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

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

ABSTRACT

The undergraduate engineering curriculum is extremely challenging, largely due to the complexity of the processes and concepts it introduces. One good way to handle this complexity and assist students in learning about the development of engineered products is by providing enhanced visualization of the processes and concepts involved. This has been recognized recently by several researchers who are attempting to harness state-of-the-art virtual reality experiences to improve the quality of engineering education. This has prompted one group to write, "Virtual reality has grown up. Once an exotic field of computer sciences, it is now an important topic for the engineers of tomorrow."[1]

The engineering research and development of a virtual reality flight simulator seems like a good way to engage undergraduate engineering students with the up-and-coming field of virtual reality. A multidisciplinary team of students at our university are pursuing this as their senior capstone design project. The completed system will serve as an addition to the engineering labs and assist future students with their design of original aircraft. With the help of a HTC Vive virtual reality headset, the system will simulate the cockpit environment and faithfully respond to pilot control inputs. The pilot will be strapped into a seat to be rigidly mounted atop a Stewart platform, which will roughly simulate the dynamics of a student’s custom aircraft design.

This virtual reality aircraft motion simulator will be developed through extensive engineering analysis that enhances engineering education both for those developing the simulator and for those who will use it in design. First, the geometry of the simulator will be mathematically analyzed and defined by the students, which will enable optimal geometries to be solved for to maximize certain ranges of motion. Then, the dynamics of the system will be simulated using MATLAB's Simulink technology to confirm the simulator's theoretical dynamic performance, verify the ranges of motion from the students' mathematical analysis, and provide the necessary specifications for the motors. Furthermore, structural analysis with SolidWorks will be used to calculate the factor of safety of the system, which will help properly size the rotary actuators. This engineering analysis of the simulator will function to increase exposure to principles of aircraft design to both technical and non-technical students alike. The simulator is tailor-made to accompany our university's Aircraft Design course. By pairing the our simulator with the course engineering students will be able to learn about aircraft design, create their custom airplane using X-Plane 11’s plane maker software, and then experience flying it on our simulator. This immediate, immersive feedback enriches the students' knowledge of aircraft design and increases interest in the topic. Additionally, the portable design of the simulator enables the system to

serve as an exciting advertisement to pre-college students considering the world of STEM studies.

RECENT WORK IN VIRTUAL REALITY AND FLIGHT SIMULATION

As virtual reality is becoming more accepted and found to be useful in industry, these experiences are finding their way into the engineering classroom and laboratory. The 2017 ASEE Annual conference saw two papers that described how virtual reality is being used in construction engineering education. Hao et al explain how virtual reality is used to recreate the complex structures and construction techniques of dougong, a unique characteristic of ancient Chinese architecture, in an environment where users can interact with objects with a high degree of realism. Students benefit by examining structures and techniques via static images, dynamics videos and VR interactivity, which are all compiled and integrated into a knowledge-based system known as the Intelligent Dougong System with Virtual Reality (IDSVR). Multiple presentation methods of dougong construction were then conducted with Autodesk 3DS MAX and virtual simulations using the Oculus Rift.[2] In another paper from last year, virtual reality was used to illuminate ancient engineering and construction methods used in the Jinshanling region of the Great Wall of China. A VR simulation using the Oculus Rift and an Xbox controller, allows students to examine the construction process in a virtual environment. Thus, this study is expected to permit students to immerse themselves in the virtual erection process of ancient structures in a classroom setting.[3]

Flight simulators are also being used to enhance engineering education. To increase student engagement and provide an enriched learning environment, Memon et al integrated a flight simulator into a Flight Vehicle Performance course. Class performance revealed that students enhanced their knowledge of aircraft stability and control through flight simulator experience. Reflections from the students showed that they benefited greatly from the intuitive theoretical learning through the use of flight simulator.[4] Indeed, an earlier paper described the benefits of integrating experience-based system simulation modules into a series of vehicle dynamics courses, including a flight dynamics course. The authors claim that, "The benefits of imitating a real process by way of simulation cannot be understated. The educational value of simulations does not necessarily lie in the program itself, but rather, in the overall experience of the simulation."[5] It is hoped that the following project can integrate a hands-on virtual reality experience with a high-fidelity flight simulator to enhance student understanding of various aspects of aircraft design and their impact on aircraft dynamics, stability, and performance.

To embark upon the complex endeavor of this project, an understanding of flight simulation first had to be obtained by the team. At the beginning of this journey, the team had discovered that the Stewart Platform was commonly used in the flight simulation field due to its ability to operate in all six degrees of freedom. Immediately, they began to seek after highly academic sources on

Stewart Platform motion and the mathematics that governed it. They viewed sources such as *Detecting Singularities of Stewart Platforms*[6] and *Stewart Platform with Fixed Rotary Actuators: A Low-Cost Design Study*.[7] These sources gave great initial understanding of the motion that a Stewart Platform can provide and the geometric constraints that must be upheld within its construction; however, they primarily provided information that was beyond the scope of this project and the mathematical understanding of the undergraduates students on the team. To gain a simpler comprehensive grasp of the topic, the team began searching online forums for assistance. This was highly beneficial to the project. The team discovered that there are many projects that have some similarity to their own. Through forum sites such as *XSimulator*[8] and *Motionsim*,[9] the team was able to observe not only successful Stewart Platform designs, but also failures that had occurred in the making of those designs. Although these sites are nonacademic, they provided very valuable information pertaining to the structural geometry and electrical interfaces of the system. While on these sites, the team mainly observed builds by users SilentChill and GA-Dawg from *XSimulator* and *Motionsim* respectively.

