EML4551-2

Team 514: HOTAS and Rudder Pedal System

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Abstract

Lockheed Martin sponsored our team to create flight controls for the F-35 jet simulator. The F-35 jet has a cockpit with fewer buttons than usual and more information displayed on computer screens, making it different from other planes and needing extra training time for pilots. Lockheed Martin wants a package that allows more pilots the chance to train in various environments around the world. Our goal is to make a low-cost portable set of flight controls for a desktop computer or 3D-printed cockpit.

We focused on the joystick, throttle, and rudder pedals as the most important parts a pilot needs for simulator training. The joystick and rudder pedals change the direction the plane flies. The throttle changes the engine thrust. The buttons on the controls provide easy access to the flight display computers, aircraft weapons, and other features of the jet. We included parts of the controls from previous senior design teams' projects. We picked a design with simple parts which are easy to replace if needed. We also made them strong enough to withstand repeated use for training. The flight controls are compatible with many different computers because they connect to Universal Serial Bus (USB) ports. The joystick, throttle, and rudder pedals weigh less than 35 pounds each making them easy for the average person to move.

To keep the production cost low, we used 3D printers for some mechanical parts. Our team created a small microcontroller with circuits to measure the control movements and send button signals to the computer. We wrote the program code and designed the printed circuit board for the microcontroller. The cases containing the moving parts and electronics of the joystick and throttle protect them and make sure they work well for a long time.

Keywords: list 3 to 5 keywords that describe your project.

Disclaimer

Your sponsor may require a disclaimer on the report. Especially if it is a government sponsored project or confidential project. If a disclaimer is not required delete this section.

Acknowledgement

These remarks thanks those that helped you complete your senior design project. Especially those who have sponsored the project, provided mentorship advice, and materials. 4

- Paragraph 1 thank sponsor!
- Paragraph 2 thank advisors.
- Paragraph 3 thank those that provided you materials and resources.
- Paragraph 4 thank anyone else who helped you.

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Project Scope

Project Description

Team 514 has been tasked with improving the rudder assembly and hands on throttle-and-stick (HOTAS) flight controls for Lockheed Martin's F-35 Training Enterprise. The team's purpose is to create a low-budget, portable desktop design Lockheed Martin can use for their own project ending in December of 2023 that will integrate with their current software. To accomplish this, it is imperative that we build off previous senior design projects and create a fully functional, finished prototype before Engineering~~Senior~~ Design Day on April 6, 2023. ~~in the late Spring of 2023.~~

Key Goals

The main goal is to create a functioning prototype of both controls that works in tandem with Lockheed Martin's simulation program, Pr3pared. To prove the product is functioning, the simulated model shall take off, perform a box flight pattern, then land. This flight pattern is shown in Figure 1. The product shall be configured for desktop use. Upon success of the prototype, the team will look for ways to better produce the parts and build upon the design to include the use of smaller applications, such as buttons and triggers.

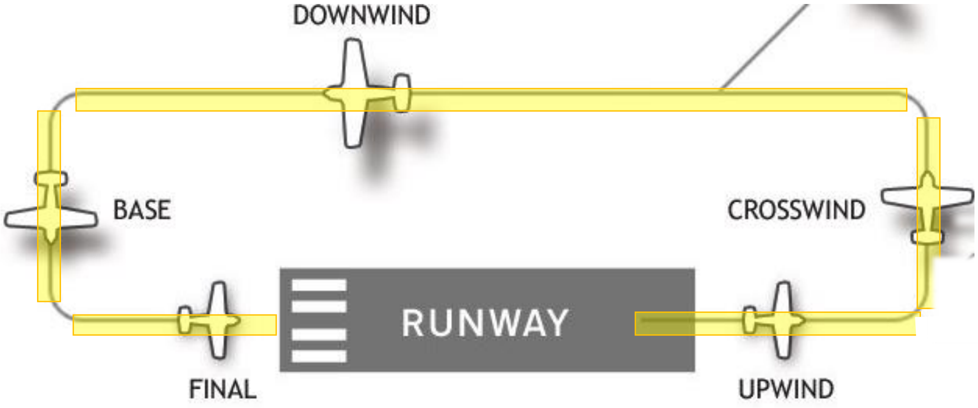


Figure 1 - Box Flight Pattern

1.2 Customer Needs

Customer Needs

To gain awareness of the needs and wants of Lockheed Martin for the Low-Cost Simulator project, Team 514 met with Andrew Filiault, the project sponsor. Table 1 is a record of the questions asked, responses received, and the interpretation of those responses.

