University of Nevada, Reno

Applications and Evaluation of a Motion Flight Simulator

A dissertation submitted in partial fulfillment of the

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by

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Abstract

This dissertation presents a collection of discoveries and results obtained in assembling and utilizing a high-fidelity flight simulation system. Two users, secured with a seatbelt and harness, can experience the simulation together (lasting 3 to 6 minutes). At appropriate intervals G-forces and quick rotations are introduced, so users can experience the feeling of control of a powerful aircraft. This effect is further enhanced through the incorporation of a virtual reality and a gesture tracking experience. In this dissertation a review of the existing literature is provided, and an enhanced solution is proposed for a flight simulator using the Maxflight platform. Details of the simulator's renovations and improvements are provided, together with a presentation of the key aspects of the platform's hardware and software integration. These activities constituted a massive engineering effort, involving work in various fields, including mechanical and electrical engineering. Furthermore, descriptions of gesture tracking, error handling, flight formation scores, and other key features of the software created are also presented. In particular, the software built to deliver an immersive flight simulation experience is described in terms of software model, including requirements specification and design, prototype implementation, and user interface design. Four research questions were formulated regarding the application of the simulator to entertainment, education, and training, and two usability studies were conducted to answer them. The results of these user studies are presented in the dissertation. Finally, two case studies illustrating the use of the simulator are also described and several potential directions of future work are outlined.

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Table of Contents

List of Tables

List of Figures

Chapter 1 INTRODUCTION

The research focuses on three applications of a flight simulation system: education, entertainment, and pilot training. The simulation framework presented in this dissertation includes hardware, a game built using Unity, flight simulation capabilities with C#, and an educational 2D experience. Tests were performed to ensure the system was reliable, and had safety procedures in place. During the course of this project over 450 users have experienced the flight simulator.

To begin this dissertation, a thorough search of the existing literature was performed. One challenge found in this type of research is that there are many different approaches to solve the same problem. A search of available research and literature left much to be desired; thus this study is somewhat in uncharted waters. System engineering principles were applied, and software engineering best practices were utilized in this work, such as requirements engineering and agile development. Those skills enabled the project to remain on course throughout the various development stages. Multiple prototypes based on old, decommissioned, previously intensively used simulators, had to be constructed and then revised to reach the final product.

A motion flight simulator can cost millions of dollars to construct. The opportunity to work on one was something that could not be passed up. There are not many people who would be willing to tinker with a flight simulator after investing so heavily to get it operational. This research is unique because I had access to a motion flight simulator, even though out of use at the time of our acquisition. This dissertation involved various approaches and activities including: taking the flight simulator apart, exchanging different components, learning how different components work, and augmenting the system in different ways to address four research questions (hypotheses). The research questions formulated pertain to using the motion flight simulator platform in various types of application, particularly in entertainment (games), education, and training. To answer the questions, two user studies involving 38 participants were performed and two case studies involving more than 400 participants took place. Three of the research hypotheses were validated by the findings of the user studies, and one was invalidated because of lack of statistical significance.

All of the above are detailed in this dissertation, as follows: Chapter 2 provides a background of flight simulation and its applications; Chapter 3 presents the hardware platform renovated and used; Chapter 4 outlines the proposed solution and scope of work; Chapter 5 provides details of the software model that was created, including details of requirements and design; Chapter 6 presents the prototype and experimental results gained from the software; Chapter 7 analyzes the data from the two usability studies performed, and addresses the four research questions outlined in this dissertation; finally, Chapter 8 completes the dissertation with a conclusion, review of the key components, and an outline for future work.

Chapter 2 BACKGROUND: FLIGHT SIMULATION

This dissertation is focused on proposing a novel framework, including new software and technologies, for incorporating flight simulations for various levels of education, entertainment, and training; therefore, a brief background in the technologies available today for flight simulation is needed. This chapter provides an introduction into flight simulation technologies that most pilots use to receive and maintain their commercial certifications. Applications of such techniques as well as advantages and disadvantages are also presented.

2.1 Industry Trends

The aviation industry is a very promising place to be right now according to Eric Rosen at National Geographic [1]. Air travel has been steadily expanding, while the number of pilots completing their training has failed to keep up with the demand. Furthermore the rapid development and economic rise of Asia has prompted further need for airplanes and the pilots who fly them. Already by 2016, the ten busiest routes took off and landed in the Asia-Pacific region, as shown in Figure 2.1. One route of note is the Seoul to Jeju Island leg; it is known as the busiest route, and is also a popular honeymoon destination for newlywed Koreans.

Figure 2.1 Ten busiest air routes in the world **[1] [2]**

The rise of commercial air travel is not just limited to Asia. Globally, there are over one hundred million new passengers entering the market annually, as shown in Figure 2.2. Some regions of exceptionally strong growth include the Pacific, Africa, and parts of South America.

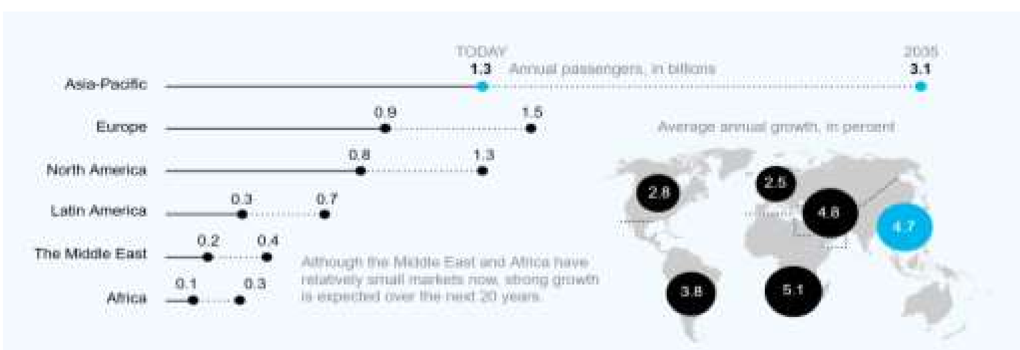

Figure 2.2 Estimated regional growth percentages through 2035 for world economies

This has all led to an epic pilot shortage among airliners. Desperate for new recruits, domestic airlines have even started setting up their own training academies. One of these is the American Airlines Cadet Academy; they include a financial aid package for obtaining a pilot's license, and provide a sign-up bonus for joining their company (a practice unheard of just a few years ago) [3]. To obtain a commercial pilots license 1,500 flight hours and an FAA credential are required for an appointment to first-officer with a regional airliner (sometimes also referred to as an ATP license, or air transport pilot license) [4]. This can cost between $60,000 and $100,000 (USD) according to Zac Armstrong of Freedom Jets and Allegiance Aviation [5]. This might seem like a preposterous sum; however, for comparison consider the National Center for Education Statistics' listed average cost for obtaining a PhD, as shown in Figure 2.3 [6].

Academic Field	Median Years to Completion	Tuition
Education	11.7	$121,774
Humanities	9.2	$95,754
Social Sciences	7.7	$80,142
Life Sciences	6.9	$71,815
Engineering	6.6	$68,693
Physical Sciences	6.5	$67,652

Figure 2.3 Listed average cost for obtaining a PhD in 2012-2013. Undoubtedly tuition has risen since **[6]**.

As demonstrated by data gathered by the National Bureau of Labor Statistics, Earnings, and Unemployment the higher educational obtainment of PhDs also correlates to higher pay, shown in Figure 2.4 [7].

Educational Attainment	Avg. Weekly Earnings	Avg. Yearly Salary	Unemployment Rate
Professional Degree	$1,639	$85,228	1.9%
Doctoral Degree	$1,591	$82,732	2.1%
Master's Degree	$1,326	$68,952	2.8%
Bachelor's Degree	$1,101	$57,252	3.5%
Associate Degree	$792	$41,184	4.5%
Some College, No Degree	$741	$38,532	6.0%
High School Diploma	$668	$34,736	6.0%
Less Than a High School Diploma	$488	$25,376	9.0%

Figure 2.4 Listed average cost for obtaining a PhD in 2012-2013 **[6] [7]**

In a similar way newly minted pilots can climb a robust career ladder, stepping up from regional routes to larger aircraft in more exotic locales. While their initial salary is lower, after some time pilots become highly compensated in their mid to late-career salaries, as demonstrated in Figure 2.5 [8]. It should also be noted that the total time from the beginning of training to becoming an airline pilot is typically three to four years according to Erica Martin at Phoenix East Aviation [9].

Of course money isn't everything. Most doctoral candidates chose to pursue a doctorate for a deeper understanding of research, instead of focusing on the money. In a similar way most pilots aren't likely to incur debt, while withstanding the strict training requirements of a career in aviation, solely for future earnings. They might rather chose the career for the unique lifestyle it brings, as well as the unbeatable views from the cockpit. Regardless, it is helpful to note that a newly minted pilot's financial prospects are looking better than ever [10].

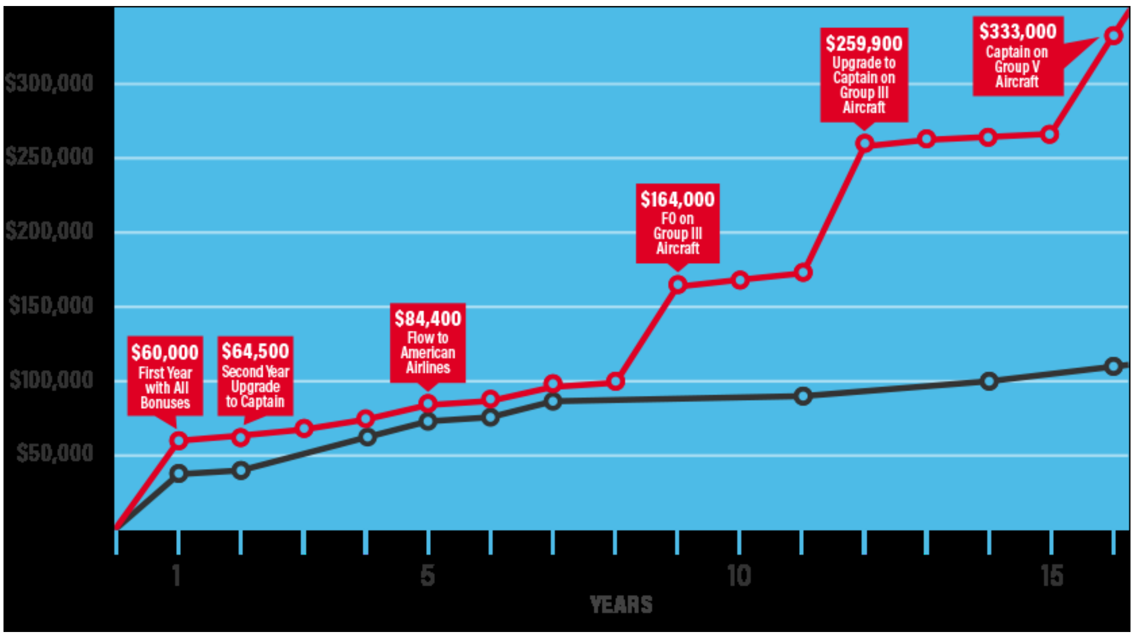

Figure 2.5 Listed salary for a pilot at Piedmont aviation in red vs a pilot instructor in black **[8]**

As of now less than 20% of the world's population has been on an airplane according to Boeing's CEO Dennis Muilenburg [11]; however, in the coming years as more airports are built [12], opening up new regions worldwide [13], 617,000 new pilots globally will be needed (as demonstrated in Figure 2.6 [1]). New data from Boeing indicates this number is even higher, as they are projecting 790,000 new pilots will be needed by 2035

[14]. Further complicating the situation is that nearly 50% of pilots flying today are Baby Boomers, an age group that will bring on a wave of retirements in the coming decades. Even if these older pilots didn't want to retire FAA rules require that commercial airliner pilots must retire by the age of sixty-five [15] [16].

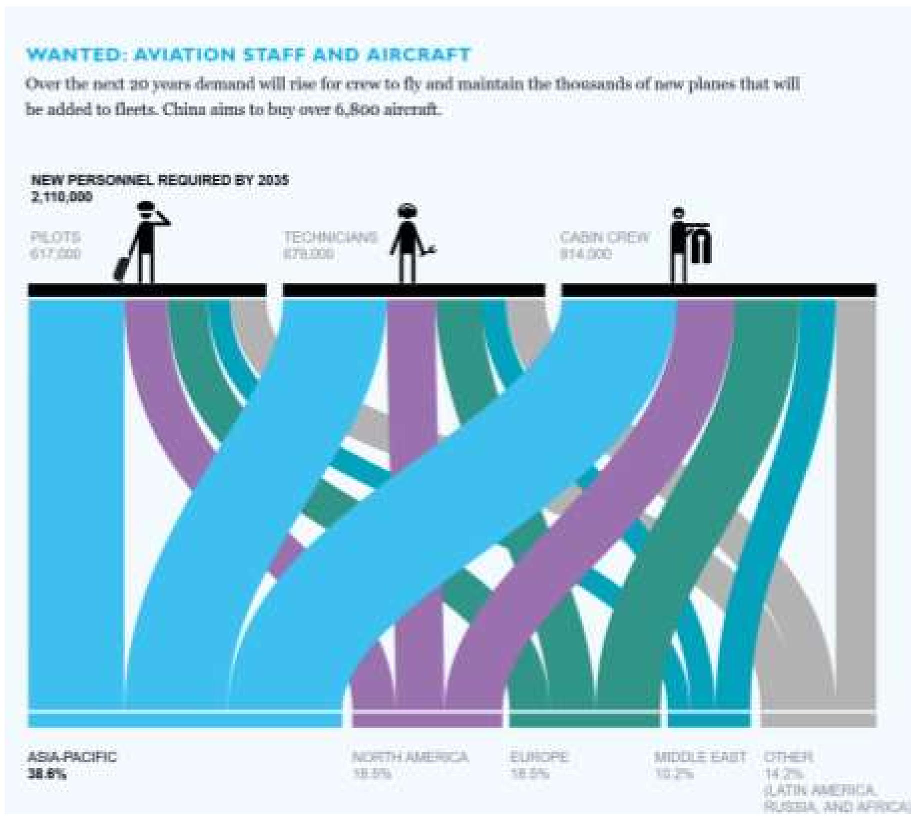

Figure 2.6 Many new pilots will be needed in the coming years **[1]**

The pilot shortage has only just begun to be felt. Domestically, the pressure is mounting as demand continues to rise, while the supply hasn't kept up. While there has been talk in congress of reducing the 1,500 flight hour experience requirement, such a move seems unlikely [14] [17].

Ultimately this means pilots in training will be pressured to complete their ATP requirements expediently so they can reap the benefits of the booming market. This presents an opportunity for new technologies to speed up the training process, while keeping the quality of the education process the same. One such technology, with a proven history of pilot training, is flight simulation.

2.2 History of Flight Simulation

Airline pilots have used flight simulators as an essential training and educational device for decades [18]. Nearly all commercial airlines since the 1960's have used flight simulators as a safer and more effective way of training their pilots [19] [20]. According to Ray Page even the space program benefitted significantly from the use of simulation technology, "it would not have been possible for man to have set foot on the moon without the training provided by simulation, and the use of simulation to assist the problems with the Apollo 13 Mission is now legendary" [21].

Simulators eventually evolved to use motors, sensors, and modern electronics; this led to more dynamic and complex systems to replicate the sensations of flight. More recently (starting in the 1990s) the industry began to see flight simulations where the experience was primarily driven through computer software [20] [22].

This software enabled users to reap the training benefits of flight simulation in the comfort of their own home. However, just software alone does not provide much feedback to the user. Piloting an airplane via keyboard and mouse doesn't translate very well into real-world flight. Thus a hardware-software solution, such as flight simulator software paired with a joystick, throttles, and a rudder, would make a more meaningful training device [23]. Flight simulators also evolved from pilot training to various teaching applications. One example of a flight simulator being used in a teaching application can be found in Thomas Siju's thesis at Ryerson University [24]. In it a flight simulator was utilized for tutoring of flight dynamics and stability control. Users did not have control over the aircraft, they were placed in a 'recorded' flight session utilizing Prepare3D [25]. Later in the experiment users were allowed to take over aspects of the aircraft, and their attempts to stabilize the aircraft were collected using a 3rd party commercially available data analysis tool called CAE Flightscape [26].

In an attempt to achieve a higher level of immersion, private citizens have started building their own flight simulators at home. These simulators, made with readily available parts from the automotive and construction industries, can deliver a surprising level of fidelity for a low budget [27] [28]. Furthermore, the use of 3D printing has enabled the development of custom parts to become even more affordable [29]. As the power of personal computing graphics has become stronger, these custom-built systems have begun to include items such as eye-trackers or VR headsets. One can currently find various handmade, custom-built simulators from members of the aviation community. Active flight simulator communities can be found on websites like Xsimulator [30].

Figure 2.7 is a historical photograph of what was quite possibly the very first flight simulator ever invented, called the Antoinette trainer [31]. It consisted of two barrel halves, and a swinging cockpit to simulate the motions of flight when men standing on either side of the platform would use levers to rock the cockpit. At the time of this invention, the Wright Brothers had flown the first aircraft only a few years earlier in 1903 [32].

As humanity had minimal experience operating an airplane at this time, one can imagine being able to simulate and visualize the feeling of flying was a tremendous asset both scientifically and psychologically for those who would make the brave choice to pilot experimental aircraft in the early 20th century.

Figure 2.7 A historical model of a flight simulator from 1910 **[22]**

2.3 Flight Simulation Examples

Using flight simulation as a form of training is not a novel concept. In fact some people are so enthusiastic about flight simulators they have pieced one together from decommissioned aircraft parts. James Price serves as a prime example of this. He built a complete 737 simulator in his garage in Pleasanton, CA. It took over 10 years to construct, countless hours, and a fortune. Figure 2.8 shows Mr. Price and his simulator [33].

Figure 2.8 James Price and his self-built Boeing 737 simulator **[33]**

The flight simulator uses a real 737 cockpit, and is so large that his garage had to be extended around the simulator. A photograph of the cockpit when it was first obtained is shown in Figure 2.9 [34].

Figure 2.9 The cockpit of the flight simulator being delivered **[34]**

Mr. Price used genuine aviation parts where possible, and substituted alternative electronics to achieve the "glass cockpit." A glass cockpit is where all the traditional analog gauges in an aircraft cockpit are replaced with a digital screen. An example of this cockpit is shown in Figure 2.10.

Figure 2.10 The inside of James Price's 737 simulator **[34]**

Flight simulations can be useful for both educational and entertainment purposes. A recent study by UCSF indicates that applied learning techniques, such as those used in simulation training, result in far more effective learning than alternative methods [35]. Professional flight simulator software and hardware in the commercial aviation industry is used to train pilot preparedness for failures and emergencies; the flight simulation industry has totaled approximately five billion dollars of economic activity in 2016 and is expected to grow over 4.89% yearly [36] [37].

Flight simulators have come a long way from their initial prototypes. Earlier hardware from the 1900's involved a wooden frame with a rocking platform (as shown earlier in Figure 2.1). According to Mr. Ray Page the 1960's marked the era of modern flight simulation: "*With the development of commercial wide-body aircrafts, there was no way to get past increasingly sophisticated motion systems. The three basic axes for the pitch, roll, and yaw motions were followed shortly thereafter by the possibility for up-and-down motion"* [21].

While flight simulation technology has advanced drastically since its creation, it still costs millions of dollars, and is normally reserved for military and commercial training. Military applications of flight simulators involve some of the most intricate and expensive set ups. One such example is the Kraken disorientation device, used by the office of Naval Medical Research. This unit located in Dayton, Ohio is designed to simulate high-g environments to research the ability of pilots to maintain focus under stress [38]. A photo of this simulator is used in Figure 2.11.

Figure 2.11 The KRAKEN of the Naval Research **[38]**

This simulator has six axes of motion, capable of generating up to 3Gs of sustained force. Unfortunately this simulator is far too expensive for most, if not all, enthusiasts and commercial applications because of its cost at an $18 million USD price tag.

Another application of flight simulation is the airline industry. Airliners have been using flight simulators for the bulk of their pilot training since the 1960's [36]. According to a safety briefing by the FAA [39], flight-training devices are simulations that include a cockpit and represent a specific aircraft configuration. Flight Safety International, a company in Flushing, NY, makes a simulator for the Airbus A320 a narrow-body jet used for regional flights. The simulator hardware is a six-axis Stewart platform capable of simulating motions in pitch, yaw, and roll [40]. However, one of the limitations of the Stewart platform is its limited range of motion in each axis. According to a frequent flier familiar with the airline industries inner-workings: "Professional-grade flight simulators cost tens of millions of dollars, and are sometimes worth even more than the actual aircraft they're simulating" [41]. An example of a flight simulation training device, rated by the FAA as a "level-D" simulator the highest level obtainable, is shown in Figure 2.12.

