator training is so widely accepted

---

[8] Michael E. McCauley, *Do Army Helicopters Simulators Need Motion Bases*? (Arlington, Virginia: U.S. Army Research Institute for the Behavioral and Social Sciences, Army Project Number 622785A790, 2006), 4.

and effective that the C17 initial pilot qualification consists of 41 missions (113 hours) in simulators and only 3 missions (19 hours) in the actual aircraft prior to certification.[9]

As mentioned, pilot training is only one facet of flight simulation. Of equal importance is the use of flight simulators in aircraft acquisition and testing. The ability to simulate an aircraft allows engineers and pilots to evaluate new systems, equipment or procedures without risk to aviation safety. Simulation allowed pilots to train on the new Boeing 777 prior to the aircraft ever being built.[10] Simulation allowed for pre-production testing of pilot ergonomics, control panels and information presentation. Moreover, simulation allows for the safe testing and evaluation of potential aerodynamic changes in post-production aircraft. In 2007, Boeing engineers wanted to adjust the algorithmic formulas controlling the C17 fly-by-wire flight control system. The new algorithms were tested and evaluated in the simulator prior to being applied in the actual aircraft.

The final application of aircraft simulation is in the field of aviation research. Aviation psychologists are able to use flight simulators to recreate previous aircraft accidents or incidents in order to access where breakdowns in communication and/or coordination may have occurred. Additionally, researchers are able to use simulators to assess and evaluate how crews behave under various stressors and stimuli. For example, the effects of sleep deprivation on aircrew performance can be safely evaluated in a

---

[9] Email Maj Jason Stark and Maj Jean Maisoneuve ref Cdn C-17 Initial Training Plan, Wednesday, 27 January 2010. Maj J. Maisonneuve, Transport and Rescue Standards Evaluation Team (TRSET) for C-17, (613) 392-2811, jean.maisonneuve@forces.gc.ca.

[10] Jonathan Gabbai: Emergent Systems, Management and Aerospace Topics, "The Art of Flight Simulation, Section 1.2," http://gabbai.com/academic/the-art-of-flight-simulation; Internet; accessed 16 January 2010.

simulator, not so in the actual aircraft.[11] The Volpe Institute in the United States has used simulators to test pilot performance in a myriad of piloting tasks. In an ironic spin, full flight simulators allow behavioural psychologists to assess the effectiveness of simulators themselves! Simulators enable researchers to evaluate skills transfer from simulators to aircraft in a safe and controlled fashion.

THE OUTLINE

In order to demonstrate that six degrees-of-freedom full motion aircraft simulation is not necessary to affect successful continuation pilot training in fixed-wing air mobility aircraft, this paper is divided in to multiple chapters. First, it is critical to understand how flight simulation evolved in order to predict where it will proceed in the future. Hence, chapter two will address the history and evolution of flight simulation. In addition, it will define the various levels of simulator fidelity. Finally, it will establish the framework in which the various levels of aircraft simulators are categorized and labelled.

In order to assess the importance of motion to flight simulation, it is imperative to delve into methods by which humans process motion. This is the focus of chapter three. The human processing of motion sensations is a complex process that combines many different systems. Some are obvious, such as the visual and vestibular systems. Others, such as the proprioceptive and auditory systems are much more subtle. Nonetheless, all

---

[11] Roach, Gregory D, Renée M. Petrilli, Drew Dawson and Matthew J.W. Thomas, *The Effects of Fatigue on the Operational Performance of Flight Crew in a B747-400 Simulator*. (Adelaide: Centre for Sleep Research, University of South Australia, 2006).

senses contribute and are crucial to the sense of immersion required to effectively simulate reality.

Chapter four is focused on how motion is physically created in flight simulators. In this chapter the latest studies conducted in the field will be reviewed and assessed. The importance of motion will be evaluated in terms of tracking and disturbance cues. Finally, the effectiveness of motion on skills acquisition and the subsequent effectiveness of transfer of training to the aircraft will be discussed.

The second last chapter will examine how civilian industry and regulating authorities are approaching the simulator motion debate. As already eluded, the modern aviation environment is already sufficiently complex and only becoming more so. Consequently, this chapter will focus on how the challenges of this new environment can best be met and in the most cost-effective manner.

Finally, chapter six will conclude the analysis and present thoughts on the future of military flight simulation. The military is a unique aerospace user and not all advances in civilian aviation are transferable. Nonetheless, the goal is similar in that both wish to create safe, effective and professional aircrew in a cost effective manner.

CHAPTER 2: SIMULATION AND SIMULATORS

INTRODUCTION

An analysis into the requirement for motion in aviation flight simulators requires the reader to have a solid foundation in the evolution of the modern simulator. Moreover, there is a baseline of knowledge and terminology that is required in order to understand the intricacies of modern simulator nomenclature. This chapter will establish the required historical context within which the motion requirement debate is framed.

The chapter is divided into three sections. The first section will explain the evolution of the modern motion flight simulator. In the past century the aviation industry has witnessed incredible leaps in technology resulting in the mainstream use of flight simulators. The history of simulation will explain where we can from and demonstrate where we appear to be headed. The second section will provide the baseline definitions of simulator fidelity. The entire motion debate is hinged on a solid understanding of the concepts of fidelity and the various types of fidelity referred to by the simulation industry. Lastly, the current simulator classification and nomenclature system will be explained and defined. This will allow the reader to appreciate how different levels of fidelity result in the full spectrum of flight simulator classifications.

THE HISTORY OF FLIGHT SIMULATION

In the era of modern aviation, simulation is an established technique used to recreate the man-machine interface required to safely and effectively operate aircraft. The principal task of a simulator is "to model the dynamic behaviour of the flight vehicle."[12] Throughout the history of aviation, this has been the overarching goal of simulators. The modern flight simulators used today are the culmination of a century of technological, psychological and engineering evolution.

Man Learns To Fly

The year 2009 marked Canada's centennial anniversary of flight. On 23 February 1909, Douglas McCurdy completed the first powered flight in Canada when he took off from Bras d'Or Lake in Baddeck, Nova Scotia. His first flight in the famed biplane *Silver Dart* lasted only a few minutes but he achieved speeds of 65 kilometres per hour and soared to a height of over nine metres.[13] This was an incredible improvement over the Wright brother's first flight at Kitty Hawk, North Carolina, a mere five years earlier. Heavier-than-air flight was evolving quickly. Accordingly, these early days of aviation were fraught with accidents, injuries and deaths.[14] Flying was immediately recognized as

---

[12] Jonathan Gabbai: Emergent Systems, Management and Aerospace Topics, "The Art of Flight Simulation, Section 1.2," http://gabbai.com/academic/the-art-of-flight-simulation; Internet; accessed 16 January 2010.

[13] Centennial Celebration Baddeck 2009, "The Flight of the Silver Dart," http://www.flightofthesilverdart.ca/; Internet; accessed 16 January 2010.

[14] On 17 September 1908, the aircraft flown by Orville Wright crashed. He survived, but his passenger, Lt Thomas Sulfridge, died. This is recorded as one of the first passenger deaths in aviation. See http://inventors.about.com/library/inventors/bl_wright_brothers.htm, Internet, accessed, 10 February 2010.

a dangerous endeavour and the quest to improve training by developing a safe simulated environment began.

The Wright brothers immediately recognized that the pilot was central in the control of an aircraft. While other scientists and inventors of the time believed that aircraft would be fundamentally stable with only minor inputs required by the pilot, the Wright brothers understood that "the pilot of an aircraft [was] a skilled active controller of an unstable vehicle."[15] They became advocates of training pilots to be active participants instead of passive observers. With this realization, the evolution of pilot training began in earnest. The human dimension of pilot training has since become so important that an entire field of psychology has been dedicated to learning how pilots process information and react to the stresses associated with flight. This focus on the human element of pilot training has been the underlying driving factor behind flight simulation development. As early as 1910 there were already two dominant flight simulators used to assess and identify potential piloting skills in prospective candidates: the Sanders Teacher and the Antoinette Apprenticeship Barrel.

Simulator Pioneers

The Sanders Teacher (Figure 2.1) was a modified aeroplane mounted on a universal joint. The concept of simulation was to orient the Teacher into the prevailing wind.[16] With sufficient wind, the pilot could experience how aircraft controls functioned, much like a pilot in a ground based glider can practice keeping the wings level in a strong headwind.

---

[15] Pamela S. Tsang and Michael A. Vidulich, "Introduction to Aviation Psychology," in *Principles and Practice of Aviation Psychology*, eds Pamela S. Tsang and Michael A. Vidulich, 1-19 (New York: CRC Press, 2003), 2.

[16] J.M. Rolfe and K.J. Staples, *Flight Simulation* (Cambridge: Cambridge University Press, 1986), 15.

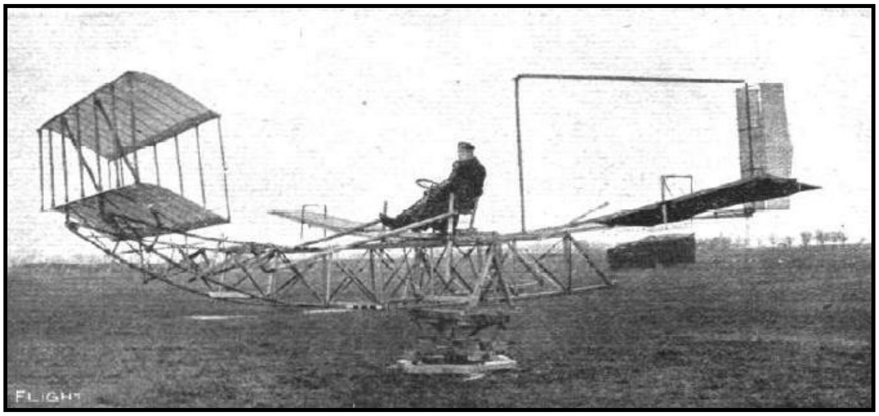

Figure 2.1: The Sanders Teacher
Source: http://www.flightglobal.com/pdfarchive/view/1910/1910%20-%201008.html

The 10 December 1910 issue of Flight Magazine heralded the Sanders Teacher as a "device which will enable the novice to obtain a clear conception of the workings of the control of an aeroplane, and of the conditions existent in the air, without any risk personally or otherwise."[17] Unfortunately, the Teacher was completely dependant on prevailing wind and as such was not an overwhelming success.

The Antoinette Apprenticeship Barrel (Figure 2.2) approached the concept of flight simulation from a different perspective. To preclude any dependence on the natural "real" environment, the Antoinette was reliant on instructor inputs. It consisted of two half-barrels mounted and moved manually in order to reproduce pitch and roll motions. The student pilot sat in the top barrel and was expected to align a lateral reference bar with the horizon.[18]

---

[17] D.M Howard, "The Sanders Teacher," *Flight* 2, no 50 (10 December 1910): 1006; http://www.flightglobal.com/pdfarchive/view/1910/1910%20-%201008.html; Internet, accessed 16 February 2010.

[18] Walter F. Ullrich, "A History of Simulation: Part II – Early Days," *MS&T Magazine* 5 (2008) [journal on-line]; available from http://www.halldale.com/MST_DigitalIssues.aspx; Internet; accessed 26 March 2010.

Figure 2.2: The Antoinette Apprenticeship Barrel
Source: http://homepage.ntlworld.com/bleep/SimHist1.html

Both the Sanders Teacher and the Antoinette Apprenticeship Barrel shared the same problem; neither simulator produced any marked improvement or ability to train pilots to fly actual aircraft. With the advent of First World War, there arose a need to produce a large number of pilots in limited time. Consequently, simulators were used primarily as selection tests for prospective pilots. Many of these devices were developed to assess pilot aptitude. For example, some devices were designed to measure pilot reaction to correcting vehicle equilibrium disturbances.[19] Other forays into flight simulation were based on false assumptions of how humans process motion and orient themselves to their surroundings. The Ruggles Orientator was one such device.

The Ruggles Orientator was developed based on a theory that the vestibular system would be as equally effective in the air as on the ground. The idea was that disorientation in flight could be prevented through training. The Orientator (Figure 2.3) was a seat mounted in a gimbal ring assembly that was capable of rotating the occupant

[19] Ray L. Page, "Brief History of Flight Simulation," in *SimTechT 2000 Proceedings* (Sydney: The SimtechT 2000 Organizing and Technical Committee, 2000) 2; available from http://citeseerx.ist.psu.edu/viewdoc/ download?doi=10.1.1.132.5428&rep=rep1&type=pdf; Internet; accessed 18 December 2009.

in all three axes.[20] Its stated purpose was to train aviators “to accustom themselves to any possible position in which they may be moved by the action of an aeroplane while in flight.”[21]

Figure 2.3: The Ruggles Orientator
Source: flickr.com/photos/nielsfrenzen/511660212/

The claims for the Ruggles Orientator would later be proven to be unattainable. Scientists and inventors had yet to develop a complete picture of how simulators could be used and how humans process motion. As the First World War started, simulator devices had virtually no impact on pilot training because it was in its infancy.[22]

The Interwar Period

There were no frontrunners in the development of flight simulation until the arrival of inventor Edwin Link and his patented Link Trainer. An aviation enthusiast, Link was disappointed with the quality of flight instruction available. As a remedy,

[20] Kevin Moore, “A Brief History of Aircraft Flight Simulation,” http://homepage.ntlworld.com/bleep/SimHist1.html; Internet, accessed 20 December 2009.

[21] Rolfe and Staples, 17.

[22] Rolf and Staples, 16.

between 1927 and 1929, he turned his attentions toward the creation of the Link Trainer (Figure 2.4).

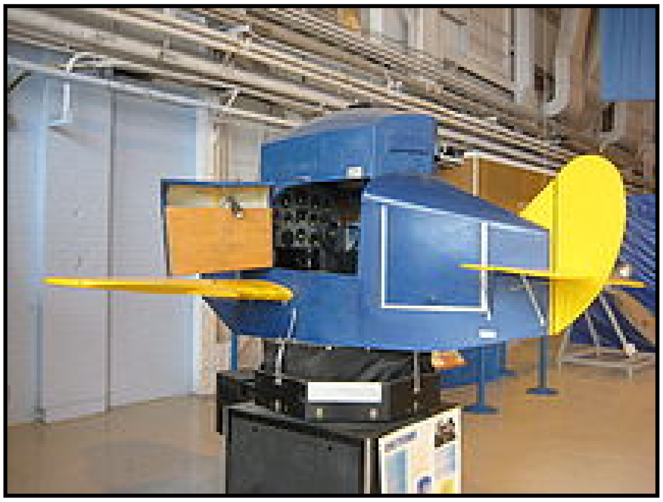

Figure 2.4: The Link Trainer
Source: Western Canada Aviation Museum

An engineer in his father's Link Piano and Organ Company, Link developed his trainer by using his expertise in organ-making to create "a machine with a pneumatic motion platform driven by bellows."[23] The bellows were used to create pitch, roll and yaw movements. The original trainer had no cockpit instrumentation but was equipped with flight controls. Movements of the control stick and rudder were transmitted to an electrically driven suction pump located in the fixed base. The pump actuated various control valves resulting in platform motion.[24] Motion accuracy was extremely subjective and achieved through trial and error. The Link trainer was designed to give student pilots a feel for how an aircraft responds to its flight controls. However, the flight controls

---

[23] Ascent-UK, "History of Flight Simulators (2007)," http://www.ascent-uk.co.uk/history.htm; Internet; accessed 26 March 2010.

[24] Ibid.

worked independently of each other and the resultant motion indicated aircraft attitude vice providing accurate motion cues.

Aviation in the late 1920s experienced a painful evolution as the requirement for "blind flying" became readily apparent. Aircraft were becoming all-weather vehicles as Lieutenant Colonel James "Jimmy" Doolittle demonstrated in 1929 when he completed a flight from take-off to landing without visual reference to the horizon.[25] However, this type of flying required special instrument training. A lack of such training proved to be fatal for pilots of the US Army Air Corps (USAAC). In February 1934, the USACC assumed responsibility for the delivery of domestic mail and the US Army Air Corps Mail Operations (AACMO) was formed. Sadly, the AACMO suffered 66 crashes and twelve fatalities before the operation was cancelled by April of the same year.[26] Many of these crashes were due to loss of aircraft control in weather.

Military flying operations were forever changed by the failed AACMO. As a result, the US Army purchased Link Trainers upgraded with full instrumentation.[27] The concept of "flying by the seat of the pants" was dead and simulators found a niche in training pilots to fly their aircraft through the use of their instrumentation. Hence, the need for simulators to recreate the motion of aircraft was brought into question. Link himself had difficulty convincing people that motion was even a requirement. Consequently, with the exception of the Link Trainer, the requirement to train for

---

[25] US Centennial of Flight Commission, "Jimmy Doolittle – Avation Star," http://www.centennialofflight.gov/essay/ Air_Power/doolittle/AP17.htm; Internet; accessed 21 February 2010.

