2021 ASEE ANNUAL CONFERENCE
Virtual Meeting | July 26–29, 2021 | Pacific Daylight Time
Paper ID #33500

Development of a Virtual Reality Flight Simulator to Assist in the Education of Aircraft Design Engineers

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Development of a Virtual Reality Flight Simulator to Assist in the Education of Aircraft Design Engineers
(Work in Progress)

ABSTRACT

The ongoing development of a Stewart platform-based flight simulator that incorporates virtual reality has provided ample opportunities for exciting project-based learning for undergraduate engineering students at Oral Roberts University. Multiple capstone design project teams have contributed to the research and development effort and benefitted from the multi-disciplinary systems engineering environment. The current senior project team consists of five students from the mechanical, electrical and computer engineering concentrations working to provide design improvements/refinements, as well as the development and execution of a testing and validation plan for all aspects of the system.

The Stewart platform provides full six-degree-of-freedom motion to the suspended pilot seat through revolute joints in response to pilot inputs via a control yoke or joystick. The pilot senses this simulated aircraft motion while enjoying a realistic virtual reality flight experience via a VIVE headset that immerses the student in a cockpit with vivid scenery outside the window. Various aircraft options are possible, including uniquely designed custom aircraft via the PlaneMaker feature of the X-Plane 11 flight simulation software. PlaneMaker will allow engineering students in the Aircraft Design course to create original aircraft designs by inputting the necessary parameters into PlaneMaker and then virtually test-flying their aircraft in X-plane 11, giving the students quicker flight performance data for iterative designs.

Providing students with timely and exciting feedback on their original aircraft designs is anticipated to be highly motivating to the engineering students. In addition, the simulator will be housed in the Virtual Reality Center at the university so that local K-12 students can experience the wonder of flight, as well as some of the engineering aspects of aircraft design. Therefore, the simulator and its interfaces must be engineered to be used as an effective flight-simulator and include the necessary safety parameters, yet simple enough for a non-expert to operate. One goal of this project is that through the experience of using the flight-simulator, K-12 students will be more motivated to pursue careers in engineering disciplines.

Although nearly complete, there are a few aspects of the system that need further engineering analysis and development. Finite element analysis will be applied to the mechanical linkages in order to firmly establish appropriate factors of safety for all mechanical elements. The development of a more realistic control yoke to receive pilot inputs is also being researched and considered. In addition, the computer interfaces for proper signal communications requires

additional work. The primary focus of this final phase is the development and execution of a test and validation plan to ensure that the system is providing a reasonably accurate simulation of the actual flight experience. This will require subsystem testing as well as integrated systems testing to faithfully reproduce vehicular dynamics for a variety of aircraft types.

INTRODUCTION

A decade ago, virtual reality was a relatively unexplored technology that was expensive and unrefined. However, times have changed. According to one education group, "…virtual reality has grown up. Once an exotic field of computer sciences, it is now an important topic for the engineers of tomorrow." [2] Now that virtual reality is more accessible to the public, the opportunity is present for education systems to revolutionize the way students learn. A team of five engineering undergraduate students at Oral Roberts University is continuing the development of a virtual reality flight motion simulator that will be used in an aircraft design class and will be housed in the virtual reality educational building on campus.

This project combines a Stewart platform, virtual reality and flight simulator software. Back in 2017, the original team modeled the Stewart platform, but the current group has been tasked with fixing and improving the circuitry and function of the original design. Computer software used include X-Plane 11, SMC3, and SimTools; these are combined to work as a single system. SMC3 combines two motors to work in pairs using Arduino Unos in conjunction with Sabertooth motor-drivers and syncs three pairs of motors to facilitate all six degrees of freedom. X-Plane 11 is a user-friendly, interactive game run on the Steam platform. X-Plane 11 provides advice on designing aircraft in-game, making it an optimal choice for the purposes of this project, as the intended audience is composed of students and the general public. When selecting a VR headset, the group considered the Oculus Rift and the Valve Index in addition to the HTC Vive. However, the Oculus has lower quality than the Vive and the Valve Index was out of stock. ORU also graciously offered an HTC Vive headset for the purpose of the project.