Figure 2.12 A commercial flight simulator used to train pilots on the airbus A320 airplane **[40]**

Chapter 3 MATERIALS & METHODS: THE MAXFLIGHT PLATFORM

The MaxFlight Corporation, based in Tom’s River, NJ, has produced a line of flight simulators, which reduces the cost of a flight simulator from millions of dollars to $160,000 (USD) for a new unit. MaxFlight Corporation does this while retaining full 360 degree motion in two axis. This device, geared for the entertainment industry, was originally introduced in Disneyland, and is currently in use in over forty Family Entertainment Centers (FECs) and museums [42].

The significantly smaller price tag allows for smaller organizations and businesses to invest in flight simulation, through which those establishments can make it accessible to the public. The MaxFlight FS2000 is a flight simulator model located in museums and amusement parks around the world [42] (and is the system used in this dissertation). The FS2000 seats two riders and allows for full 360-degree motion on the roll and pitch axes. This simulator uses Lenze Vector 8200 frequency inverters to set the speed and direction of the electric motors that moves the cabin. Integrated into the cabin is a full 1080p HD projector, speakers, two joysticks, and vents that blow air into passengers faces to simulate motion (and help ease motion sickness [43]).

The aim of this chapter is to give readers an understanding of the MaxFlight platform, so they can better understand the challenges, advantages of such a system, and the tremendous amount of effort involved in renovating a decommissioned one (by a small group of people).

3.1 Deprecated Versions – Simulators 1 & 2

In science, one does not always get the formula right the first time. This was certainly true for this project, which required many iterations of trial and error to arrive at a solid prototype. Thomas Edison once said: "I have not failed 10,000 times. I have not failed once. I have succeeded in proving that those 10,000 ways will not work. When I have eliminated the ways that will not work, I will find the way that will work" [44].

An essential requirement to answer the research questions, outlined in Section 4.1, was a working hardware prototype. This section highlights some of the prototypes that didn't make the cut.

Version 1 – hydraulic simulator: The first prototype was based on an old, out of operation, VR 2002 simulator purchased from an FEC in Florida, where it was intensively used for a good number of years. It was put together in a 20'x20' self-storage unit with limited tools and resources. After moving it to Nevada, the simulator underwent the beginning phases of assembly in February 2017 when temperatures were around freezing. As a result of the cold temperatures, and lack of heat in the storage unit, several layers and gloves had to be worn at all times to keep warm.

This project took months to put together, specialty tools were purchased, and many man hours of work. One of the specialty tools that was purchased was a forklift, used to help move the heavier objects; this was needed due to the mass of several components. Even then the forks on the forklift were too short to reach the rear part of the storage unit, and a system of straps and pulleys to leverage the larger pieces into place was rigged as demonstrated in Figure 3.1.

Figure 3.1 An example of improvisation with an irregularly long and heavy object

By early summer 2017, all the components were together in the storage unit, while the system worked, it had a number of issues. The old Windows NT 4.0 computer often crashed, the motors made strange noises, and the hydraulics were extremely loud. The motors inside the simulator were powered by hydraulics operating at 250 bar (~3500 psi); a lot of investigation went into learning how the motors operated, making progress slow.

Furthermore Version 1 lacked any sort of flight controls or joysticks in the cockpit, so even when it did work it was a completely passive experience. There was only one option built-in: an asteroid themed roller coaster. The experience was more or less the same each time. In the end, the first version was simply not satisfactory to us. While the inspiration was certainly there, it became difficult to use for our intended experimentations.

Version 2 – 1st Firmware Attempt: Realizing the pressing issue with Version 1 was its lack of reliability, Jake Lee and I collaborated to try to create a software solution to fix the reliability problem. Version 2 was inspired by the work of Alex Swann [45] and Charlie Hein [30], who appeared to have re-written another flight simulator's firmware and connectivity using an Arduino Duo and a tool called SimTools. The idea was to cut out old controls and replace it with newer microcontrollers.

After weeks of struggling to reproduce their results, in a post-mortem discussion it was discovered that all involved had run into essentially the same issues: the critical component connections used mil-spec adapters, which were hardened connections that were difficult to find, and could not fit into standard plugs or receptacles in our electronics. This is shown in Figure 3.2. Operating voltages were outside of the range of the Arduino that Jake and I were retrofitting. The solution required an OpAmp and separate relays to interpret and drive voltages, which Jake initially put together. Finally the Arduino itself was just so limited in memory and compute power that it didn't handle the multi-tasking environment of the simulator very well.

Figure 3.2 The mil-spec adapters

<u>Version 3 – Electric and Hydraulic:</u> In the end the attempt to fix old hardware with software failed, and the hydraulic flight simulator prototype was abandoned. Determined to see the project completed, alternatives were explored; eventually, it was determined that it would be better to start over with another simulator. In December 2017 another old, out of operation, previously intensively used simulator (FS 2000) was purchased from a museum in Alabama. This simulator came with a set of challenges: it lacked any video, a sound system, the pitch motor seemed seized, and there was some sort of electrical issue that kept the prior owners from utilizing it. However, it came with joysticks in the cockpit (although those later had to be re-engineered). Through the same experimentation and persistence applied earlier, eventually a working simulator prototype was developed that was utilized in this research: Version 3, a more advanced design combining elements of both hydraulic and electric systems with a newer central control circuit forgoing the older mil-spec connector design for a central register communicating to components via RS-485. Version 3 is described in detail in Sections 3.2 to 3.5 that follow.

3.2 Cockpit

The flight simulator cockpit seats two: a pilot and a co-pilot. It consists of a steel box frame, a reinforced rear firewall (that contains the flange for the main mount), and a fiberglass shell for the exterior. Two pilots are secured into the seats with a lap belt and a harness that goes over the shoulders which held them in place when rolling upside down. A picture of the cockpit can be seen in Figure 3.3.

Figure 3.3 A photo of the cockpit and harness system. Both the lap-belt and shoulder harness are unsecured in this photo. NOTE: this is an early photo of when the flight simulator first arrived, and it went through a thorough cleaning afterwards.

This simulator has similar controls to a real aircraft; both the pilot and co-pilot have identical sets of controls. Due to the cost of controllers, the setup had to be kept simple. All the aviation control surfaces are controlled by two joysticks in the simulator. There are many controls on an aircraft, but perhaps the six main controls pilots use the most would be: engine speed, ailerons, elevators, the rudder, flaps, and spoilers [46]. A NASA-made illustrating the location of each plane component and the control surfaces are shown in Figure 3.4.

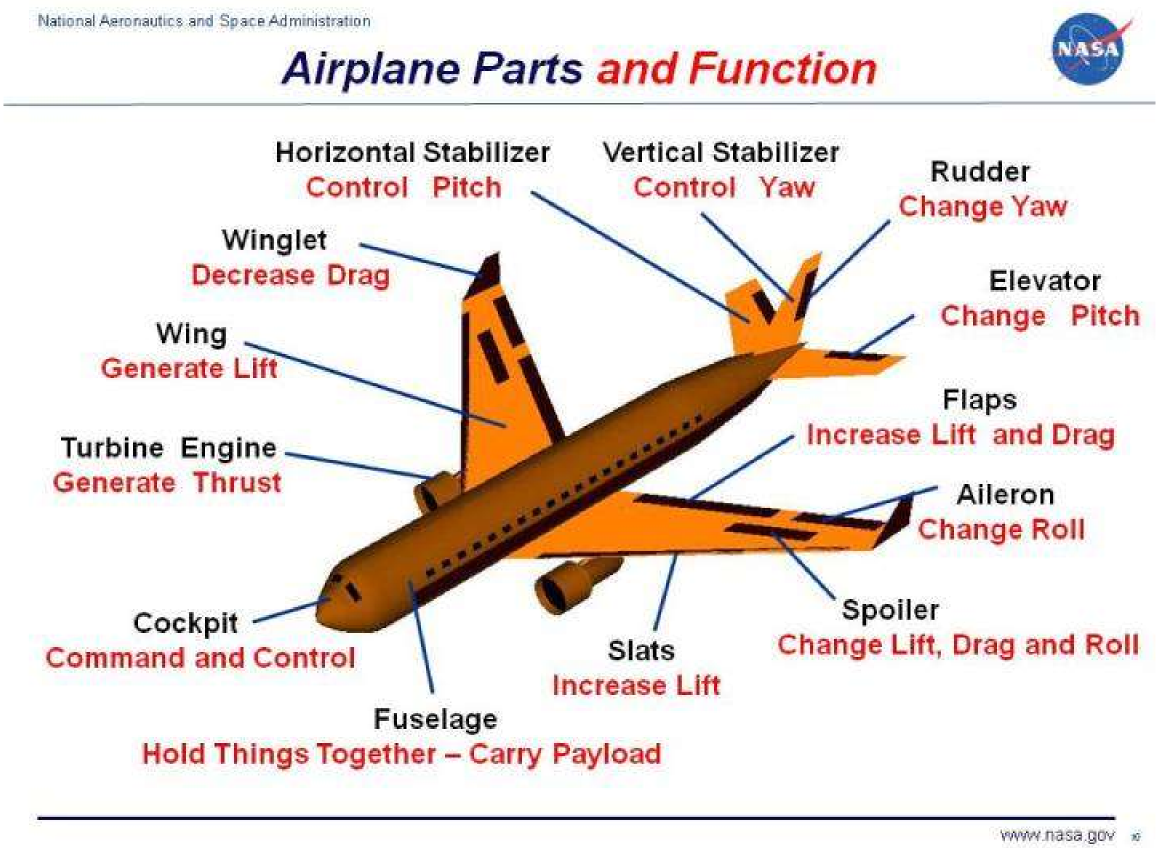

Figure 3.4 Critical systems of airplane flight **[47]**

These six controls allow the pilot to control the pitch, roll, and yaw of the aircraft (as well as its speed, and other aerodynamic properties). The pilot needs to constantly be aware of these controls, so that he or she can keep the plane flying and headed in the right direction. In the simulator, pilots have access to a joystick for controlling the ailerons and elevators of the aircraft, and a throttle for controlling the speed of the engines. While the system does not contain a rudder control at this time, it is something that may be added in the future.

As technology has improved computers have been integrated into almost all aspects of life [48]. This is no different in the aviation industry. Currently computer software is an essential part of keeping traffic organized in the air via an air traffic controller (also sometimes abbreviated as ATC) [49] [50]. An example of this software is shown in Figure 3.5. Technology has changed not just the ATC but also how the pilots fly the planes. Auto-pilot can fly a plane for hundreds of miles without needing human input.

Figure 3.5 An example of software developed by Saab for use as an air traffic controller **[49]**

In addition, according to the International Journal of Control, fly-by-wire systems (where all control surfaces of the airplane are indirectly linked to the cockpit via computer controls) have taken over the manufacturing for large commercial aircraft [51]. This means that in an Airbus A330 aircraft, when the pilot moves the joystick down to make the nose pitch down the actual joystick and the control surface on the wings are not mechanically linked. Instead the joystick feeds commands to a computer which then forwards the signal to direct the wings to turn in the appropriate way.

The controls work in the flight simulator in a similar way. The joysticks send commands to the game computer, which then directs those commands to the control surfaces in the simulation. Then the simulation engine responds by computing how the changed aerodynamic surface would affect the orientation, speed, or altitude of the airplane. The joysticks for the cockpit were described in a paper I presented at the 27th International Conference on Software and Data Engineering [52] to resolve the issue of multiple simultaneous joystick input from both pilots. These techniques are discussed in Section 5.4.

Another component of the cockpit is the display system. Over the course of this project a new display system was installed as the flight simulator did not have any display when it was purchased from the science museum. An 800x600, 600 lumens projector was first incorporated into the system, which was borrowed from one of the earlier flight simulators (version 1). While it worked, the old projector was inadequate; it was dim, had poor resolution, and it needed a projector that was higher quality. An Optoma HD141x

DLP 1080p 3000 lumen projector [53] was obtained to resolve this issue, but the projector did not work on arrival. After taking it apart the bad component was found: a defective color wheel. The color wheel was replaced, as well as the lamp (this was not necessary, but a proactive step) to get the projector functional as seen in Figure 3.6.

Figure 3.6 (Left) the defective color wheel. Notice the hazing on the color elements and the escaped bearing grease. (Right) the repaired projector with a new color wheel ready for mounting in the cockpit.

A surround-sound system was also incorporated into the cockpit. For this, a Creative I-trigue 3600 surround sound system was acquired. The subwoofer was mounted under the left pilot seat, and the speakers were mounted inside the cockpit overhead of the pilots as shown in Figure 3.7.

In this simulator, the cockpit door is actually part of the cockpit itself. Located on the front of the simulator, the cockpit is divided in two halves: a stationary lower half, and an upper half mounted to by a hinge.

Figure 3.7 The sound system

When pilots wish to enter or disembark from the flight simulator an attendant outside the flight simulator must unlatch the top half of the flight simulator from the bottom; this causes the cockpit “door” (the upper half of the cockpit) to swing open via 110 lbs pneumatic pistons. The hinge creates roughly a 6 foot 3 inch tall opening, which allows for most people to enter and exit the simulator (tall people must duck on their way in or out). When a new group of pilots has taken their seats and is ready the attendant lowers the upper half of the cockpit by grabbing a handle, and locks it into place via a latch. The cockpit is sealed via a rubber gasket that surrounds the lip of the upper half, so that light from the outside does not enter the cockpit and break the pilot’s immersion.

Finally, there is the ventilation system. There are many electronic components inside the cockpit, which produce heat: the flight controls, sound system, projector, and game computer. The ventilation system’s purpose is to bring fresh air into the cockpit for cooling. There are four ventilation fans; the first is positioned directly into the computer intake for cooling of the game computer's sensitive electronics. The second is positioned directly over the projector, for cooling the DLP projector's light bulb (which operates at a very high temperature). Finally, the last two fans have a ducting system that directs fresh air over the pilots. Having moving air inside the cockpit serves an additional purpose to cooling; it also provides alleviation of motion sickness as shown in Mr. Neil Mansfield's book, Human Response to Vibration, citing research from the US Navy on simulator sickness [54] [55].

3.3 Power Requirements

The flight simulator with its many components has a massive power requirement. In total, the system requires two different types of power: a 30-amp 3-phase 208 volt 60 hertz AC power source (for the actuators), and a 15-amp single-phase 115 volt 60 hertz AC power source (for the electronics). This is complicated by the fact that one of the requirements for set up was to make the flight simulator mobile, so that it could travel to shows; hence the power source needed to be mobile as well.

This result is achieved via a Magnum MMG35 diesel generator, which uses a John Deere 4024 tractor engine. The MMG35 provides 35kW of continuous power, and up to 42kW of standby power. The generator is trailer-mounted to make it mobile, and is capable of supplying both the 3-phase power and single-phase power simultaneously (by pulling from leg A of the 3-phase power). The internal computer's statistics demonstrates that this is a reliable power source capable of delivering a considerable amount of power, as shown in Figure 3.8.

Figure 3.8 (left) the Magnum MMG35 power source and (right) control panel

One consideration that was made when connecting the generator to the flight simulator was electrical grounding. The generator is connected directly to the simulator via cables, meaning it is not connected to another source of power, such as a building at any point. While there are ground wires in the system that can carry current back to the generator, the generator itself is not grounded. To ensure such a system would be safe for users in the flight simulator some research needed to be done. The suggestions of OSHA in their publication on generator grounding were followed; meaning the generator ground and neutral wire were bonded together. Such a configuration is valid and safe according to OSHA, given that it meets three criteria: it is the only power source, everything is connected directly to it (closed-loop), and it does not connect to any buildings (where another power source might interfere requiring a transfer switch to decide which power source is being used) [56].

In addition, managing the power source for the flight simulator was complicated by a phenomena known as total harmonic distortions, or THD, as described by the World Academy of Science, Engineering and Technology [57]. Essentially a harmonic distortion is a form of contamination of a power source where the contamination causes the power source voltage to deviate from its ideal harmonious cycle as shown in Figure 3.9 and Figure 3.10.

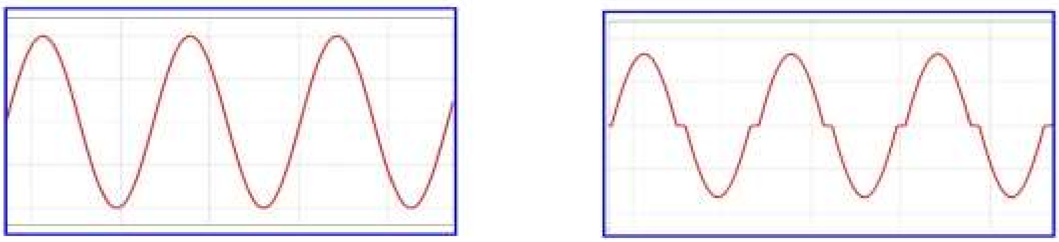

Figure 3.9 (left) the ideal, pure sine wave voltage input (right) a distorted sine wave output after having run through an electronic device. Images are courtesy of Mr. David Williams **[58]**.

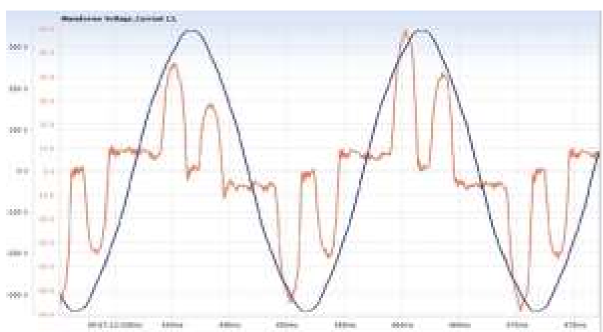

Figure 3.10 Another example of bad power harmonics **[59]**

This system is particularly susceptible to THD issues given its high proportion of current draw by the motors, and single isolated power source. For months during the construction, the project was plagued with harmonic distortion issues, which caused the critical computers of the system to reboot and were difficult to chase down given how randomly they seemed to appear (and disappear).

It was determined the issue was primarily due to the three variable frequency drives (or VFDs) being used to control the speed of the simulator motors. VFDs can emit a lot of harmonic distortion, typically 30% to 50% of their input voltage, according to Mr. Jim Corey [60].

These devices couldn't be removed as they were critical to the simulator. Instead a way to isolate their power contamination was researched. An IEEE presentation by Mr. John Houdek, titled "Eliminating Harmonic Problems Caused by VFDs," provided some insight as it list methods used for THD mitigation [61]. At first a CyberPower 1500VA uninterruptable power supply (UPS) was used to attempt to fix the dirty power issue. Unfortunately the computers would still occasionally experience power brownouts because the UPS was ill-equipped to handle the power harmonics at this intensity. In the end an APC LE1200 Line-R 1200VA automatic voltage regulator was chosen as shown in Figure 3.11; this included an isolation transformer to isolate the single-phase computer electronics from the 'dirty' variable frequency drives.

3.4 Motors

The simulator uses three high-torque 3-phase electric motors, and one single-phase hydraulic motor to achieve its range of motion. These motors are controlled in a closed-loop system with a PID controller (proportional integral derivative) which stabilizes the simulator and limits the vibration during large motor movements.

Figure 3.11 the automatic voltage regulator used to isolate sensitive computer electronics (image courtesy of APC) **[62]**

A voltage signal from +10 volts DC to -10 volts DC is sent to the motor VFD based on the desired rotation (clockwise or counter-clockwise) and speed of the calculated motor movement. Each motor and its purpose is described in this section.

Pitch Motor: This is the largest and most prominent motor in the system, a Sumitomo industrial 3-phase motor running at 208-volts AC. It delivers 5HP through a 105-ratio 90-degree gearbox [63], which is important because it takes the relatively small 5HP motor and generates a remarkable amount of torque from it (at the tradeoff of speed).

We can calculate its torque using basic physics, and some constants. First, it's important to know a constant: that one HP is equivalent to 33,000 lb-ft of work. Therefore, the formula for converting HP to torque is given by [64]:

$$T_{torque} = \frac{P_{horsepower} \times 33000}{2\pi \times S_{rotational\ speed}}$$

So knowing that the motor is rated for 5hp @ 1800 rpm, we get:

$$T_{nominal} = \frac{(5) \times 33000}{2\pi \times (1800)} = 14.5833\ (\mathrm{ft-lb}) \tag{3-1}$$

And knowing that it is connected to a 105-to-1 ratio grearbox, we get:

$$T_{gearbox} = 105 \times 14.5833 = 1{,}531.2465\ (\mathrm{ft-lb}) \tag{3-2}$$

Power isn't everything; however, in this case the motor-gearbox combo is capable of generating more torque than a diesel semi-truck (the FL-86 freightliner) [65]. Massive torque generation is a critical function of the pitch motor. It's responsible for most of the simulated acceleration you get inside the simulator. The ability of the pitch motor to take the massive weight of the cockpit and pilots and accelerate on a dime is what makes this motor special. A photo of the pitch motor is shown in Figure 3.12.