[26] John T. Corell, "The Air Mail Fiasco," *Air Force Magazine* 91, no 3 (March 2008) [journal on-line]; available from http://www.airforce-magazine.com/MagazineArchive/Pages/2008/March%202008/ 0308airmail.aspx; Internet; accessed 15 February 2010.

[27] Kevin Moore, "A Brief History of Aircraft Flight Simulation," http://homepage.ntlworld.com/ bleep/SimHist1.html; Internet, accessed 20 December 2009.

instrument flying resulted in the use and development of fixed base simulators until "the era of true motion cue simulation."[28]

The Second World War

Although flight simulation was not instrumental in pilot training during the First World War, the Second World War witnessed the rapid expansion of the use of training simulators. The role of aviation had indeed changed dramatically during the interwar period. US AACMO resulted in a strong desire for improved training. Between 1939 and 1945 over 10,000 Link trainers were used to train Allied pilots.[29] Increased aircraft range required pilots to learn new skills in navigation. The increasing complexity of aircraft required crews to learn complex procedures and crew management. For these roles, fixed based simulators were ideal.

The Second World War witnessed the creation and invention of a myriad of fixed based simulators in addition to the use of the Link trainer. Early developments consisted of instructional fuselages housed in hangars. There was no associated motion but all the instrumentation, indicators, controls and systems were made to work in the same manner as the real aircraft.[30] These fixed base, no motion simulators allowed crews to train both normal and emergency procedures such as bomb-dropping and bailout procedures respectively. The Silloth trainer (Figure 2.5) was one such training device.

Developed in 1941, the Silloth trainer was developed at RAF Station Silloth, hence the name. The original trainer was a Lockeed Hudson light bomber and aerial

---

[28] Rolfe and Staples, 20.

[29] Ascent-UK, "History of Flight Simulators (2007)," http://www.ascent-uk.co.uk/history.htm; Internet; accessed 26 March 2010.

[30] Rolfe and Staples, 27.

reconnaissance aircraft mounted on an immovable base. The fuselage was equipped with and pneumatics used to "simulate instrument readings, engine sound, and movement for "realistic" training.[31] It was designed to train aircraft procedures and is considered by some to be the precursor to the modern aircraft simulator. Other aircraft types such as the Wellington, Lancaster, Halifax and Dakota aircraft were all made into Silloth trainers prior to the end of the war.[32]

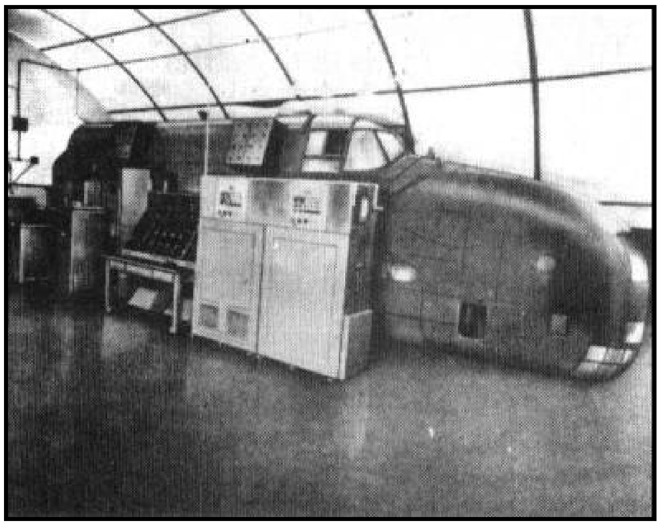

Figure 2.5: The Silloth Trainer
Source: www.iradis.org/education/history/ww2

Despite the questionable significance of motion, Link motion trainers continued to dominate the aviation simulation industry. In 1941, the Link Corporation included a rudimentary visual system when it delivered the first Celestial Navigation Trainer to the Royal Air Force. Designed to train aircrew in the fundamentals of celestial navigation, it comprised of a large Link motion platform flown by the pilot with crew positions for the bombardier and navigator. The navigator was provided with a large collimated view of

---

[31] Wartime Memories Project, "Information," http://www.wartimememories.co.uk/ airfields/silloth.html; Internet; accessed 29 March 2010.

[32] John M. Rolfe, "Two Cambridge Inventors," *Royal Aeronautical Society: Flight Simulation Group* [journal on-line]; available at http://www.raes-fsg.org.uk/18/The_Cambridge_Cockpit; Internet; accessed 29 March 2010.

twelve stars that moved across a domed ceiling and could be used to plot his position. The entire simulator was massive by the standards of the era and housed in a 45 foot high silo-shaped building.[33]

Post Second World War and the New Motion Platform

The Second World War proved the validity of simulation in flight crew training. As illustrated, the military dominated the initial era of aviation and simulation development. However, as large commercial aviation became a viable business model, civilian airlines became initially interested and then enamoured with simulation. The Curtis-Wright Corporation entered the flight simulation field in 1943 and developed the first Boeing 377 Stratocruiser full aircraft simulator. Another company, Rediffusion, was contracted by British Overseas Airways Corporation (the pre-cursor to British Airways) to build a similar simulator. However, motion simulators remained in the minority until the late 1950s and early 1960s. Despite their predominant use as procedural trainers, the concept of full motion flight training remained and manufacturers continued to develop motion proposals. However, it was not until 1958 that the airlines decided to purchase them. Rediffusion produced the first motion simulator in the form of pitch motion.[34]

In the arena of the simulator motion debate, 1966 marks the next technological leap. That year, while working for the Space and Weapons Research Establishment for aviation, D. Stewart published a proposal for "a flight simulator motion base in which a

[33] Rolfe and Staples, 26.

[34] Ibid., 33.

moveable triangular platform was supported by three articulate legs."[35] This proposal, when combined with research completed by researcher V.E. Gough, lead to the invention of the Stewart-Gough Platform (commonly referred to as merely the Stewart Platform). The Stewart-Gough Platform (Figure 2.6) permitted an aircraft cockpit to be place on top of a moveable platform and experience motion in six degrees-of-freedom.

Figure 2.6: Modern 6 Degrees-of-Freedom Motion Simulator
Source: http://www.amtonline.com/article/article.jsp?id=7781&siteSection=1

At this point it is important to clearly define "six degrees-of-freedom." All aircraft movement in flight occurs either along (translational) or around (rotational) the lateral, longitudinal and vertical axes (Table 2.1). Rotational motion *around* the lateral axes is referred to as pitch, while motion around the longitudinal axes is referred to as roll and motion around the vertical axes is yaw. Translational motion *along* the lateral axes is referred to as sway, while motion along the longitudinal axes is referred to as surge and

[35] E.F. Fichter, D.R. Kerr and J Rees-Jones, "The Gough-Stewart Platform Parallel Manipulator: A Retrospective Appreciation," *Journal of Mechanical Engineering Science* 223, no1 (January 2009), 243.

motion along the vertical axes is heave. Aircraft in flight are subjected to all six motions and the quest for accurate motion simulation needs to replicate these motions; hence the term "six degrees-of-freedom" motion simulator platforms.[36]

Axes	**Rotational Motion**	**Translational Motion**
Lateral	Pitch	Sway
Longitudinal	Roll	Surge
Vertical	Yaw	Heave

Table 2.1: Rotational and Translational Motion

Simulation in the Modern Age and the Future

While researchers like Stewart and Gough were developing a platform to simulate the six degrees-of-motion, others were improving other areas of simulation such as visual systems. Prior to the computer age, simulators used closed circuit television (CCTV) screen mounted outside of the cockpit simulator windows. A camera was then moved over a terrain board in coordination with simulator inputs to provide the pilot with a visual representation of flight.[37] The advent of computer age and computer generated images (CGI) replaced this technology. CGI technology removed the requirement for a terrain board and opened up an endless possibility of scene generation. The computer images were projected on collimated (infinity-focused) screens and allowed pilots to be further immersed in the virtual reality of simulation. As technology has evolved, it has

---

[36] This explanation of the six types of motion is derived from the field of applied physics and aerodynamics. See William F. Moroney and Brian W. Moroney, "Flight Simulation," in *Handbook of Aviation Factors*, eds Daniel J. Garland, John A. Wise and V. David Hopkin, 355-288 (Mahwah, New Jersey: Lawrence Erlbaum Associates, 1999), 366-367. For additional information about translational and rotational motion see John D. Anderson, *Introduction to Flight* (New York: McGraw-Hill, 2000).

[37] Rolfe and Staples, 131.

permitted "for continuous viewing in excess of 180 degrees,"[38] allowing users to be exposed to both direct and peripheral visual cues.

Modern simulators currently employ advanced visual systems and complicated motion base systems. The future of simulation will continue to reap the benefits of evolving technologies. Visual systems currently replicate extremely accurate scene detail. The weakness in modern simulators continues to be the motion base. Although the conundrum of six degrees-of-freedom has been resolved, the acceleration motion problem remains unsolved. Acceleration requires the movement of mass over distance. This is not feasible within housing constraints. However, the simulator with the greatest level of promise is the Desdemona Simulator in the Netherlands (Figure 2.7).

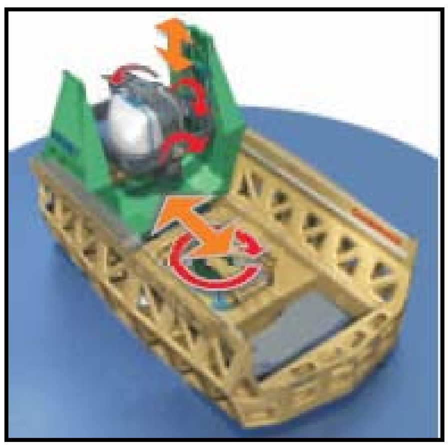

Figure 2.7: Desdemona Simulator
Source: TNO Netherlands

Developed by the independent research organization TNO, Desdemona is heralded as the next step in simulation. The cockpit is mounted on a Stewart-Gough platform. However, the platform is mounted in a sliding cage mounted on a rotating

[38] Page, 10.

base. The base rotates like a centrifuge, allowing the occupant to experience up to three sustained G force.[39] The issue with Desdemona is a matter of cost. Although not releasable, the cost is estimated to be well in excess of $60 million. This places Desdemona in a class of its own and not something that is attainable for either commercial or military simulation. Desdemona was developed primarily for aviation research; a task for which it is ideally suited.

SIMULATOR FIDELITY

The fuel crisis during the 1970's resulted in the airline industry searching for more cost effective ways to train aircrew without the high costs associated with flight in real aircraft.[40] Whereas the military had previously been the driving force behind simulator development, economics drove the commercial industry to fund and develop better simulators.[41] Increases in technology, the advent of digital computers and computer generated graphics urged the airlines to seek a higher level of accuracy in flight simulators. Finally, the invention of the now industry standard Stewart-Gough Platform, with its ability to simulate limited acceleration cues, propelled motion simulation into

---

[39] Bernd de Graaf, et al, "MSC: Vehicle Validation of Military Flight Simulation," available from http://ftp.rta.nato.int/Public/PubFullText/RTO/MP/RTO-MP-HFM-136/MP-HFM-136-16.pdf; Internet; accessed 10 January 2010.

[40] Wei L. Chen, "Simulation for Training and Decision-Making in Large-Scale Control Systems: Part 2: Civil Aircraft Pilot Trainers," *Simulation* 35, no 2 (Agust 1980): 42-44.

[41] The military, especially the Canadian Air Force, has lagged behind the commercial industry in the use of flight simulators. The Air Force Automation Policy and Planning Development (APPD) Automation Analysis Report conducted in 2008 referred to the Air Force as "sim-phobic," citing that 1 Canadian Air Division orders state that "normally using the simulator for performing [Instrument Rating Tests] will be approved as a backup to the IRT being flown in the actual aircraft." Page 3.26.

mainstream industry by the 1980s.[42] The subsequent increased use of flight simulators in pilot training added new fuel to the simulator motion debate. Central to the debate is simulator fidelity. Many researchers have defined fidelity and continue to debate an all encompassing meaning. By strict definition, the Oxford English Dictionary defines fidelity as the "the degree of exactness with which something is copied or reproduced."[43] For the simplicity of this analysis, flight simulator fidelity means the degree to which flight is accurately reproduced. In broad terms, fidelity can be subdivided into two broad categories: objective and perceptual.[44]

Objective fidelity is easily explained and defined. It refers "to the physical correspondence between the flight simulator and the aircraft."[45] Objective fidelity is concerned with the physical realm and requires the exact reproduction of switches, controls and instrumentation. The level of objective or physical fidelity can be easily compared to the real aircraft. The elusive perceptual fidelity is much more complicated to assess and involves subjective interpretation. *Perceptual fidelity* refers to the pilot's perception or comparison of simulator and aircraft performance.[46] Perceptual fidelity is the domain of the motion debate. For the purpose of this analysis, perceptual fidelity can be further subdivided into *motion fidelity*, *visual fidelity* and *cognitive fidelity*.

---

[42] Dave Higdon, "Flight Training – Simulators Review," *AV Buyer* (March 2008) [journal on-line]; available from http://www.avbuyer.com/articles/detail.asp?Id=1072; Internet; accessed 3 February 2010.

[43] Catherine Soanes, *Pocket Oxford English Dictionary* (New York: Oxford University Press, 2002), 332.

[44] Michael E. McCauley, *Do Army Helicopters Simulators Need Motion Bases*? (Arlington, Virginia: U.S. Army Research Institute for the Behavioral and Social Sciences, Army Project Number 622785A790, 2006), 4.

[45] Ibid.

[46] Ibid.

Motion fidelity is very difficult to perfect in land-based flight simulators. As the name implies, it refers to the "extent to which the motion-induced forces experienced in the simulator reflect those of the actual flight environment."[47] The Stewart-Gough Platform allowed these forces to be replicated better than ever before, but it is still limited by an inability to simulate sustained G forces. In 1989, researchers concluded that without an unforeseen technological breakthrough, it was "hopeless to provide realistic force and motion stimuli in the sense that acceleration forces produced by aircraft can be replicated in a simulator."[48] As will be explained in a later chapter, the Stewart-Gough Platform manipulates the gravity force vector on the occupants and can simulate basic acceleration and decelerations. However, these forces are limited in nature and modern engineering is used to trick the human motion processing system. Consequently, since 100% motion fidelity is unattainable, science should focus on the "perceptions associated with force and motion."[49]

Visual fidelity refers to the accuracy of the scene detail in relation to the real world. Although visual technology has resulted in great advancements in scene generation, there still exist limitations of computer generated images used in flight simulation. The current technology cannot fully recreate "the richness and complexity of

---

[47] Mary K. Kaiser and Jeffrey A. Schroeder, "Flights of Fancy: The Art and Science of Flight Simulation," in *Principles and Practice of Aviation Psychology*, eds Pamela S. Tsang and Michael A. Vidulich, 435-471 (New York: CRC Press, 2003), 439.

[48] Yorke Brown, Frank Cardullo and John Sinacori, "Need-Based Evaluation of Simulator Force and Motion Cueing Devices," in *Flight Simulation Technology Conference and Exhibit* (Boston: American Institute of Aeronautics and Astronautics, 14-16 August 1989), 79.

[49] Judith Bürki-Cohen, Nancy Soja and Thomas Longridge, "Simulator Platform Motion – The Need Revisited," *The International Journal of Aviation Psychology* 8, no 3 (Fall 1998), 299.

the visual world."[50] The amount of computer processing power required to depict both fine detail and large picture currently surpasses what is available. However, simulator visual systems continue to evolve and Moore's Law (computing processing power doubling every two years) gives reason to have high expectation for future improved visual systems at reasonable cost.[51] One of the greatest breakthroughs in visual technology is the wide field of view now available in simulators. This provides critical visual inputs to both the peripheral and focused visions.

Cognitive fidelity is the last, yet perhaps the most complicated, sub-component of perceptual fidelity. Cognitive fidelity combines all fidelity types to create operator "buy-in" to the simulation. It refers to the engagement of the pilot's cognitive skills such as situational awareness, decision-making and problem solving.[52] Historically, flight simulators have sought the other forms of fidelity without much appreciation for cognitive fidelity. However, in the modern age of flight simulation, cognitive fidelity has arguably become the most important. It requires full immersion in the simulated environment. Increases in aircraft complexity and the use of flight automation systems have created a need for high cognitive fidelity simulators in order to train crew and flight management skills.[53]

---

[50] Kaiser and Schroeder, 453.

[51] Gordon Moore was the founder of Intel. In 1965, he postulated that the processing power of computer chips would double every two years based on the assumption that the number of transistors on an integrated circuit would continue to grow exponentially. This would drive the cost down and quality up in computer power for the foreseeable future. His prediction has been proven correct for over 40 years. See S. Furber, "The Future of Computer Technology and Its Implications for the Computer Industry," *The Computer Journal* 51, no 6 (November 2008): 735-740.