Table 1: Customer Needs Breakdown

Question	Sponsor Response	Interpretation
1. How should the rudder pedals behave?	Pedals don't need adaptive feedback; resistance is all that is needed.	The rudder pedals behave with a linear response.
2. What uses are the HOTAS and rudder pedals being made for?	The HOTAS and RPS will be used in a 3D printed F-35 cockpit or desktop flight simulation training.	HOTAS and RPS systems can fit a desk and in a cockpit.
3. What about the current systems (or products on the market) do you like?	Stick switches were correct.	The new system uses similar stick switches to the last project.
4. What about the current system (or products on the	Inputs not correctly mapped to simulator. The disc brake design for the rudder pedals	The rudder pedals feature fewer moving parts than a disc brake

market) do you dislike?	was not ideal due to the number of moving parts.	design from the previous team.
5. What is the reason for creating another HOTAS and RPS if others exist?	The current training equipment is very expensive and not as similar to the F-35 equipment as we desire.	Our design will be cheaper to manufacture and tailored specifically to the F-35 platform
6. What is likely to be our budget?	$2000	There is a budget of $2000.
7. What minimum and maximum dimensions should the system fit in between? Cockpit sizing?	Cockpit dimension constraints will be provided.	The system will be dimensioned specifically to fit the 3D printed F-35 cockpit.
8. What flight conditions and maneuvers should we be able to simulate?	Since the rudders are not responding to a variation of forces, the aircraft should taxi, takeoff, make a box, and land in any flight condition.	The system will simulate aircraft taxi, takeoff, make a box, and land in any flight conditions.
9. What type of interface is required between the simulator and the HOTAS/RPS? (USB?)	Assume either USB or RJ-45 (cat6/cat5e) connector is fine.	USB or Ethernet connection is acceptable.
10. What simulation program will the HOTAS and RPS be required to interface with?	Prepar3D, Lockheed Martin's simulator program	The equipment will be integrated with the Prepar3D program.
11. What are the computer specs required to run Prepar3D?	The computer is recommended to have an 8 core CPU, 16 GB RAM, RTX 2080Ti, and 3070 Series Graphics Display.	The Prepar3D program is run on a computer with an 8 core CPU, 16GB RAM, RTX 2080Ti, and 3070 Series Graphics Display.
12. How many units will be produced?	One demo for this project.	One setup of the equipment will be produced.
13. Define "low cost."	The throttle, stick, and rudder pedals should be less than $1000 each in materials. Include manufacturing costs and material costs even if we	The stick, throttle, and rudder pedals will be less than $1000 each in materials cost. Labor costs will be tracked separately.

	do not have to pay something. Labor costs should be calculated separately.	
14. Any specifications for the grip design?	Mold or model will be provided later.	The specific dimensions for the grip will be provided by Lockheed Martin.
15. What are the expectations for the feedback of the HOTAS?	No feedback to the controls. Only signals sent, none received. Linear throttle. Not rotary, no longer modular.	The HOTAS system will only send signals and throttle will move linearly.
16. Are there specific dimension requirements for the cockpit mounted system?	There are specific dimensions for the cockpit mounted version. I will have to get those dimensions to you. I will get you an envelope for the throttle and stick assembly.	We are awaiting dimensioning information from our sponsor.
17. How soon can we get the mold that was mentioned previously? Was it a mold or a model of the stick?	There is a current model, and we are awaiting approval for its release. The soonest we will get is in a couple of weeks.	We are anticipating large files of the HOTAS model from Andrew.