Figure 3.12 A picture of the Sumitomo motor-gearbox combo used as the pitch motor taken February 3rd, 2018 during disassembly and transport of the flight simulator

Roll Motor: This is the second largest motor in the system, and responsible for rolling the pilots in the cockpit commensurate with the commands given by the aircraft. A Sumitomo 3-phase 208-volts AC motor powers the setup, but this time it only delivers 3HP through a 72-ratio gearbox. Using the formula described earlier, we can calculate the torque delivery:

$$T_{nominal} = \frac{P_{horsepower} \times 33000}{2\pi \times S_{rotational\ speed}} = \frac{(3hp) \times 33000}{2\pi \times (1800rpm)} = 8.75\ (ft - lb) \quad (3 - 3)$$

$$T_{gearbox} = 8.75 \times 72 = 630\ (ft - lb) \quad (3 - 4)$$

Six hundred and thirty foot pounds of torque, while not monumental like the pitch motor, is important for the roll motor's ability to handle an unbalanced cockpit. One of the most stressed components of the system is the shaft that connects the cockpit to the roll motor' motor-gearbox combo via a large planetary bearing. Another essential feature in addition to the motor-gearbox combo is the system's electromagnetic braking. This is used to help the simulator hold positions while reducing the energy expended and wear on the motors. The roll motor is shown in Figure 3.13.

Figure 3.13 The roll motor and gearbox

<u>Balance Motor:</u> This is a 3-phase 208-volts AC motor. The manufacturer of this motor is unknown as well as the power rating, and unfortunately the labels have fallen off. The balance motor is connected to a counterweight via a worm-drive, which does something critical for the system. It allows the flight simulator to lose power on the system and yet retain the counterweight position. If the counterweight were driven by some other mechanic, such as a linear motor, loss of power at extreme simulator positions would lead to the counterweight sliding off uncontrolled. This would be a catastrophic failure that would likely cause great damage to the simulator.

Consider the following scenario: the flight simulator cockpit needs to accommodate two pilots, room for controllers, an armrest, etc., and is roughly 5 feet from the center of rotation of the simulator. The cockpit itself weights about 380 lbs, and the pilots combined can weight another 500 lbs (250 lbs each is a standard in the aviation industry [66]). The simulator needs to be able to pitch and roll the pilots in intense maneuvers (up to 360 degrees in each axis), however, having such a heavy weight at length makes this demanding. Consider the calculations for leverage many of us learned in the 6th grade math in Figure 3.14 [67].

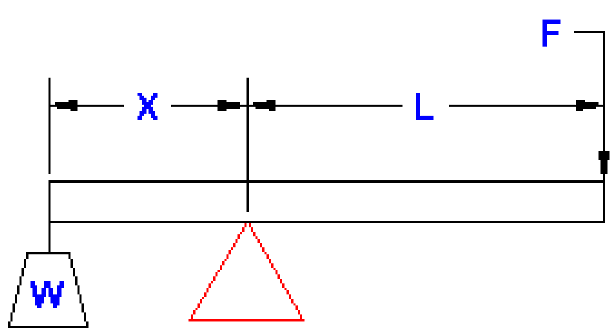

Figure 3.14 A lever with force F acting upon weight W. The red triangle represents the fulcrum.

In order to keep steady such a weight at a 5 foot length, the amount of torque required would be:

$$F_{torque} = \frac{X_{cockpit\ distance\ to\ fulcrum} \times \mathrm{W}_{weight\ of\ cockpit}}{L_{lever\ arm}}$$

$$= \frac{(5ft) \times (380\mathrm{lbs}+500\mathrm{lbs})}{(1ft)} = 4{,}400\ (ft - lbs) \tag{3 - 5}$$

This calculation is simply showing what it takes to keep the simulator static. As you can imagine the amount of torque required to produce an intense movement would be much greater. Thankfully this is where the small yet useful counterweight motor plays an important role. The simulator is rotated about the fulcrum, but the weight of a cockpit is balanced using a 500 lbs counterweight that is mounted on a 7 foot sliding shaft. The counterweight's distance from the fulcrum is determined via a worm-drive connecting back to the counterweight motor (allowing the motor to increase or decrease the distance of the weight to the fulcrum). Driving the counterweight towards the fulcrum allows the simulator to operate with lighter or empty loads, while driving the counterweight to the rear allows the simulator to operate with a full cockpit (the cockpit weight + 500 lbs for the pilots). The counterweight motor is shown in Figure 3.15.

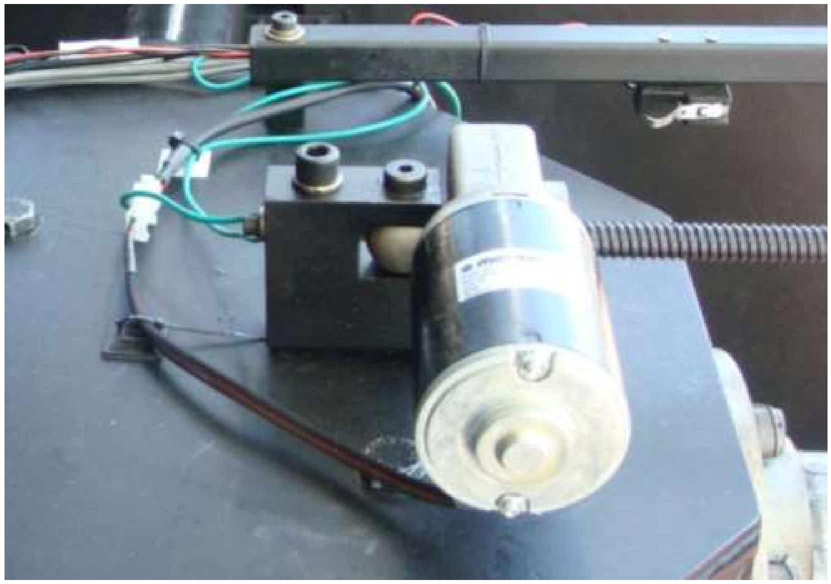

Figure 3.15 A picture of the counterweight motor. Notice the motor is mounted on a worm-drive shaft.

Lift Motor: The final motor in the system is the lift motor, which is a Northern Tool single-phase 1.5HP AC electric motor [68]. It is responsible for lifting the simulator off the ground so it has enough clearance to perform maneuvers. During runtime the base of the simulator sits about 7 feet above the ground, and during loading / unloading of the pilots, it is 27.5 inches (around 2.3 feet) off the ground. Therefore, the motor lifts the simulator roughly 4.5 feet into its operating position. The weight estimate for the cockpit, center fulcrum, and counterweight assemblies, is that it weighs around the same as a small car, at around 2,500 – 3,200 lbs.

3.5 Safety Implications

As mentioned previously the pitch and roll motors are equipped with an electromagnetic braking system, which is spring-loaded to trip the brakes into action in the event of a power failure. This is an important safety feature as it prevents the flight simulator from swinging aimlessly in case of a loss of power. A tradeoff to this mechanism is that it effectively locks the simulator into place without power to override it. To overcome this there is a handle installed in each of the Sumitomo motors, near the braking disks. With the pull of the lever, it separates the brake pads, allowing the motor and system to move freely on that axis. An example of this mechanism is shown in Figure 3.16, notice the small gap in the brake material on the right image, which allows the motor to spin freely. The blue cylinder at the bottom of the photo is a Stegmann optical encoder used to track the simulator position, is not part of the braking system.

Figure 3.16 (left) shows the safety brake release in its nominal state. Notice the brake materials are touching each other, freezing the system from moving. (right) shows the safety brake-release handle engaged.

Additional safety features are in place as well. The cockpit contains a large red e-stop style button, placed in the center of the console. This button can be pressed by either of the pilots, and sends a command to the computers to immediately stop the simulation and return to the unloading position. In the rear of the cockpit there are also additional safety sensors that ensure that the shoulder restraints and seat belts are bucked and in place. If one of the pilots were to break free of their restraints, the sensor would be tripped and the simulation would instantly shut down.

3.6 Platform Advantages

We chose the FS2000 platform because its advantages outweighed the disadvantages and challenges it took to get the system running reliably. Conventionally pilots train on expensive six-axis flight simulators that are built by the manufacturers of the airplanes themselves, as described in Section 2.3. This makes the interior of the cockpit very detailed and realistic to the actual airplane, but can be also limiting.

To achieve their range of motion, commercial flight simulators use the Stewart platform. The Stewart platform utilizes six actuators resulting in six axis of motion: pitch, yaw, roll, heave, sway, and surge as shown in Figure 3.17. This is also sometimes called a Hexapod simulator.

Figure 3.17 A depiction of the Stewart platform **[69]**

While the Stewart platform is capable of delivering a lot of motion to the simulator, a disadvantage to the Stewart platform approach is that it's limited in the range of motion that it can provide across each axis. For example, it is impossible for the Stewrt platform to perform a 90-degree bend, let alone simulate a full inversion (going upside down in an aircraft). Performing a single movement requires a chorus of motor activity to keep the platform stable, because all the motors are mechanically interlinked.

This is a clear advantage of our approach: the Maxflight hardware is capable of providing a continuous 360-degree rotation capability across the two main axes used in aviation: pitch and roll. Furthermore, those axis and their motions are completely independent from each other. This presents us with the ability to simulate certain maneuvers, such as inverted flight and barrel rolls, with greater realism and fidelity than the hexapod simulators used in expensive commercial flight simulation setups.

Chapter 4 SCOPE OF WORK

In a training environment the learning curve can be greatly reduced by offering immediate and focused feedback to the person being trained [70]. In the realm of pilot training this feedback is especially crucial, seeing as good training is of the utmost importance. The correct maneuvering and operation of an aircraft can result in a life or death situation. Motion simulators are an innovative training tool that were developed to address this problem. They help pilots learn the ropes of flying an aircraft, and train for emergency disasters and component failures without the risk of death.

The closer the simulation is to real life, the more meaningful the experience will become. This means that any simulation system must provide a constant feedback loop to its pilots. Such feedback can come in many forms: from audible alerts, to visual feedback, to the tactile responses of a control mechanism.

This dissertation utilizes a motion flight simulator, described in Section 3, to collect data and perform an analysis of four research questions. The flight simulator has been augmented with realistic joystick controls and virtual reality to immerse pilots in the training scenario. This platform has been amplified with additional software simulations, such as the space game and our flight formations simulation. In addition two human-computer interaction peripherals were integrated, virtual reality and gesture tracking, to more readily immerse users in the training scenario. Based on the information gathered in our user studies, we will answer our research questions, which will be of interest to members of the aviation and human-computer interaction communities.

4.1 Research Questions

Per the discussions with the dissertation committee on July 2nd, 2018, four research questions were being addressed as part of this research. They are:

- Research Question 1: *How does adding a motion simulator to a game change the human-computer experience?*
- Research Question 2: *Do the participants retain information about the game any better than if they are immersed in a motion simulator?*
- Research Question 3: *What do the participants enjoy more: a static, 3D, or VR-experience flight simulator experience?*
- Research Question 4: *Will the participants' ability to follow a flight formation increase if they receive feedback in motion simulator?*

To address these questions, two user studies were performed: one addresses RQ1, RQ2, and RQ3 and the other addresses RQ4.

4.2 Significance

A motion flight simulator typically costs hundreds of thousands to millions of dollars. The opportunity to work on one was something that could not be passed up. This project couldn’t have been completed alone; a lot of help was needed from my advisor, teammates, friends, and family, as mentioned in the acknowledgements section.

The chosen platform, according to the manufacturer, is the only one of its kind that can perform 360-degree barrel rolls and flips [42]. This unique adaptability opens up a world of possibilities for research. Some interesting technical challenges included: tracking head movements in a moving environment, an evaluation of the HTC Vive vs Oculus Rift tracking systems, and a scoring mechanism for flight maneuvers. Not to mention the journey encountered getting the power requirements right, fixing the buggy built-in software, or communicating with the motor controllers.

Given the expense of acquiring a full-motion flight simulator, I assume there are not a lot of people out there tinkering around with a working one. It is highly unlikely after having invested so much to obtain a motion flight simulator that one would want to risk damaging it with modifications. However, this experiment freely experiments with the flight simulator: taking it apart, learning how it works, and finding ways to improve it. No one else has conducted research like this, making this project one of a kind. This makes this project significant and citation-worthy.

Chapter 5 SOFTWARE MODEL

This chapter focuses on software modeling, which in software engineering encompasses the following: requirements, specification, use case modeling, and software design (architectural design, detailed design, data design, component interface design, and user interface design). While most of these are described here, elements of the user interface design and screenshots of the simulation itself are covered in Chapter 7.

5.1 Concept

The software design described aims to provide an innovative way of tying a software simulation (be it a space game or a flight training software) to a motion flight simulator. In order to ensure the robustness of the software, loose coupling and interchangeability were accounted for in the design. To achieve this a n-tier style architecture was implemented to separate components [71].

5.2 Use Cases

For describing use cases and presenting the artifacts of the proposed software model a UML (Unified Modeling Language) was used. This language represents the modern standard notation for modeling software-inclusive systems. The structure outlined by Dr. Ian Sommerville in his book on software engineering was followed [72]. The use case diagram for the joystick system is shown in Figure 5.1.

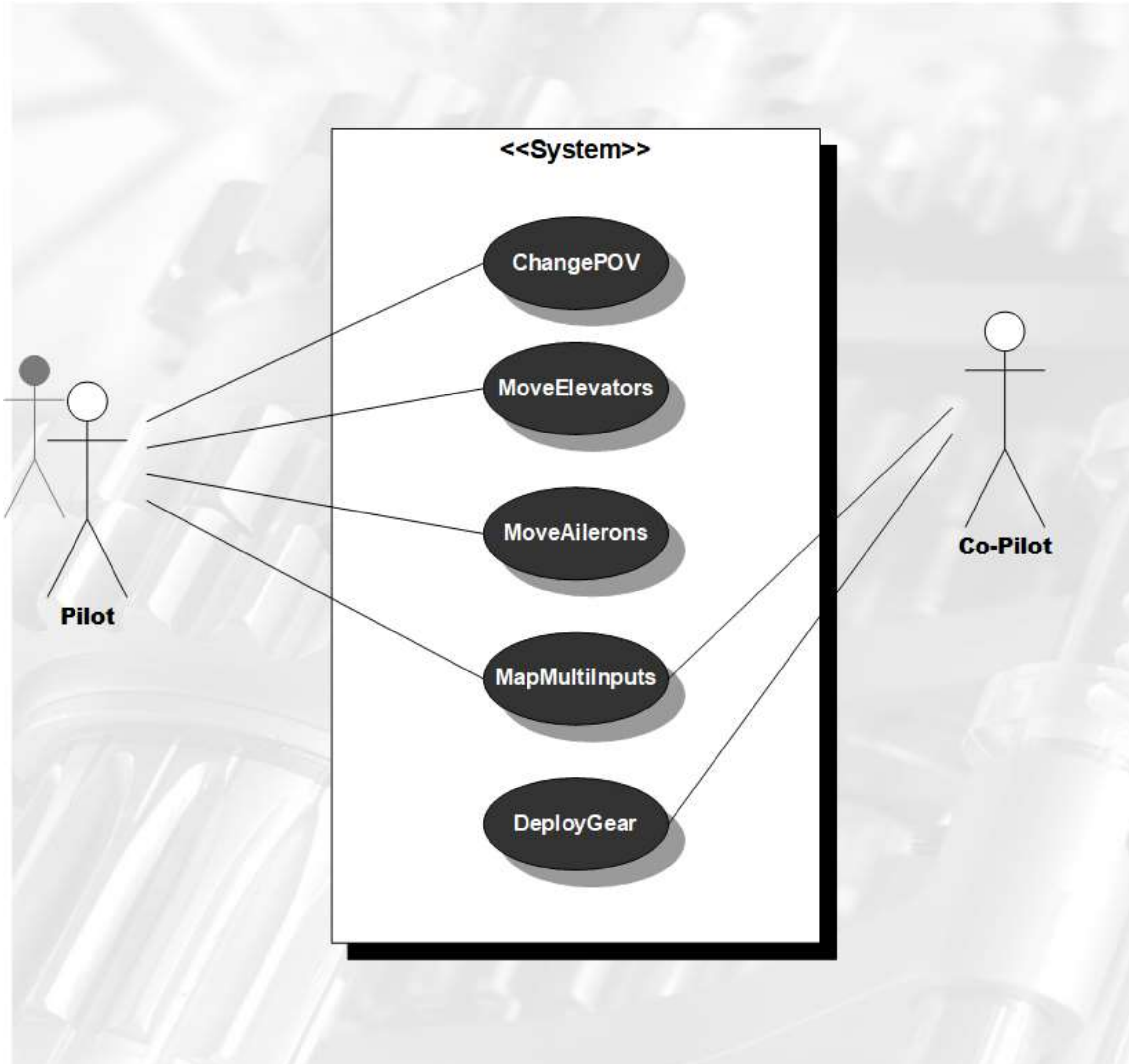

Figure 5.1 Use case diagram showing pilots in the cockpit and their usage of the joystick system

The use case descriptions and an expanded use case for the joystick system is shown in Table 5.1 and Figure 5.2 respectively.

Table 5.1 Use case descriptions

Use Case Descriptions		
UC01	ChangePOV	The pilot hits the assigned button on the joystick to change their point of view in the flight simulation
UC02	MoveElevators	The pilot presses forwards or backwards on the y-axis of the joystick to pitch the aircraft nose down or up
UC03	MoveAilerons	The pilot presses sideways on the x-axis of the joystick to roll the aircraft right or left
UC04	MapSimultaniousInputs	Both co-pilot and pilot make simultaneous joystick input to the flight simulation
UC05	DeployLandingGear	The co-pilot presses the assigned button to cause the landing gear to deploy (or retract) in the simulation

Use Case: Move Elevators

USE CASE ID	UC02
ACTOR	Pilot or Co-Pilot
PRECONDITION(S)	The system must be started and the aircraft in the flight simulator must be off the ground
FLOW OF EVENTS	1. The pilot enters the cockpit and sits down, securing their lap belt and shoulder harness 2. The operator closes and ‘arms’ (secures with the safety latch) the cockpit door 3. The simulation is started 4.The simulator is raised and balanced according to the pilot(s) weight in the cockpit 5. The game starts 6. Pilot or co-pilot moves the joystick input forward or backward, along the y-axis to signal their desire to move the aircraft pitch 7. The software reads the analog potentiometer, converting the voltage value to a 0-1023 integer value 8. The software emulates a virtual joystick command via the converted value, copying the corresponding movement on the simulated joystick 9. The game performs the pitch movement based on the feedback from the virtual joystick.
POSTCONDITION(S)	None

Figure 5.2 Detailed use case for moving the elevators

The use case diagram for the space game is shown in Figure 5.3.

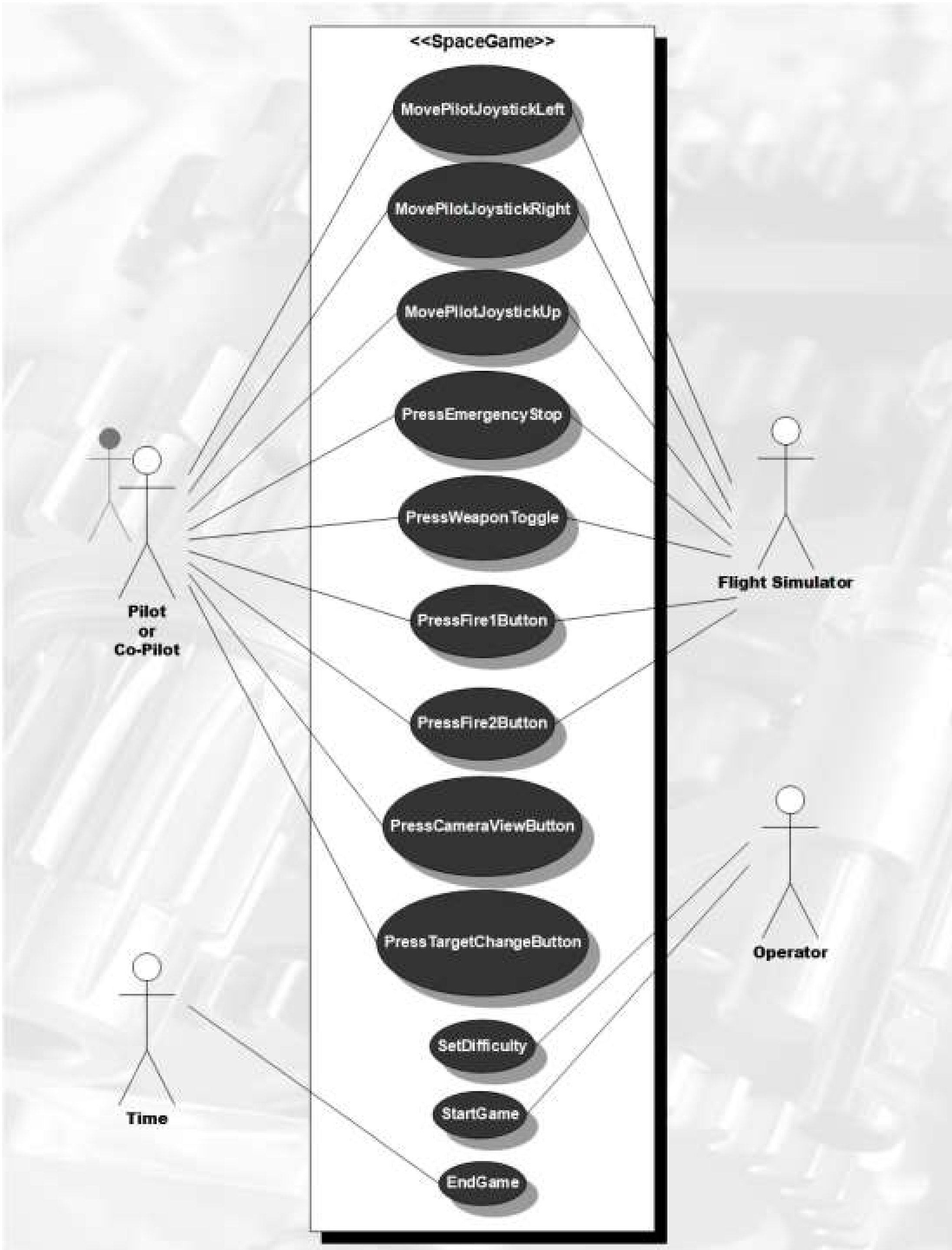

Figure 5.3 Use case diagram showing the space game system and its 4 actors

The use case descriptions are shown in Table 5.2 and Table 5.3.