[52] Kaiser and Schroeder, 440.

[53] Alfred T. Lee, *Flight Simulation: Virtual Environments in Aviation* (Burlington: Ashgate Publishing Company, 2005), 71.

In the final analysis, it is important to acknowledge that simulator fidelity types are not mutually exclusive and a significant amount of overlap exists. Visual fidelity can affect motion fidelity which can affect cognitive fidelity and so on. Although high cost and high fidelity simulators are used for pilot training, research "has shown that high fidelity simulators may not be necessary to produce effective training results."[54]

MODERN SIMULATION CLASSIFICATION SYSTEM

The level of fidelity, both objective and perceptual, is critical in the industry standard for the classification of flight training devices. It is assumed that the more sophisticated the simulator, the more training can be transferred to the aircraft. North America shares the same classification system after Canada adopted the same nomenclature as the Federal Aviation Authority's Aviation Circular 120-40C in January 1998. Europe's classification is also similar in accordance with regulations established by the Joint Aviation Authority (JAA) in JAR-FSTD A issued in May 2008.[55]

When discussing the various types of flight simulators, it is important to establish a baseline of definitions. The term "Flight Simulation Training Device" (FSTD) is an all-encompassing term for all simulator training devices. Underneath the umbrella of FSTD are "Full Flight Simulators" (FFS) and "Flight Training Devices" (FTD). An FFS is a full size replication of an aircraft's flight deck. It consists of all instrumentation and the

---

[54] Beth Blickensderfer, Dahai Liu and Angelica Hernandez, *Simulation-Based Training: Applying Lessons Learned from Aviation to Surface Transportation Modes* (Daytona Beach: Emery Riddle Aeronautical University, 2005), 21.

[55] Joint Aviation Authority, "Joint Aviation Regualtions," available from http://www.jaa.nl/publications/jars/JAR-FSTD-A_sec1_0508.pdf; Internet; accessed 26 February 2010.

computer programming required for the duplication of the aircraft in ground and flight operations, as well as a visual system providing out of the flight deck view and a force cueing motion system. The major difference in an FTD is that it does not require the visual or force cueing motion systems. [56]

There are four levels of FFS spanning a range from level "A" to level "D," with Level D being the most sophisticated level of simulation. In accordance with Transport Canada, "the more sophisticated the simulator, the more training and checking may be approved for that simulator."[57] Transport Canada publication TP9685 clearly defines the levels of required fidelity in each level of simulator.

At the low end of the spectrum, Level A and B simulators require a minimum of four degrees-of-freedom of motion. The major difference between the two levels is the quality of the visual system. A Level B simulator is required to be able to reproduce such visual cues as sink rate and depth perception in during landing, whereas a Level A simulator is not.[58]

There is a significant technological and monetary jump to Level C and D simulators. Mainly, both levels require six degrees-of-freedom of motion. This, by default, requires the use of a Stewart-Gough full motion platform. This results in second and third order associated costs that include the construction of a suitable building and a higher level of maintenance and computer support. Again, similar to the difference

---

[56] Joint Aviation Authority, "Joint Aviation Regulations," available from http://www.jaa.nl/publications/jars/JAR-FSTD-A_sec1_0508.pdf; 1-B-1; Internet; accessed 26 February

[57]Transport Canada, "TP 9685," available from http://www.tc.gc.ca/civilaviation/publications/tp9685/chapter2/menu.htm; Internet; accessed 26 February 2010.

[58] Transport Canada, "TP 9685," available from http://www.tc.gc.ca/civilaviation/publications/tp9685/chapter2/menu.htm; 2-A-7; Internet; accessed 26 February 2010.

between Level A and B simulators, the major difference between Level C and D simulators is the quality of the visual system. Where both levels require the ability to replicate night and dusk scenes, Level D simulators are required to replicate daylight visual scenes. Level D simulators are required to reproduce all scenery "with sufficient content to recognize airport, terrain and major landmarks."[59] Additionally, Level D simulator daylight visual scenes need to include sufficient cockpit lighting to replicate the actual cockpit lighting on an overcast day.

SUMMARY

The history of the development of aviation simulators is nearly as long as the history of flight itself. Flying is an inherently dangerous act for mankind. The purpose of simulators has been to recreate this unsafe act in a safe environment. As technology evolved so has the quality of simulation available to pilots and aircrew.

Central to the motion requirement debate for flight simulators is a solid understanding of simulator fidelity types and subtypes. The ability to accurate recreate the aviation environment has led to an internationally adopted simulator classification system. The two major delineators in the classification system are the visual and motion systems, where the motion system is the more expensive of the two.

Establishing a baseline of knowledge is crucial prior to examining the merits of motion in aviation flight simulators. However, understanding the history and nomenclature is only one minor facet of the motion debate. It merely provides the

---

[59] Transport Canada, "TP 9685," available from http://www.tc.gc.ca/civilaviation/publications/tp9685/chapter2/menu.htm; 2-A-8; Internet; accessed 26 February 2010.

framework for the discussion. In order to *evaluate* the need and requirement for motion in aircraft simulators, it is important to understand how humans process motion and motion cues. This is the focus of the next chapter.

CHAPTER 3: HOW HUMANS PROCESS MOTION

INTRODUCTION

The most important trait required for human survival is our ability to orient ourselves to our surroundings. Spatial orientation is "a fundamental and primitive need for humans."[60] It is this ability that governs human interaction with the rest of the physical realm. Children develop this ability over time and, as their sense of balance and spatial orientation improves, they develop the ability to first crawl and then walk. Early man required this ability in order to hunt and stalk prey. Modern man requires this ability to carry on with our everyday activities; from walking to the bus stop to flying aircraft.

Embedded in the human ability of orientation is our ability to process motion. There exist only two types of physical motion; translational (linear) motion and rotational (angular) motion.[61] As humans have evolved, we have developed overlapping and redundant systems to identify these motions. Motion perception is "built up by the central nervous system at various levels of consciousness by synthesizing the nervous signals from a wide variety of sensory organs."[62] Weaknesses in one system are often compensated for by the remaining systems. Much in the same manner that a blind person's sense of hearing is improved as a compensatory reaction, when humans are

---

[60] Michael E. McCauley, *Do Army Helicopters Simulators Need Motion Bases*? (Arlington, Virginia: U.S. Army Research Institute for the Behavioral and Social Sciences, Army Project Number 622785A790, 2006) 8.

[61] Kent K. Gellingham and James W. Wolfe, "Spatial Orientation in Flight," in *Fundamentals of Aerospace Medicine,* ed Roy L. DeHart, 299-381 (Philadelphia: Lea and Febiger, 1985), 299.

[62] Yorke J. Brown, Frank M. Cardullo and John B. Sinacori, *Effects of Motion on Skill Acquisition in Future Simulators, Study Report 2006-07* (Arlington, VA: United States Army Research Insitute for the Behavioral and Social Sciences, May 2006), 78.

deprived of a motion sensing system the other systems will compensate. The human ability to identify and process motion is derived mainly from the visual, vestibular, proprioceptive and aural systems.

Understanding how humans process motion is critical to understanding the significance of motion both in actual and simulated flight. Once a solid understanding is achieved of how the human motion sensing systems interact, it will be possible to explain how modern simulators are able to trick the human brain into believing it is experiencing something it is not. To achieve this understanding, this chapter is divided into four parts. First, the visual system will be examined in depth. Second, the inner workings along with the strengths and weaknesses of the vestibular system will be explained. Third, this chapter will explain how secondary sensing systems like the auditory and proprioceptive systems indirectly contribute to motion sensing. Lastly, how all the systems combine to create total motion sensing will be explored.

THE VISUAL SYSTEM

The visual system is arguably the most important human system for the accurate and correct processing of motion. It is critical to spatial orientation, especially in moving vehicles. Consequently, flight would be impossible without it whereas “this would not necessarily be the case in the absence of the vestibular or other sensory systems.”[63] Human vision is a complex process habitually taken for granted. The human eye is often compared to a camera, and although the construction may be similar, the operation is very different. Unlike a camera, the human eye does not capture a picture and then

---

[63] Gellingham and Wolfe, 308.

transmit that picture to the brain. Rather, the brain uses signals detected by the optic nerve to “infer a concept of the physical space surrounding a person.”[64]

The human visual system is an extremely sensitive detection system. In fact, the sheer volume of information which can be processed by the visual system “exceeds that of any other sensory mechanism by several orders of magnitude.”[65] In order to process the sheer magnitude of sensory cues, Dr. Laurence R. Young, Apollo Professor of Aeronautics and Astronautics at the Massachusetts Institute of Technology (MIT), determined that human eye differentiates between two types of visual cues: central field (foveal) cues and wide field (peripheral) cues.[66] To process these cues, vision must be considered as two separate systems. The first vision system is focal vision whereas the second system is ambient vision.

Vision Types: Focal and Ambient Vision

Foveal cues are the high acuity, high information density, central *focal vision* cues. These cues must be read in order to be processed by the human brain. In aviation, these vision cues are presented to the pilot through his instruments, runway markings, approach/enroute charts and checklists. Focal vision is the domain of fine detail. When a pilot is flying in instrument conditions with no reference to the outside world, focal vision is used to read instruments such as the artificial horizon. In this manner the pilot uses his focal vision to combat miscues from the vestibular system that could lead to

[64] Brown, Cardullo and Sinacori, 79.

[65] A.R. Buffett, “Visual Cueing Requirements in Flight Simulation,” in *Advances in Flight Simulation – Visual and Motion Systems*, 127-149 (London: The Royal Aeronautical Society, 1986), 127.

[66] Laurence R. Young, “Visually Induced Motion in Flight Simulators,” in *Advisory Group for Aerospace Research and Development (AGARD) Conference Proceedings* No 249, (Brussels: AGARD,1978), 16-1.

spatial disorientation, such as the "leans."[67] In this situation, focal vision does not directly contribute to a sense of motion, but it does provide visual information to assist orientation.[68]

Focal vision is not limited to reading instruments. The foveal cues used in focal vision are critical for the judgment of both depth and distance.[69] This makes focal vision critical for high intensity tasks such as such as low level contour flying and landing manoeuvres. Accordingly, focal vision typically requires specific effort and attention whereas ambient or peripheral vision is more reflexive in nature.[70]

Ambient vision is the visual system that directly affects how humans process motion and is integral to spatial orientation. It is regularly referred to as peripheral vision and is often processed directly by our subconscious vice requiring specific effort. It is generally accepted that ambient vision plays the dominant role in spatial orientation.[71] The function of ambient vision is independent of the function of focal vision. A person who has fully engaged their focal vision with a task such as reading is capable of simultaneously walking down the street, orientated by their peripheral vision.

Ambient vision is primarily concerned with the detection of large object motion within a wide field of view and the detection of "self-motion with respects to the visual

---

[67] The "leans" is probably the most common type of pilot spatial disorientation in flight. It is the result of a quick return to level flight with no reference to the natural horizon following a slow a gradual turn. The vestibular system is confused and senses that the pilot is not in straight and level flight, but rather in a banked turn in the opposite direction of the original turn.

[68] Gillingham and Wolfe, 310.

[69] Ibid., 310.

[70] H Liebowitz and C.L. Shupert, "Two Modes of Visual Processing: Implications for Spatial Orientation," in *Peripheral Vision Horizon Display,* 41-44 (Edwards, California: NASA Conference Publication 2306, 14 November 1984), 42.

[71] K.E. Money, "Theory Underlying The Peripheral Vision Horizon Device," in *Peripheral Vision Horizon Display*, 45-55 (Edwards, California: NASA Conference Publication 2306, 14 November 1984), 52.

environment."[72] Imagine sitting in a train reading a book. Outside the window is a stationary freight train on the adjacent track. As you continue to read your book, the flanking freight train starts to slowly advance. Your ambient vision system detects this motion and you jerk your head up thinking that *your* train has started moving. As soon as you look outside you realize that your train is not moving and the illusion of motion disappears. This illusion of self-motion is a product of the ambient vision system and is referred to as "vection." The uses for vection are widely applicable to both the entertainment and simulation industries. Vection in flight simulation is central to the argument for reducing simulator platform motion requirements.[73]

Vection

The illusory effect of vection has been study for almost a century.[74] Consequently, accepted truths and facts have been established. To successfully create the optical illusion, a wide field of view visual system is required to provide a coherent optical flow.[75] The technological ability to create large visual scenes with sufficient resolution to obtain the required coherent optical flow is something that has only recently become available to the simulator industry. In previous years, visual systems in flight simulators were not able to create the now almost industry standard 200 degree field of view or greater. Vection in early simulators was almost non-existent as visual systems

---

[72] Laurence Young, "Spatial Orientation," in *Principles and Practice of Aviation Psychology*, eds Pamela S. Tsang and Michael A. Vidulich, 69-113 (New York: CRC Press, 2003), 72.

[73] Young, "Visually Induced Motion in Flight Simulators," 16-1.

[74] For an excellent and in depth explanation of vection see: L.J. Hettinger, "Illusory Self-Motion in Virtual Environments," in *Handbook of Virtual Environments*, ed Kay M. Stanney, 471-492 (Mahwah, NJ: Lawrence Erlbaum Associates, 2002).

[75] McCauley, 8.

consisted of small cathode ray tube (CRT) television screens that never engaged the ambient vision system.

There are governing factors affecting both the onset and strength of vection. The importance of a wide field of view in engaging the peripheral vision has already been discussed. To reinforce the importance of peripheral vision to vection, research has concluded that visual stimulus within 50 degrees of centre has little to no effect.[76] In addition to the importance of a wide field of view, vection is affected by human focus points, onset delays and visual field velocity.

The importance of focus points has been well documented in the creation of vection. In 1975, researchers determined that "background stimulation dominates over foreground stimulation."[77] Simply put, a stationary window frame or marks on a window itself do little to *inhibit* visually induced motion when the background picture is moving. However, recent studies have concluded that focus points in the foreground while the background moves may actually *enhance* visually induced motion. Dr. Riecke et al concluded in a recent experiment that vection could be reliably and consistently reproduced in all test subjects.[78] Moreover, the experiment used stationary marks on viewing windows to enhance onset. These marks were unknown to the test subjects and the experiment concluded that "quick vection onset [could] indeed be reliably induced in a virtual reality simulator in a non-obtrusive way . . . under natural, relaxed viewing

---

[76] Fred H. Previc, "Visual Orientation Mechanisms," in *Spatial Disorientation in Aviation*, ed Paul Zarchan, 95-144 (Reston,Virginia: American Institute of Aeronautics and Astronautics, 2004), 106.

[77] Young, "Visually Induced Motion in Flight Simulators," 16-2.

[78] Bernhart E. Riecke, et al, "Enhancing the Virtually Induced Self-Motion Illusion under Natural Viewing Conditions," in *Presence 2004: Conference Proceedings*, 125-132 (London: University College London, September 2004).

conditions."[79] A possible conclusion from this experiment is that vection in flight simulator might be enhanced by intentionally marking the windscreens with either unobtrusive dirt or bug stains.

Vection onset delay in virtual reality is a concern for flight simulation. It has been addressed in part by ongoing research as indicated in the previous paragraph. An ongoing concern is that vection onset is highly variable among individuals. Studies continue to address this concern and the entertainment industry will surely be instrumental in onset delay reduction studies. Onset delays can be mitigated by other sensory inputs such as limited onset motion cues. This is the fundamental concept behind the Mechtronix Full Flight Trainer discussed in chapter 5.

Finally, vection is directly affected by the visual field velocity. The illusion of vection can only be maintained as long as the visual field can clearly replicate the sense of motion. If the image starts to blur or resolution is decreased, the illusion disappears.[80] Additionally, slowly moving or changing scenes tend to create the greatest sense of vection.[81] For this reason, airline and air mobility simulators are better suited to this type of simulation vice fast/fighter jet simulators.

THE VESTIBULAR SYSTEM

The human vision system is the dominant system for the processing of human motion and does not habituate to constant velocities. However, when visual cues are removed, motion perception begins to break down and our "orientation in Earth-fixed

---

[79] Ibid., 131.

[80] Young, "Visually Induced Motion in Flight Simulators," 16-2.

[81] Previc, 107.

space suffers."[82] With the absence of vision cues, motion perception is derived from other motion sensing systems such as the vestibular system.

Understanding of the vestibular system has made great advancements since the days of the Ruggles Orientator. In 1917, the creators of the Orientator believed that the vestibular system could be trained to adjust to any possible postural orientation. Since then this has proven to be unequivocally false. The vestibular system is an important source of acceleration and orientation information but it is also susceptible to a series of false cues. The vestibular system is the non-auditory portion of the inner ear. It provides a pilot with the sensations of both translational (along) and rotational (around) movements in the three axes. It consists of two components; the semi-circular canals and the otolith organs which consist of both the utricle and saccule (Figure 3.1).