The backbone of the flight simulator is powered by SimTools, which serves as the link between the Arduinos, Sabertooth motor-drivers, and X-Plane 11. SimTools sends data via UDP packets sent over a network port, as well as through serial USB ports. Movement data, such as axis location, speed, direction, and force, is retrieved from the X-Plane 11 software via SimTools, and then sent through the SMC3 Utility to the Arduino. The Arduino sends serial data to the Sabertooth drivers, which updates the motors and sends feedback to the Arduinos. SimTools allows for a customizable virtual-reality experience through the use of Proportional-Integral-Derivative (PID) control feedback. Each proportion can be changed as necessary, which will allow the project to achieve a believable flight experience. SimTools will serve as the main software used to test the safety of movement on each axis, and ensure that all motors are running optimally and perform as expected under the specified operating conditions.

The scope of this project extends beyond just assisting engineering students, however. Several pre-programmed flights will be available for the general public, exposing anyone, regardless of prior knowledge, to the world of aircraft design. This makes the simulator a very powerful tool to enhance learning experiences for all types of people. With this in mind, one goal is to inspire the next generation of engineers by giving them a chance to experience the power of virtual-reality flight.

PROJECT HISTORY

In Fall 2017, a multi-disciplinary team of six undergraduate engineering students at Oral Roberts University (ORU) began developing a Stewart-platform-based virtual reality flight simulator prototype. In doing this, they hoped to develop a more innovative approach to enhance the understanding of engineering design principles and custom aircraft design. This project took the form of the students' senior capstone project, a university graduation requirement.

By Spring 2018, the students had successfully designed and constructed a prototype that was able to simulate the motion of aircraft based on control inputs initiated by the user.1 However, when testing the motors used to drive the motion, they proved to not be powerful enough to execute all necessary functions without sustaining damage. At the end of the school year, the team determined that more powerful motors would be necessary. More funding was requested and eventually granted, but not before the senior students had graduated from ORU. The next year's class of students installed the new motors in the Spring of 2019, but testing the prototype was very limited due to the School of Engineering moving all labs and classrooms to new facilities across the street. Boxing up the simulator and all required equipment proved to be a large challenge. Another group of seniors attempted to rebuild and test the simulator during the 2019-20 school year. However, the COVID-19 pandemic severely limited any progress due to the shutdown of facilities.

Now, a new multi-disciplinary team (three electricals, one mechanical, one computer) of senior engineering students is completing this project as a senior capstone project. This includes rebuilding the Stewart platform as the original group designed in 2017 but with the addition of the improved motors, as well as thorough testing of the simulator while implementing the virtual reality experience.

The choice of a Gough-Stuart Platform by the ORU 2017 Team was informed by resources such as Detecting Singularities of Stewart Platforms[5], as this specific model is among the most cost-effective options to achieve six-degrees of freedom with its six actuary motors. This project is not unique in its design; its uniqueness focuses on its educational applicability. The specifics of the educational application are two-fold: the flight simulator will exist first as a tool to interest students in the general field of engineering through its nature as a senior project, which serves as a practical example of engineering school, and as a tool for Dr. Dominic Halsmer's Aircraft

Design class at ORU. This specific focus within the project is what the 2017 team established as its vision, and the 2020 team is committed to realizing that vision and making the flight simulator not only function as intended but also to make it accessible to students at the university as well as guests visiting ORU’s Global Learning Center where it will be displayed.

Figure B – Completed Assembly

One issue present within the system has been the debouncing circuit used for the emergency cut-off switch, which is a primary safety feature established by the 2017 team. The 2020 team has been required to implement the cut-off switch, which will require some ingenuity to implement due to the layout of the current electrical system. In transit to ORU’s new Nursing and Engineering Complex, the flight simulator’s emergency cut-off switch circuitry was damaged and will need to be replaced. The location of the switch is being moved to make it more accessible, and the circuitry is currently being redesigned. The inclusion of the cut-off switch is in conjunction with the simulator’s designed factor of safety of 2. testing using Finite Element Analysis is still needed to confirm the desired factor of safety. This will make the system safe and accessible for non-technical users.