Table 5.2 Space game use case descriptions

Use Case Descriptions		
UC01	MovePilotJoystickRight	The pilot will be able to move the pilot's joystick to the left. When the joystick is moved left the Space Game will react by rolling the spaceship to the left. This signal will be analog. The analog signal allows for fine control over the ship. The Simulator Hardware also reacts to this left roll.
UC02	MovePilotJoystickLeft	The pilot will be able to move the pilot's joystick to the right. When the joystick is moved right the Space Game will react by rolling the spaceship to the right. This signal will be analog. The analog signal allows for fine control over the ship. The Simulator Hardware also reacts to this right roll.
UC03	MovePilotJoystickForward	The pilot will be able to move the pilot's joystick forward. When the joystick is moved forward the Space Game will react by pitching the spaceship forward. This signal will be analog. The analog signal allows for fine control over the ship. The Simulator Hardware also reacts to this forward pitch.
UC04	MovePilotJoystickBackward	The pilot will be able to move the pilot's joystick backward. When the joystick is moved backward the Space Game will react by pitching the spaceship backward. This signal will be analog. The analog signal allows for fine control over the ship. The Simulator Hardware also reacts to this backward pitch.
UC05	PressEmergencyStop	Either pilot or copilot will be able to press the Emergency Stop button inside the cabin. When the button is pressed the hydraulics engine will shut down and the game will shut down immediately.
UC06	PressWeaponToggle	Pressing weapon toggle will allow the player to change between bullets and beam weapons. This will allow for more variety in the types of weapons used.

Table 5.3 Space game use case descriptions (cont.)

Use Case Descriptions (cont.)		
UC07	PressFireButton1	Pressing fire button 1 will allow the copilot to fire the bullet weapon. This weapon will fire two projectiles, one from either side of the ship. When the projectiles are fired, they will travel to a point at the center of the screen in front of the ship. The projectiles will have a firing rate so that it cannot spawn an instant and continuous wave of bullets, but instead takes a little bit of time in between bullets.
UC08	PressFireButton2	Pressing fire button 2 will allow the copilot to fire a homing missile. The missile will lock on to any target that has two red-boxes around it, indicating lock on. If the homing missile does not have a lock on target, it will simply fire forward.
UC09	PressCameraViewButton	Pressing and holding the camera view button will allow the camera to go to third person mode. Third person mode follows the spaceship from behind, allowing the players to see more around them.
UC10	PressTargetChangeButton	Pressing the target change button will allow the copilot to change the focusing target to the ship that is in front of them. A ship must be targeted for homing lock on to begin.
UC11	SetDifficulty	The operator will be able to set the difficulty of the Space Game. The different difficulties will change how challenging the piloting and shooting/science will be. This will allow for varied experiences for the pilot and copilot.
UC12	StartGame	The operator will be able to start the game after all safety requirements are meet.
UC13	EndGame	After a set time, the Space Game will be able to end in a non-emergency state. The pilot and copilot have a limited time playing. This time is agreed on before they are able to play.

The use case diagram for the flight formation simulation is shown in Figure 5.4 along with the use case descriptions in Table 5.4. Two expanded use case diagrams are shown in Figure 5.5 and Figure 5.6, respectively.

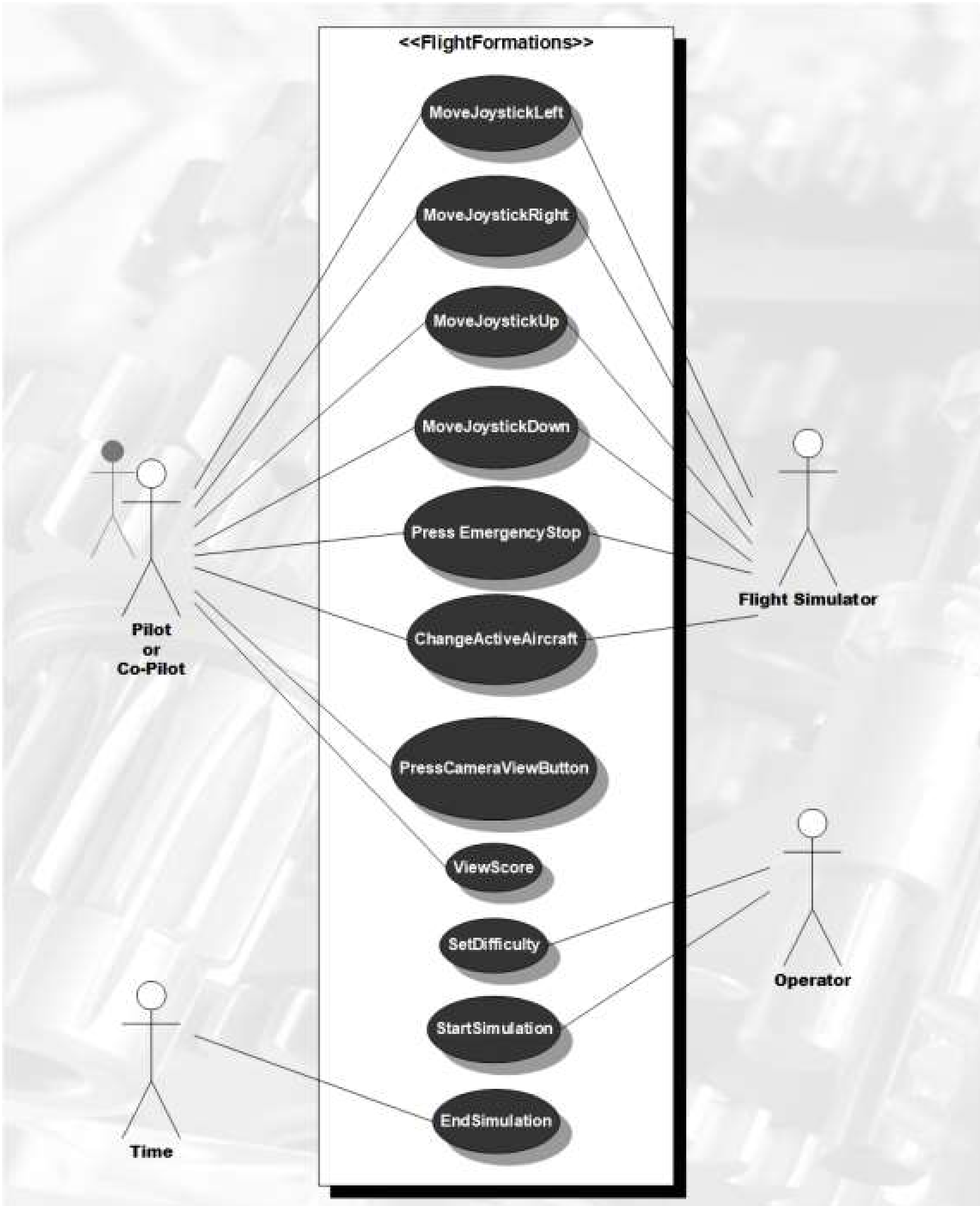

Figure 5.4 Use case diagram for the flight formations simulation

Table 5.4 Use case descriptions for flight formations simulation

Use Case Descriptions		
UC01	MoveJoystickLeft	The pilot pulls left on the x-axis of the joystick to roll the aircraft left
UC02	MoveJoystickRight	The pilot pulls right on the x-axis of the joystick to roll the aircraft right
UC03	MoveJoystickUp	The pilot pulls back on the y-axis of the joystick to pitch the aircraft up
UC04	MoveJoystickDown	The pilot pushes forwards on the y-axis of the joystick to pitch the aircraft down
UC05	PressEmergencyStop	The pilot or co-pilot presses the emergency stop button, causing the simulation to stop immediately
UC06	ChangeActiveAircraft	The operator uses the GUI to change the current aircraft used in the simulation
UC07	PressCameraViewButton	The co-pilot presses the assigned button to change the point of view of the aircraft (options include: cockpit view, birds eye view, and tower view
UC08	ViewScore	The pilot, co-pilot, or operator uses the GUI to request the formation score of the previous simulation
UC09	SetDifficulty	The operator uses the GUI to select the difficulty level for the next simulation
UC10	StartSimulation	The flight formation simulation begins with all safety checks performed and the simulator balanced and raised
UC11	EndSimulation	The flight formation simulation ends after the elapsed time, with the simulator being lowered and the pilot and co-pilot being allowed out of the cockpit

Use Case: ViewScore

USE CASE ID	UC08
ACTOR	Pilot or Co-Pilot
PRECONDITION(S)	The simulator has completed a run of the flight formation simulation is in the unloading state
FLOW OF EVENTS	1. The pilot or co-pilot hits the assigned button on their joystick to request their flight path score. 2. The system calculates the "ideal" flight path, and calculates an average distance from the ideal score for the pilot's aircraft. 3. The score is adjusted based on the average distance and other factors (such as falling behind too much or recovering after a bad maneuver). 4.The score is displayed to the pilot and co-pilot via the GUI.
POSTCONDITION(S)	None

Figure 5.5 Detailed use case for viewing the score of the flight path

Use Case: SetDifficulty

USE CASE ID	UC09
ACTOR	Operator
PRECONDITION(S)	The simulator be in the loading position and the operator computer must not be detecting any safety violations (such as the seatbelt being unbuckled)
FLOW OF EVENTS	1. The pilot (and potentially co-pilot) enters the cockpit and sits down, securing their lap belt and shoulder harness. 2. The operator closes and 'arms' (secures with the safety latch) the cockpit door. 3. The operator goes to the console computer and selects one of the available missions. 4.The operator selects the level of difficulty for the mission.
POSTCONDITION(S)	None

Figure 5.6 Detailed use case for selecting the simulation difficulty

5.3 Requirements

The functional requirements for the cockpit joystick system are shown in Table 5.5.

Table 5.5 Functional Software Requirements of the Joystick System

Requirement	Description
FR-1	The software must be able to convert an analog axis input to a digital 0-1023 value
FR-2	The software must be able to convert button presses into a digital 0/1 value
FR-3	The software must be able to handle at least 4 analog axis of input
FR-4	The software must be able to handle at least 6 different types of button presses
FR-5	The software should be able to handle simultaneous input from multiple sources (analog axis, buttons, etc)
FR-6	The software should be able to map the analog axis to a software control in simulation (such as the rudder, throttle, elevators, or ailerons)
FR-7	The software should be able to prioritize multiple inputs from the pilot or co-pilot
FR-8	The software may be able to emulate keyboard presses

The non-functional requirements for the cockpit joystick system are shown in Table 5.6.

Table 5.6 Non-Functional Software Requirements of the Joystick System

Requirement	Description
NFR-1	The software must run on an ATMega 32u4 chipset
NFR-2	The software must emulate a virtual joystick using the inputs from the two physical joysticks in the cockpit
NFR-3	The software must be able to poll the joysticks with less than a $1/10^{th}$ of a second delay between updates

The functional requirements for the Space game are shown in Table 5.7 and Table 5.8. These requirements were developed with Paul McFarlane, director of the Northern

Nevada Challenger Center and four undergraduate team members from senior projects in computer science: Austin Bachman, Sven Diaz-Juarez, Jake Lee, and Jervyn Seguitan.

Table 5.7 Functional Software Requirements of the Space Game

Requirement	Description
FR-1	The motion platform must be controlled via a joystick that allows the pilot to control the pitch and roll of the motion platform
FR-2	The in-game spaceship must be controlled with the joystick and reflect the movements in the motion platform
FR-3	The simulator must have a safety button in the cockpit that can stop the simulation immediately when pressed
FR-4	The software must display a warning message to the user when the safety button is pressed stating that motion cannot commence until the safety button is reset
FR-5	The simulator must be able to display the space game inside the cabin on a high resolution projector (>=768p)
FR-6	The simulator must be able to immediately cease operation from the press of a safety button on the outside operator panel
FR-7	The software should allow the gunner to fire weaponry and collect resources through the use of their joystick
FR-8	The software should be continuously running automatic checks to ensure the system is safe
FR-9	The software should have homing missiles to fire at enemies
FR-10	The software should allow for the user to change the camera angle to look at the spaceship
FR-11	The software should allow for the tracking of enemies on a radar in the ship HUD (heads up display)
FR-12	The software should highlight each enemy in view of the player's HUD using a red box
FR-13	The software should allow for the spaceship to have a shield capability to provide some leniency for incoming fire.
FR-14	The spaceship shield may display an effect when the spaceship is hit.
FR-15	The software may have a test mode that checks all the movement of the simulator
FR-16	The software may have several levels of difficulty
FR-17	The software may detail the safety features of the simulator at the beginning of the game through an in-game tutorial
FR-18	The software may have science fiction energy weapons for mining minerals and firing at enemies
FR-19	The software may allow for an additional movement about the Yaw axis for easier turning
FR-20	The simulator may have an in-cabin camera so viewers outside the simulator can view the pilots inside the simulator
FR-21	The software may tie a unique access card that determines what levels of difficulty the user has unlocked to play

Table 5.8 Non-functional Software Requirements of the Space Game

Requirement	Description
NFR-1	The space game should be implemented using the Unity game engine
NFR-2	The game should last 3-6 minutes
NFR-3	The simulator must use a plugin for synchronizing the spaceship orientation in Unity with the motion platform
NFR-4	The software must ensure both users are following the safety requirements during the game
NFR-5	The software should not allow the game to play without an outside operator present for safety
NFR-6	A separate software will marshal the pitch and roll values between the game and the simulator with less than a 1/10 second total latency
NFR-7	The simulator movement area will be closed off when in operation

A requirements traceability matrix for the space game, showing how each of the requirements and their priorities are utilized in the use cases, is described in Figure 5.7.

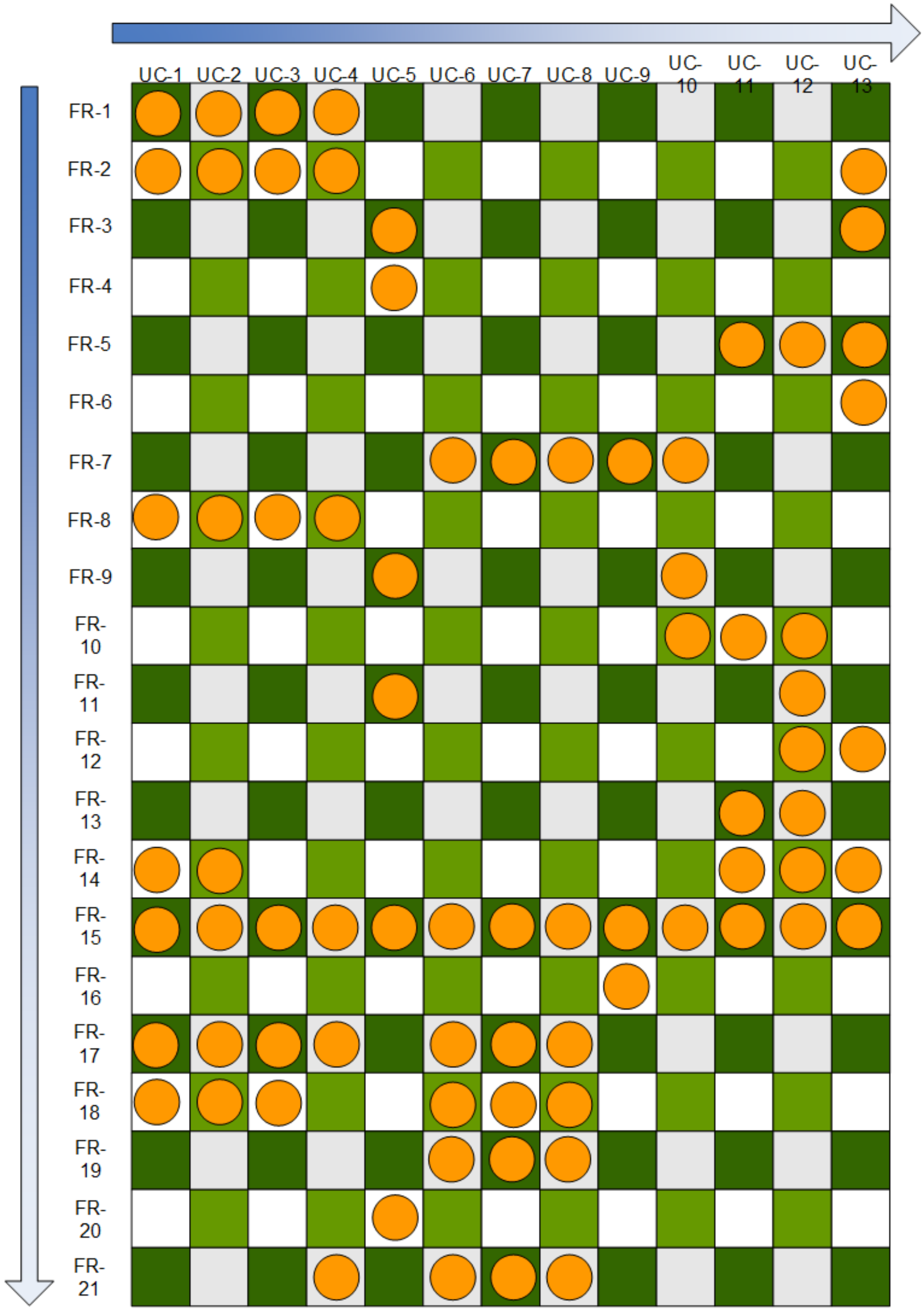

Figure 5.7 Use case traceability matrix for the space game

Finally the requirements for the flight formation simulation is shown in Table 5.9

and Table 5.10.

Table 5.9 Functional Software Requirements of the Flight Formation Simulation

Requirement	Description
FR-1	The flight formation simulation must have a HUD that accurately displays the cockpit of the aircraft
FR-2	The flight formation simulation must be controlled with the joysticks and reflect the movements in the motion platform
FR-3	The simulator must have a safety button in the cockpit that can stop the flight formation simulation immediately when pressed
FR-4	The flight formation simulation must accurately simulate the mechanics and physics of sub-sonic flight.
FR-5	The flight formation simulation must include at least two additional aircraft to fly in formation with during the simulation
FR-6	The simulator must be able to immediately cease operation from the press of a safety button on the outside operator panel
FR-7	The flight formation simulation should calculate the ideal flight trajectory of the formation
FR-8	The flight formation simulation should be continuously running automatic checks to ensure the system is safe
FR-9	The flight formation simulation should determine when the user has drifted too far off-course from the formation
FR-10	The flight formation simulation should score the user’s position against the ideal flight path.
FR-11	The flight formation simulation should allow for the tracking of aircraft on radar in the HUD (heads up display)
FR-12	The flight formation simulation may have several levels of difficulty
FR-13	The flight formation simulation may allow for a replay feature so users can see their performance in hindsight and find where they went wrong
FR-14	The simulator may have an in-cabin camera so viewers outside the simulator can view the pilots inside the simulator
FR-15	The flight formation simulation may allow the user to pick from a variety of aircraft to follow the formation with

Table 5.10 Non-functional Software Requirements of the Flight Formation Simulation

Requirement	Description
NFR-1	The simulation must run using the flight simulator
NFR-2	The simulation should allow for a configurable experience from 3-20 minutes depending on intensity
NFR-3	The software should not allow the game to play without an outside operator present for safety
NFR-4	A simulation should support virtual reality within the cockpit
NFR-5	The simulator movement area must be closed off when in operation

A requirements traceability matrix for the flight formation simulation, showing how each of the requirements and their use cases are linked is shown in Figure 5.8.