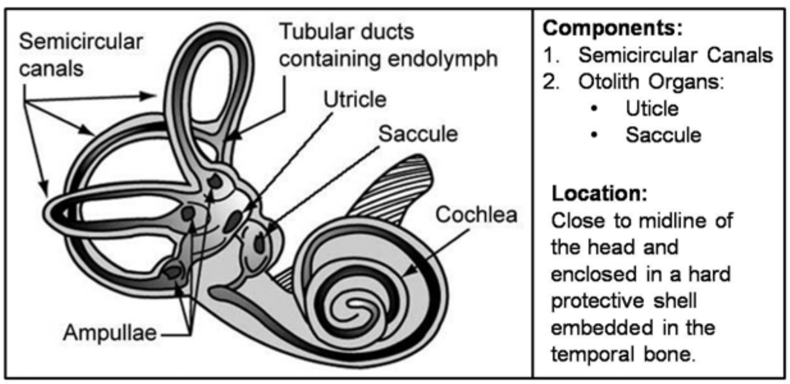

Figure 3.1: The Vestibular System
Source: http://weboflife.nasa.gov/learningResources/vestibularbrief.htm

The Semicircular Canals

The semicircular canals are the sensors for rotational acceleration around the three axes. The three canals coincide with the orientation of the three axes and are filled with fluid known as endolymph. The walls of the tubes are filled with very sensitive hairs. As

[82] Previc, 95.

the head is rotated in any of the three directions, the fluid is displaced which in turn displaces the hairs within the canals. These hairs then transmit the rotational displacement to the brain as motion.[83]

As the endolyphm is displaced by rotation movement, it will eventually push up against and then be stopped by a membrane known as the cupula that prevents the fluid from entering the ampullae. Consequently, the semicircular canals are very accurate for brief head movements, but for sustained constant velocity motion their ability to sense decays to zero.[84] The semicircular canals are susceptible to the density and viscosity of the endolyphm. Very gradual motion cannot be sensed. This is known as an effective threshold in human perception of rotation. There is no absolute threshold as all individuals differ slightly. However, laboratory tests with fully attentive subjects have determined the rotational sensing threshold can be as low as $0.2^{o}/sec^{2}$ for yaw and only slightly higher values of $0.5^{o}/sec^{2}$ for pitch and roll.[85] Modern simulator motion platforms use these sensing thresholds to trick users by returning the platform to level without the occupants' knowledge.

Otolith Organs

The otolith organs are used to sense linear accelerations in both the vertical and horizontal planes. Both the utricle and saccule are constructed the same way. The

---

[83] David C. Edwards, *Pilot: Mental and Physical Performance* (Ames: Iowa State University Press, 1990), 15.

[84] Young, "Spatial Orientation," 75.

[85] Ibid., 76.

difference between the two is that the utricle senses acceleration in the horizontal plane while the saccule is responsible for the vertical plane.[86]

The otolithic membrane consists of dense calcium carbonate crystals known as otoconia resting on endolymph fluid. Consequently, the membrane is denser than the surrounding endolymph. Small hair cells extend from the underlying maculae and extend into the otolithic membrane. As a person leans forward, the effect of gravity pulls the otoconia forward (Figure 3.2). The motion is sensed by the small hair cells and, in this case, the signal is interpreted by the brain as either forward tilt or linear decceleration. The same concept applies to the saccule for processing vertical accelerations.

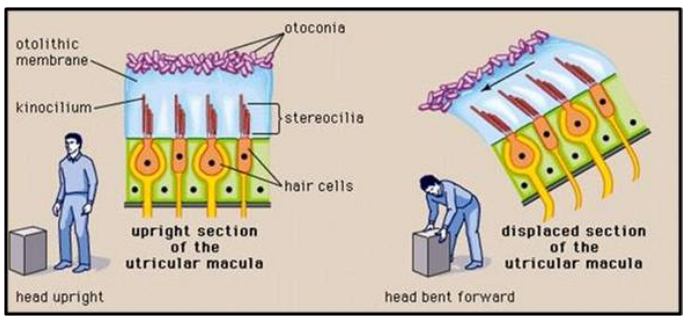

Figure 3.2: Otolith Organ
Source: www.britannica.com

The organs are capable of determining postural vertical orientation to within two degrees. They are very sensitive to linear accelerations but are also susceptible to an effective perception threshold. For sustained horizontal accelerations, laboratory tests have indicated a sensitivity of 5 to 10 cm/sec^2, while the vertical is less accurate at 20 cm/sec^2. Much like the semicircular canal perceptual threshold, motion platforms use these sensitivity thresholds in order to simulate unachieved motion. For example, by tilting simulators forward on a motion platform, the otolith organs can be tricked into

[86] Columbia University, "The Vestibular System," http://www.columbia.edu/itc/hs/medical/neuralsci/2004/slides/32_LectureSlides.pdf; Internet; accessed 17 March 2010.

signalling a linear deceleration when the visual inputs are removed or manipulated accordingly. [87]

PROPRIOCEPTIVE AND AURAL SYSTEMS: THE REINFORCING SYSTEMS

The application of the visual and vestibular systems in the human processing of motion is intuitive to most people. The proprioceptive system is more subtle. The proprioceptive system comprises the total collection of inputs "from the pilot's joints and muscles, which provide information regarding the position of the limbs relative to the body." [88] Every muscle, joint and tendon in the human body contains mechanoreceptors that provide spatial orientation information to the brain. Every movement of the head, shoulders, arms, legs, finger and toes "stretches mechanoreceptors and inundates [the] brain with impulses that [are sorted] out into positional awareness."[89] Even while standing still, small tendons and muscles make positional corrections to maintain vertical posture.

The proprioceptive system involves the brain sending out instantaneous and subconscious signals to the body in order to achieve balance and movement. For a pilot this is critical information. The sense of motion is therefore reinforced by the proprioceptive system. The pressure on the rudder pedals and control stick is sensed by the limbs and confirms in the brain that the aircraft is actually in motion. The illusion of

---

[87] Alfred Lee, *Flight Simulation: Virtual Environments in Aviation* (Farnham, England: Ashgate Publishing Company, 2005), 41.

[88] Ibid., 42.

[89] David L. Phillips, "The Proprioceptive Nervous System," http://www.suite101.com/article.cfm/chiropractic_health_care/102364; Internet; accessed 19 March 2010.

motion simulation is defeated or tainted if the aircraft controls do not react with the appropriate force. This is achieved in flight simulators through the use of control loading.[90]

Like the proprioceptive system, the auditory system also reinforces the sense of motion. On the ground, auditory cues play an important role in spatial orientation. A revolving sound source can create a sense of vection in the form of rotational self-motion.[91] However, high ambient noise, especially in military aircraft, can negate auditory-induced vection. Nonetheless, pilots do extract reinforcing auditory orientation information. Aircraft make subtle sound changes in varying regimes of flight. Changing angles of attack affect sound patterns as the airflow is manipulated over the fuselage and wings is changed. Engine noises increases during high workload manoeuvres. In fact, the C17 engines make entirely different sounds during flap and slat extended assault approach landings as compared to straight and level flight.[92] All of these auditory cues combine to reinforce a sense of motion in the pilot.

Scientific research into the field of auditory vection has been surprisingly minimal. However, new research has been conducted by an ongoing European Union research project on Perceptually Orientated Ego Motion Simulation (POEMS). In an overarching attempt to create an effective and convincing self motion simulator, POEMS has concluded that auditory vection has certain limitations. First, auditory vection only occurs in 25-60% of subjects. Second, although auditory vection can occur, auditory

[90] Lee, 58-60.

[91] Gillingham and Wolfe, 330.

[92] This is based on the author's experience flying C17 aircraft as an exchange pilot with the United States Air Force from 2005 to 2008.

cues "alone are clearly insufficient to reliably induce a compelling self-motion sensation that could be used in applications."[93] However, POEMS has concluded that auditory cues can be used to reinforce visual vection and therefore improve overall immersion into a virtual environment.

HOW THE SYSTEM COMBINE FOR TOTAL MOTION SENSING

The human sensing systems normally work together seamlessly and miscues in everyday life are rare for healthy individuals. However, the interaction between the visual, vestibular, proprioceptive and auditory systems is often altered in the flying environment.[94] Spatial orientation combines the subconscious incorporation of vestibular and proprioceptive cues and the conscious analysis of visual and auditory cues. Each system has strengths and weakness that are either exploited or neglected in flight. When visual cues are removed from the equation, proprioceptive and vestibular cues try to compensate but are often subjected to their own limitations.

Vestibular perception thresholds allow for the misinterpretation or complete inability to identify subtle motions. Moreover, where the visual system receives constant updates, the vestibular system habituates to motion over time. An example of this is the cues identified by the pilot during a climbing manoeuvre to a new cruising altitude without visual references. When the climb is initiated, the vestibular otolith organs will indicate a linear acceleration. Over time the system will readjust to neutral as the otoliths

---

[93] Bernhard E. Riecke, et al, "Influence of Auditory Cues on the Visually-Induced Self-Motion Illusion in Virtual Reality," in *Presence 2005: Conference Proceedings*, 49-57 (London: University College London, September 2005), 49.

[94] Edwards, 16.

adapt to the constant motion. When the aircraft is levelled off at cruising altitude, the pilot will sense that the aircraft has started a dive. If the pilot has visual reference to the horizon, the sense of diving will be overcome by the visual information provided to the brain.

Unresolved conflicting motion sensory information can result in motion sickness. In flight simulators where sensory limitations are exploited, the conflicting sensory inputs can result in a specific type of motion sickness referred to as simulator sickness. There are currently two accepted theories concerning the causes of simulator sickness; sensory conflict theory and postural instability theory with the former being the most widely accepted.[95]

Sensory conflict theory suggests that motion sensing inputs are "provided in parallel to both a neural store of past sensory patterns of spatial movement and to a comparator unit."[96] This "comparator unit" analyzes the currently sensed motion against a store of previously experienced motions. A mismatch between the two causes sickness. Postural instability theory suggests that simulator sickness is a result of a subject's inability to maintain postural control during unfamiliar motion environments.[97] Regardless, both theories suggest that simulator sickness can be overcome through exposure as either the subject's neural store of sensory patterns is adjusted or motion environments become familiar.

---

[95] David M. Johnson, "Helicopter Simulator Sickess," *International Journal of Applied Aviation Studies* 7 no 2 (Spring 2007): 184.

[96] Ibid.

[97] Ibid.

Regardless of the causal theories for simulator sickness, researchers agree upon four common factors. First, some people are more affected than others. Second, mental attitudes (i.e. expectations of being sick) significantly affect a subject's susceptibility. Third, a subject's control of the motion tends to reduce the effects on sickness. Finally, most people can adapt simulator sickness through exposure.[98]

In 1989, the US Navy reported that simulator sickness "threatens the long term utility of ground-based flight trainers as integral components of military and civilian flight training."[99] Many have suggested that the lack of a motion platform causes the sensory mismatch between the vestibular system and the other sensing systems. Consequently, simulator sickness has been used in the argument in favour of motion platforms. The hypothesis that high motion fidelity simulator motion platform would reduce simulator sickness occurrences was tested by National Aeronautical and Space Agency (NASA) researchers. Comparing subjects in both motion and non-motion test groups, it was determined that occurrences of simulator sickness were not significantly different. Based on the results of the experiment, guidelines to minimize simulator sickness were created; however adding a motion base was not one of the recommendations.[100]

---

[98] Edwards, 17-18.

[99] Lawrence M. Fisher, "Sickness in the Cockpit Simulator," *The New York Times*, 20 February 1989, D1.

[100] T.J Sharkey and M.E. McCauley, *Does A Motion Base Prevent Simulator Sickness – AIAA Report 92-4134-CP*, (Washington DC: American Institute of Aeronautics and Astronautics, 1992).

SUMMARY

The human body has created a complicated and overlapping series of systems to process motion. For those not involved in the world of simulation, these systems are taken for granted and the interrelationship between them is not important. However, for flight simulators a solid understanding of the interrelationship is critical for the recreation of flight in the virtual environment. Motion sensing is predominantly completed through a combination of the vestibular and visual systems while the proprioceptive and auditory systems act in a reinforcing or confirming role.

No motion platform is able to create an exact replication of flight. Motion platforms use the known limitations of all the sensing systems to create the illusion of flight. The idea that a lack of a motion base causes simulator sickness due to a sensory mismatch was successfully debunked by NASA nearly twenty years ago. Having examined the way in which humans process motion and the interaction between the sensing systems, the following chapter will address how current Category D simulators use the Stewart-Gough platform to simulate six degrees-of-freedom motion and whether this level of motion is actually required.

CHAPTER 4: THE MOTION REQUIREMENT

INTRODUCTION

The history of aviation training has witnessed a marked increase in the use of simulators, especially over the last twenty years. Both the FAA and TC have implemented Advanced Qualification Programs (AQP) for pilot training. The dramatic technological advances in computer-based training and flight simulators have forced both regulatory agencies to allow "an air operator to develop innovative training and qualification programs that incorporate the most recent advances in training methods and techniques."[101] As simulators are much less expensive to operate than aircraft, commercial aviation has spearheaded a change to pilot training under AQP to allow for zero flight time training (ZFTT). ZFTT refers to training on an aircraft type rating course that is given entirely in a Level D flight simulator. This type of training is not available for all pilots and minimum experience levels are required prior to approval.[102] Most air operators would prefer to complete type training in simulators, however the prohibitive associated acquisition costs of Level D simulators prevent this from becoming a reality for all but the large air carriers.

The most expensive portion of a Level D simulator is the platform motion base. Accordingly, a substantial amount of research has been conducted on how to improve

---

[101] Transport Canada, *Development and Implementation of an Advanced Qualification Program* (Ottawa: Transport Canada, 2005), 19; available from http://www.tc.gc.ca/civilaviation/commerce/aqp/menu.htm

[102] Transport Canada, *Canadian Aviation Regulations (CARS) and Commercial Air Service Standards (CASS) – Part VII – Subpart 5 – Guidance Material* (Ottawa; Transport Canada, 2005), S745.124(8); available from http://www.tc.gc.ca/civilaviation/commerce/manuals/guidance705/menu.htm

motion cuing generators. However, this research has been misguided by the "unsubstantiated opinion that better training can be achieved by immersing pilots in higher *motion* [italics added] realism."[103] Even in 2010 it is not clear if the general preference of pilots for a full motion simulator is the result of a psychological bias for motion. What can be agreed upon is that pilots do prefer motion. However, the method in which motion is achieved is irrelevant. Current motion research needs to focus not on the recreation of motion itself but rather on the recreation of the *perception* of motion, something that is very different than the use of an advanced motion platform. Although the bulk of research has been conducted in the field of commercial aviation, parallels can be drawn to fixed-wing military air mobility aircraft. When not operating in the tactical military realm such as low level flight and airdrop, air mobility aircraft share many commonalities with civil air carriers while in transit and during strategic resupply.

In order to assess the requirement for motion this chapter is divided into four parts. First, it will evaluate how motion is recreated using the industry standard Stewart-Gough platform and its existing limitations. Second, the significance of the different types of motion cues will be explained and their applicability to pilot actions and reactions with be evaluated. Next, this chapter will review the concept of skills transfer and the applicable studies to demonstrate that not all skills learned in flight simulators are necessarily completely transferable to aircraft handling. Lastly, the Volpe Center has conducted numerous studies and produced associated deductions concerning the effectiveness of motion in flight simulators. The Volpe Center serves as a US

---

[103] Judith Bürki-Cohen, et al, "Effects of Visual, Seat, and platform Motion During Flight Simulator Air Transport Pilot Training and Evaluation," in *Proceedings of the 15th International Symposium on Aviation Psychology* (Wright State University, Dayton, Ohio, 27-30 April 2009), 4.

Department of Transportation sponsored vital research link between the transportation and technological communities.[104] Their studies form the backbone of contemporary research and will be examined in depth.

THE STEWART-GOUGH MOTION PLATFORM

As described in chapter 2, the Stewart-Gough motion platform was created based on research conducted in the early 1960s. D. Stewart concluded in 1966 that his design could "simulate true flight without any approximations within the amplitude limits set by the scale of the machine."[105] His design, combined with Eric Gough's Universal Tyre Text Machine design, created the current Stewart-Gough motion platform (Figure 4.1).

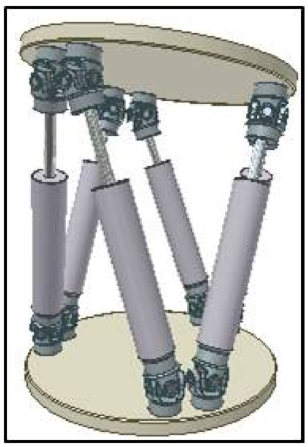

Figure 4.1: Stewart-Gough Hexapod Motion Platform
Source: http://www.answers.com/topic/stewart-platform

Modern flight simulator cockpits are mounted on top of a platform articulate by six hydraulic or electrically powered legs. By manipulating the legs, the platform can be

---

[104] Research and Innovative Technology Research, "Volpe National Transportation Systems Center," http://www.volpe.dot.gov/about/index.html; Internet, accessed 21 November 2009.