DESIGN GOALS

When this project was first created in 2017, the original group had three main goals before completion. These three checkpoints remain mostly unchanged. First, the team wanted to build a Stewart platform to simulate flight with six degrees of freedom while also implementing VR equipment. This means the user will feel the platform realistically move with the software as though he or she was experiencing flight. Secondly, the simulator should be partnered with ORU's aircraft design class, allowing for the option of customizability. This means students would be able to parameterize their own aircraft, then experience the feeling of piloting the plane on the simulator, allowing for a better understanding of how certain design characteristics affect flight. Finally, the third goal was to build the Stewart platform so it could be housed in ORU's virtual reality department in the Global Learning Center. There, it could be used as a promotional tool for the university's engineering department. This means the platform needs to carry a professional look, be relatively portable, and be user-friendly so less knowledgeable people can be led through a flight with relative ease.[1]

The current team has added a new goal to these, however. In addition to being user-friendly for the general public, the group will also be making a detailed user manual for the simulator. This will allow for general maintenance and instructions for anyone to operate the platform, creating a way for the simulator to be useable for anyone well after the students graduate from ORU.

THIS YEAR'S PROGRESS

One of the biggest issues going into this project was the lack of detailed documentation passed down from group to group. Being the third group to attempt to complete the prototype, the current team made it their greatest priority to thoroughly document each edit made to the original schematics and the Arduino codes. When the team compared the relay circuits on the actual device to the schematics in the old reports, there were many inconsistencies in resistor values and various connections. To save time, the team decided to scrap the old circuits and rebuild them with a new relay circuit design.

There are two main circuits necessary for the mechanism to work as designed; the first of those is an emergency cut-off switch. The safety of the user is paramount, so the team had to ensure that the switch was in good working order, it was easily accessible, and it was simple enough for anyone to use safely.

The team used an approach similar to that of the original design, but they made a few key changes. The design method to ensure that the switch would respond quickly enough in case of an emergency is by implementing a debouncing circuit. Normally, a power supply takes close to five seconds to stop outputting power once the input has been cut off, but that is far too much time if a perilous situation is occurring. A debouncing circuit smooths the input signal from the emergency cut-off switch when it naturally oscillates due to its mechanical nature. *Figure C* and *Figure D* show a before and after view of the signal with debouncing accounted for. *Figure E* shows a schematic of the improved emergency cut-off switch circuit.

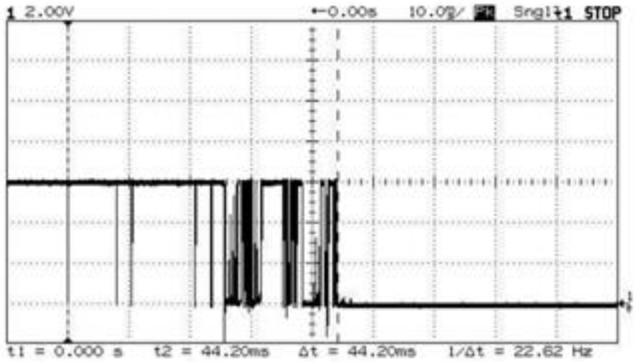
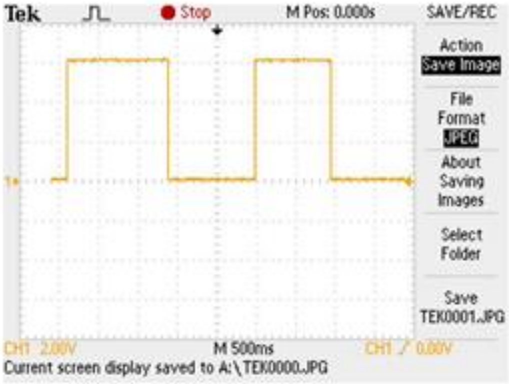