INTRODUCTION

A team of six engineering students, under the direction of two faculty members from Oral Roberts University (ORU), is researching a new, innovative approach to deepen undergraduate students' practical understanding of aircraft design. These undergraduate seniors are developing, fabricating, and fine-tuning an aircraft flight simulator, which, along with the help of VR technology, will realistically produce the motion effects of flight. This simulator will allow undergraduate engineering students taking an aircraft design course to accelerate the iterative aircraft design process. Also, students will be able to experience a higher degree of project completion, flying their custom virtual aircraft by taking the flight controls in their own hands.

In the Aircraft Design course at ORU, students learn how to design an experimental aircraft using "correct" specifications according to theoretical values. This educational process will be improved by providing further connection between actual flight handling and the supporting aircraft design theory. This paper will demonstrate students' attempt to bridge this gap by the use of their VR aircraft motion simulator. By the end of the 2017-2018 academic year, students will be able to accurately test their custom aircraft designs at intermediate and final stages, speeding up the iterative aircraft design process. Also, students will have the capability to realistically experience flight in their own custom designed aircraft, and further solidify their understanding as to why their aircraft flies the way it does.

The scope of this project, however, reaches beyond just enhancing educational opportunities for engineering students. Several passive flights will be programmed for the general public's immersion, exposing prospective and nontechnical students to the world of aircraft design. Additionally, the intentional portability of this simulator opens the doors for this simulator to be presented in multiple unique locations. As a whole, this project functions as a powerful tool of engineering education, providing an immersive learning experience to many, regardless of the individual's prior level of knowledge.

DESIGN GOALS

The project has three specific goals that the team aims to complete by the end of the Spring 2018 semester. First and foremost, the team is building a Stewart platform to simulate flight with six degrees of freedom and virtual reality equipment. Therefore, the platform will have to realistically move with the chosen software so as to allow for the user to feel like they are experiencing the motion of the airplane. The chosen software also needs to connect with virtual reality so as to further immerse the person in the flight experience. Next, the goal of the project is to partner with the Aircraft Design course taught by Dr. Halsmer. In doing so, the chosen software will allow for the option of customizability, so that students can create/model their own original aircraft and see how their designs produce unique flight dynamics. The student can then sit inside their virtual plane in the simulator and experience what it would be like to pilot their aircraft. This will allow for students to get a first-hand experience of how certain design parameters truly affect the overall flight characteristics of aircraft.

In addition to these design goals, the last major goal of the project is to house the Stewart platform within ORU's virtual reality lab in the Global Learning Center. In addition to educating engineering students, the simulator will also be used as a promotional tool, both for the university and the engineering department, and allow it to be a resource for what other needs the university might have for a Stewart platform. With this in mind, a few more practical design goals are being pursued. First, the simulator must be safe enough for people of all ages and sizes to ride in. Also, the platform must carry a professional look so that the university can showcase it and people will feel confident to ride in it. In addition to all this, since most of those riding in the simulator will not have experience in controlling the simulator, the software chosen must allow for passive flights so that the user doesn't have to understand the mechanics of flying but instead can be led through a flight without their having to do much. These secondary goals will serve to increase access to the experiences of flight, and aircraft design (and their relationship to STEM) to a wide swath of the general public.

CAD: DIGITAL CONSTRUCTION

Due to the complex nature of the flight simulator's Stewart platform geometry, the team decided upon the use of Computer-Aided Design (CAD) to digitally construct the system. Because of its accessibility and wide range of capabilities, SolidWorks® was chosen as the CAD design software best suited for the teams needs. Seeing as the team's design of the Stewart platform is a quite intricate system of rotary actuated arms, many preliminary design iterations were performed to gain an understanding of the range of motion that the simulator will undergo within its movement, and the geometry that dictates its structure. These initial iterations were primarily drafted around other flight simulator models. Once a general understanding of the platform geometry and mechanics had been obtained through CAD modeling, the team turned its attention to designing their own custom simulator.

The designing process began on paper, as many do. Geometric relationships pertaining to the platform had to be determined before a unique system could be developed within the SolidWorks® software. Considering the complexity of the complete structure, simplifications and constraints were required so that the geometry of the system could be established. This was accomplished by observing an isolated pair of the dual actuation arm subsystem in a planar configuration and having motion confined to vertical heave. By defining the arbitrary constants of total heave displacement, the expected seat height, and the theoretical center of gravity of a seated man, a complete set of geometric relationships was then obtained. These calculations resulted in a one-to-five length ratio for the lower and upper actuator arm pair, or, more precisely, a 5.5 inch lower actuating arm and 27.5 inch upper actuating arm. Pairs of this configuration were then aligned along each side of an equilateral triangle, such that there are six pairs total. A visual of the isolated subsystem can be observed below in Figure 1.