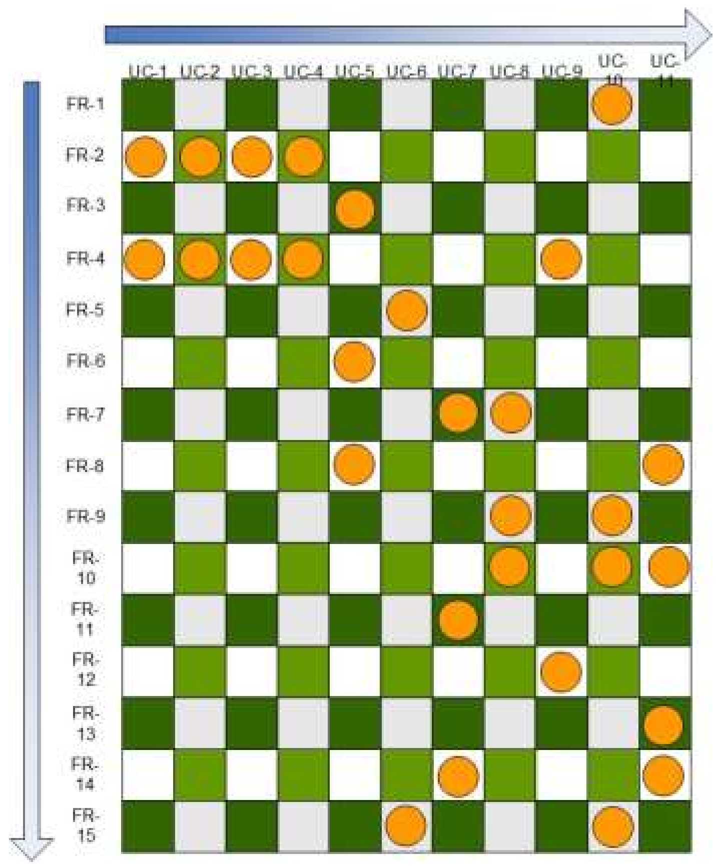

Figure 5.8 Use case traceability matrix for the flight formation simulation

5.4 High Level Design

The overall system architecture is comprised of several subsystems as shown in Figure 5.9. The links between subsystems are established through a transport network, in our case USB, RS 485, or Ethernet.

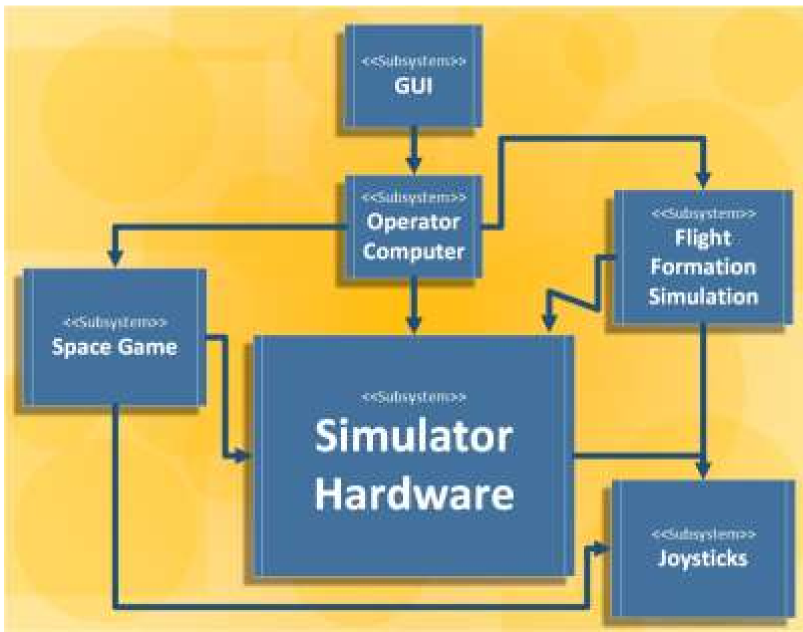

Figure 5.9 A visual representation of the interaction between subsystems of the flight simulator

A brief description of each subsystem is as follows:

GUI: The graphical user interface subsystem provides the visual effects and menus that serve as the starting point and controls for the operator. They are written in WPF using C# and .NET 4.0. Using the GUI, the user can select things such as game difficulty, what type of aircraft they'd like to fly, or the duration of the experience. This subsystem connects to the operator computer subsystem by launching the desired simulation.

Operator Computer: The operator computer subsystem delivers a comprehensive data set from the simulation, or game, to the flight simulator motors. It also performs the safety checks ensuring everyone's seatbelt is on, and that the stop buttons have not been pressed. In addition the operator computer subsystem keeps track of the elapsed time of the simulation.

Space Game: The space game subsystem delivers the space game experience to the user(s). It provides the three main states of the game: flight check, mineral collection, and drone battle.

Flight Formation Simulation: The flight formation simulation subsystem provides the flight simulation experience to the user. It scores the user's distance from the "ideal" flight path, provides realistic flight mechanics, and renders the virtual cockpit. It can also be configured to include different locations or types of aircraft.

Simulator Hardware: The simulator hardware subsystem is the core of the experience. It includes all the hardware that powers the simulation including a game computer with an NVidia 1080 graphics card which runs the desired simulation (whether it be the space game, flight formation simulation, the water cycle ride, or one of the built-in Maxflight rollercoasters).

Joysticks: Finally, the joysticks subsystem handles the user(s) input from the flight simulator cockpit.

5.5 Detailed Design

Good software engineering principles dictate that a detailed design of a flight simulator system should outline items such as class diagrams of the system. A class diagram of the space game is shown in Figure 5.10.

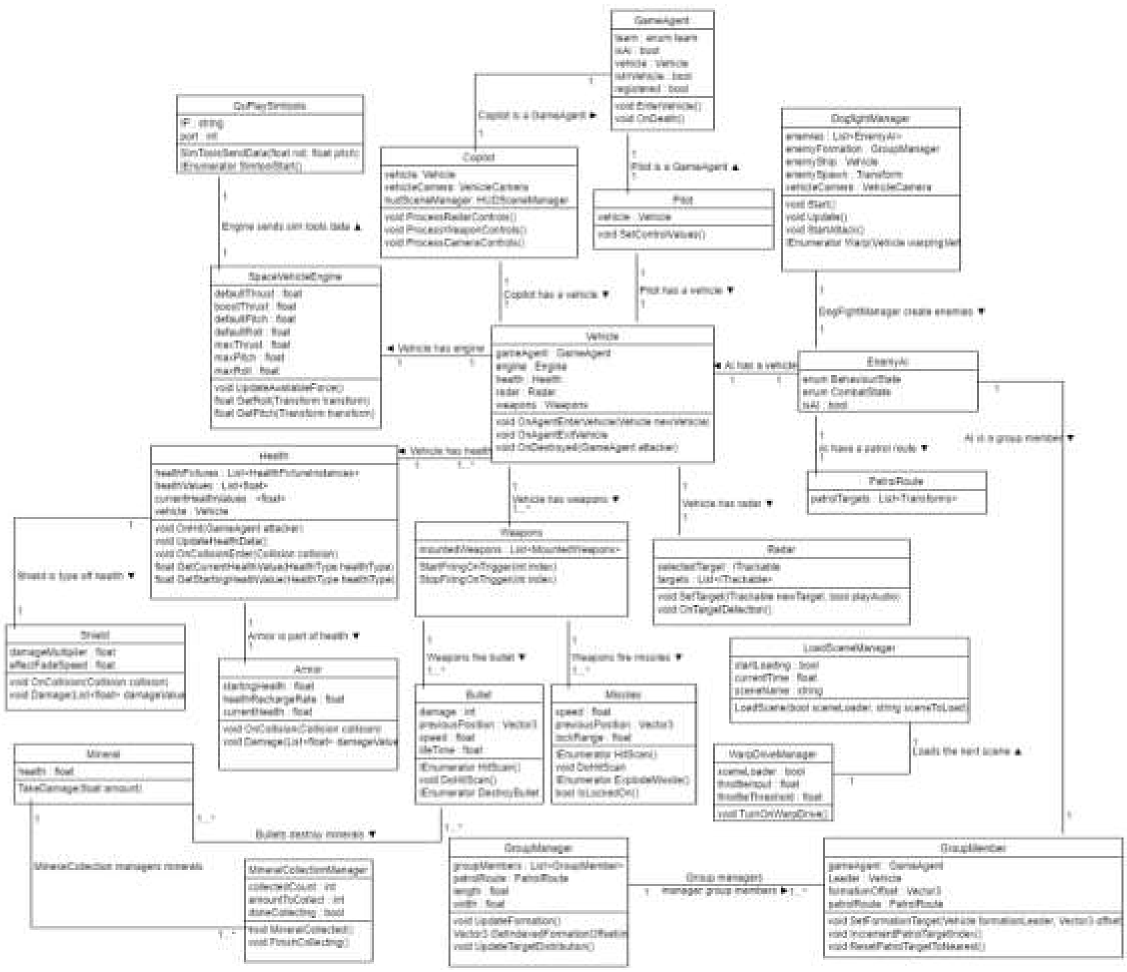

Figure 5.10 A class diagram for the space game design

In addition to Figure 5.10, a software to convert quaternion rotations (those used by Unity [73]) into Euler axis rotations (those used by the simulator's motors and encoders) was developed. A class diagram for this addition to the space game is shown in Figure 5.11.

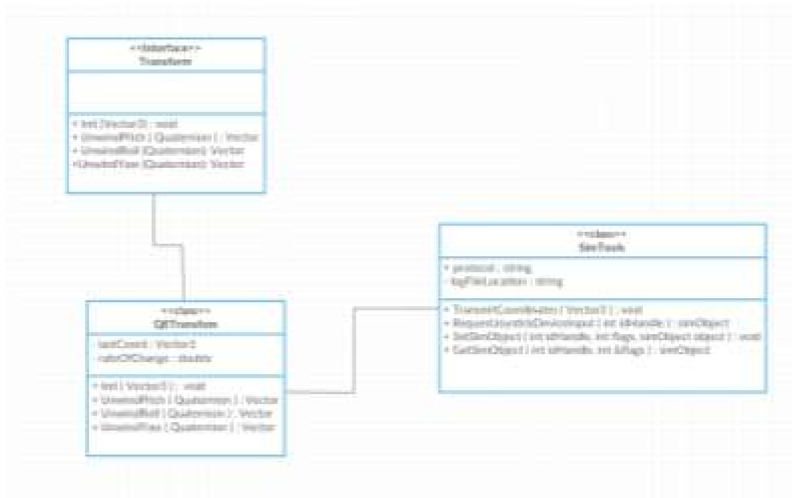

Figure 5.11 Class diagram for the Quaternion to Euler transformation system

Another addition to the space game was the revision of the joystick controls. Figure 5.12 demonstrates the joysticks were producing glitches where even if the pilot would keep the joystick straight, it would produce false aircraft movements read from the analog potentiometers. The joysticks were revised using C++ code that was developed for the ATMega32u4 microcontroller in the Arduino IDE (v1.6.5) [74]. A library developed by Mattias Heironimus was utilized for the USB communication [75].

Figure 5.12 An example of the joystick glitch

5.6 Data Design

The software uses a hashtable that maps key frames in a video to specific motion coordinates. A timestamp is also used to help ensure the motion and video are in sync. An example hashtable motion file is shown in Table 5.11. This table shows how the water cycle experience is achieved, mapping the NASA-Ames educational video [76] to simulator movements, which is discussed in more detail in Section 6.3.

Table 5.11 Simulator Motion Hashtable Example

Motion File	Timestamp (*milliseconds*)	Video Frame	Pitch (°)	Roll (°)
Data point 1	33	1	0	0
Data point 2	66	2	+3	-2
Data point 3	99	3	+5	+7
…	…	…	…	…

5.7 Technologies and Tools

Many technologies were utilized in the creation of this dissertation. The space game used Unity's game engine as its backbone, and C# as the main programming language. It handled the physics, rendered the graphics, and provided cross-platform capability [77]. The space game also utilized assets from Unity, such as the spaceships, the asteroids, and space flight mechanics.

For the joystick drivers an ATMega32u4 chipset was utilized to emulate a virtual joystick through USB [75] [78]. The virtual joystick also allowed it to perform conflict resolution between conflicting joystick commands from the pilot and co-pilot, a topic that was discussed in my paper in the 27th International Conference on Software Engineering and Data Engineering [52]. The C++ programming language was used here to program the microcontroller.

Extensible Markup Language, or XML, was used to track the position of the F-18 jets in the flight formations simulation [79]. Separately it was also used to structure the mission parameters, goals, and duration of the mission.

The virtual reality experience was delivered through the use of an Oculus Rift CV1 headset and an external sensor. Originally development was attempted with the Vive due to the research from Dr. Oliver Kreylos demonstrating the Vive headset has a root-mean-square tracking accuracy of 1.5mm to 1.9mm (which is a highly accurate system) [80] [81]. Unfortunately the sensors used by the HTC vive, called "Lighthouse" sensors, employ two motors to beam infrared light to track objects [82]. This is shown in Figure 5.13. These motors are mounted in the enclosure in a non-gyroscopically stable way, meaning they are thrown off when they experience the force of external accelerations, something that is happening constantly in the cockpit of the flight simulator.

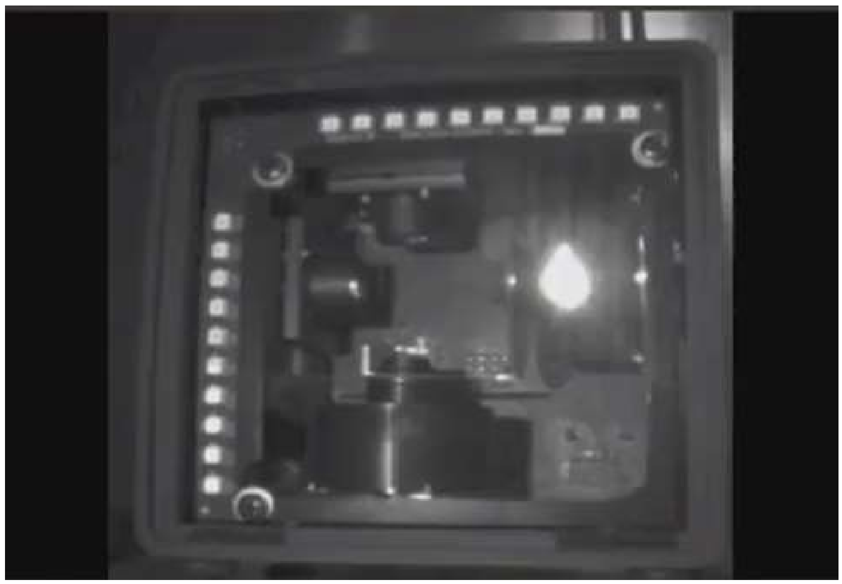

Figure 5.13 Internals of the Lighthouse sensor as viewed by an infrared camera **[83]**

Finally, the Orion beta software was used to perform the gesture-tracking demonstrated in Section 6.6 [84]. This involved tracking the position of both hands simultaneously, and estimating the position of each finger.

Chapter 6 PROTOTYPE AND EXPERIMENTAL RESULTS

This chapter focuses on the software prototype and experimental results. Through a series of screenshots the prototype's user interface and the experience generated through using the flight simulator are shown. In addition detailed descriptions of how an operator would interact with the system are provided. The case studies at the end of the chapter demonstrate several successful interactions of the prototype with members of the general public.

6.1 Introduction

This section describes the prototype developed and the user experience working with the software, as well as the experimental design of the data that was collected. There are several different experiences developed for the flight simulator, described in this section, such as the *space game* described in Section 6.2, the *water cycle ride* outlined in Section 6.3, the *flight formation simulation* detailed in Section 6.4, and the *virtual reality* component in Section 6.5. Furthermore, a *gesture-enabled virtual cockpit* is demonstrated in Section 6.6 and two *case studies* are outlined in Sections 6.7 and 6.8.

6.2 The Space Game

The space game consists of 3 level areas: an *introductory* level where users explore navigating the spaceship, a *mineral collection* level where users mine asteroids to collect minerals, and finally a *combat* level where users fight drones. In the *introductory level*, users explore navigating their environment in the flight simulator and their virtual spaceship. In the *mineral collection* level, users mine asteroids by shooting at them, collecting minerals and along the way, learning something about the composition of minerals. Finally, in the *combat level*, users fight waves of 5 drone enemies in an open combat theatre. The three areas are shown in Figure 6.1**Error! Reference source not found.**, Figure 6.2, and Figure 6.3.

Figure 6.1 Screenshot from the first area of the space game

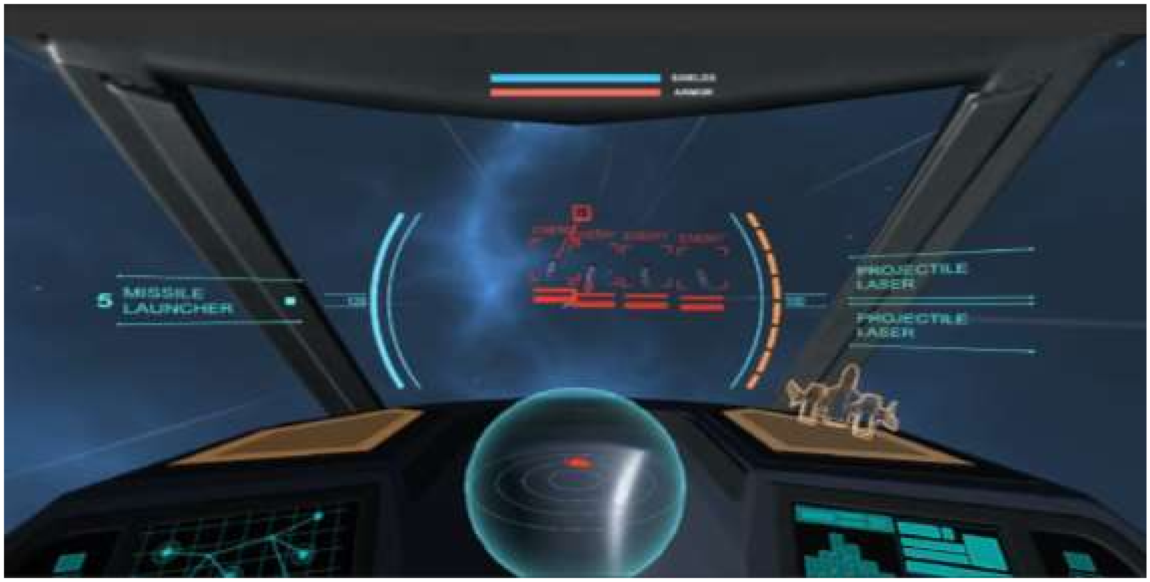

Figure 6.2 Screenshot from the second area of the space game

Figure 6.3 Screenshot from the third area of the space game

The space game was originally developed by four undergraduate students: Seven Diaz-Juarez, Jervyn Seguitan, Austin Bachman, and Jake Lee which I mentored as part of a capstone course: senior projects in software engineering. The students created the game. However, this research contributed several additions to the space game including: converting the spaceship’s quaternion coordinates to Euclidian rotations, debugging the lagging interface between the simulator state and the game state, adding three visual elements to the GUI to monitor FPS (frames per second) and the pitch and roll positions of the simulator (shown in Figure 6.4), generic joystick controls for both the pilot and co-pilot (only one joystick, the Thrustmaster HOTAS X was allowed originally which did not fit in the cockpit neatly) shown in Figure 6.5, and some improved sound effects.

Figure 6.4 A screenshot showing the FPS, Pitch, and Roll counters that were added on the upper left of the HUD

Figure 6.5 Analog joysticks added to the game

The space game was showcased on innovation day, May 4th 2018, with the booth being one of the busiest at the event. In addition to the general observers who walked by and asked the team questions, 38 people competed for the highest score playing the space game on our operator console, shown in Figure 6.6.

Figure 6.6 A picture of the four undergraduate researchers from left to right: Jervyn Seguitan, Austin Bachman, Sven Diaz-Juarez, and Jacob Lee, and our space game running at innovation day

Finally Figure 6.7 shows the space game running on the flight simulator game computer. It also shows the game sending motion commands back to the motors using the updated Quaternion to Euler axis calculations that were developed and described in Section 5.5.

Figure 6.7 A screenshot of the game running and sending motion commands to the flight simulator, as well as the improved runway-themed staircase.

6.3 The Water Cycle Ride

According to a recent paper by UCSF students it is not enough to simply lecture from the podium anymore [35]. Students need to engage and connect; hearing a lecture doesn't engage their brain as well as more interactive learning techniques [85]. In our fast paced society students struggle to keep focused for the entire duration of class. Failure rates under traditional lecture-style teaching increase 55% compared to active learning techniques. The old way of doing things just is not sufficient anymore. Hence new methods to engage students and facilitate their learning are needed to keep students engaged. One method of achieving this is by presenting educational subjects with an entertaining flare, which is dubbed “edutainment.” As silly as that sounds, it is a big business.

Dora the Explorer, an edutainment television show, pulled in $250 million (USD) in sales the last four years [86]. Baby Einstein is estimated to have brought in $400 million (USD) in retail [87]. This new field has had explosive growth recently.