Figure C - Before



Current screen display saved to A:\TEK0000.JPG

Figure D - After

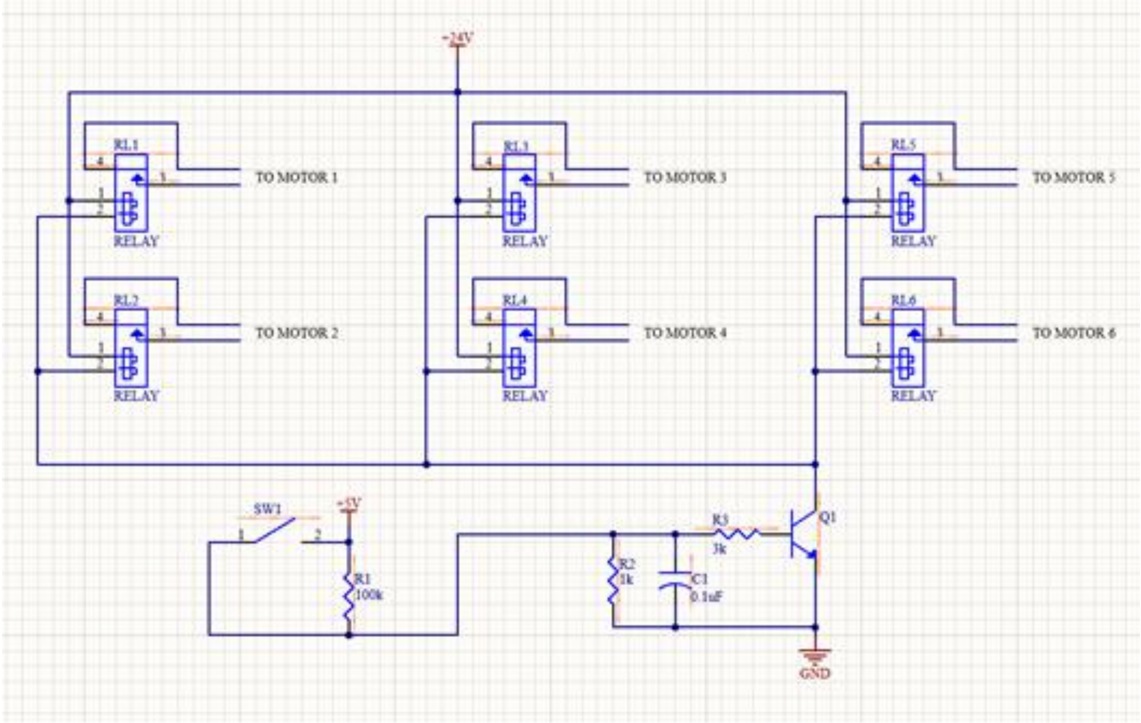


Figure E - Improved Design

Much of this year's progress has been in the form of debugging circuits, analyzing electrical components, and getting up to speed with where the previous groups left off. Due to some electrical design information being lost from group to group and certain components breaking during the move to the Nursing and Engineering Complex, the current group had to work quickly to get up to speed and determine the root causes of the issues in the system. Thus, much time was spent determining the values of components and discovering through testing why certain components were included in the first place.

WEIGHTED TESTING – FACTOR OF SAFETY PERFORMANCE

The weighted testing procedure was able to be conducted after the system was in working order. Safety is paramount for this system to function, and as a Factor of Safety of 2 is one of the design requirements, weighted testing had to be performed before a human test could be conducted. The weighted test consists of multiple stages, starting from 0 lbs, up to a maximum of 250 lbs of added weight. The weight at each stage is increased by increments of 25 lbs.

As we conducted the testing for this stage, we measured the tilt angle of each motor for all 6 maneuvers: Roll, Pitch, Yaw, Heave, Surge, and Sway. The goal was to determine if the added weight would cause the motors to budge under the added stress from the weights. However, upon examination from 0 lbs to 250 lbs, the motors had nearly the same angular tilt regardless of the weight difference. After this, we added extra weight, up to 270 lbs, to ensure that there was no question of the simulator's performance at such a heavy load. We booted up X-Plane 11, and conducted an in-flight test with 270 lbs - it worked flawlessly. This proved that the simulator was capable and safe enough to carry the weight of a human, without any major reduction in performance. The tables showing the comparison between tilt angles are given below. The negative angles represent angles whose position was below the gravitational zero level. The measurements were performed with the electronic levels in the machine shop.