[105] D. Stewart, "A Platform with Six Degrees of Freedom," *Proceedings of the Institute of Mechanical Engineers* 180, no 15 (1965-1966): 386.

tilted in any direction. Pilot controls are linked to a computer system that interprets the inputs and manoeuvres the platform accordingly. In this manner all six motions of roll, pitch, yaw, surge, heave and sway are recreated. The controlling computer combines a mathematical aerodynamic model of the aircraft and "creates the appropriate physical effects such as stiffening the control column or adding bumps and vibration to simulate turbulence."[106] Leading simulator production company Thales claims that their simulators can achieve "total realism."[107] Unfortunately, this claim is misleading and inaccurate.

In order to achieve "total realism" a simulator platform would require sustained displacement over time. For example, a force of 0.1g vertical acceleration at a frequency of 0.1 rad/sec would require the motion platform to move vertically 322 feet.[108] Obviously, space constraints preclude any simulator platform from achieving this kind of motion. Scientists have deduced two ways of reducing the amount of platform motion required. First is to only move the platform a percentage of the full motion. Second, is to move the platform at rates commensurate with human sensing perception thresholds, applying what is referred to as washout filters.[109] Both of these approaches are combined in modern flight simulators.

---

[106] Thales, "A Layman's Guide to Full Flight Simulators," http://www.thalesgroup.com/News_and_events/2009-01-27_UK_FOC_Aero_Laymans_Guide_FFS/; Internet; accessed 14 January 2010.

[107] Thales, "Civil Aviation Training Capabilities," *Thales Pamphlet 5A-26-0220078* available at www.thalesgroup.com

[108] Mary K. Kaiser and Jeffery A. Schroeder, "Flights of Fancy: The Art and Science of Flight Simulation," in *Principles and Practice of Aviation Psychology*, eds Pamela S. Tsang and Michael A. Vidulich, 435-471 (New York: CRC Press, 2003), 456.

[109] Ibid., 456.

The most important thing to keep in mind with regards to simulator motion platforms is that the simulator does not actually move in the same manner as an aircraft in motion. Flight simulators manipulate the way the gravity vector is exerted on its occupants in order to recreate a sense of vestibular motion. By manipulating perceptual cues to all the human sensing systems, a simulator can fool the human brain in to believing it is experiencing an acceleration motion. Figure 4.2 depicts gravity vector manipulation. If visual cues to reality are provided, in scenario B the simulator occupant would correctly identify the motion as a tilt upward. However, if visual cues are absent or a visual system presents cues of straight and level, the motion will be interpreted as a linear acceleration as depicted in scenario C.

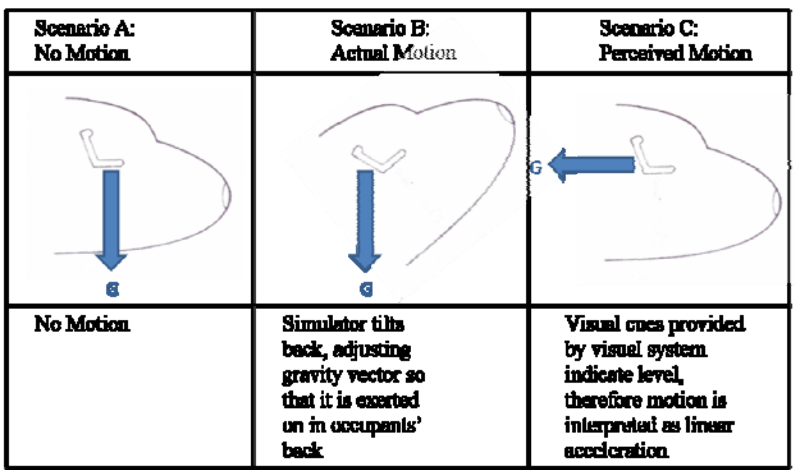

Figure 4.2: Manipulation and Misinterpretation of the Gravity Vector

The above scenario described in Figure 4.2 can be used to explain the force and motion sensations experienced by the pilot during a takeoff conducted in a typical full motion simulator. As the simulated aircraft "accelerates" down the runway, the motion platform tilts backward at a rate above the otolith organs' perception threshold. As the initial acceleration wears off after brake release, the simulator starts to tilt forward at a rate below the otolith organs' perception threshold. At all times, the simulator's visual system maintains a level picture. As the aircraft attains takeoff speed, the pilot applies back pressure to the stick and the aircraft starts a "climb." The simulator platform again rotates backward at a rate greater than the perception threshold. As the aircraft attains a steady climb, the platform again tilts forward to a level attitude at a rate below perception thresholds. Finally, as the aircraft reaches "cruise" altitude, the sense of levelling off is simulated by rotating the platform forward above perception levels and then slowly rotating back to level at a rate below perception levels. The interpretation of these motions is solidified by a visual representation that confirms the illusion.[110]

The rate at which motion is attenuated is the work of algorithmic washout filters. There has been extensive research conducted to maximize these washout filters in order to achieve realistic motion. However, as the motion is not true motion, there exist significant limitations. Most flight simulators subject their occupants to miscues along with the primary motion cues they are trying to simulate. Consider a standard bank right turn. In the aircraft, the plane is smoothly rolled to and maintained at specific angle. As the turn stabilizes at a constant bank angle, the vestibular system habituates to the motion. To recreate this motion in a simulator, the platform is initially rolled right and then slowly rolled left back to neutral. The return to level is meant to be below perception thresholds.[111] However, because not all humans share the same vestibular threshold perception levels, the left roll or motion miscue is often felt.

In 1997, a study was conducted to evaluate how a simulator replicates the initial rolling, yawing and pitching motions associated with an outboard engine failure of a

[110] David Allerton, *Principles of Flight Simulation* (Reston, VA: American Institute of Aeronautics and Astronautics, 2009).

[111] Kaiser and Schroeder, 457.

multi-engine aircraft after takeoff. A comparison between the simulator and aircraft motions produced the following results. Classic platform washout algorithms reproduced only 15% of the actual roll rate, 19% of the yaw rate and only 50% of the pitch rate.[112] The motions associated with an aircraft malfunction such as an engine failure are critical for pilot reaction. In a simulator that cannot produce a completely true representation of such cues, the requirement for motion changes. The new question becomes: what motion cues are most important to pilots?

TYPES OF MOTION CUES

The goal of flying is to maintain an aircraft on an assigned flight path. This is conducted by processing and assessing different types of motion cues. Motion cues were identified and classified as manoeuvre and disturbance motion cues by Paul W. Caro in 1979.[113] Consequently, researchers have determined that the control tasks associated with flying can be broken down into two general types: manoeuvre task and disturbance task management.[114]

Manoeuvre management is conducted through the completion of manoeuvre tasks which are sometimes referred to as tracking tasks. Manoeuvre tasks are "where the

---

[112] Alfred Lee, *Flight Simulation: Virtual Environment in Aviation* (Surrey, England: Ashgate Publishing Company, 2005), 48.

[113] Paul W. Caro, "The Relationship Between Flight Simulator Motion and Training Requirements," *Human Factors* 21, no 4 (August 1979): 493-501.

[114] Shane A. Bowen, Brian P. Oakley and John S. Barnett, *Effects of Motion on Skill Acquisition in Future Simulators: Study Report 2006-07* (Arlington, VA: US Army Research Institute for Behavioral and Social Science, 2006), 6.

discrepancy between the target and current flight path is controlled" by the pilot.[115] These tasks are the domain of the visual system which uses visual rate feedback.[116] In visual flight conditions, the pilot will rely on visual scene detail to provide feedback for controlling the aircraft. Completing an approach to a landing field, formation flying and low level flying all require the pilot to maintain control through a visual comparison between the desired and actual flight paths. In instrument flight conditions, the pilot completes manoeuvre tasks by visually comparing his instrumentation to his desired and actual flight paths. Maintaining the localizer needle centred on a primary flight display (PFD) during an instrument landing system (ILS) approach is a good example. Regardless of the type of flying, the pilot must often learn to ignore vestibular inputs in order to avoid spatial disorientation during manoeuvre tasks.[117]

Unlike manoeuvre management tasks, disturbance management tasks use vestibular feedback.[118] Disturbance tasks are not the result of pilot control input but rather external forces, such as turbulence or engine malfunctions, that are exerted on an aircraft. Disturbance cues are not expected by the pilot and therefore play a significantly different role in overall aircraft control tasks. They serve as alerting cues to an unknown or unexpected situation. Although a major weakness of the vestibular system is that it habituates to motion over time, its greatest strength is that initial accelerations and motions are instantaneously identified. Often, disturbance cues may be the primary cue

---

[115] Air Line Pilots Association, *ALPA White Paper: The Need for Motion in Flight Simulation* (Washington DC: ALPA International, September 2007), 3.

[116] Rudd Hosman, Sunjoo Advani and Nils Haeck, *Integrated Design of Flight Simulator Motion Cueing Systems*, (London: Royal Aeronautical Society Conference on Flight Simulation, May 2002), 6.

[117] Lee, 49.

[118] Ibid.

to a system malfunction such as an engine failure. The Air Line Pilots Association (ALPA) in the United States has used the importance of disturbance task management as its central argument in favour of simulator motion. Their White Paper concluded that "motion is required because pilots operate in an arena of motion and the vestibular system provides them with the most powerful and rapidly sensed cue for self-motion control."[119] The problem with ALPA's conclusion is that it assumes that skills learned in a full-motion simulator are fully transferable to the aircraft.

SKILLS TRANSFER FROM SIMULATOR TO AIRCRAFT

The value and effectiveness of a flight simulator needs to be evaluated against its ability to transfer learned skills to the flight environment.[120] At the end of the day the only thing that matters is a pilot's proficiency in the actual aircraft. For this reason a significant amount of research has been invested in skill transfer studies. Stanley Roscoe concluded in 1991 that motion could be turned off in full motion simulators without being noticed by the pilots and that no loss in training transfer occurred.[121] Consequently, he questioned the cost effectiveness of expensive motion platforms.

There exist three types of transfer of training (ToT); positive, neutral and negative. Positive transfer occurs when an individual correctly applies "knowledge,

---

[119] ALPA, 6.

[120] Richard S. Jensen, *Aviation Psychology* (Brookfield: Gower Technical, 1989), 117.

[121] Stanley N. Roscoe, "Simulator Qualification: Just as Phony as It Can Be," *The International Journal of Aviation Psychology* 1, no 4 (Winter 1991): 336.

skills, and/or attitudes learned to a different setting."[122] This is the goal of any training system or aid. However, if there is no transfer whatsoever then ToT would be assessed as neutral. Finally, negative transfer occurs when existing knowledge and/or skills "impede proper performance in a different task and/or environment."[123] For the purposes of this study, the skills to which we are referring are skills that result from the presence of a motion platform. This means the reactions and skills learned in response to the vestibular cues used to identify disturbance cues.

The main concern with conducting ToT studies in aviation is that they are difficult, expensive and potentially dangerous.[124] To conduct ToT studies two or more subject groups are required. In the training system this normally attains a level of risk to the training outcome of pilots that is unacceptable to the training institution. It can interrupt the training flow and schedule. A pure ToT experiment in the aviation field would ideally consist of two groups; one trained in a full motion simulator and the other trained in a no-motion simulator. The success of the training would then be evaluated in a real aircraft. Understandably, the level of risk associated with either the loss of life or equipment, as well as the operating costs associated with the aircraft, normally prelude these types of experiments from being conducted. Nonetheless, a few pure ToT

---

[122] Beth Blickensderfer, Dahai Liu and Angelica Hernandez, *Simulation Based Training: Applying Lessons Learned in Aviation to Surface Transportation Modes* (Dayton Beach: Emery Riddle Aeronautical University, 30 Jun 2005), 25.

[123] Ibid., 25.

[124] McCauley, 10.

experiments have been conducted, most notably by Robert Jacobs and Stanley Roscoe at the Universtiy of Illinois in 1975.[125]

Jacobs and Roscoe completed their ToT experiment using a non-visual Link trainer for training and a Piper Cherokee Arrow airplane as the test platform. There were 27 subjects divided into three groups with an additional dedicated test control group. The first group was trained in the simulator without motion, the second group with normal motion and the third group with random negative motion. The test control group received no simulator training at all. Jacobs concluded that the group trained with normal motion performed better in the simulator than the other two simulator groups. However, when all three groups transferred to the aircraft there was no marked improvement over the performance of the test control group. This led to the conclusion that simulator motion aids students in flying the simulator but that the skills did not transfer to the aircraft.[126]

Although the results of Jacobs and Roscoe's experiment are interesting, they were limited by the level of technology available at the time. The simulator industry has made great advances in motion generating technology. It is conceivable that today's more advanced simulators with improved motion fidelity could produce better training transfer.

The majority of ToT studies now employ test methodology referred to as "quasi-transfer." In this type of testing, a full motion simulator is used as a stand-in for the actual aircraft. This allows for one test group to be trained in a no-motion simulator while the other group is trained in a full-motion simulator. Evaluation of both groups is

---

[125] Robert S. Jacobs and Stanley N. Roscoe, "Simulator Cockpit Motion and The Transfer of Initial Flight Training," *Human Factors and Ergonomics Society Annual Meeting Proceedings* 19, no 2 (Spring 1975): 218-226

[126] Ibid.

then conducted in the full motion simulator and the performance of the no-motion group is assessed to see if they performed better or worse than the full-motion trained group. This type of testing has some significant advantages over pure ToT experiments. Using the motion simulator as a test bed vice the actual aircraft allows the researchers to control extraneous factors such as aircraft performance, weather, lighting and time of day.[127] The effectiveness of the quasi-transfer experiment methodology was validated by Henry Taylor, Gavan Lintern and Jefferson Koonce in 2001.[128]

The Volpe Center has been at the forefront of the majority of quasi-transfer experiments. Between 2000 and 2005 researchers at Volpe have completed three significant quasi-transfer experiments. All three experiments focused on the effect of motion on pilot reactions to disturbance motion cues by simulating engine failures after take-off in multi-engine aircraft. All three experiments concluded that there were no "operationally relevant effects of motion."[129]

VOLPE CENTER STUDIES

The purpose of the Volpe Center studies in the field of aviation quasi-transfer experiments has been to assist an FAA initiative "towards promoting affordable flight

[127] Henry L. Taylor, Gavan Lintern and Jefferson M. Koonce, "Quasi-Transfer as a Predictor of Transfer From Simulator to Airplane," *The Journal of General Psychology* 120, no 3 (Fall 2001): 258.

[128] Ibid.

[129] Judith Bürki-Cohen, Andrea L. Sparko and Young Jin Jo, "Effects of Visual, Seat, and Platform motion During Flight Simulator Air Transport Pilot Training and Evaluation," *Proceedings of the 15th International Symposium on Aviation Psychology* (Dayton, OH: Wright State University, 27-30 April 2009), 2.

simulators for US commuter airline training."[130] Aside from assisting the FAA, their studies are beneficial to all simulator users, manufacturers and procurers, including the military. Their three significant quasi-transfer experiments were completed in a building block approach. The first experiment utilized a Level C simulator as the test platform simulating a 30 passenger twin-engine turboprop aircraft. Unfortunately, this study was limited by quality of the simulator. They concluded that the simulator utilized may have "failed to provide lateral acceleration cueing representative for the test manoeuvres."[131] Accordingly, the next test conducted in 2003 addressed this concern by utilizing the Level D NASA Ames flight simulator attenuated to augment lateral motions that were found lacking in the 2000 experiment. This test also concluded that motion appeared to have no beneficial effect on recurrent training.[132]

The third Volpe study conducted in 2005 was the culmination of the two previous experiments. Where the previous studies evaluated qualified pilots on the type of aircraft being simulated, this experiment was designed to examine the "effect of simulator platform motion on initial training of airline pilots that have never flown the simulated aircraft."[133] Consequently, 49 newly hired pilots were evaluated in a Level D Boeing 717-200 simulator after having completed requisite ground school. The experiment

---

[130] Judith Bürki-Cohen, et al, "Simulator Fidelity – The Effect of Platform Motion," in *Proceedings of the International Conference Flight Simulation – The Next Decade* (London: Royal Aeronautical Society, 10-12 May 2000), 1.

[131] Ibid., 7.

[132] Judith Bürki-Cohen, et al, "Simulator Fidelity Requirements for Airline Pilot Training and Evaluation Continued: An Update On Motion Requirements Research," in *Proceedings of the 12th International Symposium on Aviation Psychology* (Dayton, OH: Wright State University, April 2003), 7.