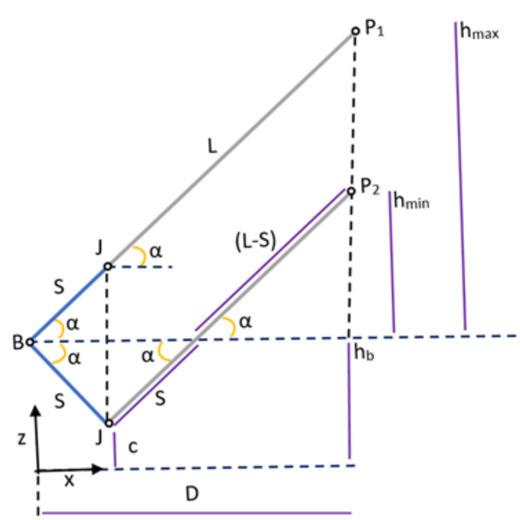


Figure **1**: Dual Actuating Arms Isolated in Heave (observing maximum and minimum position)

After using graphical and mathematical analyses to develop the dimensional basis of the structure, components and assemblies were drafted within SolidWorks. The rods and lever arms were first designed, and additional assemblies, such as the lower and upper platforms, followed. To test and visualize the system geometry, multiple prototype models were manufactured through 3D printing scaled down by a factor of ten. These models were developed to provide a functional test and proof of concept to the team's design. The scaled prototype models have behaved as expected and have proven the aforementioned analysis as operational.

Once the final system geometry was established and tested, the geometric framework drafted in SolidWorks was converted into actual industrial components that could be purchased. These parts were designed and chosen alongside a selection of vendors taking into account both cost and availability. The parts were modeled to the exact specifications of the vendor or in some cases, the vendor provided a premade, dimensionally accurate CAD model available for download. The system was organized into a variety of assemblies and sub-assemblies. All necessary drill holes were also added to the system components, and a few larger bolts were also added to increase the factor of safety. By using mates to fix the lever arms of the Stewart Platform in key positions, the team is also able to use the model to prove the system geometry that was mathematically established as well as predict and design around any geometric collisions. Several simulation exercises were run to ensure structural stability in key locations. The accurate model also allowed us to generate weight estimates for the system. With the model complete, a full bill of materials was developed, vendors were identified, and materials were purchased. Drawings and blueprints were drafted and printed to ensure accurate manufacturing of each component. Developing a complete and accurate model of our system in SolidWorks is an important part of the teams educational vision as it shows students the power of CAD design software and gives them the opportunity to compare a virtual rendering with manufactured reality.

ENGINEERING DESIGN

Early on in the design of the platform, it was decided that the best positioning of the connecting rods to the upper platform would be to have them at the center of gravity. This would theoretically ensure that the center of gravity would not be changing and all movement could be based around a fixed point. To solve this, a study done Dr. John J. Swearingen was used called *Determination of Center of Gravity of Man.*[10] The following analysis, illustrated in Figure 2, comes from this study.

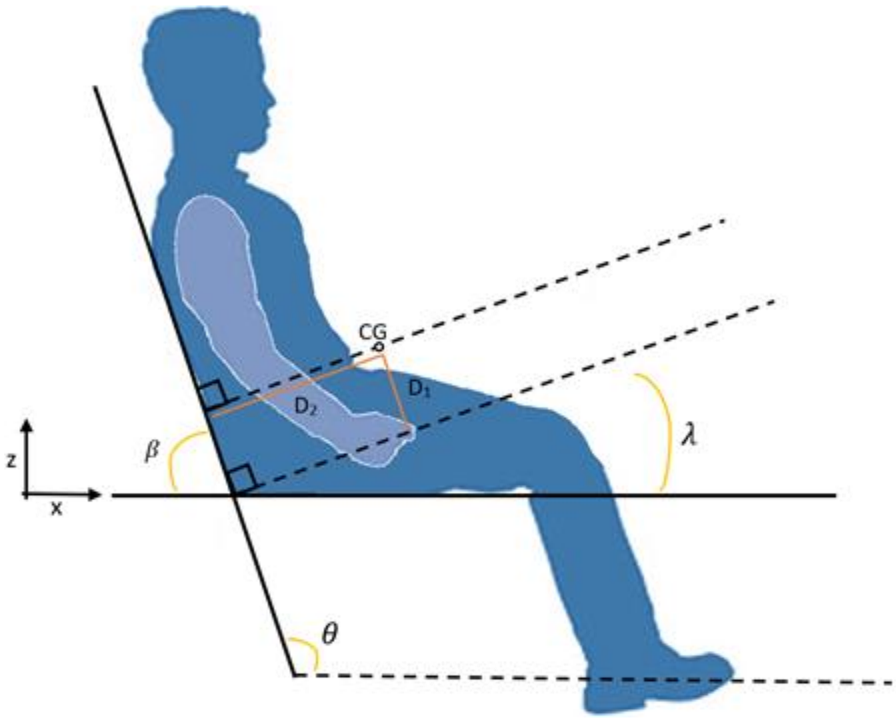


Figure 2: The Center of Gravity of a Seated Man

From page 20: Trunk 115°, knees 145°, hands on lap.