Customer responses were gathered over the course of several team meetings with the sponsor of the project. SD T514 asked the sponsor the questions above and recorded the responses. The Hands-On Throttle and Stick (HOTAS) and Rudder Pedal System (RPS) are to be created for a standard desktop setup and 3D printed F-35 cockpit. The RPS will behave linearly. The sponsor has tasked us to integrate both systems into their Prepar3D program and produce a “polished” finished product. The sponsor desires a simpler RPS than previous attempts to reduce production costs and maintenance while keeping the same ergonomics as previous years. All communication between the controls and interface will be through a USB or ethernet connection. The sponsor will provide the dimensions and specifications of the HOTAS.

Assumptions

Most of the assumptions for the project pertain to what there will be access to throughout our prototyping process. In order to successfully create and test the prototypes, access to the Senior Design 3D printers, Mechanical Engineering Machine Shop, and the donated computer from Lockheed Martin containing their most recent version of the Pr3pared program will be needed. While prototyping, it will be assumed the general scale for the size of the controls will be provided, the proposed budget will be $2000, and access will be granted to older senior design projects and their parts.

The main assumptions include:

- Access to SD 3D printing
- Machine Shop
- Access to Pr3pared and admin login
- Accurate dimensions of older joystick and pedals
- Access to previous projects and parts
- Estimated budget of $2000

Markets

The primary market for this project is Lockheed Martin. Secondary markets include the military, commercial flight simulators, and international partners of the United States. The purpose of this project is to create a working, portable prototype for Lockheed Martin, but there could potentially be other uses down the line. If Lockheed Martin integrates this into their current Training Enterprise, is it likely that this will end up in the hands of the US military in order to save money from F-35 flight time. Although this project will not be designed for commercial use, this system could be integrated into Advanced Aviation Training Devices (AATDs), such as the RedBird FMX 1000. Finally, this design could potentially be shared with international partners in order to train under the same airframe.

Stakeholders

The stakeholders in this project include Lockheed Martin, the U s international partners, and the FAMU-FSU College of Engineering. Through the success of this product, Lockheed Martin and the U.S. military (and its allies) will bring down the cost and complexity of pilot training for the F-35. Within the U.S. military, the service men and women that pilot the F-35 aircraft will benefit from the lower costs of operating a simulator, allowing for more training. The FAMU-FSU College of Engineering will be represented by the success in development and implementation of the product, further solidifying its reputation of developing critical thinkers into dependable engineers. This is a similar situation for the staff of the FAMU-FSU College of Engineering, including but not limited to Dr. McConomy and Dr. Krick. Other stakeholders include the additive manufacturing groups that will create this product in the future. Manufacturing will consist of 3D printers, primarily, so companies that design and manufacture the printers will benefit from the product.

1.3 Functional Decomposition

1.3.1 Introduction

The functional decomposition was done for our project by breaking down our project into its major systems and the functions that it must perform. The project was broken into 3 main systems to be analyzed: the rudder-pedal system, the throttle, and the joystick. All three of these systems have two main functions each: to interact with the user and to communicate with the simulation program. Our design was divided into three different subsystems: *Rudder Pedal System, Throttle and Joystick.*