Table A: Weighted Test Data – 0 lbs

0 lbs	**Axis 1**	**Axis 2**	**Axis 3**	**Axis 4**	**Axis 5**	**Axis 6**
	Tilt Angle:	Tilt Angle:	Tilt Angle:	Tilt Angle:	Tilt Angle:	Tilt Angle:
Roll	-9°	11.5°	-13.5°	-16°	13°	10.5°
Pitch	-9.5°	-15.5°	11.5°	-1.5°	1°	12°
Heave	15.5°	14.5°	12.5°	14°	14.5°	12°
Yaw	-9.5°	13°	-13.5°	12.5°	-14°	11°
Sway	19°	-19.5°	-6.5°	6°	-7°	5.5°
Surge	3.5°	-2°	5.5°	14.5°	15.5°	-8.5°
Resting	3°	1.5°	0.5°	1°	0°	2°

Table B: Weighted Test Data – 250 lbs

250 lbs	**Axis 1**	**Axis 2**	**Axis 3**	**Axis 4**	**Axis 5**	**Axis 6**
	Tilt Angle:	Tilt Angle:	Tilt Angle:	Tilt Angle:	Tilt Angle:	Tilt Angle:
Roll	-8.5°	10.5°	-13.5°	-15°	11°	9.5°
Pitch	-9.5°	-15.5°	10.5°	-2°	1.5°	11°
Heave	12.5°	10.5°	12°	12°	12.5°	11°
Yaw	-9°	10.5°	-12.5°	11.5°	-14°	11°
Sway	18.5°	-17.5°	-5.5°	4°	-6.5°	4.5°
Surge	3°	-3.5°	5°	15°	16°	-8°
Resting	3°	1.5°	0.5°	1°	0°	2°

The tilt test data shows that the system unloaded, compared against 250 lbs loaded, has a maximum angular deviation of 2°. However, the Resting angular tilt data is identical for both sets of data. The small deviation of 2° could be a result of inaccuracies within the Arduino control system code. Thus, from the angular tilt measurements alone, we can conclude the simulator is more than capable of holding 250 lbs of weight. However, from an electrical standpoint, it would be beneficial to measure the current passing through the motors while playing X-Plane 11 with 250 lbs loaded. Currently, the team does not possess a means of measuring the high currents passing through the motors.

SIMULATOR RESULTS & PERFORMANCE

The simulator is in working order and is capable of human-operated flight. The below figure shows the first human passenger, mid-flight.

Figure F: Human Operated Flight

All components of the simulator are in working condition, and there are presently no issues preventing motion in the system. Each motor has been proven to work through the SMC3 utility, the SimTools game engine, and in-flight using X-Plane 11 with the Oculus Rift VR-headset. We also conducted full-weight testing and determined that the simulator is capable of handling weight up to 250 lbs, which means the simulator has achieved a factor of safety of 2. We performed live human testing. More testing is being done to determine how the simulator compares with a real aircraft.

A desired performance requirement of the simulator is that it should have the ability to shift about the x/y-axes by at least 15°. This is because if there is any less of a tilt, it will be hard to notice a difference in performance when different planes are being analyzed. To achieve a measurement, we will use a GY-521 MPU 6050 Gyroscope/Accelerometer chip.