$$\theta = 115°$$

$$\beta = 180° - \theta = 65°$$

$$\lambda = 180° - 90° - \beta = 25°$$

$$\left.\begin{aligned} D_1 &= 7.75\ inches \\ D_2 &= 9.4\ inches \end{aligned}\right\} \text{(Results of the study)}$$

From the figure above:

$$\overrightarrow{CG_x} = -D_1 \cos\beta + D_2 \cos\lambda$$

$$\rightarrow \overrightarrow{CG_x} = \ -7.75 \cos 65° + 9.4 \cos 25° = \mathbf{5.24}\ inches$$

$$\overrightarrow{CG_z} = D_1 \sin\beta + D_2 \sin\lambda$$

$$\rightarrow \overrightarrow{CG_z} = 7.75 \sin 65° + 9.4 \sin 25° = \mathbf{11}\ inches$$

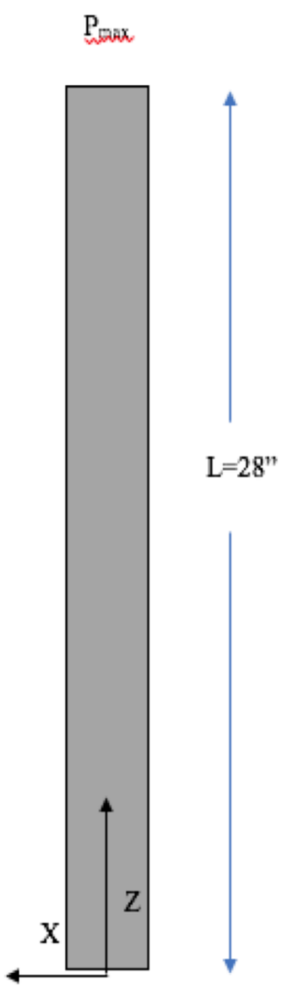
Thus, the vertical positioning for the location of the connection rods was set 11 inches above the bottom portion of the chair so as to be closer to the center of gravity. Likewise, the chair was set

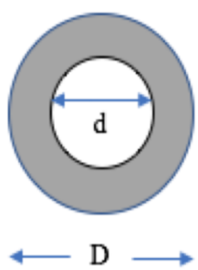
5.24 in back from the center of the connection rods to try to account for the offset position of the center of gravity.

A unique complication within the design portion was the stress analysis of the members of the system. With such a complicated inverse dynamics problem to solve for the individual torques and forces being experienced, the team was running out of time for solving what needed to be done so that they could order the motors, and other parts. So the team needed to find a simpler way to estimate the stresses the individual components would experience so as to quicken the process. The solution was to create a "worst case" nearly impossible scenario. Since the maximum weight of the top of the platform will be 300 lbs, stress estimations were made by applying the entire load to single members. Due to the setup of the platform, this scenario should never occur, but if it can be proven that the design can hold up well under this case, then there should be no chance of failure at any point during use. A factor of safety of 2 was implemented for the analysis. Using these parameters, stress analysis has been conducted on the upper connecting rods and bolts that connect to the Heim joints and are as follows.

Upper connecting rod:

Analysis for Buckling:





A513 Steel

Material Properties:
Modulus of Elasticity E_{avg}: 29007.5 ksi
Yield Strength σ_y=84,100 lb/in^2
d=0.75 in

Defined Variables:
P_{max}=300 lb
L=28 in

$$Factor\ of\ Safety\ (F.S.) = 2$$

$$P_{Cr} = P_{max} \cdot F.S. = 600\ lb$$

$$I_x = \frac{\pi}{32}(D^4 - d^4)\ in^4$$

$$P_{Cr} = \frac{\pi^2 EI}{L^2}$$

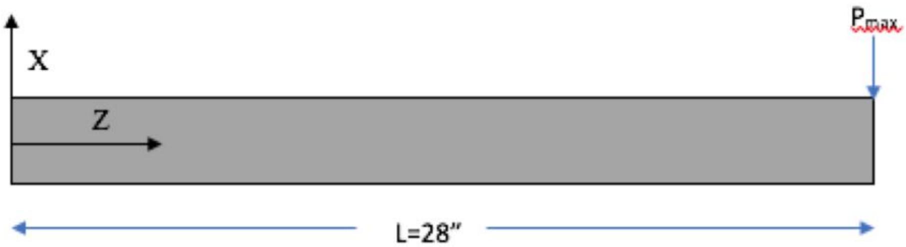
Rearranging and inserting Moment of inertia equation

$$\frac{\pi}{32}(D^4 - d^4) = \frac{P_{Cr} L^2}{\pi^2 E}$$

$$\frac{1}{32}(D^4 - 0.75^4) = \frac{600 \cdot 28^2}{\pi^3 \cdot 29{,}007 \cdot 10^3}$$

$$D = 0.759727\ \text{in}$$

The outer diameter will be larger than 0.76 in so no chance of buckling



Analysis for Bending:

$$\sigma_y = \frac{Mc}{I_y}$$

$$M = P_{cr} \cdot L$$

$$I_y = \frac{\pi}{32}(D^4 - d^4)$$

$$c = \frac{D}{2}$$

$$\sigma_y = \frac{2 \cdot P_{max} L \frac{D}{2}}{\frac{\pi}{32}(D^4 - d^4)}$$

Rearranging:

$$\frac{32\, P_{max}\, L\, D}{\pi\, \sigma_y} = (D^4 - d^4)$$

$$\frac{32 \cdot 300 \cdot 28 \cdot D}{\pi \cdot 84{,}100} = (D^4 - 0.75^4)$$

$$D = 1.093 \text{ in}$$

Therefore, if the outer diameter of the connecting rods is greater than 1.093 in, there should be no chance of failure due to buckling.[11]