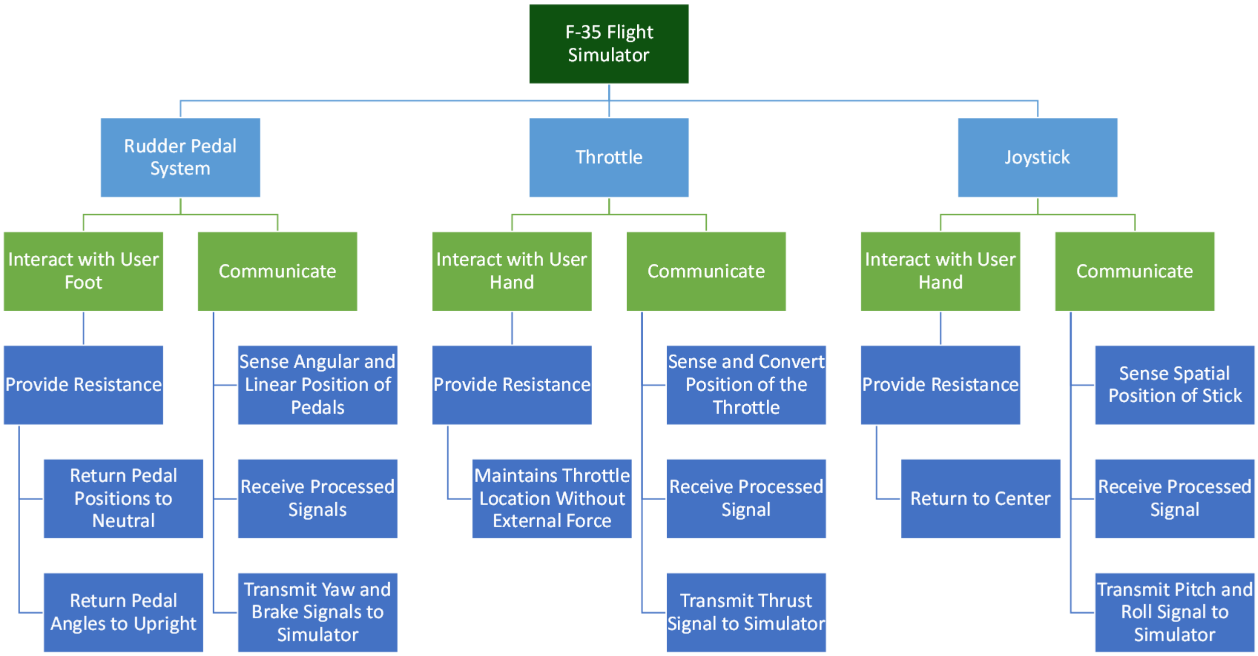


Figure 1 - Hierarchy Chart of Functions

1.3.2 Explanation of Hierarchy

The *Rudder Pedal System* (RPS) is designed to allow the pilot to interact with the simulation to deflect the rudders and operate the brakes of the model. The first branch components are divided into two: the user’s direct interaction by utilizing their foot and the other is the communication between the user’s input and the system. When the user interacts with their foot the system should be able to provide resistance in the opposite direction, return the pedals to their neutral position when there is no force applied, and make the return pedals to an upright angle.

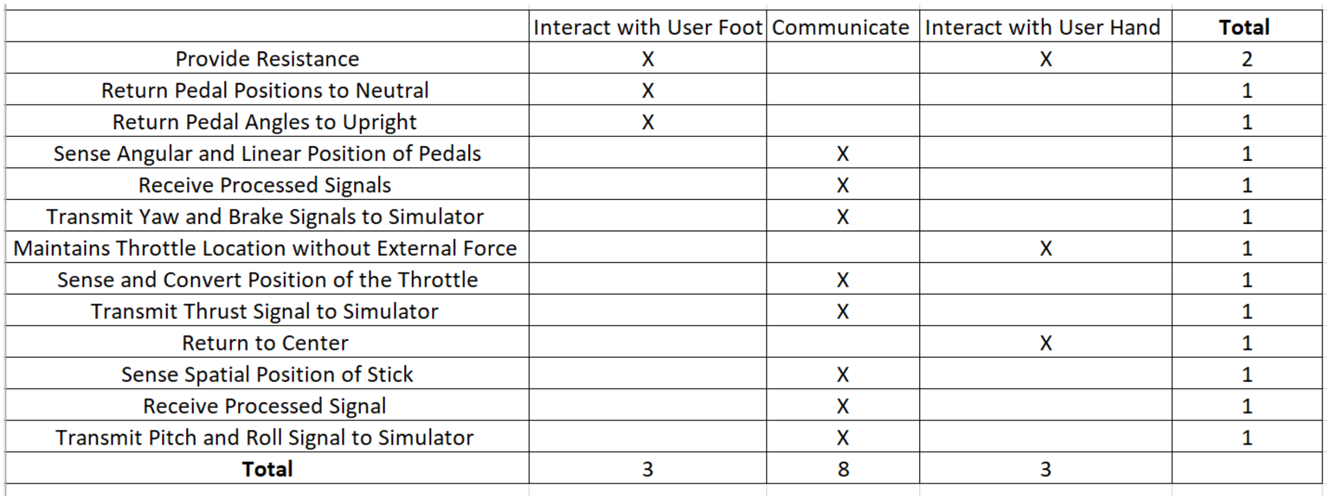
The second branch of the F-35 Flight Simulator is the *Throttle*, which regulates the engine’s power. The way its components are divided is the user interacting with the system with its hand and its communication. The way the system will obtain its throttle is by the user providing constant resistance and by doing that it will maintain the throttle location without external force. The system will sense and convert the position of the throttle into power and after it has received the signal, it will process the information so it can transmit a thrust signal into the simulator.