Motived by the issue of student engagement this research developed an edutainment prototype seeking to utilize the flight simulator platform, exploring new methods to enhance learning outcomes for the natural sciences. This is done by incorporating high definition graphics, surround sound, the motion simulator, and an educational video from NASA-Ames [76]; a new level of thrill is introduced to a subject most would not be interested in. Two riders secured with a seatbelt and harness can experience the “water-cycle ride,” which lasts about 3 minutes. Together they are taken through water’s three states: solid, liquid, and gas, and its hydrogeology on earth (runoff and groundwater). At appropriate intervals g-forces are introduced; this leads to riders experiencing a rising feeling when evaporation is being explained, or a falling feeling when rain droplets are racing back to Earth. When the camera zooms out to a NASA / NOAA satellite image, the riders experience a rolling effect as the camera banks left or right. Screenshots from the video are introduced in Figure 6.8, Figure 6.9, and Figure 6.10 .

Figure 6.8 Video introduction of the water cycle by NASA Ames Research **[76]**

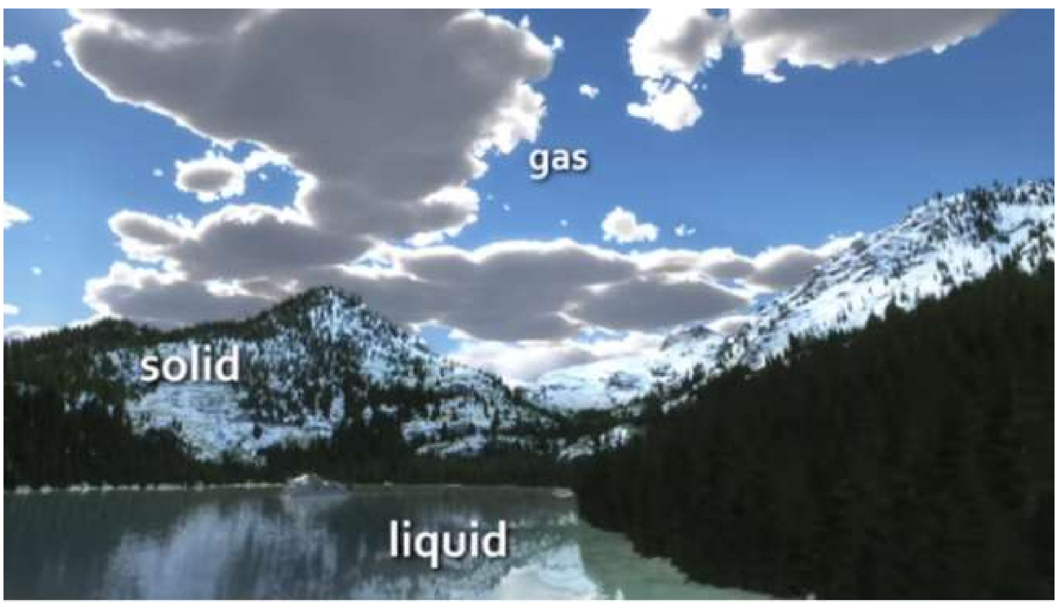

Figure 6.9 NASA Ames' water cycle video introducing the phases of matter of water on Earth **[76]**

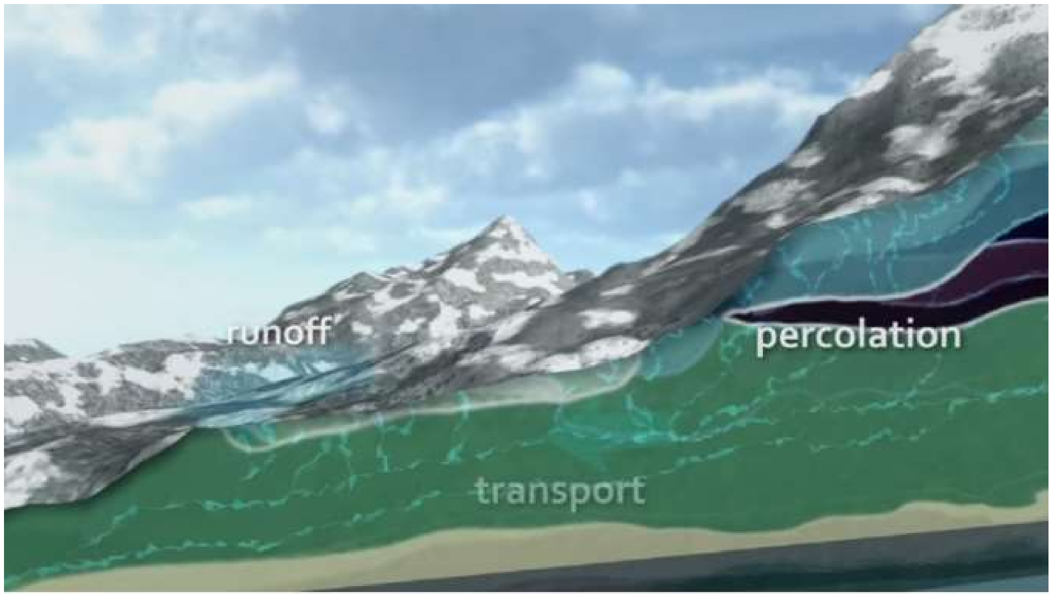

Figure 6.10 NASA Ames video showing parts of the water cycle **[76]**

Figure 6.11 shows both the motion simulator and the water cycle video. The water cycle ride video is playing on the television screen on the right (which is a mirror of the visuals inside the cockpit).

Figure 6.11 Photos of the water cycle ride in action. (Left) shows the intro and the simulator in the neutral position (Right) the passenger is taught about water condensation into rain droplets and simultaneously experiencing a slight falling effect.

6.4 The Flight Formation Experience

The flight formation experience is a mission-style simulation allowing the pilot to train in rapid maneuvers and advanced piloting techniques. Highlighting some of the unique aspects of the platform, the pilot can train in realistic motions of inverted flight, quick dives or climbs, and high-intensity rolls.

The pilot(s) start their experience by entering the cockpit and securing their lap belt and shoulder restraint as before, then the operator uses the console to load the flight formations simulation. The pilot may choose put on a VR headset, as described in the following section, or monitor the simulation through the projector. While the simulation is loading the simulator raises and balances the cockpit according to the pilot(s) weight. Finally the operator radios the pilots to begin the simulation, they are placed on the runway and given control of an F-18 Hornet, as shown in Figure 6.12.

Figure 6.12 An F-18 Hornet in Blue Angels livery used for the flight formations simulation

Shortly thereafter they are joined by three other F-18 Hornet aircraft, and the challenge begins where they must follow the aircraft formation, as shown in Figure 6.13.

Figure 6.13 Three F-18s with engines on and myself (furthest right) in formation ready to take off

At this point, the simulation begins scoring the pilot in their ability to follow the formation, as shown in Figure 6.14, using the scoring mechanism described in Section 5.5. The pilots use the controls as shown in Figure 6.15 to stay in formation.

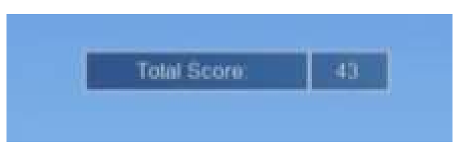

Figure 6.14 The scoring counter on the upper-right corner of the screen

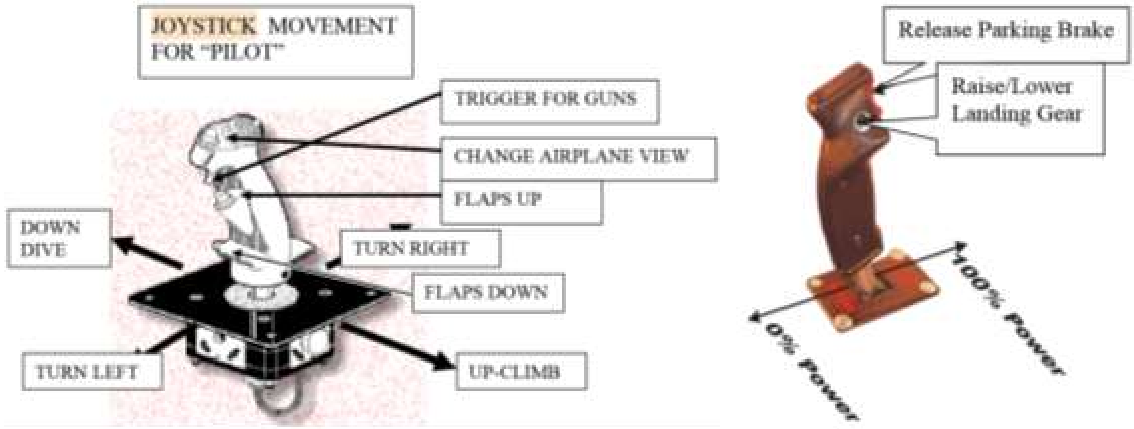

Figure 6.15 (Left) joystick control for the pilot and (Right) throttle control for the pilot

Depending on the difficulty level selected by the operator, the pilots are challenged with following the formation for 3-6 minutes. At harder levels, the flight paths become more intense. The formations simulated are modeled after the real maneuvers used by the U.S. Navy to train their ace pilots.

6.5 Virtual Reality

A virtual reality headset was incorporated into the cockpit for one of the pilots (the left seat). The virtual reality experience is driven by three components: an Oculus Rift CV1 headset, an infrared constellation sensor mounted onto the upper corner of the flight simulator, and an NVidia 1080 Ti graphics card.

Since the pilot in the cockpit sits stationary, there is no locomotion within the virtual reality, although the pilot's view can be adjusted via a change view button on the joystick, as shown in Figure 6.16.

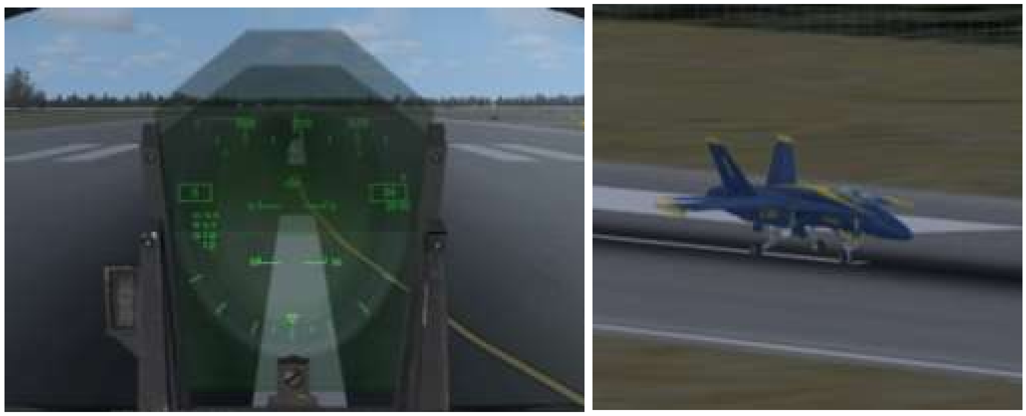

Figure 6.16 (Left) cockpit view and (Right) tower view. Views outside the cockpit can be particularly disorienting in VR because your controls are still piloting the aircraft, but your frame of reference is something else

6.6 Gesture-Enabled Cockpit

As a part of realistic flight simulation training, there is a hand-tracking system that is integrated as part of the virtual reality experience. This system uses an infrared tracking system, the LeapMotion controller [88], to enable the pilot to reach out and interact with instruments in the virtual cockpit using their index finger. The LeapMotion controller is shown in Figure 6.17.

Figure 6.17 A picture of the leapmotion controller **[89]**

The LeapMotion controller is mounted onto the Oculus headset via a USB connection that provides power to the unit and allows for imagery to be sent back to the host computer for processing. The controller is mounted in front of the headset so it can have the best view of the hands, as shown in Figure 6.18:

Figure 6.18 A picture of the leapmotion controller mounted on the Occulus headset

An example of the hand tracking is shown in Figure 6.19 where the leap motion is able to detect that a pen has been gripped. This was produced using the Orion beta software. You can see in the figure that not only is the hand position tracked, but also a vector is generated for the estimated position of each finger. Surprisingly finger positions could be tracked even when some fingers were obstructed by an object, but as expected the accuracy is a lot lower.

Figure 6.19 (Left) a photo of me holding a pen vs (Right) tracking my hand and finger positions via the leap motion

A screenshot of the hand-tracking interface in the flight formation software is shown in Figure 6.20 and Figure 6.21. The user is able to interact with elements of the virtual cockpit, such as the controls, which is shown on the right half of Figure 6.20.

Figure 6.20 (Left) an example of the hand-tracking in the cockpit of the flight formations simulation and (Right) an example of increasing the throttle control with a fist gesture

Figure 6.21 An example of using both the joystick control and gestures to fly a simulated Bell helicopter around Reno (NOTE: you can see the Grand Sierra, highway 395, and the Silver Legacy and downtown outside the cockpit)

NOTE: Hand-tracking is not implemented for the space game or for the water cycle ride, it only works with the flight formation simulation at this time.

6.7 Case Study 1: Reno Air Races

On September 12th – 17th the first case study, with 120 users during the Reno Air Races, was started. As a result of the slower pace of the event, there was more time to get feedback from real pilots (including detailed feedback on the flight controls which inspired the revision of the joystick system and led to the paper presented at the 27th International Conference on Software Engineering and Data Engineering in October 2018).

People were interested in simulating World War II planes, like Japanese Zeros and American PII – Lightning's, as the Reno air racing association focuses on these types of historic aircraft. While the WWII simulation game came with the simulator, it was good to test out the various sound and visual additions as well as the overall reliability of the simulator. Since this was the first time moving the flight simulator on its mobile platform there were some issues to be worked out (especially with stabilization), which were resolved by Saturday morning. A photo of the simulator at the Reno Air races is shown in Figure 6.22.

Figure 6.22 The flight simulator at the Reno Air Races, taken September 15th, 2018

6.8 Case Study 2: Aviation Roundup

The second and largest case study took place over the weekend of October 13th and 14th 2018 at the Minden Aviation Roundup event. This event was particularly exciting because the Blue Angels, an elite group of pilots from the U.S. Navy, were performing at the airshow. This group includes some of the top aviators in the world, and are known for the daring formations they fly in, sometimes coming within 18-inches of each other. Some of their signature moves and their aircraft is shown in Figure 6.23.

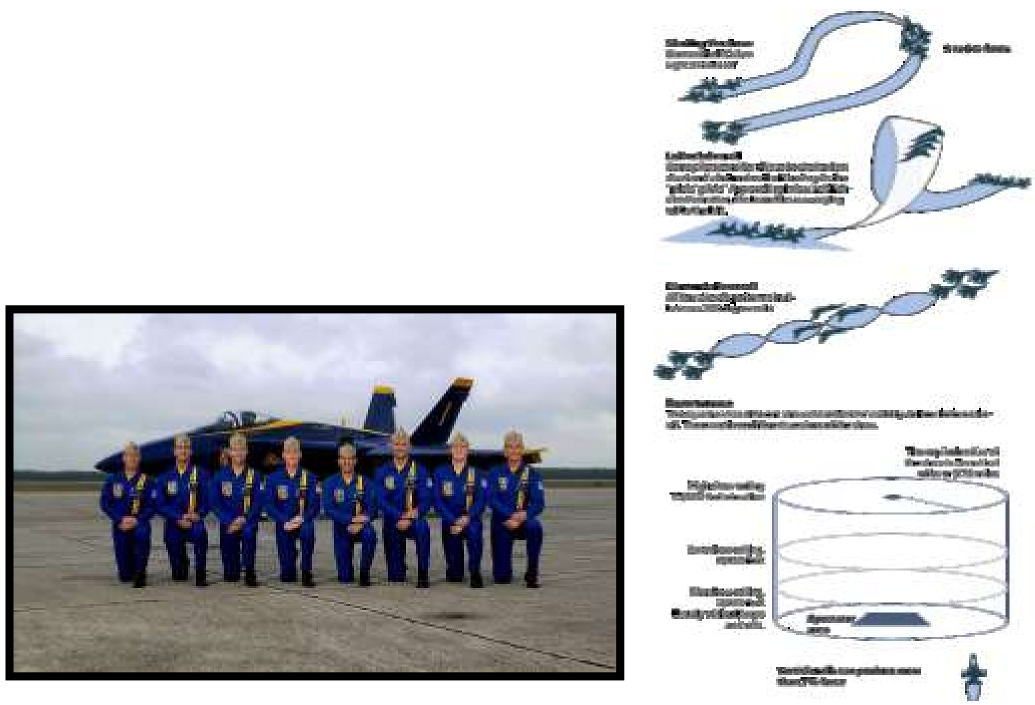

Figure 6.23 (Left) the 2018 Blue Angel team alongside their F-18 aircraft and (Right) an example of some of the maneuvers they perform

The public response was overwhelming (over 40,000 people attended the event) and specifically 300 showed up to try the flight simulator that weekend. 30 minutes before the doors opened, there was already a line of people waiting. At its most intense point, there was a wait of 2.5 hours. People in line watched as acrobatic planes flew overhead and users attempted to duplicate their stunts in the simulator, as shown in Figure 6.24.

Figure 6.24 The Blue Angels fly in the background of the simulator

There were even two Blue Angels who tried the experience, flying the very F-18 Hornet they were demonstrating at the airshow (in a primitive version of the flight formations software developed in this dissertation). We were invited to their hanger to meet the team afterwards, and got autographed posters as shown in Figure 6.25. This was a proud moment for me to have some of the people who inspired aspects of this dissertation test out the software and give feedback. Aircrew woman Marjorie Tolton is one of only 3 female Blue Angels on the team (and was the first Blue Angel to ride the simulator).

Figure 6.25 Alex Redei with (Left) Crew Chief Admiral Robert Weitershausen at the Blue Angels hangar (Right) Lt. Sargent Jonathan Bartlette after expericing the flight simulator and (Bottom) Logistics Support Aircrewman Marjorie Tolton

Reactions from the public were overwhelmingly positive. It was later learned that the flight simulator, and this research on flight formations was actually mentioned the day before, Friday October 12th, 2018 on a radio talk show on FM 103.7 ("The River") at around 8am [90].

Chapter 7 USABILITY STUDIES

7.1 Introduction

This chapter presents the user studies that were performed as part of the system validation. Specifically it looks at the human aspects of flight simulation through the lens of the research questions presented in Chapter 4.

This research involves human-subjects, and as a result of that an IRB (Institutional Review Board) approval was obtained prior to the start of both studies. To get an IRB approval, a fourteen chapter training on ethical research (by a partner of the University called CITI [91]) needed to be done. Elements of the training included reading the Belmont report, an overview of federal regulations on sponsored research, the definition of consent and how to obtain what's called "informed consent" from participants, working with protected groups such as children or prisoners, avoiding conflicts of interests, and more. The training was completed, and the certificate was obtained on July 31st, 2018.

Approval by the IRB was received August 27th, 2018; data collection began shortly after in September and October. The results of both user studies are shown in Sections 7.2 and 7.3.

7.2 User Study 1

The first study was performed using a mixed-methods research approach with 28 participants. Both quantitative and qualitative elements of data analysis were employed.

For the quantitative component participants rated their experience on a Likert scale [92]. A Likert scale is a simple numeric rating system gradient such as: rate your experience from one to five where one was a terrible experience and five was a fantastic experience. In this case the participants were asked to only select integer entries (so a rating of three and a half was not possible for any user). Participants were asked 14 questions about their experience, along with 5 questions on desired features, which they then rated using the numbering system outlined above. In addition, we interviewed each participant afterwards with seven open-ended questions. The questions asked are listed in Table 7.1, Table 7.2, and Table 7.3. The full interview script and user survey can be found in Appendix A.

Table 7.1 Quantitative Instrument 1 - User Experience Questionnaire

User Questionnaire	
Q01	▪ I learned more during the game
Q02	▪ I could recall the composition of minerals in the asteroids.
Q03	▪ I enjoyed the game
Q04	▪ I felt challenged by the game
Q05	▪ I felt motion sick
Q06	▪ I preferred being the pilot
Q07	▪ I preferred being the gunner
Q08	▪ I felt the motion simulated was accurate
Q09	▪ I felt in control
Q10	▪ I felt the scoring system was fair
Q11	▪ I felt the participant should not be able to 'die' in the game
Q12	▪ I enjoyed the back story part of the game
Q13	▪ I enjoyed the mineral collection part of the game
Q14	▪ I enjoyed the combat part of the game

Table 7.2 Quantitative Instrument 1 – Feature Request Questionnaire

User Questionnaire	
F01	▪ I'd like a 3D experience (like in the movies)
F02	▪ I'd like smells added (such as smelling oranges when flying through an orange grove)
F03	▪ I'd like a virtual reality experience
F04	▪ I'd like a roller coaster experience (no joysticks)
F05	▪ I'd like an educational experience (such as about the water cycle)

Table 7.3 Qualitative Instrument 1 – Interview

Participant Interview	
I01	▪ Tell me what you enjoyed about the experience.
I02	▪ Tell me what you would improve on this experience.
I03	▪ What change would increase your usage of the game?
I04	▪ What sticks out about this interview? Obstacles? Insights? Big themes?
I05	▪ What big reactions ("wow", "this is awful") did you have?
I06	▪ Was the user interface understandable?
I07	▪ Do you have any questions for me?