Analysis for Fatigue (based on the greater stress due to bending):

Outer diameter set to 1.125 in:

$$\sigma = \frac{Mc}{I_y}$$

$$M = P_{cr} \cdot L$$

$$I_y = \frac{\pi}{32}(D^4 - d^4)$$

$$c = \frac{D}{2}$$

$$\sigma = \frac{P_{max} L \frac{D}{2}}{\frac{\pi}{32}(D^4 - d^4)}$$

$$\sigma = \frac{150 \cdot 28 \cdot 1.125}{\frac{\pi}{32}(1.125^4 - 0.75^4)}$$

$$\sigma = 37.4\ ksi$$

Due to the graph given below from the Mechanics of Materials textbook, the beams should be able to support about 0.5 million cycles at this load. Since this load should never occur and the platform won't be in constant use to approach this value, the platform is not expected to fail due to fatigue.

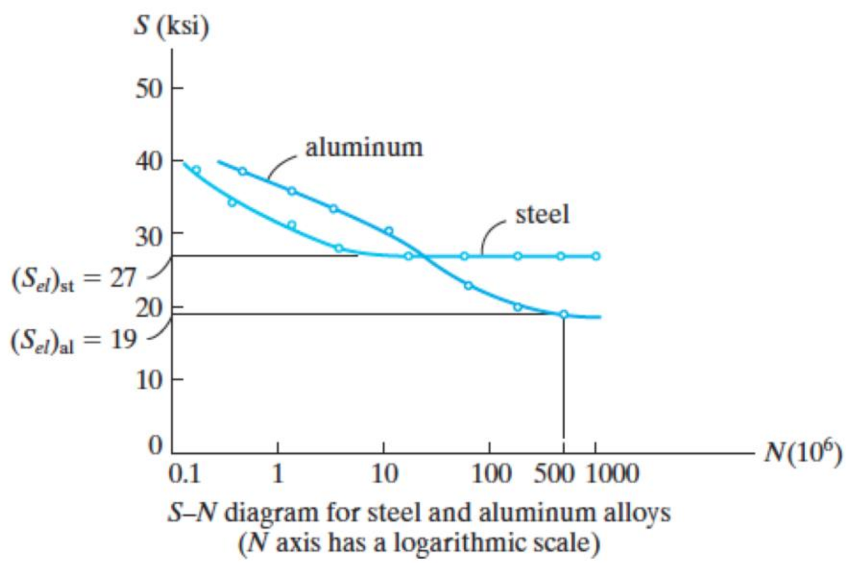


Figure 3. S-N Diagram

The electrical design of the system was primarily structured after a Systems Engineering and Computing professor whose alias is SixDegreesOfFlight on the reputable XSimulator forum. His design was a compilation of previous designers on the website. The design comprises one primary module which is repeated three times. This module consists of one Sabertooth 2x60 amp drive, one Arduino Uno, two 24V 30A AC/DC Switching Power Supply Units (PSUs), two 12V Lead-Acid Batteries to capture regenerative current from the Sabertooths, two 100A stud diodes to protect the PSUs, one 60A resettable fuse, two 12V car relays, two 10k Ohm 10-turn potentiometers for positional feedback, two 0.1uF noise-filtering capacitors placed on the Arduino, and 24V DC permanent magnet motors which are each a part of a customized linear actuator.