[133] Judith Bürki-Cohen and Tiauw Go, *The Effect of Simulator Motion Cues on Initial Training of Airline Pilots* (Reston, VA: American Institute of Aeronautics and Astronautics, 2005), 1.

focused on pilot reaction to an engine failure after take-off and the subsequent engine out precision instrument approach.

Pilot reaction to engine failures after take-off was logical test criteria for the Volpe quasi-transfer experiments. When an engine fails immediately following take-off the aircraft will immediately present disturbance cues in the form of roll, pitch and yaw. These motions are accentuated by the remaining engines being at full power. The manoeuvre is a particularly time sensitive one due to the proximity to the ground. Pilot reactions need to be correct and prompt. In order to remain in controlled flight, the pilot must maintain aircraft airspeed greater than Vmca (Velocity – Minimum Control Air). Vmca is the minimum airspeed at which an aircraft can maintain controlled flight with one engine inoperative. Although the speed differs by configuration and aircraft type, the definition and parameters remain the same. The C17 Performance Data Flight Manual, similar to all aircraft manuals, stipulates that initial pilot reaction requires the immediate use of the rudder to counter the yawing motion and up to five degrees angle of bank away from the inoperative engine to counter the rolling motion.[134]

The third Volpe Center experiment followed the same methodology as the previous experiments. One group of pilots was trained with no motion while the other group was trained with full motion. After the training, both groups were evaluated in the full motion Level D simulator. The results with respect to pilot reaction to an engine failure after take-off were conclusive (Figure 4.3).

---

[134] United States Air Force, *C-17 Flight Manual Performance Data – Change 1* (Wright Patterson Air Force Base: Department of Defense, 2007), 3-6.

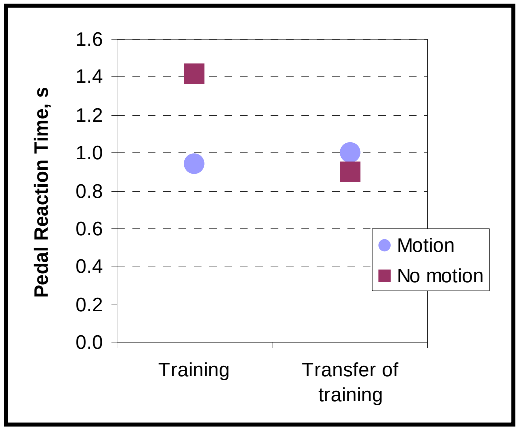

Figure 4.3: Rudder Reaction Time Following Engine Failure
Source: Bürki-Cohen and Go.[135]

In training, the motion trained group sensed the yawing disturbance cue associated with the engine failure quicker than the no-motion trained group. Consequently, figure 4.3 indicates that the motion group was approximately 0.5 seconds faster in applying the appropriate pressure to the required rudder pedal. This faster reaction is significant for all the reasons that engine failures after takeoff are critical manoeuvres. The most interesting fact is that the difference in reaction time was not transferred to the test platform. Despite having trained without motion, the no motion group reacted just as quickly as the motion trained group when the sequence was repeated with motion disturbance cues present.[136]

The experiment proved two significant facts. First, disturbance motion cues *do* provide an alerting function to pilots. Even when forewarned of the impending engine failure, pilots without motion cues were unable to react as quickly as those with motion cues. Second, and perhaps most noteworthy, the no-motion trained pilot's delay in reaction did *not* transfer. In other words, the no-motion pilots "did not have to be trained

[135] Bürki-Cohen and Go, *The Effect of Simulator Motion Cues on Initial Training of Airline Pilots*, 7.

[136] Ibid., 7.

with motion to recognize the cues signalling an engine failure on takeoff."[137] When transferred to full motion, the recognition of an engine failure was intuitive and natural for all the tested pilots. Consequently, the real question is what does motion contribute to training? The apparent answer is disconcerting to most pilots: nothing.

SUMMARY

Recent advances in the understanding of the purpose of motion in flight simulation have questioned the requirement for motion. Technology has permitted full motion simulators to replicate motion; however the replicated motion is not, and has never been one hundred percent true to actual aircraft motion. A rudimentary understanding of the relationship between the human motion sensing systems permitts technology to trick the human brain by manipulating how the force of gravity is exerted on simulator occupants. Nonetheless, these tricks are not perfect. The subtle motions used to reset a Stewart-Gough platform are often sensed by the occupants, creating sensory miscues.

Modern simulators are required to recreate two types of motion: manoeuvre and disturbance motions. While manoeuvre motions are detected by the visual system, disturbance cues are sensed by the vestibular system. These disturbance motions are instantaneously processed by the vestibular system and serve an alerting function to abnormal flight conditions for the pilot. For this reason, many propose that motion is required. However, the scientific evidence indicates that some skills learned in the simulator are not transferred to the actual aircraft. While cognitive skills such as

---

[137] Ibid., 11.

procedure training, decision making and crew resource management are transferred to the aircraft, handling skills are not. Study results support this finding as pilot reactions to an engine failure after takeoff were handled equally well by both motion trained and non-motion trained pilots.

It appears that the only function for motion in flight simulators is to provide disturbance motion cues. If so, then the new question in the motion debate is what kind of motion is required to provide motion cues? Does the simulator need to have 60 inches of motion travel or can small motions produce the same result? What is the future of the full motion simulator? This is the topic of the next chapter.

CHAPTER 5: THE FUTURE OF FULL MOTION FLIGHT SIMULATION

INTRODUCTION

The heated and often contested motion requirement debate in aviation simulators often neglects the true goal of flight simulation. From its inception, flight simulation has been designed to train better pilots. The intention is to provide a safe and controlled environment where pilots can hone their skills. The problem with the motion debate is that it concerns itself with only one small aspect of the overall world of flight simulation. The constant desire to create realistic mimicking of the real-world environment has caused many to forget that a simulator is "just a tool for training."[138]

What does full-motion do to enhance the overall goal of pilot training? Previous chapters have explained how platform motion is not a true replication of aircraft motion. Moreover, due to limitations on displacement and subsequent acceleration forces, platform motion can create perceptual miscues as the motion base is manipulated at rates and frequencies assumed to be below human perception thresholds.

It is currently accepted that motion perceived by pilots can be divided into manoeuvre motion cues and disturbance motion cues. Motion does little to assist with manoeuvre tasks as this is predominantly completed by the visual system as the pilot maintains an aircraft in controlled flight along a designated flight path. There is a place for physical motion in the completion of disturbance tasks as disturbance motion cues

---

[138] Eduardo Salas, Clint A. Bowers and Lori Rhodenizer, "It Is Not How Much You Have but How You Use It: Toward a Rational Use of Simulation to Support Aviation Training," *The International Journal of Aviation Psychology* 8, no 3 (Fall 1998): 200.

have been shown to serve as an alerting function for pilots as aircraft flight is disrupted by external forces. However, all the recent research indicates that disturbance cue reactions may not transfer to the aircraft. Apparently, pilots do not need to feel a simulator motion-kick in order to realize that an aircraft will react the same way in response to disrupting forces, such as engines failures after take-off. Put in other words, an intelligent individual does not need to be hit in the head with a baseball bat to realize that it hurts.

MOTION IS ONLY A SMALL PART OF SIMULATION

So where does motion fit into the overall framework of flight simulation? It is by far the most expensive component of a Level D simulator. These simulators are typically large machines requiring separate and type specific infrastructure as well as a high degree of technical expertise and maintenance support.[139] Are the large financial expenditures cost effective? Unfortunately, they are not. As early as 1975, Edward Huff and David Nagel proposed a simple model of the ideal flight simulation. The model is still applicable today. As depicted in Figure 5.1, the ideal simulation involves multiple, interrelated factors that directly contribute to pilot performance and consequent training. What is interesting to note is that motion generation, as highlighted, is only one portion of this ideal simulation.

[139] Berhard E. Riecke, et al, *Towards Lean and Elegant Self-Motion Simulation in Virtual Reality* (Bonn, Germany: IEEE Virtual Reality, 2005), 131.

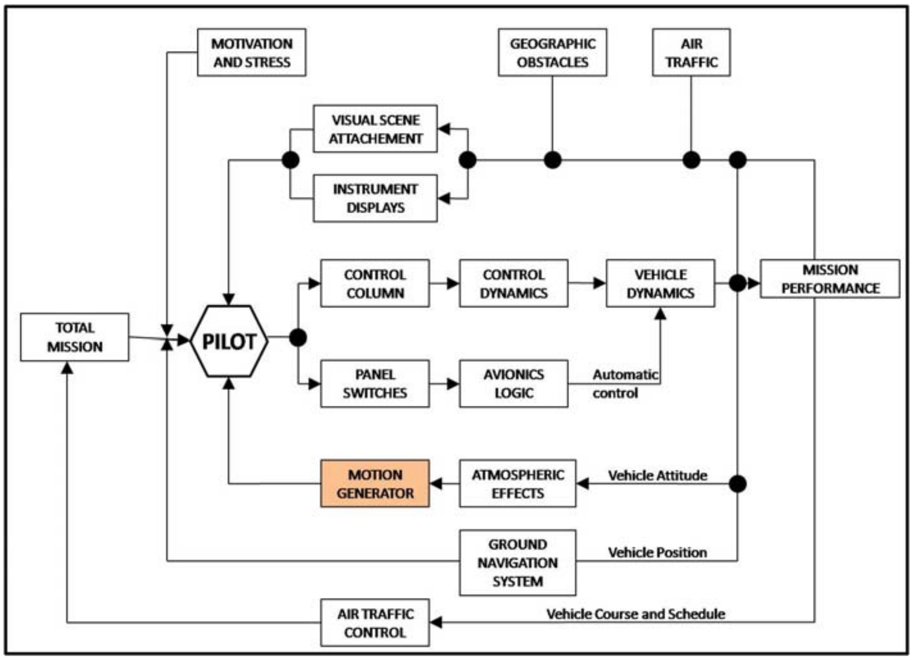

Figure 5.1: Ideal Simulation
Source: Huff and Nagel[140]

If motion only has limited applicability to pilot training in terms of disturbance motion cues and if quasi-skill transfer experiments demonstrate little operational relevance for motion, why does industry persist to push for Level D simulators? The answer to this question is complex. Essentially, although motion has not been proven to enhance skill transfer, it certainly has not been proven to *impede* transfer. The onus remains on the scientific community to prove that a lack of motion will not adversely affect pilot training. As with anything else in life, any change to the status quo is very difficult. Moreover, the status quo of the motion requirement is endorsed by most pilots, not for scientific reasons but rather perceptual ones. The Air Line Pilots Association is adamantly against even opening discussions on reducing the motion requirement.

---

[140] Edward M. Huff and David C. Nagel, "Psychological Aspects of Aeronautical Flight Simulation," *American Psychologist* 30, no 3 (March 1975): 427.

ALPA's official position is:

> If the purpose of pilot training is to develop and evaluate the required skills, knowledge and performance necessary to pilot an aircraft, then it is essential to recreate the actual flight environment as closely as possible. Other senses (i.e. visual, aural, tactile) are important, but complementary. . . ALPA policy is that the highest level flight simulators shall be used to the maximum extent possible [emphasis in original document].[141]

The idea that the "other senses are complimentary," goes against the science behind how humans process motion as described in chapter 3. The dominant spatial orientation system is the visual system, followed by the vestibular system, not vice versa. The mindset of organizations such as ALPA will have to change over time. Fortunately, regulatory agencies such as the Federal Aviation Administration (FAA), Transport Canada (TC) and the Joint Aviation Authority (JAA) in Europe are exploring alternatives to full motion simulators. The most promising advance has been the recent JAA-certification of a no-motion full-flight trainer (FFT-X) produced by Canadian, Montreal-based company Mechtronix. In a relatively dramatic turn, the JAA has granted the FFT-X "training, testing, and checking credits equivalent to the ones usually granted to a Level B Full Flight Simulator (FFS)."[142] By allowing the FFT-X to conduct training that previously required a Level B motion simulator, the JAA implicitly acknowledged that full motion platforms are not always required and that other technologies can achieve the same results.

---

[141] Air Line Pilots Association, *ALPA White Paper: The Need for Motion in Flight Simulation* (Washington DC: ALPA International, September 2007), 6.

[142] Judith Bürki-Cohen, Andrea L. Sparko and Tiauw H. Go, *Training Value of a Fixed-Base Flight Simulator with a Dynamic Seat* (Hilton Head, South Caroline: AIAA Modeling and Simulation Technologies Conference, 20-23 August 2007), 10.

THE NON-MOTION ALTERNATIVE

An emerging alternative to six degrees-of-freedom of motion flight simulators are fixed base flight simulators with a dynamic pilot seat providing initial disturbance cues via heave onset cues. It was exactly this type of alternative that the Avions de Transport Regional (ATR) Training Centre in Toulouse, France, used to convince the JAA to grant aircraft type-rating without the use of motion. ATR is the world's largest manufacturer of regional turboprop aircraft and houses its own pilot training centre in order to support its airline customers.[143] Regional European airlines regularly send their pilots to Toulouse to complete both ab initio training and recurrent training. The ATR Training Centre recently partnered with Mechtronix to provide cost-effective pilot training through the use of a "FFT 'brain-motion' simulator program."[144]

Mechtronix's FFT-X is actually an FFS without the motion.[145] It employs all of the human motion processing systems to create a virtual *immersive* environment for pilot training. To engage the visual system, it employs a 200 degree by 40 degree field of view collimated visual system comparable to those used in a level D simulator. The vestibular system is engaged by an electrically driven dynamic seat used to provide the motion cueing effects of acceleration, deceleration and turbulence. The proprioceptive system is engaged by a high-fidelity aerodynamic and flight control force models. Additionally, the cockpits are exact replicas of the aircraft they are simulating, providing tactile feel of

---

[143] ATR, "Company Profile," www.atraircraft.com; Internet; accessed 15 February 2010.

[144] Jeff Apter, "ATR Mulls Option for Larger Turboprop," *Aviation International News Online* (14 July 2008) [jounal on-line]; available from http://www.ainonline.com/news/single-news-page/article/atr-mulls-options-for-larger-turboprop/; Internet; accessed 8 March 2010.

[145] Email Maj Jason Stark and Xavier Lalonde. 28 January 2010. Xavier Lalonde, Sales Coordinator Mechtronix, (514) 342-0800x2340, xlalonde@mechtronix.com.

the panel and switches. Finally, the auditory system is engaged through the use of high-end sound simulation, including a subwoofer mounted on the structure to provide constant aircraft vibration and engine noise.[146] In accordance with Huff and Nagel's model of ideal simulation, Mechtronix has focused on the immersive nature of flight simulation where the pilot's brain extrapolates information and sensory inputs from multiple feedback loops.

In the fall of 2006, the French National Aviation Authority (NAA) under the JAA successfully completed the type-rating of six pilots using the Mechtronix FFT-X non-motion simulator. This was a ground breaking and world first occurrence. Observant during the training were researchers from the Volpe Center. Having completed quasi-transfer studies in full motion simulators, they were eager to observe and assist with the proof-of-concept of a non-motion simulator used for aircraft type-qualification. In 2007 they released a report of their findings. The pilots who successfully completed the aircraft type qualification consisted of two experienced and four non-experienced pilots. The two experienced pilots held multi-pilot type-rating licenses. They held a total of 14,000 and 11,000 hours for flight experience, respectively. The four non-experienced pilots held single-pilot licenses and had no airline experience. Their flying experience ranged from 6,000 hours to 563 hours.[147]

The Volpe researchers found that the pilots' performance in the actual aircraft after transition was rated by flight line instructors as the same as a typical pilot trained in

---

[146] Mechtronix, *There Is Nothing General About The Way We Approach Aviation* (Montreal: Mechtronix Headquarters, 2009), 15.

[147] Judith Bürki-Cohen, Andrea L. Sparko and Tiauw H. Go, *Training Value of a Fixed-Base Flight Simulator with a Dynamic Seat* (Hilton Head, South Caroline: AIAA Modeling and Simulation Technologies Conference, 20-23 August 2007), 9.

an FFS. Moreover, while completing certain flight sequences in the simulator, such as engine-out instrument approaches and abnormal landing configurations, the trainees performed “moderately better” and “much better” than a typically full motion trained pilot respectively.[148] Only the trainees themselves were asked to rate the acceptability of the FFT-X both prior to and following experience in the actual aircraft.

Prior to flying the actual aircraft, trainees rate the FFT-X as only needing “minor improvements” or better for 77 percent of the manoeuvres trained. This assessment was based on their impression of how the actual aircraft would feel and react to pilot input. However, following their experience in the actual aircraft, trainees rated the FFT-X as not lower than only “slightly different from the airplane.”[149] There were, however, some differences in trainee opinions on the lack of motion. Two trainees stated that the FFT-X motion was “very different than the airplane.” Nevertheless, these rating were offset by other individual ratings that stated that the FFT-X motion was “same as the airplane.”[150] This indicates that motion perception is extremely subjective and it could be interpreted that the difference in opinions would have been present in a transition from an FFS to the actual aircraft.