These 14 survey questions, 5 feature questions, and 7 interview questions were formulated at the same time in June of 2018 as the study underwent IRB review. While the study was reviewed by the University's office of research integrity, unfortunately, due to the difficulty in transporting participants to the study location, and time limitation, an outside panel of experts was not consulted regarding the appropriateness of each question. In an ideal world, outside experts would have been consulted to formulate each question, debating the purpose and appropriateness of each query before participants ever saw the questionnaire. The questions shown in Table 7.1, Table 7.2, and Table 7.3 are completely my own creation and reflect my personal curiosity regarding how participants would feel about the experience, as well as my interpretation of how this questionnaire could help answer the formulated research questions.

Reliability and validity are important metrics when developing an instrument for a quantitative analysis (in our case, the 3 surveys are our instruments). Reliability summarizes the consistency of the findings if the study were repeated, whereas validity reflects how well the research measures what it is actually set out to do [93]. In our case, participants were randomly selected members of the public. All participants were adults, but the exact age of each participant was not collected due to privacy concerns. Of the participants whose age we knew, age ranged from 19 years old to 62. Over three-quarters of the participant group were university students younger than 30 years old. There was about an equal mix of female and male participants. There were 28 participants total in this study. The difficulty in transporting contributors and the numerous man hours required to setup the simulator beforehand limited the pool of participants. Regarding reliability, while 28 participants is not a tremendous amount, it is typical in the field of human-computer interaction (HCI) to have smaller participant groups than say, Psychology. Considering that usually fewer participants are involved in HCI user studies, and given a participant pool of the same age distribution, together with the same pre-test and post-test, I believe the findings here are repeatable, and hence fit the definition of “reliable.”

Regarding the survey's validity, as discussed before, a weakness of this study is that questions were formulated by myself and not a panel of experts. Ten questions were aggregated to address RQ 1, three questions for RQ 2, and two questions for RQ 3. The questions do not overlap; none of the 10 questions used for research question one were used to analyze research questions two or three. This strengthens the validity claim, as each research question had a subset of the instrument specifically formulated to answer the question. Overall, determining the "validity" of the instruments was ambiguous given the particularities of the research questions (for example, RQ1 asks how adding motion to a game might change the human experience).

The questions were formulated to answer the research questions as follows: questions #3 through #13 were designed to address the first research question (RQ1), which was a general investigation into how a motion flight simulator might change the human experience in a game. Because the question was broad, multiple survey questions were created to gather how motion might have affected the participant's experience. Questions #1, #2, and feature question #5 were aimed at addressing research question two (RQ2), which evaluated whether adding motion would assist people with learning and recollection. Research question three (RQ3) asked whether users preferred a static, 3D, or VR experience; this was addressed in survey feature questions #1 and #3.

The results of the user survey indicate that users prefer a more interactive and motion-enabled experience. Figure 7.1 shows a full tally of each of the pre-test and post-test survey results for all questions in the user survey. This includes responses from both the participant and simulator groups.

Question	Post-Test: Strongly Agree	Post-Test: Agree	Post-Test: Neutral	Post-Test: Disagree	Post-Test: Strongly Disagree	Pre-Test: Strongly Agree	Pre-Test: Agree	Pre-Test: Neutral	Pre-Test: Disagree	Pre-Test: Strongly Disagree	Gain +/- pts
Q1. Learned Something	28.57%	14.29%	28.57%	0.00%	28.57%	10.71%	10.71%	46.43%	17.86%	14.29%	0.29
Q2. Recollection Minerals	0.00%	3.57%	39.29%	42.86%	14.29%	0.00%	0.00%	21.43%	60.71%	17.86%	0.29
Q3. Enjoyed Game	57.14%	28.57%	14.29%	0.00%	0.00%	71.43%	14.29%	14.29%	0.00%	0.00%	-0.14
Q4. Challenged By Game	85.71%	0.00%	14.29%	0.00%	0.00%	57.14%	14.29%	14.29%	14.29%	0.00%	0.57
Q5. Felt Motion Sick	14.29%	14.29%	0.00%	14.29%	57.14%	0.00%	0.00%	14.29%	0.00%	85.71%	0.86
Q6. Preferred Pilot	57.14%	28.57%	14.29%	0.00%	0.00%	57.14%	14.29%	28.57%	0.00%	0.00%	0.14
Q7. Preferred Gunner	28.57%	28.57%	14.29%	14.29%	14.29%	28.57%	14.29%	42.86%	0.00%	14.29%	0.00
Q8. Felt Simulation Was Accurate	57.14%	42.86%	0.00%	0.00%	0.00%	71.43%	14.29%	14.29%	0.00%	0.00%	0.00
Q9. Felt in Control	42.86%	28.57%	28.57%	0.00%	0.00%	42.86%	28.57%	14.29%	14.29%	0.00%	0.14
Q10. Player Shouldn't Die	28.57%	14.29%	28.57%	0.00%	28.57%	14.29%	28.57%	14.29%	0.00%	42.86%	0.43
Q11. Enjoyed Backstory	28.57%	14.29%	42.86%	0.00%	14.29%	28.57%	14.29%	42.86%	0.00%	14.29%	0.00
Q12. Enjoyed Mineral Collection	57.14%	14.29%	14.29%	14.29%	0.00%	42.86%	14.29%	42.86%	0.00%	0.00%	0.14
Q13. Enjoyed Combat	71.43%	14.29%	0.00%	14.29%	0.00%	71.43%	14.29%	14.29%	0.00%	0.00%	-0.14
Q14. Scoring was Fair	42.86%	57.14%	0.00%	0.00%	0.00%	42.86%	28.57%	28.57%	0.00%	0.00%	0.29
F1. 3D Viz	42.86%	14.29%	0.00%	28.57%	14.29%	42.86%	42.86%	0.00%	0.00%	14.29%	-0.57
F2. Smells	28.57%	14.29%	14.29%	28.57%	14.29%	28.57%	14.29%	14.29%	28.57%	14.29%	0.00
F3. VR	60.71%	21.43%	0.00%	3.57%	14.29%	25.00%	7.14%	50.00%	14.29%	3.57%	0.75
F4. Roller Coaster	57.14%	14.29%	0.00%	0.00%	28.57%	42.86%	25.00%	3.57%	14.29%	14.29%	0.04
F5. Educational Experience	42.86%	14.29%	42.86%	0.00%	0.00%	14.29%	14.29%	71.43%	0.00%	0.00%	0.57

Figure 7.1 Comparison of the distribution of results from pre-test to post-test

The top row of Figure 7.1 enumerates the possible user responses, where "strongly agree" on the far left indicated a response of 5 on the Likert scale, and "strongly disagree" on the far right indicated a response of 1 on the scale. The summarized post-test and pre-test scores for all participants are displayed in a manner that facilitates easy identification of the change in disposition. It should be noted that both control and the simulator groups' questionnaire responses are aggregated in Figure 7.1.

The strongest observation was that 28.58% of users felt some level of motion sickness after playing the simulator game (as shown in Figure 7.1, Q11, in the post-test results), whereas 0% of users felt motion sickness after playing the PC version of the game. A further break down of these results is shown in Figure 7.2, where the survey responses (1-5) are tallied and summed according to the three research questions addressed. The mean survey of scores for research question one increased from 39 to 43, rose on average for research question two from 8.04 to 8.60, and finally increased 7.18 to 10.68 for survey items in research question three.

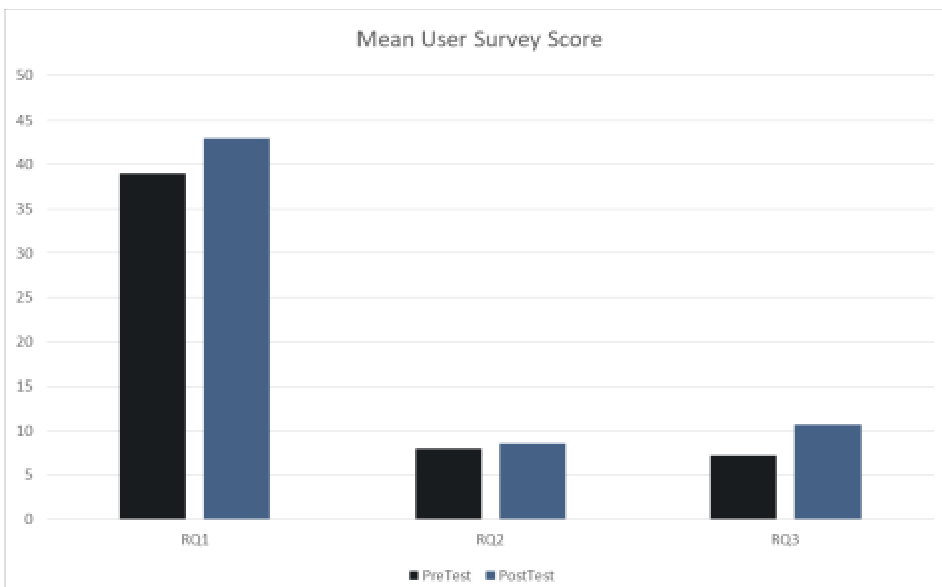

Figure 7.2 Mean user survey score

As discussed regarding research question two, the pre-test and post-test mean survey results stayed pretty much the same. Further exploration into the results took place by looking at the survey responses for each question individually, as shown in Figure 7.3. This subscale revealed that users scored their recollection of the asteroid minerals and educational experience of the space game lower after playing the game in the motion simulator than they did when just playing the game on PC. My observations seem to agree with this, participants found the motion game more challenging, and the added intensity probably reduced their focus on the educational aspects of the mineral collection portion of the game.

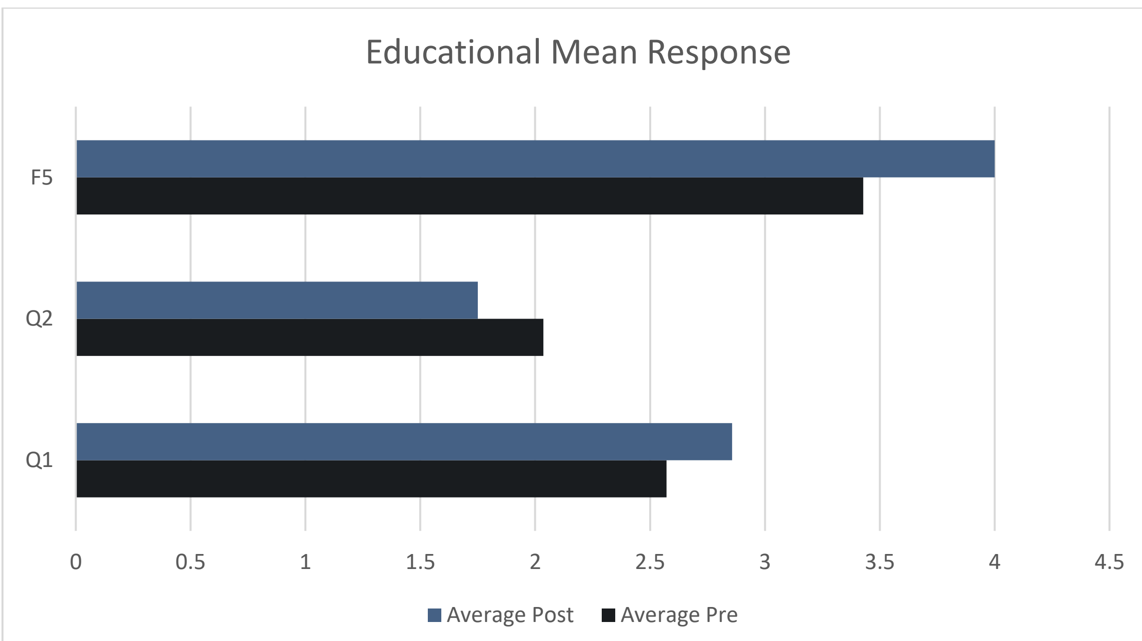

Figure 7.3 Survey Response to qquestions #1 and #2: on recollection and educational aspects of the space game, pertaining to research question RQ2

While users didn't find the space game particularly educational (mean survey response was less than 3), they also ranked their desire for a more educational experience 0.57 points higher on the post-test survey.

Next there was a need to determine whether the results obtained had statistical significance. For this, a portion of Chapter 6 of Dr. Mackenzie's book on human-computer interaction [94] and an online course on user studies by Dr. Bude Su [95] was followed. To check for statistical significance, an ANOVA analysis of variance test was used. Confounding variables were controlled by keeping a separate control group (a group who never rode the flight simulator). This group was comprised of roughly 29% of the participant population. In addition, structuring the survey into a pre-test and a post-test also strengthens the claims of statistical significance of the study. It does this by capturing the state of the participant before and after the experiment, so that one can see what sort of variance was introduced by the survey itself. The results of the first ANOVA test is shown in Table 7.4.

Table 7.4 ANOVA results for research question one

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
Control	8	40	0.8	1.143
Simulator	20	16	5	4.379

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	100.8	1	100.8	28.737	1.301E-5	4.225
Within Groups	91.2	26	3.508			
Total	192	27				

Table 7.4 relates to the ANOVA analysis of the first research question (how adding motion to a game might affect the human experience). The null hypothesis states that of the 10 survey questions asked to address the first research question (Q3-Q13), the changes in survey responses between the control group and the simulator group were not significant. The ANOVA results shown in Table 7.4 demonstrate that there is a statistically significant difference between the average response of the two groups for research question one, because the p-value (.0001301) was less than the alpha (0.05). Additionally, an ANOVA test was run for the second research question (pertaining to memorization of facts during a motion game), whose results are shown in Table 7.5.

Table 7.5 ANOVA results for research question two

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
Control	8	9	0.125	1.554
Simulator	20	7	0.35	1.082

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	3.432	1	3.432	2.840	0.104	4.225
Within Groups	31.425	26	1.209			
Total	34.857	27				

Table 7.5 show the results of an ANOVA analysis performed to address the second research question. For this research question, the null hypothesis states that the ability of participants of one group to recall the mineral composition of asteroids is not significantly

different from the other group. In the ANOVA results shown in Table 7.5 the p-value is highlighted. Based on these results we must accept the null-hypothesis because the calculated p-value (0.104) is greater than the alpha (0.05). Furthermore, an ANOVA test was run to address research question three, as shown in Table 7.6.

Table 7.6 ANOVA results for research question three

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
Control	8	-112	-14	0
Simulator	20	-216	-10.8	10.274

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	58.514	1	58.514	7.794	0.010	4.225
Within Groups	195.2	26	7.508			
Total	253.714	27				

In Table 7.6, an ANOVA analysis was performed to address the third research question. The null hypothesis states that preferences of participants (VR, 3D, or static experiences) do not significantly change between the control and simulator groups. The ANOVA results demonstrate that there is a statistically significant difference between the average responses of research question three. The p-value for research question three (0.010) is less than the alpha value of (0.05), indicating that the null hypothesis can be rejected. Furthermore the ANOVAs were followed-up with three t-tests for each of the research questions. Since all participants completed the pre and post-surveys, I used a paired t-test for two sample means. The results of the t-tests for the first three research questions are shown, respectively, in Table 7.7, Table 7.8, and Table 7.9.

Table 7.7 t-test Question one (left)
Table 7.8 t-test Question two (right)

	Pre	*Post*
Mean	39	43
Variance	32.889	22.815
Observations	28	28
Hypothesized Mean Difference	0	
df	27	
t Stat	-3.969	
P(T<=t) one-tail	0.001	
t Critical one-tail	1.703	

	Pre	*Post*
Mean	8.036	8.607
Variance	2.851	3.6555
Observations	28	28
Hypothesized Mean Difference	0	
df	27	
t Stat	-1.059	
P(T<=t) one-tail	0.006	
t Critical one-tail	1.703	

Table 7.9 t-test Question three (bottom)

	Pre	*Post*
Mean	7.183	10.679
Variance	7.667	7.337
Observations	28	28
Hypothesized Mean Difference	0	
df	27	
t Stat	-2.661	
P(T<=t) one-tail	0.328	
t Critical one-tail	1.703	

Since the three research hypotheses are directional the absolute value of the t-stat was compared to the t-critical one tail value [96]. The absolute value of the test statistic was greater than the t-critical one tail; therefore, **the null hypothesis was rejected for two of the three research questions: research questions one (RQ1), and three (RQ3). For research question two (RQ2) there was not strong enough data to be able to show that the difference was significant, leading to a failure to reject the null hypothesis** [97] (the sample means were similar, and the t-statistic was not greater than the t-critical).

For the qualitative component participants were observed in several ways. Firstly, their body language and non-verbal cues were observed when entering and exiting the flight simulator. Their reactions to the controls and safety procedures were also observed. While it had originally been planned to observe their body language during the simulation, through the cockpit camera, the camera was not able to get a clear view of the participants due to the low resolution of the display. Since the cockpit could not be recorded it was decided to instead base the qualitative feedback directly on the reactions obtained before and after the participant experiences the simulation.

Hilarious reactions of participants to the simulator included “Gaah,” “Oh no!” and “Woops.” 20% of the participants mentioned, in passing, how they didn’t play video games. About half the participants observed had a difficult time maneuvering the space ship in game. This seemed due to two factors: the participant’s unfamiliarity with analog joystick finesse, and the in-game space ship’s slow turning speed.

When interviewed, a handful of participants (about 7) showed great excitement over the incorporation of virtual reality into the simulator (which was done in user study #2, not as part of this study). Users also demonstrated interest in other human-computer interaction peripherals such as the use of gesture and hand-tracking for interacting with the cockpit.

7.3 User Study 2

The second study was focused on flight formation simulation, and again a mixed-methods approach was employed. This study was much smaller in size, with 10 participants, 2 in the control group and 8 in the simulator group, but each participant received more time and discussion in the pre-test and post-test interviews.

For the quantitative component metadata was gathered from the flight formations simulation. This data included a recording of the simulation, a flight path, and the formation score, as shown in Section 6.4. The duration of the user study was kept to 40 minutes for each participant, with simulations inside and outside the simulator timed at 5 minutes long. The qualitative data was collected via interviews with participants before and after the experiment. Interview questions are displayed in Table 7.10, and a complete copy of the user questionnaire is available in Appendix A.

Table 7.10 Quantitative Instrument two - User Experience Questionnaire two

User Questionnaire	
Q01	▪ Are you a licensed pilot
Q02	▪ Have you tried VR before
Q03	▪ Rate your comfort level with VR
Q04	▪ I felt motion sick
Q05	▪ I found it easy to navigate
Q06	▪ I was able to keep the aircraft in control
Q07	▪ I felt the simulation was challenging
Q08	▪ I felt the motion simulated was accurate
Q09	▪ I felt the simulation game itself was accurate
Q10	▪ I enjoyed the experience
Q11	▪ I would do that again
Q12	▪ I felt the scoring was fair
Q13	▪ I play flight simulation games at home
Q14	▪ I am interested in the aviation community

As in user study #1 a control group was also utilized in user study #2, and the latter study was also performed blind (meaning participants had no idea whether they were in the experimental group or the control group). The results of the survey are shown in Figure 7.4.

	Post-Test					vs Pre-Test					Gain
Question	Strongly Agree	Agree	Neutral	Disagree	Strongly Disagree	Strongly Agree	Agree	Neutral	Disagree	Strongly Disagree	+/- pts
Q3. VR Comfort	40.00%	30.00%	30.00%	0.00%	0.00%	50.00%	0.00%	20.00%	10.00%	20.00%	0.60
Q4. Felt Motion Sick	10.00%	10.00%	40.00%	0.00%	40.00%	10.00%	0.00%	0.00%	20.00%	70.00%	0.90
Q5. Easy to Navigate	20.00%	20.00%	60.00%	0.00%	0.00%	0.00%	0.00%	60.00%	30.00%	10.00%	1.10
Q6. Kept Aircraft in Control	40.00%	20.00%	40.00%	0.00%	0.00%	30.00%	20.00%	40.00%	10.00%	0.00%	0.30
Q7. Simulation Was Challenging	40.00%	30.00%	10.00%	10.00%	10.00%	0.00%	40.00%	50.00%	0.00%	10.00%	0.60
Q8. Motion Was Accurate	50.00%	40.00%	10.00%	0.00%	0.00%	40.00%	0.00%	50.00%	0.00%	10.00%	0.80
Q9. Simulation Was Accurate	50.00%	30.00%	20.00%	0.00%	0.00%	20.00%	40.00%	30.00%	0.00%	10.00%	0.70
Q10. Enjoyed Experience	80.00%	20.00%	0.00%	0.00%	0.00%	20.00%	20.00%	40.00%	0.00%	20.00%	1.60
Q11. Would Do Again	60.00%	10.00%	20.00%	0.00%	10.00%	30.00%	30.00%	40.00%	0.00%	0.00%	0.20
Q12. Scoring Was Fair	60.00%	20.00%	10.00%	10.00%	0.00%	20.00%	30.00%	50.00%	0.00%	0.00%	0.60
Q14. Aviation Interest	60.00%	20.00%	20.00%	0.00%	0.00%	50.00%	20.00%	20.00%	10.00%	0.00%	0.30
Q1. Licensed Pilot	20.00%	0.00%	0.00%	0.00%	80.00%	20.00%	0.00%	0.00%	0.00%	80.00%	N/A
Q2. Tried VR	20.00%	0.00%	0.00%	0.00%	80.00%	20.00%	0.00%	0.00%	0.00%	80.00%	N/A
Q13. Play Flight Sims at Home	50.00%	0.00%	0.00%	0.00%	50.00%	50.00%	0.00%	0.00%	0.00%	50.00%	N/A

Figure 7.4 Pre-test and post-test results for the second user study

Significant findings in the data included a strong increase in motion sickness feeling, strong levels of enjoyment for the participant group that experienced the motion flight simulator, and a small increase in interest in the aviation industry. Participants reported only a small increase, 0.3 points on average, of their perceived ability to control the aircraft in the motion simulator. However, from my perspective of observing the participants outside the simulator, I noted much better control of the aircraft when the participants were in the motion simulator vs the static experience, perhaps due to the increased sense of presence inside the simulator.