The third branch of the F-35 Flight Simulator is the *Joystick*, which is divided into two components: The user interaction and communication between its user input and the system's output. The user will communicate with the system with its opposite hand and by providing resistance it will make inputs and return to its center. The system will sense the spatial position of the stick and after it has been processed, the system will transmit a pitch and roll signal to the simulator.

1.3.3 Connection to Systems

Table 1 below shows a cross-functional relationship matrix. This table is meant to show how different functions of the system may relate to other systems outside of the branch they are located in. “Provide Resistance” is a part of the major functions “Interact with User Foot” and “Interact with User Hand.” The major function “Communication” has the most subfunctions, which should take priority. This agrees with SD T514’s project scope since a major goal is to integrate the RPS, HOTAS, and simulator software so they call communicate smoothly with each other. To achieve this goal, a heavy focus will be placed on the interpretation of mechanical positions to electrical signals in a form compatible for transmission to the computer and compatible for the Prepar3d simulator to receive.

Table 1: Functional Decomposition Cross-Functional Relationship Matrix



	Interact with User Foot	Communicate	Interact with User Hand	**Total**
Provide Resistance	X		X	2
Return Pedal Positions to Neutral	X			1
Return Pedal Angles to Upright	X			1
Sense Angular and Linear Position of Pedals		X		1
Receive Processed Signals		X		1
Transmit Yaw and Brake Signals to Simulator		X		1
Maintains Throttle Location without External Force			X	1
Sense and Convert Position of the Throttle		X		1
Transmit Thrust Signal to Simulator		X		1
Return to Center			X	1
Sense Spatial Position of Stick		X		1
Receive Processed Signal		X		1
Transmit Pitch and Roll Signal to Simulator		X		1
Total	3	8	3	

1.3.4 Integration

Table 1 contains the three different operations of the F-35 flight simulator. These three operations are cross-functional across the subsystems. The operations performed by the system are the following: interact with user foot, communicate, and interact with user hand. The first three functions are physical in nature. The next three functions rely on the conversion of physical phenomena into electrical signals. As the rudder pedals are moved, the sensors process the data of the angular and linear positions of the pedals and then send an output signal to adjust model in the Prepar3d software. The next three functions are based on the user's input with its hand on the throttle. The location of the throttle will be sensed and converted into thrust signals. The last four functions of Table 1 are dependent on the user's input and the sensor will obtain the spatial position of the joystick. After converting physical position to electrical signals, pitch and roll signals will be transmitted from the system into the computer.

1.3.5 Action and Outcome

The Low-Cost F-35 simulator will be a physical product that integrates a *Rudder Pedal System, Throttle,* and *Joystick* that senses the physical inputs provided by a user to control a model of an F-35 aircraft in Prepar3d. Through angular and linear displacements, system components will transmit signals to the Prepar3d simulation software to emulate the flight of an F-35 aircraft. The force felt by the user when displacing the systems from their default positions will be easily overcome by any user but have enough stiffness to inform the user the component is being displaced without visual aid. Receiving and interpreting the position of the rudder pedals, throttle, and joystick as electrical signals usable by a computer will guide our targets and metrics.