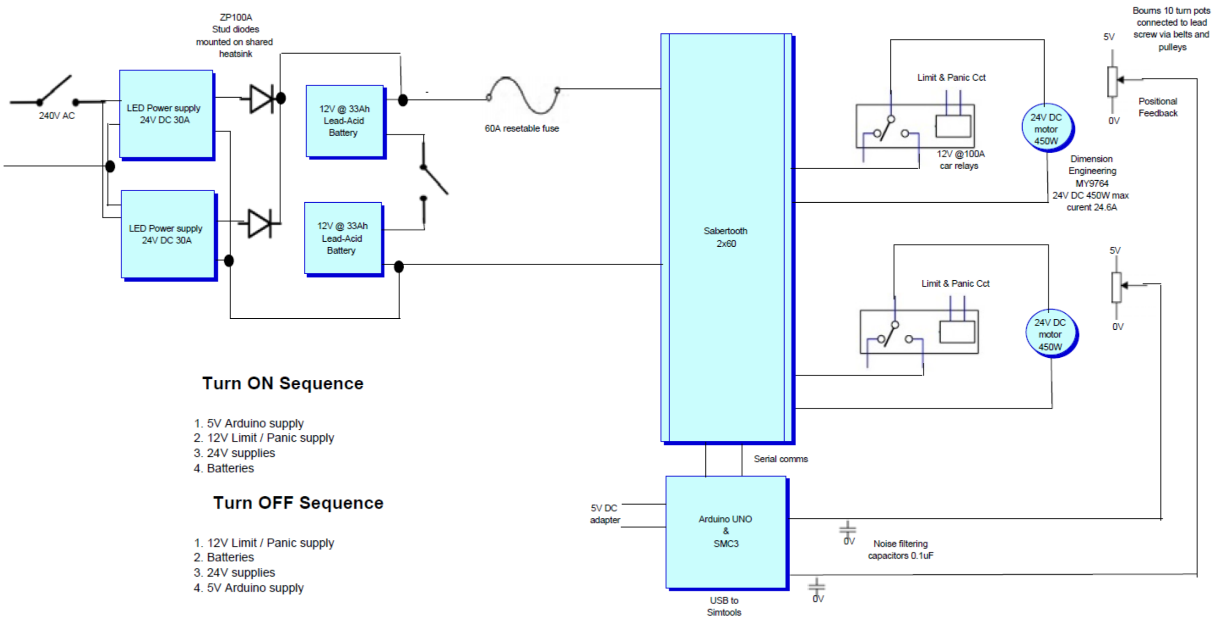


Figure 4: Foundational Electrical Module Design by SixDegreesOfFlight

There are several differences in our team's design. First, we will not be using customized linear actuators, but will instead be using solely the 24V DC permanent magnet motors with worm-gearboxes attached. Secondly, the team will substitute each of the modules' Arduino Unos for one Arduino Mega microcontroller. This is done for both cost reasons and a compiled design of the Arduino IDE program. Additionally, the team will have no need for the 10-turn potentiometers but will instead use single turn potentiometers. This is also for simplicity and cost reasons. Another variance in the designs which doesn't provide much discrepancy regards the input power. Because SixDegreesOfFlight is based in Australia, the design is powered using standard Australian 240V AC power outlets, with a maximum current of 10 Amps. However, our design is based in the USA, and will be using 120V AC power outlets with a maximum current of 15 Amps for their system. Shown in Figure 5 is a block diagram of the current but evolving state of the design.