The goal of flight simulation in the realm of aircraft type training is whether there are issues, concerns or difficulties in the transition to the actual aircraft. All six pilot trainees were unanimous in their evaluation that they experienced no problems in transition. This was echoed by the flight line instructors who noted that all six pilots

---

[148] Ibid., 14.

[149] Ibid., 16.

[150] Ibid., 16.

were well equipped and trained for the actual aircraft and that there did not "appear to be a difference between FFS and FFT training."[151]

At the end of the training, the National Aviation Authority decision maker found that there were no training problems associated with the lack of motion in the FFT-X. Moreover, the NAA official emphasized that the focus of flight simulation "should be on effective stimulation of the pilot, rather than emphasizing rote simulation of the aircraft."[152] This progressive attitude is slowly starting to change the aviation industry. It is this type of forward thinking that is required of the Canadian Air Force.

SUMMARY

Regulatory agencies, especially the JAA, are looking to the future and exploring alternative technologies to provide the same level of training as an FFS. The impetus for the quest for non-motion effective simulators is born out of a desire by the airline industry to reduce costs; both in terms of initial acquisition and maintenance. The military, although not a profit based organization, shares these same desires. The problem for the military is that we are not taking the lead at exploring these new technologies.

The role of simulators is to train pilots to operate in the complex aviation environment. The goal of simulators is to provide much more than simple motion cues. The quest for realistic motion is a phantom dream that industry and the military have

[151] Ibid., 17.

[152] Ibid., 17.

been chasing at the expense of achieving realistic immersion. The cost associated with large full motion base platforms is not justified when one considers Huff and Nagel's model of ideal simulation. Motion is such a small portion of simulation yet it seems to consume such a large part of the thought process. Creating an *immersive* environment is much more important than creating a *mobile* one.

For the military, the majority of Canadian Forces pilots are post-OTU and Wings qualified. This is a mass market that is that could significantly benefit from a high quality immersive non-motion simulator such as the FFT-X. Senior Air Force leadership need to look to the future and re-evaluate the allocation of resources. The Air Force trains some of the best pilots in the world. Now we need to look at how to maintain that high level of proficiency in a cost-effective, logical and continuing way.

CHAPTER 6: CONCLUSION

The original question posed at the start of this analysis was whether simulator platform motion was required in aviation flight simulators. Throughout the course of the discussion, the question was refined to what types of motion were required in flight simulators? It is now evident that the most accurate question should be: what type of simulator training requires motion? The nuance in the question change is subtle yet significant.

This analysis was logically organized to address the motion debate from a critical point of view. Chapter two established the baseline of terminology and nomenclature in order to enter the debate arena with a common understanding. The evolution of flight simulation from the time of the Wright Brothers to the use of the Desdemona simulator in the Netherlands indicates how the virtual reality world constantly evolves as science and technology are improved. Chapter three provided an in-depth explanation of how humans process motion. A solid understanding of the human motion perception systems and their interaction are instrumental in understanding how motion can be a mental perception vice a physical movement. Inputs from the visual, proprioceptive and auditory systems can effectively compensate for a lack of vestibular motion cues, especially with respect to manoeuvre motion cues. Chapter four differentiated between manoeuvre and disturbance motion cues. Although physical motion is required for disturbance cues, the latest research in transfer of training studies indicates that skills acquisition associated with disturbance motion cues do not appear to transfer to the aircraft. Transfer of training research reinforces the fact that simulators are better suited for training higher cognitive skills. Lastly, after demonstrating that motion is not necessarily required for continuation pilot training, chapter five presented a non-motion alternative to the current industry Level D flight simulator.

Motion *is* required in certain types of simulator training. There is a specific niche for full-motion flight simulators, even extremely advanced ones like Desdemona. The testing of pre-production and established aircraft fleets requires full motion. Aviation research requires full motion in order to continue quasi-transfer studies into the field of transfer of training. However, *the continuation training of qualified pilots does **not**.* Research indicates that pilot performance in aircraft is actually a factor of their inherent flying skills, plus "what they have learned from the visual system about attitudes and perspectives."[153] The goal of flight simulation in continuation pilot training should be to immerse the pilot in a virtual aviation environment. With that as the goal, it is apparent that motion only plays a minimal role.

The purpose of traditional platform motion is to engage the vestibular motion system. However, as chapter 4 illustrated, vestibular motion is only useful for the recognition of disturbance motion cues. The primary human motion sensing system remains the visual system. With the vestibular system understood as serving an alerting function to aircraft disturbance, research needs to focus more on how much physical motion is actually required. The use of a dynamic seat may suffice. Already industry is slowly retreating from full-motion by permitting Level D simulators to reduce the amount

---

[153] David Learmount, "Civil Simulator Special: Going through the motions – are motion systems for simulators on their way out?" *Flight International* (27 April 2009) [journal on-line]; available from http://www.flightglobal.com/articles/2009/04/27/325612/civil-simulators-special-going-through-the-motions-are-motion-systems-for-simulators-on-their-way-ou.html; Internet, accessed 6 January 2010.

of motion travel from 60 inches to 35 inches.[154] The large Stewart-Gough motion platforms have served their purpose; however, industry needs to look forward at new technological solutions to create the illusion of aircraft motion in flight.

The battle surrounding the motion requirement for flight simulators involves many players. The airline industry is always looking for less expensive means of completing flight training. Regulatory agencies want to ensure that training remains relevant, effective and controlled. Simulator manufacturers want to maintain profit margins. Finally, unions and associations such as ALPA do not want to make any changes to the status quo and invoke fears of catastrophic pilot failures.

Following the 12 February 2009 fatal crash of a regional airline in Buffalo, NY, the National Transport Safety Bureau (NTSB) made a call for expanded simulator training in order to equip pilots with the requisite skills to recognize and recover from loss of control (LOC) scenarios. Accordingly, ALPA immediately issued a statement that there is “no excuse not to” use enhanced motion flight simulators to provide pilots with the hands-on training on how to recover from aerodynamic stalls and other extreme scenarios.[155] However, FAA officials have a more balanced and responsible approach. The FAA position is that it would rather focus pilot training to avoid LOC scenarios in the first place.[156] The goal of effective pilot training should not be to qualify pilots to recover from extreme attitudes or situations, but rather to avoid those situations all together.

---

[154] Ibid.

[155] Alan Levin, “Simulators Target Crash Scenarios,” *USA Today*, 9 March 2010, A1.

[156] Ibid.

The military is in a unique position to once again take the lead in the development of flight simulation technologies, much like during the Second World War. Unlike the civilian industry, the military is not subject to same rules and regulations imposed by Transport Canada, the Federal Aviation Authority or the Joint Aviation Authority. The military, although cost conscious, is not a profit based organization and the effective training of pilots will always remain paramount in the view of the Chief of the Air Staff. Once trained to operational status in the Air Mobility community, Canadian military pilots can complete better continuation training at lower cost by using less expensive flight simulators to create a virtual flight environment. The goal is to develop the cognitive pilot skills such as decision making and crew resource management. Less expensive simulators would allow for the purchase of greater numbers, thus permitting greater access to training for pilots. However, this better training at lower financial cost is associated with a higher level of risk.

The purpose of this paper has not been to address the effects of motion in flight simulators for initial pilot training. Moreover, there will always be certain military skills and flight profiles that no current level of flight simulation can simulate. Even the successful type rating of pilots at the ATR Training Centre using non-motion simulators, as described in chapter 5, did not deal with teaching initial “stick-and-rudder” skills. The subject pilots were already fully licensed and experienced aviators. However, what the ATR Training Centre and the JAA did demonstrate is that full motion is not always required.

The most intense training a military pilot receives after initial flight training is the aircraft type-specific training conducted at the Operational Training Units (OTU). This type of training requires pilots to fly the actual aircraft and zero flight time training (ZFTT) will never be achievable. However, continuation or recurrent training on a yearly basis is normally focused on emergency procedures, crew resource management and mission management. In the Air Mobility community, this type of training is very similar to the airline philosophy of Line Orientated Flight Training (LOFT). According to the FAA, LOFT is designed to give "crewmembers the opportunity to practice line operations (i.e., manoeuvres, operating skills, systems operations, and the operator's procedures) with a full crew in a realistic environment."[157] Because all military mobility pilots have this yearly requirement, the associated training bill is very high. For example, the only CC130 Hercules simulator in Canada is located at 8 Wing Trenton, Ontario. Therefore to conduct continuation simulator training, crews from Nova Scotia and Manitoba are required to fly to Trenton. Similarly, C17 Globemaster and CC150 Polaris crews are required to leave the country to use simulators not currently owned by Canada.[158]

There will always be a requirement to have full motion simulators at the Operational Training Units. Military pilots who attend initial training courses at these units are very inexperienced, often with just over 200 hours of total flight experience. The systems used to simulate motion may not need to be large and expensive Stewart-Gough platforms. Technology is advancing quickly and eventually physical motion will

---

[157] Federal Aviation Authority, *Line Operation Simulations, Advisory Circular 120-35C* (Washington DC: US Department of Transportation, 2004), v.

[158] Telecon Maj Jason Stark and LCol Dave Murphy, Tuesday, 13 April 2010. LCol Dave Murphy, Wing Operations Officer, 8 Wing Trenton, 613-392-2811.

be able to be replaced with ego-motion.[159] However, we may not necessarily be there yet. Where there is immediate room to advance is in the area of continuation training.

Non-motion flight simulators, like the FFT-X, that employ sensory cues to all human perception systems should have a niche in continuation training. They are substantially less expensive. Multiple units could be purchased and placed at all the applicable bases so that pilots have increase accessibility. This would involve less travel time to simulator locations, less expenditures for travel and accommodations for crews, as well as less impact to the operational environment. Typically, one continuation training simulator session at a third location normally involves two days of travel for one day of training. The operational tempo in Air Mobility shows no signs of diminishing and alternative means of training will be required sooner rather than later. Changing the status quo of how we operate and employ simulator training, and the platforms we use to achieve it, will require future leaders to have the courage to look forward and not backwards.

Civilian associations such as ALPA have no desire or inclination to challenge the pilot training status quo. Their position is that the large, expensive full motion simulators will always be the best tool for pilot training. The Air Force needs to have greater vision. How the illusion of aircraft motion is recreated is irrelevant to a pilot. The mechanics behind motion processing, the functions of the visual and vestibular systems, and the illusion of vection are all things that do not matter to a pilot. The true litmus test of an

[159] Ego-motion is motion perceived yet not physically experienced. The human ego is the part of the human personality that is responsible for defensive, perceptive, cognitive-intellectual and executive functions. For more information on ego refer to Snowden Ruth, *Teach Yourself Freud* (New York: McGraw Hill, 2006). For more information on ego-motion refer to PEOMS at www.poems-project.info.

effective flight simulator is whether the pilot feels immersed in the simulation. Is there pilot buy-in to the overall virtual environment?

Continuing studies by Volpe Center in the United States and the Perceptual Oriented Ego-Motion Simulation (POEMS) program in the European Union will be instrumental in breaking down the pre-conceived notions about the significance of physical motion. Until these notions are successfully debunked, organizations such as the military will default to positions forwarded by civilian organizations such as ALPA. Consequently, this requires the scientific community to continue pursuing alternative means of simulation. Scientists need to provide policy makers with sufficient support to "make the proper evidence based decisions on military flight simulation."[160]

This author has not doubt that years from now we will look back at the current Level D, 6 degrees-of-freedom, fully articulated flight simulator with its associated infrastructure and wonder at the folly of our ways. Much like we currently look back at the massive computers of the 1960s, we will look back at the Level D simulator as an overpriced and inefficient flight simulation platform. Science is currently well aware of the fact that the effects of motion can be simulated and compensated for by the overlapping human processing systems. It now requires technology to determine the optimum way to correlate this information in a cost effective simulator. The area for the greatest amount of progress is in post-wings pilot continuation training.

Consider the questions posed at the start of this chapter. Is simulator platform motion required in aviation flight simulators? The answer is not always. What type of

[160] Bernd de Graaf, et al, "MSC: Vehicle Validation of Military Flight Simulation," available from http://ftp.rta.nato.int/Public/PubFullText/RTO/MP/RTO-MP-HFM-136/MP-HFM-136-16.pdf; Internet; accessed 10 January 2010.

motion is required in flight simulators? The answer is disturbance motion. Finally, what type of flight simulator training requires motion? The answer is certainly ***not*** pilot continuation training.

APPENDIX 1 - GLOSSARY OF TERMS AND ACRONYMS

ALPA: Air Line Pilot's Association.

AQP: Advanced Qualification Program.

ATC: Air Traffic Control.

ATR: Avions de Transport Regional.

BOAC: British Oveseas Airways Corporation, the pre-cursor to British Airways.

C130: Lockheed C130 Hercules Transport Aircraft.

C17: Boeing C17 Globemaster Transport Aircraft.

CCTV: Close Circuit Television.

CGI: Computer Generated Images.

CRM: Crew Resource Management.

CRT: Cathode Ray Tube.

FAA: Federal Aviation Administration.

FFS: Full Flight Simulator.

FOV: Field of View.

FSTD: Flight Simulator Training Device.

FTD: Flight Training Device.

G Force: One "G" force is the equivalent of the force of gravity exerted on a static, immobile object.

ILS: Instrument Landing System.

JAA: Joint Aviation Authority.

JAR: Joint Aviation Regulation.

LOFT: Line Orientated Flight Training.

Level A FFS: Four degrees-of freedom of motion, basic visual system. See Transport Canada, TP 9685 available at http://www.tc.gc.ca/civilaviation/ publications/tp9685/ chapter2/menu.htm for further detail.

Level B FFS: Four degrees-of-freedom of motion, visual system is capable of reproducing depth perception and sink rates. See Transport Canada, TP 9685 available at http://www.tc.gc.ca/civilaviation/publications/tp9685/ chapter2/menu.htm for further detail.

Level C FFS: Six degrees-of-freedom of motion, visual system capable of reproducing better than Level B along with night and dusk scenes. See Transport Canada, TP 9685 available at http://www.tc.gc.ca/civilaviation/publications/tp9685/ chapter2/menu.htm for further detail.

Level D FFS: Six-degrees-of-freedom of motion, visual system capable of producing better than Level C along sufficient scene detail to recognize terrain, airports and major landmarks. Simulator needs to be able to recreate full daylight lighting and scene detail. See Transport Canada, TP 9685 available at http://www.tc.gc.ca/ civilaviation/publications/ tp9685/ chapter2/menu.htm for further detail.

MIT: Massachusetts Institute of Technology.

MTBF: Mean Time Between Failure.

NAA: National Aviation Authority.

NASA: National Aeronautical and Space Agency.

OTU: Operation Training Unit.

PFD: Primary Flight Display.

POEMS: Perceptually Orientated Ego Motion Simulation is a European Union sponsored research program into non-motion virtual reality simulators.

TC: Transport Canada.

ToT: Transfer of Training.

Volpe Center: The John A. Volpe National Transportation Systems Center in Cambridge, Massachusetts, is an internationally recognized center of transportation and logistics expertise sanctioned by the US Department of Transportation.

ZFTT: Zero Flight Time Training.

BIBLIOGRAPHY

Articles

Apter, Jeff. “ATR Mulls Option for Larger Turboprop,” *Aviation International News (AIN) Online* (14 July 2008). Jounal on-line; available from http://www.ainonline.com/news/single-news-page/article/atr-mulls-options-for-larger-turboprop/; Internet; accessed 8 March 2010.

Bürki-Cohen, Judith, Nancy Soja and Thomas Longridge. “Simulator Platform Motion – The Need Revisited.” *The International Journal of Aviation Psychology* 8, no 3 (Fall 1998): 293-319.

Caro, Paul W. “The Relationship Between Flight Simulator Motion and Training Requirements.” *Human Factors* 21, no 4 (August 1979): 493-501.

Chen, Wei L. “Simulation for Training and Decision-Making in Large-Scale Control Systems: Part 2: Civil Aircraft Pilot Trainers.” *Simulation* 35, no 2 (Agust 1980): 42-44.

Corell, John T. “The Air Mail Fiasco,” *Air Force Magazine* 91, no 3 (March 2008). Journal on-line; available from http://www.airforcemagazine.com/Magazine Archive/Pages/2008/March%202008/ 0308airmail.aspx; Internet; accessed 15 February 2010.

Fichter, E.F., D.R. Kerr and J Rees-Jones. “The Gough-Stewart Platform Parallel Manipulator: A Retrospective Appreciation.” *Journal of Mechanical Engineering Science* 223, no1 (January 2009), 243-244.

Fisher, Lawrence M. “Sickness in the Cockpit Simulator.” *The New York Times*, 20 February 1989.

Furber, S. “The Future of Computer Technology and Its Implications for the Computer Industry.” *The Computer Journal* 51, no 6 (November 2008): 735-740.