1.4 Target Summary

1.4.1 Summary of Targets and Metrics

Each target and metric can be derived from a component of the functional decomposition pertaining to one of the three systems in our design. Although some systems share similar functions, their deliverables are quantified differently. The purpose of these targets is to use specifications outlined by the sponsor to guide our design during the prototyping stage. These are tangible marks that we aim to achieve with a tolerance of plus or minus 5%. Some targets that are not associated with any listed function include a quicker response time, safety, weight, cost, and size restrictions of the HOTAS and RPS assembly.

Table 1 - Target Summary Table

Targets Table		
The prototype costs under $2,000	Required 18in for the rudder pedal to travel	Each component's weight should be less than 35lb
Accommodates 11-inch foot length	Force required to move rudder pedals should not be more than 15lbf	Allow joystick to deflect 13 degrees in all directions
Required 6 inches for the throttle to travel	Realistic ergonomics	Smooth bearings that allow pilots to adjust the desired throttle
Simulation should operate for 1 hour without problem	20 milliseconds of input delay	Equipment should fit in an area of 6 ft x 2ft x 2ft
No-slip components	Withstand 7.5lbf required for joystick deflection	Return the joystick to the initial position

1.4.2 Critical Targets

There are some targets that are more critical to the overall success of our project. The first of these critical targets is keeping manufacturing costs low. It was requested that the cost of materials alone for each of the three components be kept below $1000. This cost does not include labor time. Another critical target is the latency of the three components. It is important that the input from the equipment is processed as quickly as possible into the simulation so that there is little to no perceivable delay in the simulation. If the response of the simulation trails too far behind the input from the user, the simulated flying experience will be disorienting and far from a true in-flight experience. The latency should be within 20 milliseconds.

1.4.3 Method of Validation

Various tools will be used to test and validate the targets. Such equipment includes a ruler, caliper, force gauge, ultrasonic sensor to measure the input delay, protractor for control deflection range, and slow-motion camera for signal latency measurements. Raw sensor data will be logged using a prototyping apparatus constructed with an Arduino for developing the sensor set points to use for calibration. Consultation with jet pilots will be considered, if possible, to discuss the simulator demonstration. The simulator demonstration will include a graphical video from the cockpit and a spot-view outside the jet during the flight test. A camera will also be used to film the operator from an angle that shows all the flight controls.

1.4.4 Derivation of Targets and Metrics

The various targets and metrics listed here were collected from speaking with our sponsor from Lockheed Martin, from research on existing flight simulator software specs, and from military documents about the F-35. The document MIL-STD-1472H had many general requirements for designing for humans that applied to the simulator. This document included information for us to design around pertaining to the force applied to the equipment and general ergonomics for military equipment. SD T514 is still awaiting the release of the HOTAS model from Lockheed Martin, so some targets were set from an educated guess.

1.4.5 Discussion of Measurements

In this project we will need to obtain various measurements and to do so we will need a variety of tools. To obtain the specific dimension of the cockpit and components we will use rulers and calipers. To measure the angle of deflection of the joystick, a protractor will be used. Last, to measure the delay between our pilot and the system we will use slow-motion cameras and an ultrasonic sensor to measure the delay between the input action and the response of the model in Prepar3d.

1.5 Concept Generation

To meet the customer's needs efficiently and completely, many avenues of thought were applied to solution generation. SD T514 has compiled a list of 100 design concepts, ranging in fidelity. Only the most important concept generation methods and concepts are discussed in this section. The complete list of concepts can be found in Appendix D.

1.5.1 Concept Generation Tools

SD T514 is designed for three independent pieces of equipment that will be electronically integrated together. For this project we generated 100 different concepts for the low-cost F-35 flight simulator. The first fifty concepts were generated from the morphological chart in Figure #. This was useful because the project has 4 categories to design for: the RPS, the joystick, the throttle, and the electronic equipment used to integrate the systems. Cells from each column were randomly selected to be combined into one complete design idea. Concepts for the morphological chart were created from customer wants and needs, forced analogy, and crap shooting to see how an integrated and ergonomic design that would bolster F35 pilot training could be constructed. Inspiration was gained from gaming consoles, controllers, existing flight simulators, and existing joysticks and rudder pedals.