The MPU 6050 contains 3 axes for the gyroscope, as well as 3 axes for the accelerometer. This device will allow us to measure the angles between different maneuvers in 3-Dimensional space. The MPU 6050 will be placed in the seat of the flight-simulator. A measurement will be taken of the neutral position, to account for any offset due to the placement of the chair. The coordinate system of the simulator will be determined by the location of the MPU 6050 in relation to the chair. The positive x-axis will be placed to the front of the chair, the positive y-axis to the left when looking out from the chair, and the positive z-axis will be going up above the chair. This device will be used to measure the angles of different maneuvers, which will be compared with the motion data from X-Plane 11. This will allow us to determine how the simulator is performing relative to what type of motion is being performed in X-Plane 11. The 6-step testing procedure is as follows:

1. Measure the angular tilt of the platform and collect in-game angular data for the Cessna 172 on take-off.
2. Measure the angular tilt of the platform and collect in-game angular data for the Cessna 172 on ascent.
3. Fly level with no angular tilt. Measure the angular tilt of the platform when at a constant velocity.
4. Measure the angular tilt of the platform and collect in-game angular data for the Cessna 172 on descent.
5. Measure the angular tilt of the platform and collect in-game angular data for the Cessna 172 on landing.
6. Plot the angular tilt data against the angular data from the simulator to determine if the motors change in a pattern consistent with real Cessna 172 flight data.

The error between the tilt angle measurement, compared with that of the game, will give us an estimate of the deviation between the accuracy of the flight simulator when compared to the in-game data. We can then compare these results to the angular tilt measurement of a real Cessna 172 aircraft to determine if the simulator is performing to a real-life standard.

In conclusion, the team feels that this project has served as a good experience in practical engineering work, especially when one considers that not every project taken on begins from the start. A valuable lesson learned was the importance of documenting every step in the design phase, from theory to implementation, to analysis, testing, and operation. So that future members of the project know why things were designed the way they were.

EDUCATIONAL BENEFIT

To better assist students in designing an aircraft using the simulator, the team will design a streamlined process using X-Plane 11. They will be able to select various parameters and enter dimensions to create their own custom aircraft. Some of these parameters include engine power, maximum coefficient of lift, wing taper ratio, stall speed, and many more. Using two resources, *Dan Raymer's Simplified Aircraft Design for Homebuilders*, [3] and *Aircraft Design: A Conceptual Approach*, [4] as well as knowledge gained from the aircraft design class at ORU, the students should be able to define the necessary variables in X-Plane 11's "PlaneMaker" software. Then, once the airplane is complete, the students will be able to accurately experience flying their custom plane.

As an additional feature to assist people who have not taken the aircraft design course, the group will also provide several passive flight experiences. This will allow for non-technical students or the general public to also partake in the experience of piloting an aircraft without having the need to know all of the other intricacies of the system. A few examples of such flights include takeoff, landing, and a short flight around the airport. This will allow for others to benefit from the simulator, not just ORU engineering students.

The flight simulator showcases the power of virtual reality as an educational tool, and serves as an interactive gateway into the field of engineering. The use of virtual reality and not a simple computer simulation game is critical to the immersion necessary to convey the power of flight, and the innovation that goes into designing and flying aircraft. Of course, one can simply buy a plane ticket and experience flying for themselves. However, few will ever get to experience what it is like to actually pilot a Boeing 737. The simulator accomplishes its purpose as a free-to-use, interactive experience that can help to inspire the next generation of engineers.

BIBLIOGRAPHY

1. Halsmer, D. M., Voth, J. A., McCain, C. A., Reutter, J. D., Frailey, N. S., Samuelson, M., & Ahrens, D. (2018, June), *Development of a Virtual Reality Flight Simulator to Assist in the Design of Original Aircraft* Paper presented at 2018 ASEE Annual Conference & Exposition , Salt Lake City, Utah. https://peer.asee.org/30326.
2. P. Hafner, V. Hafner, J. Ovtcharova, "Teaching Methodology for Virtual Reality: A Practical Course in Engineering Education," Procedia Computer Science, Vol. 25, pp. 251-260, 2013
3. Raymer, Daniel P., Dan Raymer's Simplified Aircraft Design for Homebuilders. Los Angeles, CA: Design Dimension, 2003.
4. Raymer, Daniel P., Aircraft Design: A Conceptual Approach, 5th Ed., American Institute of Aeronautics and Astronautics, Inc., Reston, VA, 2012.
5. Charters, T, et al. "Detecting Singularities of Stewart Platforms." *Mathematics-in-Industry Case Studies Journal*, vol. 1, 2009, pp. 66–80.