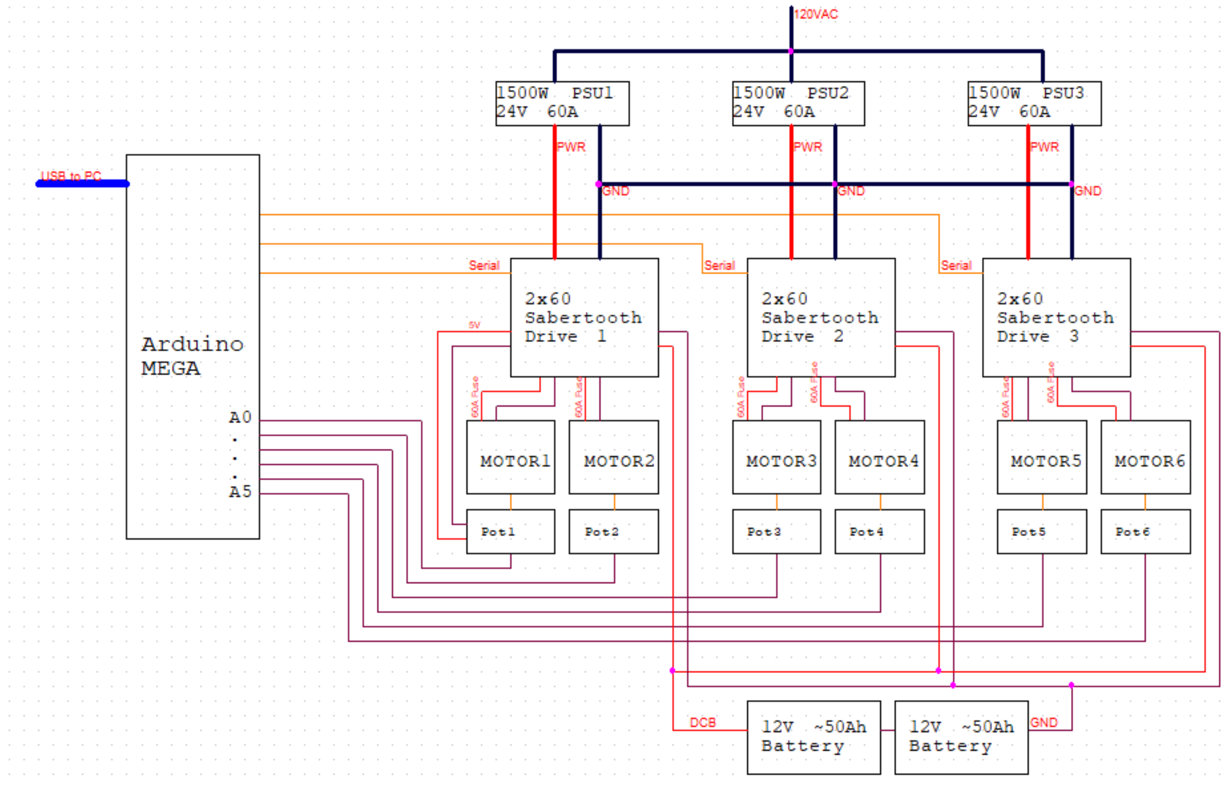


Figure 5: Master Electrical Block Diagram

FABRICATION

The fabrication of the system is being performed fully in-house at our university. Each component is first fabricated according to its dimensions and the specifications of its SolidWorks drawing. This includes all cuts and holes or any other modifications. Once each component has been prepped for assembly, the team will move into the assembly phase. By following a directional assembly procedure, each part will be fastened together using bolts and mending plates for aluminum parts, and welding for steel. The system will be split into three major subassemblies: the upper platform, the rods, and the base. Once these sub-assemblies have been assembled, they will be combined into the final system. Figure 6 is a current SolidWorks rendering of the system, and Figure 7 is a photograph that shows the current state of assembly. The system is on schedule to be fully functional by the end of the Spring 2018 semester.

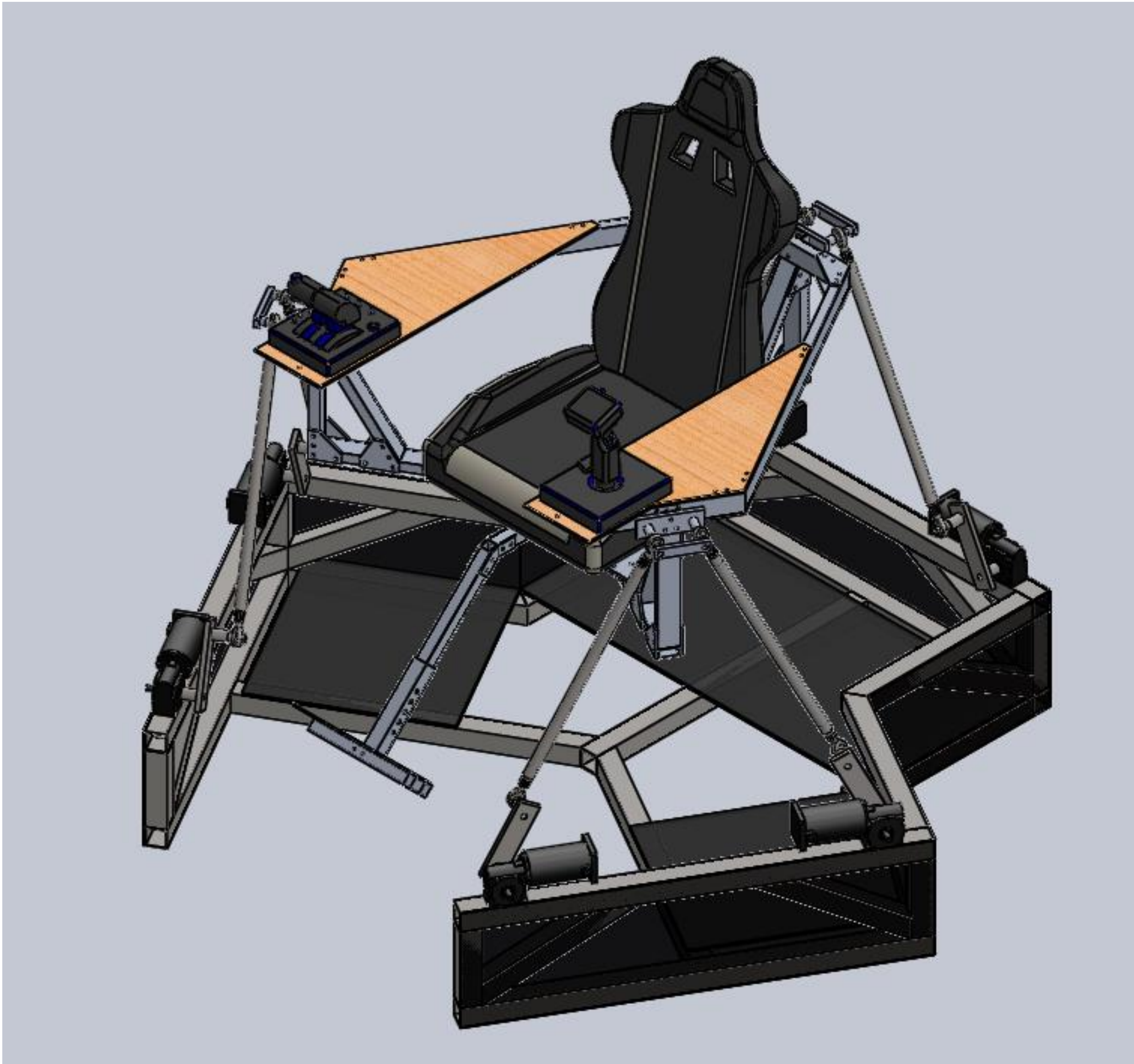


Figure 6: SolidWorks Model of the Stewart Platform for the Custom VR Flight Simulator