Inside our morphological chart we have written viable solutions that as a team discussed would be the best way to proceed to make our component in the most efficient manner possible. Ideas were generated for four aspects of the project: the Rudder Pedal System, the joystick, the throttle, and the electrical components of our systems. First, we start with some of our high-fidelity concepts of the electrical components of our system that include the use of a potentiometer that we are going to utilize to sense positions by utilizing a mechanical variable resistor. Then we were thinking of utilizing a hall sensor. The hall effect sensor works by detecting the magnitude and presence of magnetic fields and in doing so it can detect the position the rudder pedal system and the HOTAS are located at a specific time. Another high-fidelity concept was using individual controllers since they allow us to use less wires meaning less interference in our cockpit and means more USB ports are going to be required than normal. The last high-fidelity concept of electrical integration is to make a common controller which has less USB ports allowing room for more equipment to be installed in less space. A few high-fidelity concepts for each component of the project were selected to be put through the Pugh chart process.

Ideas for the joystick included a single spring ball joint, which in the end is not an effortless way for our team to integrate the sensors into the joystick without damaging the equipment but it is a lot easier for us to design and construct. The other concept for the joystick was that we decided to design a multiplane gimbal which separates the planes making it easier for us to differentiate the position the joystick is at currently.

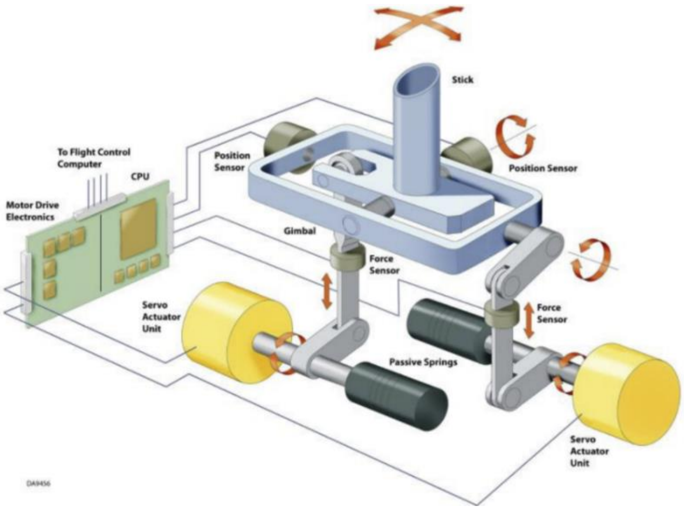


Figure 2 - Multiplane Gimbal

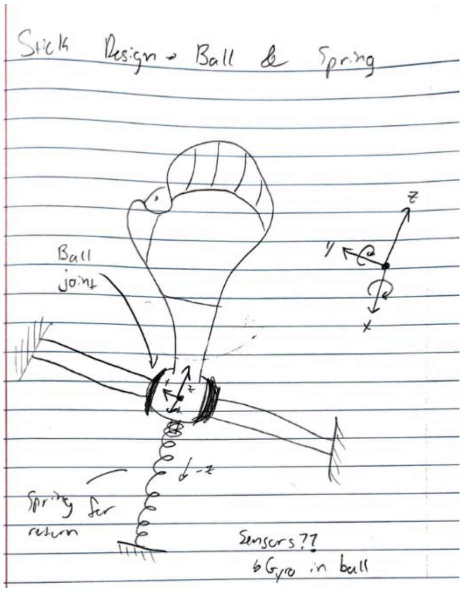


Figure 3 - Single Spring and Ball Gimbal

The last concepts of high fidelity are related to the throttle. We thought that a single rail would be the best idea to assemble the throttle stick allowing it to slide along a single rectangular rail with little to no resistance. The second idea we had was to have a multi-rail throttle slide along two parallel tube rails. By having two tubes we were going to create more support in the rails allowing the throttle to travel in the same direction with more support and reduce energy loss. Another high-fidelity concept was to utilize gears in our design. The idea was to have a potentiometer attached to the pinion to measure the distance the throttle has traveled. The last high-fidelity concept for the throttle was to utilize a belt and by using a belt the tension cable would be attached to the trolley that would go around the pulley and the position sensor of the throttle, measuring the distance the throttle travels.