In addition the flight formation scores were captured as shown in Figure 7.5 and Figure 7.6. Participants in the control group, of which there were only two, experienced some score growth, 50.5 points on average, but participants in the simulator group, of which there were 8, experienced a significantly stronger average score growth of 224.25 points.

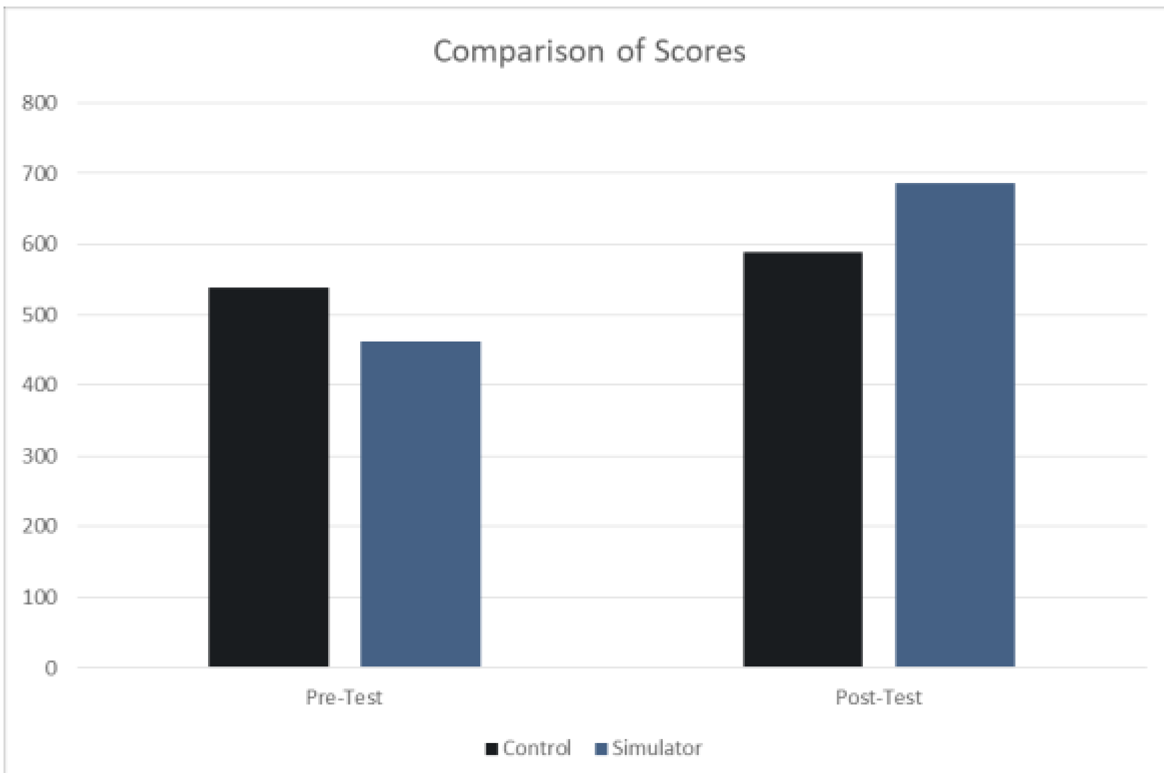

Figure 7.5 Pre-test and post-test flight formation score comparison

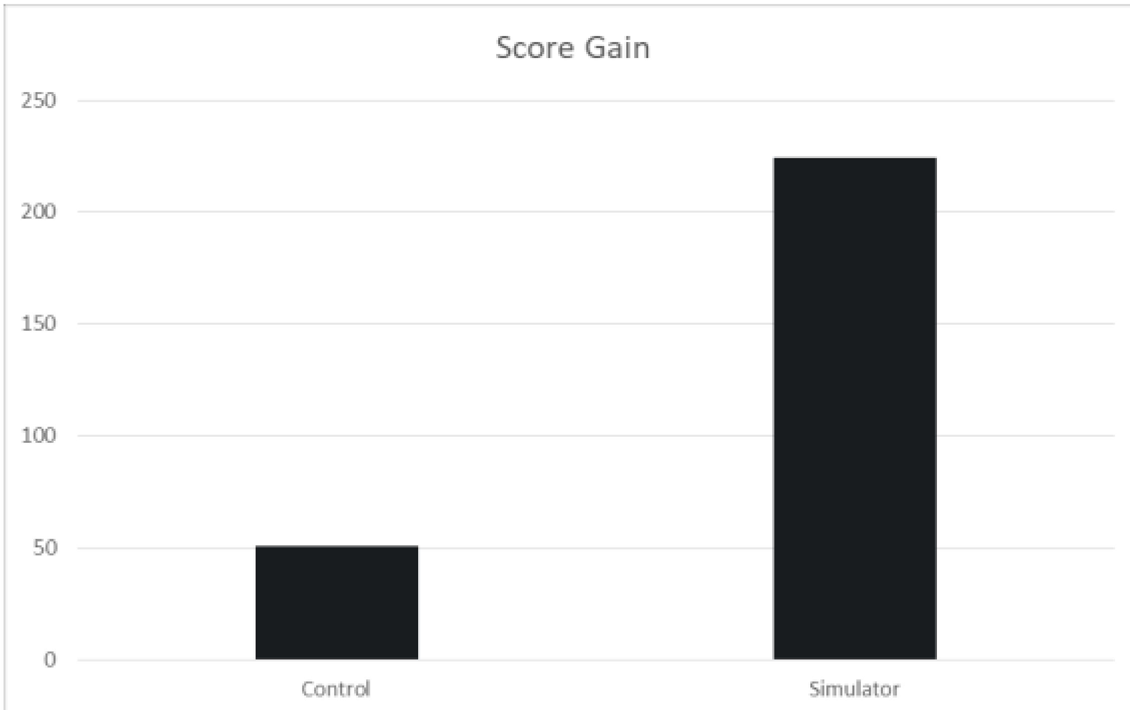

Figure 7.6 Average score gain for the control and simulator participant groups

The question here is whether the increased median score of the simulator group, seen in Figure 7.6, was actually due to enhanced flight formation learning, or other factors such as the distribution of the participants. In order to answer this question an ANOVA analysis test was performed. With alpha set to 0.05, the following results were obtained in Table 7.11.

Table 7.11 ANOVA calculation for user survey 2

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
Control	2	101	50.5	1012.5
Simulator	8	1794	224.25	8412.214

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	48302.5	1	48302.5	6.451	0.035	5.3177
Within Groups	5898	8	7487.25			
Total	108200.5	9				

Research question 4 (RQ4) asked: “Will the participants’ ability to follow a flight formation increase if they receive feedback in motion simulator?” The null hypothesis for this research question states the average scores for the simulator and control groups are not statistically different. **The ANOVA rejects the null hypothesis for RQ4**, given that the p-value is less than the alpha value of 0.05. Thus, the final conclusion is that participants in the motion simulator scored 173.75 points higher on flight formation learning, indicating that the flight simulation platform developed in this dissertation has indeed improved the flight formation capabilities of the targeted participants over the control group.

Chapter 8 CONCLUSIONS AND FUTURE WORK

This dissertation presented a combination of hardware and software incorporated into a system for delivering a high-fidelity, virtual reality enabled, flight simulation experience. The proposed solution has direct applications in several fields. Various utilizations of the flight simulator for educational, entertainment, and pilot training purposes were explored. These were demonstrated in several applications developed for this purpose: a water cycle ride, a space game, and a flight formation training simulation.

Four research questions were formulated, addressed, and answered, pertaining to various aspects of human experience, learning retention, preferred user interface technologies, and efficacy of pilot training in a motion flight simulator. These questions address how the features of a high-fidelity flight simulator may be used to improve human learning, training, and entertainment. To answer these questions, two user studies involving 38 participants were performed, both comprising quantitative and qualitative assessments. Three of the research questions (RQ 1, RQ 3, and RQ 4) were statistically validated by the findings of the user studies, while one question (RQ 2) was not answered with sufficient statistical significance.

The research discussed in this dissertation also contributes to a better understanding of the following:

- Balancing harmonic distortions of variable frequency drives in a 3-phase power environment containing sensitive electronics

- Transformation of axes of rotation from quaternion to Euler within Unity
- Using the ATMega32u4 microcontroller to handle simultaneous joystick inputs
- Engineering a trailer mount for the simulator frame (enabling it to become mobile)
- Development of an educational and entertaining ride for the promotion of Earth sciences
- Marshalling time-critical data from the simulation software to the motors using UDP and RS-485.

To the best of our knowledge, this is the first successful synthesis of a motion flight simulator with virtual reality capabilities and a gesture-tracking experience. Furthermore, the enhanced platform created shows commercial promise, and has already been used to facilitate partnerships with three non-profit museums in the Northern Nevada area.

Future research can be continued by leveraging the FAA's recently expanded opportunities for flight simulators in 14 CFR part 61 [98]. This can be done specifically by enhancing the fidelity of the experience through incorporating voice recognition for an air traffic controller, and using machine learning techniques to develop randomized new challenges and environmental conditions for the pilots. Cloud computing could also be used to network simulators together for further formation training, and keep track of pilot hours.

Another aspect of future work could involve collecting data from sensors and software during the pilots' training sessions, which could then be leveraged to train an autonomous flight system (something that Dr. Kostas Alexis from the University of

Nevada, Reno mentioned could be of particular interest to the Office of Naval Research and perhaps their X-47B project). Areas of grant funding might include NASA solicitation #80JSC018N0001, which presents an opportunity to explore neuro-ocular syndrome [99], and AFAR solicitation #USAFA-BAA-2018, which is an open solicitation by the U.S. Air Force to explore how to enhance the cadet learning experience [100].

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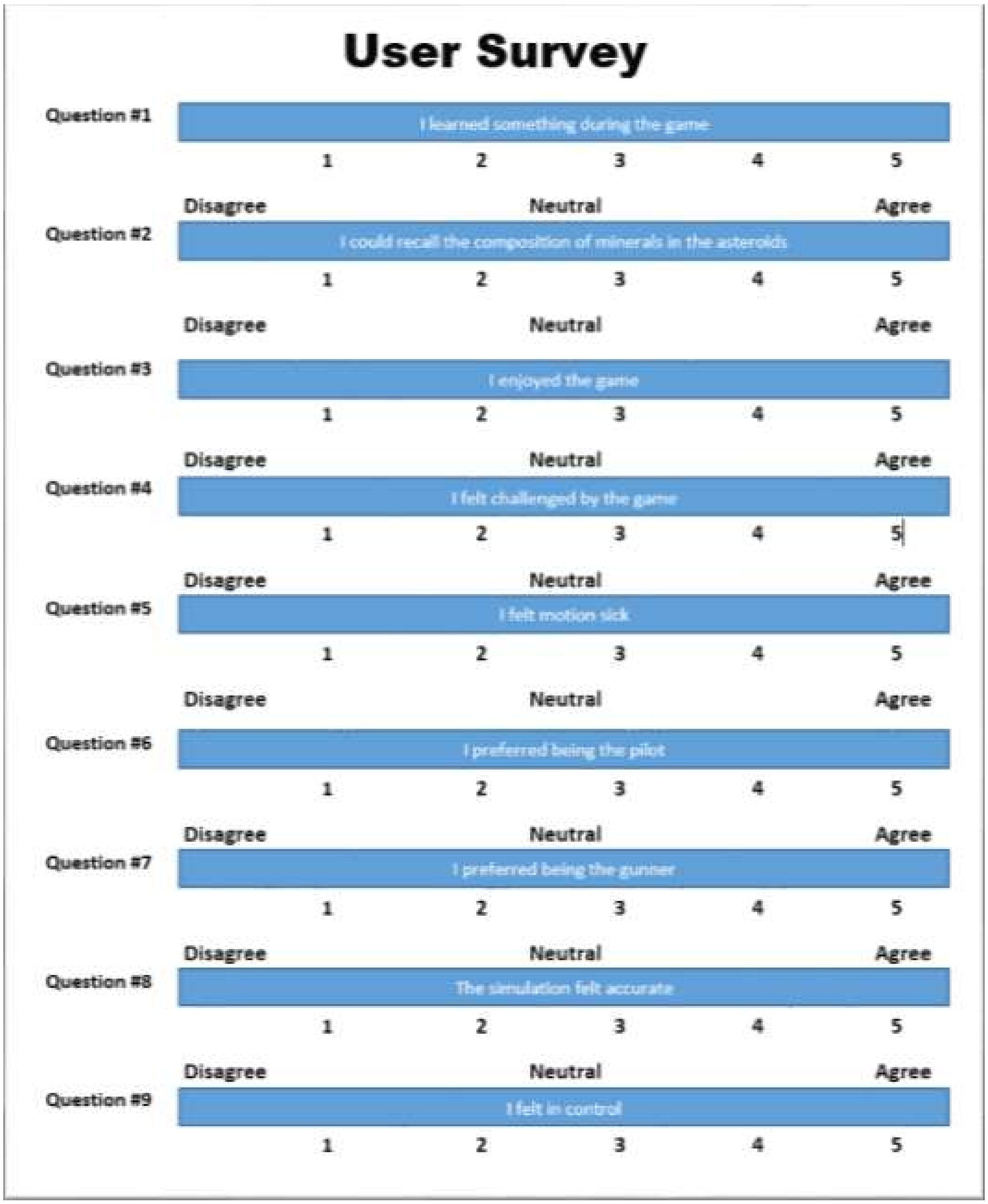
Appendix A – User Study Instruments

This survey was given to all participants twice as a pre-test and a post-test:



User Survey

Question #1 — I learned something during the game

1 2 3 4 5

Disagree Neutral Agree

Question #2 — I could recall the composition of minerals in the asteroids

1 2 3 4 5

Disagree Neutral Agree

Question #3 — I enjoyed the game

1 2 3 4 5

Disagree Neutral Agree

Question #4 — I felt challenged by the game

1 2 3 4 5

Disagree Neutral Agree

Question #5 — I felt motion sick

1 2 3 4 5

Disagree Neutral Agree

Question #6 — I preferred being the pilot

1 2 3 4 5

Disagree Neutral Agree

Question #7 — I preferred being the gunner

1 2 3 4 5

Disagree Neutral Agree

Question #8 — The simulation felt accurate

1 2 3 4 5

Disagree Neutral Agree

Question #9 — I felt in control

1 2 3 4 5

User Survey – Page 1

Question #10 I felt the player should not be able to 'die' in the game

1 2 3 4 5

Disagree Neutral Agree

Question #11 I enjoyed the back story part of the game

1 2 3 4 5

Disagree Neutral Agree

Question #12 I enjoyed the mineral collection (asteroid shooting) part of the game

1 2 3 4 5

Disagree Neutral Agree

Question #13 I enjoyed the combat part of the game

1 2 3 4 5

Disagree Neutral Agree

Question #14 I felt the scoring system was fair

1 2 3 4 5

Below is a list of five features. Please rate the features below in their importance to you:

Feature #1 I'd like a 3D visualization experience (like in the movies)

1 2 3 4 5

Disagree Neutral Agree

Feature #2 I'd like smells added to the game or simulator

1 2 3 4 5

Disagree Neutral Agree

Feature #3 I'd like a virtual reality experience

1 2 3 4 5

Disagree Neutral Agree

Feature #4 I'd like a roller coaster experience (no joystick control)

1 2 3 4 5

Disagree Neutral Agree

Feature #5 I'd like an educational experience

1 2 3 4 5

User Survey – Page 2

In addition, the following checklist was used to ensure test consistency & capture participant observations:

Simulator: __Static__ Control: __ User Study 1 Participant #: ________

PARTICIPANT OBSERVATION CHECKLIST

1. BEFORE THE INTERVIEW

- ☐ Introductions
- ☐ Participants are asked for consent & handed the consent information sheet.
- ☐ Participants are informed they can stop the study at any time. Participants are informed of the flight simulator's stop button.

2. PRE-TEST: THE STATIC GAME

- ☐ A participant is directed to the game console.
- ☐ A 5 minute timer is started and participant is asked to play the game.
- ☐ When the timer elapses, the participant is asked to stop playing, the game is exited, and the participant's score is recorded

3. POST-TEST: SIMULATION OR CONTROL

- ☐ The participant is directed to the simulator (or interviewed if control group).
- ☐ A researcher helps the participant secure their lap-belt and shoulder restraint. Two participants may ride in the simulator at once, and the participants are reminded of the stop button.
- ☐ The canopy is shut and the game is loaded.
- ☐ A 5 minute timer is started (automatically by the software).
- ☐ When the timer elapses, the motion stops, and participants are lowered and exit the simulator.

4. INTERVIEW QUESTIONS

- ☐ The participant is given the user survey to fill out. Then, the participant is interviewed as such:
- ☐ Tell me what you enjoyed about the experience:

____

____

____

- ☐ Tell me what you would improve on this experience:

____

____

____

Interview Checklist – Page 1

- [ ] What big reactions ("wow", "this is aweful") did the participant have?
- [ ] What would increase the participant's enjoyment?
- [ ] What sticks out about this interview? Obstacles? Insights? Big themes?
- [ ] What change would increase the participant's usage of the game?
- [ ] What surprising things did you hear?
- [ ] Do you have any questions for me?

Interview Checklist – Page 2

The following surveys were given to all participants of research question 4:

User Study 2

Participant #: ________

Sim: __ Stat: __ C: __

User Survey

On the questions below, please rate your disposition to each question on a scale of 1 to 5, with 1 meaning strongly disagree, 3 meaning neutral, and 5 meaning you strongly agree with the statement:

Question #1 Are you a licensed pilot?

Yes **No**

Question #2 Have you tried VR before?

Yes **No**

Question #3 Level of comfort with virtual reality:

1 **2** **3** **4** **5**

Disagree **Neutral** **Agree**

Question #4 I feel motion sick:

1 **2** **3** **4** **5**

Disagree **Neutral** **Agree**

Question #5 I found it easy to navigate:

1 **2** **3** **4** **5**

Disagree **Neutral** **Agree**

Question #6 I was able to keep the aircraft in control:

1 **2** **3** **4** **5**

Disagree **Neutral** **Agree**

Question #7 I felt the simulation was challenging:

1 **2** **3** **4** **5**

Disagree **Neutral** **Agree**

Question #8 I felt the simulation was accurate:

1 **2** **3** **4** **5**

User Survey for Flight Formations – Page 1

User Study 2

Participant #: ________
Sim: __ Stat: __ C: __

Question #9 — Disagree / Neutral / Agree

I enjoyed the experience:

1 2 3 4 5

Question #10 — Disagree / Neutral / Agree

I would do that experience again:

1 2 3 4 5

Question #11 — Disagree / Neutral / Agree

Do you play flight simulation games at home?

Yes No

Question #12 — Not Interested / Neutral / Very Interested

Rate your level of interest in the aviation community?

1 2 3 4 5

Simulation Level: 2D 3D VR

Difficulty Level: Easy Medium Hard

Formation Score: ______________________________

Aircraft Flown: ______________________________

Location: ______________________________

# of Crashes: 1 2 3 4 5+

User Survey for Flight Formations – Page 2

Appendix B – Acronyms and Glossary

Term	Meaning
ATP	Airline Transport Pilot
RARA	Reno Air Racing Association
VR	Virtual Reality
Livery	A paint scheme of an aircraft, for example, the Alaskan man is painted on the tail of every aircraft owned by Alaska Airlines and is part of their brand.
COM	Component-Object Model
DLL	Dynamically Liked Library
UML	Unified Modeling Language – a design language used by software engineers
WPF	Windows Presentation Foundation
XAML	Extensible Application Markup Language
IDE	**I**ntegrated **D**evelopment **E**nvironment
GUI	**G**raphical **U**ser **I**nterface
HP	Horsepower
AC	Alternating Current
ANOVA	Analysis of Variance
Glass Cockpit	Where the traditional analog gauges and instruments inside an aircraft cockpit are replaced with newer digital displays
Fly-By-Wire	A system where an aircraft's controls are managed through computer signals from the cockpit rather than via a mechanical linkage
PID	Proportional integral derivative, a popular type of control loop feedback mechanism.