Higdon, Dave. “Flight Training – Simulators Review.” *AV Buyer* (March 2008). Journal on-line; available from http://www.avbuyer.com/articles/detail.asp?Id =1072; Internet; accessed 3 February 2010.

Howard, D.M. “The Sanders Teacher.” *Flight* 2, no 50 (10 December 1910): 1006; http://www.flightglobal.com/pdfarchive/view/1910/1910%20-%201008.html; Internet, accessed 16 February 2010.

Huff, Edward M. and David C. Nagel. “Psychological Aspects of Aeronautical Flight Simulation.” *American Psychologist* 30, no 3 (March 1975): 426-439.

Jacobs, Robert S. and Stanley N. Roscoe. "Simulator Cockpit Motion and The Transfer of Initial Flight Training." *Human Factors and Ergonomics Society Annual Meeting Proceedings* 19, no 2 (Spring 1975): 218-226.

Johnson, David M. "Helicopter Simulator Sickess." *International Journal of Applied Aviation Studies* 7 no 2 (Spring 2007): 178-201.

Learmount, David. "Civil Simulator Special: Going through the motions – are motion systems for simulators on their way out?" *Flight International* (27 April 2009). Journal on-line; available from http://www.flightglobal.com/articles/2009/04/27/325612/civil-simulators-special-going-through-the-motions-are-motion-systems-for-simulators-on-their-way-ou.html; Internet, accessed 6 January 2010.

Levin, Alan. "Simulators Target Crash Scenarios." *USA Today*, 9 March 2010.

Pugliese, David. "Air Force Short 250 Pilots But Getting A Handle On Retention," *Defence Watch* (June 2008). Journal on-line; available from http://communities.canada.com/ottawacitizen/blogs/defencewatch/archive/2008/06/13/air-force-short-250-pilots-but-getting-a-handle-on-retention.aspx; Internet; accessed 6 January 2010.

Rolfe, John M. "Two Cambridge Inventors." *Royal Aeronautical Society: Flight Simulation Group.* Journal on-line; available at http://www.raes-fsg.org.uk/18/The_Cambridge_Cockpit; Internet; accessed 29 March 2010.

Roscoe, Stanley N. "Simulator Qualification: Just as Phony as It Can Be." *The International Journal of Aviation Psychology* 1, no 4 (Winter 1991): 335-339.

Salas, Eduardo, Clint A. Bowers and Lori Rhodenizer. "It Is Not How Much You Have but How You Use It: Toward a Rational Use of Simulation to Support Aviation Training." *The International Journal of Aviation Psychology* 8, no 3 (Fall 1998): 197-208.

Stewart, D. "A Platform with Six Degrees of Freedom." *Proceedings of the Institute of Mechanical Engineers* 180, no 15 (1965-1966): 371-386.

Ullrich, Walter F. "A History of Simulation: Part II – Early Days." *MS&T Magazine* 5 (2008). Journal on-line; available from http://www.halldale.com/MST_Digital Issues.aspx; Internet; accessed 26 March 2010.

Taylor, Henry L., Gavan Lintern and Jefferson M. Koonce. "Quasi-Transfer as a Predictor of Transfer From Simulator to Airplane." *The Journal of General Psychology* 120, no 3 (Fall 2001): 257-276.

Books

Air Line Pilots Association. *ALPA White Paper: The Need for Motion in Flight Simulation* Washington DC: ALPA International, September 2007.

Allerton, David. *Principles of Flight Simulation*. Reston, VA: American Institute of Aeronautics and Astronautics, 2009.

Anderson, John D. Introduction to Flight. New York: McGraw-Hill, 2000.

Benson, Alan J. "Spatial Disorientation – General Aspects." In Aviation Medecine, edited by John Ernsting, Anthony N Nicholson and David J Rainford, 419-436, Oxford: Butterworth Heinemann, 2000.

Buffett, A.R. "Visual Cueing Requirements in Flight Simulatio." In *Advances in Flight Simulation – Visual and Motion Systems*, 127-149 London: The Royal Aeronautical Society, 1986.

Edwards, David C. *Pilot: Mental and Physical Performance*. Ames: Iowa State University Press, 1990.

Gellingham, Kent K., and James W. Wolfe. "Spatial Orientation in Flight." In *Fundamentals of Aerospace Medicine*, edited by Roy L. DeHart, 299-381. Philadelphia: Lea and Febiger, 1985.

Hettinger, L.J. "Illusory Self-Motion in Virtual Environments." In *Handbook of Virtual Environments*, edited by Kay M. Stanney, 471-492. Mahwah, NJ: Lawrence Erlbaum Associates, 2002.

Jensen, Richard S. *Aviation Psychology*. Brookfield: Gower Technical, 1989.

Kaiser, Mary K. and Jeffrey A. Schroeder "Flights of Fancy: The Art and Science of Flight Simulation." In *Principles and Practice of Aviation Psychology*, edited by Pamela S. Tsang and Michael A. Vidulich, 435-471. New York: CRC Press, 2003.

Lee, Alfred T. *Flight Simulation:Virtual Environments in Aviation* Burlington: Ashgate Publishing Company, 2005.

Mechtronix. *There Is Nothing General About The Way We Approach Aviation* Montreal: Mechtronix Headquarters, 2009.

Moroney William F. and Brian W. Moroney. "Flight Simulation." In *Handbook of Aviation Factors*, edited by Daniel J. Garland, John A. Wise and V. David Hopkin, 355-288. Mahwah, New Jersey: Lawrence Erlbaum Associates, 1999.

Previc, Fred H. "Visual Orientation Mechanisms." In *Spatial Disorientation in Aviation*, edited by Paul Zarchan, 95-144. Reston,Virginia: American Institute of Aeronautics and Astronautics, 2004.

Rolfe, J.M. and K.J. Staples. *Flight Simulation.* Cambridge: Cambridge University Press, 1986.

Ruth, Snowden. *Teach Yourself Freud.* New York: McGraw Hill, 2006.

Soanes, Catherine. *Pocket Oxford English Dictionary*. New York: Oxford University Press, 2002.

Tsang, Pamela S. and Michael A. Vidulich. "Introduction to Aviation Psychology." In *Principles and Practice of Aviation Psychology,* edited by Pamela S. Tsang and Michael A. Vidulich, 1-19. New York: CRC Press, 2003.

Young, Laurence. "Spatial Orientation." In *Principles and Practice of Aviation Psychology*, edited by Pamela S. Tsang and Michael A. Vidulich, 69-113. New York: CRC Press, 2003.

Conference Proceedings

Blake, Mathew W. "The NASA Advanced Concepts Flight Simulator: AIAA Paper 96-3518." In *AIAA Meeting Papers on Disc*. San Diego, CA: AAIA Flight Simulation Technologies Conference, 29-31 July 1996.

Brown, Yorke, Frank Cardullo and John Sinacori. "Need-Based Evaluation of Simulator Force and Motion Cueing Devices." in *Flight Simulation Technology Conference and Exhibit*. Boston: American Institute of Aeronautics and Astronautics, 14-16 August 1989.

Bürki-Cohen, Judith, Andrea L. Sparko and Tiauw H. Go. *Training Value of a Fixed-Base Flight Simulator with a Dynamic Seat*. Hilton Head, South Caroline: AIAA Modeling and Simulation Technologies Conference, 20-23 August 2007.

Bürki-Cohen, Judith, Andrea L. Sparko and Young Jin Jo. "Effects of Visual, Seat, and Platform motion During Flight Simulator Air Transport Pilot Training and Evaluation." In *Proceedings of the 15th International Symposium on Aviation Psychology*. Dayton, OH: Wright State University, 27-30 April 2009.

Bürki-Cohen, Judith, Tiauw H. Go, William W. Chung, Jeffrey Schroeder, Sean Jacobs and Thomas Longridge. "Simulator Fidelity Requirements for Airline Pilot Training and Evaluation Continued: An Update On Motion Requirements Research." In *Proceedings of the 12th International Symposium on Aviation Psychology*. Dayton, OH: Wright State University, April 2003.

Bürki-Cohen, Judith, Thomas Longridge, Edward M. Boothe, Nancy N. Soja, Robert DiSario and Tiauw Go. "Simulator Fidelity – The Effect of Platform Motion." In *Proceedings of the International Conference Flight Simulation – The Next Decade*. London: Royal Aeronautical Society, 10-12 May 2000.

Bürki-Cohen, Judith, Andrea L. Sparko, Young Jin Jo and Tiauw H. Go. "Effects of Visual, Seat, and platform Motion During Flight Simulator Air Transport Pilot Training and Evaluation." In *Proceedings of the 15th International Symposium on Aviation Psychology*. Wright State University, Dayton, Ohio, 27-30 April 2009.

Hosman, Rudd, Sunjoo Advani and Nils Haeck. *Integrated Design of Flight Simulator Motion Cueing Systems*. London: Royal Aeronautical Society Conference on Flight Simulation, May 2002.

Liebowitz H. and C.L. Shupert. "Two Modes of Visual Processing: Implications for Spatial Orientation." In *Peripheral Vision Horizon Display*, 41-44. Edwards, California: NASA Conference Publication 2306, 14 November 1984.

Money, K.E. "Theory Underlying The Peripheral Vision Horizon Device." In *Peripheral Vision Horizon Display*, 45-55. Edwards, California: NASA Conference Publication 2306, 14 November 1984.

Page, Ray L. "Brief History of Flight Simulation." In *SimTechT 2000 Proceedings*. Sydney: The SimtechT 2000 Organizing and Technical Committee, 2000; available from http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.132.5428&rep=rep1&type=pdf; Internet; accessed 18 December 2009.

Riecke, Bernhart E., Jörg Schulte-Pelkum, Marios N. Avraamides and Heinrich H. Bülthoff. "Enhancing the Virtually Induced Self-Motion Illusion under Natural Viewing Conditions." In *Presence 2004: Conference Proceedings*, 125-132. London: University College London, September 2004.

Riecke, Bernhard E. Jörg Schulte-Pelkum, Franck Caniard and Heinrich H. Bülthoff. "Influence of Auditory Cues on the Visually-Induced Self-Motion Illusion in Virtual Reality." In *Presence 2005: Conference Proceedings,* 49-57. London: University College London, September 2005.

Young, Laurence R. "Visually Induced Motion in Flight Simulators." In *Advisory Group for Aerospace Research and Development (AGARD) Conference Proceedings* No 249. Brussels: AGARD,1978.

Government Documents

Canadian Air Division. *C-12-130-00/MB-005, CC130 Hercules Flight Crew Checklist Change 2000-02-18*. Ottawa: Department of National Defence, 1998.

Federal Aviation Authority. *Line Operation Simulations, Advisory Circular 120-35C*. Washington DC: US Department of Transportation, 2004.

Joint Aviation Authority. "Joint Aviation Regualtions." Available from http:// www.jaa.nl/publications/jars/ JAR-FSTD-A_sec1_0508.pdf; Internet; accessed 26 February 2010.

Transport Canada. *Canadian Aviation Regulations (CARS) and Commercial Air Service Standards (CASS) – Part VII – Subpart 5 – Guidance Material*. Ottawa; Transport Canada, 2005. Available from http://www.tc.gc.ca/civilaviation /commerce/manuals/guidance705/menu.htm

Transport Canada. *Development and Implementation of an Advanced Qualification Program*. Ottawa: Transport Canada, 2005. Available from http://www.tc.gc.ca/ civilaviation/commerce/aqp/menu.htm.

Transport Canada. "TP 9685." Available from http://www.tc.gc.ca/civilaviation/ publications/tp9685/ chapter2/menu.htm; Internet; accessed 26 February 2010.

United States Air Force. *C-17 Flight Manual Performance Data – Change 1*. Wright Patterson Air Force Base: Department of Defense, 2007.

United States Air Force. *1C-17A-1: C-17 Flight Manual Change* 4. Wright Patterson Airforce Base: Department of Defense, 2006.

Reports

Blickensderfer, Beth, Dahai Liu and Angelica Hernandez. *Simulation-Based Training: Applying Lessons Learned from Aviation to Surface Transportation Modes*. Daytona Beach: Emery Riddle Aeronautical University, 2005.

Boeing Aviation Safety. *Statistical Summary of Commercial Jet Airplane Accidents*. Seattle, WA: Aviation Safety Boeing Commercial Airplanes, July 2009. Available from http://www.boeing.com/news/techissues; Internet; accessed 17 February 2010.

Bowen, Shane A., Brian P. Oakley and John S. Barnett. *Effects of Motion on Skill Acquisition in Future Simulators: Study Report 2006-07*. Arlington, VA: US Army Research Institute for Behavioral and Social Science, 2006.

Bradshaw, Gary, Henry Taylor, Gavan Lintern and Don Talleur. *The Potential of Subjective Estimates of Transfer, Technical Report ARL-99-6*. Dayton, Ohio: Innovative Technologies Corporation, May 1999.

Brown, Yorke J., Frank M. Cardullo and John B. Sinacori. *Effects of Motion on Skill Acquisition in Future Simulators, Study Report 2006-07* Arlington, VA: United States Army Research Insitute for the Behavioral and Social Sciences, May 2006.

Bürki-Cohen, Judith, and Tiauw Go. *The Effect of Simulator Motion Cues on Initial Training of Airline Pilots* Reston, VA: American Institute of Aeronautics and Astronautics, 2005.

de Graaf, Bernd, Wim Bles, Mark Wentink and Willem Tielemans. "MSC: Vehicle Validation of Military Flight Simulation." Available from http://ftp.rta.nato.int/Public/PubFullText/RTO/MP/RTO-MP-HFM-136/MP-HFM-136-16.pdf; Internet; accessed 10 January 2010.

Kobierski, R and C Stickney. *Air Force Automation and Planning Development (APPD) Project – Automation Analysis Report, PWGSC Contract No. W8485-0-XKCF/01/BQ*. Ottawa, ON: Public Works and Government Services, 29 September 2008.

McCauley, Michael E. *Do Army Helicopters Simulators Need Motion Bases*? Arlington, Virginia: U.S. Army Research Institute for the Behavioral and Social Sciences, Army Project Number 622785A790, 2006.

Riecke, Berhard E., Jörg Schulte-Pelkum, Franck Caniard and Heinrich H. Bülthoff. *Towards Lean and Elegant Self-Motion Simulation in Virtual Reality* Bonn, Germany: IEEE Virtual Reality, 2005.

Roach, Gregory D, Renée M. Petrilli, Drew Dawson and Matthew J.W. Thomas. *The Effects of Fatigue on the Operational Performance of Flight Crew in a B747-400 Simulator*. Adelaide: Centre for Sleep Research, University of South Australia, 2006.

Sharkey, T.J. and M.E. McCauley, *Does A Motion Base Prevent Simulator Sickness – AIAA Report 92-4134-CP*. Washington DC: American Institute of Aeronautics and Astronautics, 1992.

Websites

Ascent-UK. "History of Flight Simulators (2007)." http://www.ascent-uk.co.uk/history.htm; Internet; accessed 26 March 2010.

ATR. "Company Profile." www.atraircraft.com; Internet; accessed 15 February 2010.

Centennial Celebration Baddeck 2009. "The Flight of the Silver Dart." http://www.flightofthesilverdart.ca/; Internet; accessed 16 January 2010.

Columbia University. “The Vestibular System.” http://www.columbia.edu/itc/hs/medical/neuralsci/2004/slides/32_LectureSlides.pdf; Internet; accessed 17 March 2010.

Jonathan Gabbai: Emergent Systems, Management and Aerospace Topics. “The Art of Flight Simulation, Section 1.2.” http://gabbai.com/academic/the-art-of-flight-simulation; Internet; accessed 16 January 2010.

Moore, Kevin. “A Brief History of Aircraft Flight Simulation.” http://homepage.ntlworld.com/bleep/SimHist1.html; Internet, accessed 20 December 2009.

Phillips, David L. “The Proprioceptive Nervous System.” http://www.suite101.com/article.cfm/chiropractic_health_care/102364; Internet; accessed 19 March 2010.

Research and Innovative Technology Research. “Volpe National Transportation Systems Center.” http://www.volpe.dot.gov/about/index.html; Internet, accessed 21 November 2009.

Thales. “A Layman’s Guide to Full Flight Simulators.” http://www.thalesgroup.com/News_and_events/2009-01-27_UK_FOC_Aero_Laymans_Guide_FFS/; Internet; accessed 14 January 2010.

Thales, “Civil Aviation Training Capabilities.” *Thales Pamphlet 5A-26-0220078* available from www.thalesgroup.com

US Centennial of Flight Commission. “Jimmy Doolittle – Avation Star.” http://www.centennialofflight.gov/essay/ Air_Power/doolittle/AP17.htm; Internet; accessed 21 February 2010.

Wartime Memories Project. “Information.” http://www.wartimememories.co.uk/airfields/silloth.html; Internet; accessed 29 March 2010.