Figure 7: Photograph Showing the Current Status of Stewart Platform Fabrication

EDUCATIONAL BENEFIT

To enrich the feedback within the aircraft design process, the design team will streamline a process within pre-existing aircraft design software, X-Plane 11, so that students may easily create their own custom aircraft based on an assortment of parameters that they select. These parameters include: engine power, power loading, maximum coefficient of lift, aspect ratio, wing taper ratio, stall speed, and much more through the inputting the necessary dimensions for each part of the aircraft. Using *Dan Raymer's Simplified Aircraft Design for Homebuilders*.[12] and *Aircraft Design: A Conceptual Approach*,[13] also by Raymer, the Aircraft Design students will select or define the necessary components to input into X-Plane 11's "Plane Maker" software. For each detail of the aircraft, the students will be able to draft or alter their aircraft inside the program. Then, using the VR aircraft motion simulator that our team designed and built, students will be able to experience flying their custom aircraft in an immersive, highly accurate manner.

Along with the Aircraft Design course, the motion simulator will be used to explain basic aerodynamic properties in a course, called Introduction to Engineering, for freshman engineering students. They will learn about concepts such as lift, drag, and the relationships formed by altering the design of an aircraft by virtually flying multiple aircraft. The program will have several aircraft with severe design conditions to enhance or hinder the performance of certain characteristics to provide a clear visual representation. For example, the students would be able to fly a traditional design as well as a design with an extremely exaggerated wingspan. Because lift depends on the area of the wing, the students will notice the second aircraft takes off at a much slower speed than the traditional design. Other example aircraft would have exaggerated fuselage diameters to explain drag, or even altered airfoil shapes to show the different factors within airfoil design. The students would first receive a lecture to discuss the properties being exhibited, and then allowed to schedule time to operate the motion simulator.

In addition to these technical applications of the motion simulator, several passive flights will be programmed into the system, allowing prospective or non-technical students to experience realistic aircraft flight. Passive flights allow anyone to experience the feeling of flying the uploaded aircraft without the need to learn any of the control aspects. Such ventures are pre-specified by the software and include takeoff, a short flight around the airport, and landing. This additional application of the simulator increases interest, experience, and enthusiasm in aerospace design to a wide audience, presenting STEM studies in an exciting light and providing the university with an excellent recruitment tool. Not only will the current engineering students benefit from the motion simulator, but the university as a whole will be able to use the project as a representation of the scholastic excellence of the university. With the motion simulator located inside the Global Learning Center at ORU, school field trips, university assessments, and prospective student visits will all be able to watch and operate the educational tool being designed by ORU engineering students.

FLIGHT SIMULATOR ASSESSMENT

In order to provide a complete assessment for the project, the design team will execute each of the design goals as part of their senior design project. As previously specified, for a successful project, they will develop a Stewart platform with six degrees of freedom and virtual reality compatibility, clear applications for the Aircraft Design coursework, and permanent residence in the virtual reality lab at the Global Learning Center. The latter goal separates into three specific categories: the simulator must be safe for all ages and sizes as specified, model a professional appearance, and provide the opportunity for passive flight. If all of these goals have been met, the project can be considered successful.

EDUCATIONAL ASSESSMENT PLAN

The ORU Aircraft Design course will be taught again to upper division undergraduate engineering students in the 2018-2019 academic year. It is planned to utilize the custom VR flight simulator to assist in motivating students during their aircraft design projects, and provide additional insight into the aircraft design process. After students get an idea of the size of their original aircraft, by estimating the power loading, wing loading, drag, lift-to-drag ratio and fuel fraction, the take-off weight can be approximated. This is followed by engine sizing and selection, wing geometry and placement, airfoil selection and tail geometry and sizing. Before too long, the student will be able to "rough out" their original aircraft in X-Plane by specifying all the necessary design parameters. This will give students the opportunity to take their first draft aircraft on its virtual maiden voyage. (Of course, it will be helpful if they have some kind of flight performance baseline with which to compare. For this reason, every student will be required to spend a certain amount of virtual flight time in a standard trainer, such as a Cessna 150, prior to trying out their designs.) Virtual flight performance can then be compared to predicted/desired performance and appropriate design modifications made. Multiple design iterations are expected until students are satisfied with performance and the resulting designs.

Since this will be the first time to use the custom VR flight simulator in the Aircraft Design course, student learning in this course will be compared to student learning previously taught Aircraft Design courses. Exam and final project performance will be compared on an inter-course absolute scale to see if the understanding of aircraft design has improved since the introduction of the simulator. Survey data will also be collected from students in an effort to assess motivation, enjoyment, learning, skill and confidence in aircraft design.

CONCLUSION

This paper has demonstrated the promise of using student-led innovation to improve the educational experience of engineering students. From its inception, this project has been team-focused and interdisciplinary, and it has provided a wonderful learning experience for the six engineering students involved. They have had much experience in applying their theoretical knowledge from class into the practicality of the build, gaining invaluable problem solving skills along the way. But most excitingly, once this project is completed in a few weeks, the motion simulator will benefit engineering and non-technical personnel alike for many years to come. The students of this project cannot wait to conclude the project soon so that their efforts may make engineering education more appealing and inviting. They are proud of their work and excited that they have been making a positive contribution to their learning environment.

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