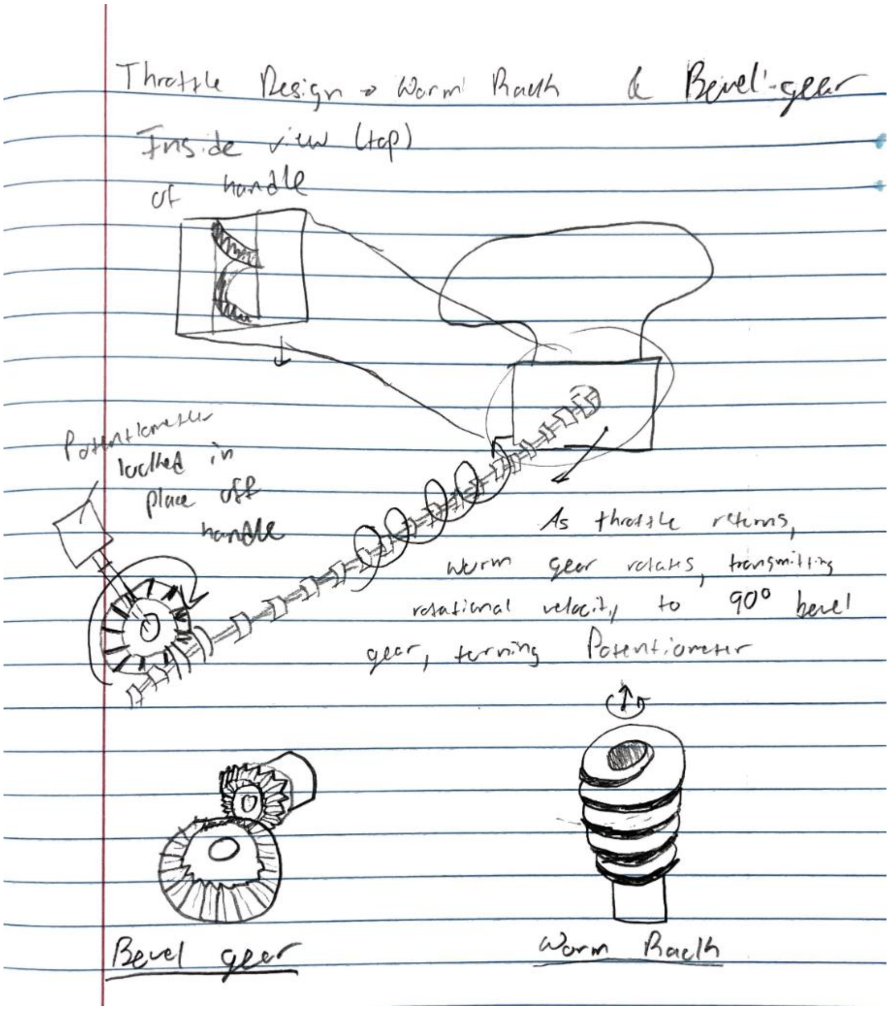


Figure 4 - Worm and Bevel Gears for Throttle

1.6 Concept Selection

1.6.1 Introduction

Concept selection begins with brainstorming what parameters of design determine the overall performance of the final product. A few of parameters that could influence the simulator include, but are not limited to, the durability of components, the mechanical complexity, and the cost of materials. These parameters are weighted to consider what is most important to the customer and applied to the generated concepts. This narrows down the extensive list of options down to higher fidelity options and eventually to the preliminary concept moving forward.

1.6.2 Weighting the Design Parameters

Through meetings with Lockheed Martin and gathering details about the desired product, nine aspects of the design were weighed against each other. If one attribute has priority over the other, it was given a value of one while the other was given a zero. As each attribute is compared to all the others, the final weighting of each of the nine attributes is summed up. These weights are used to guide the design process. This weighting is called a binary pairwise comparison and the table below displays how it was applied to the simulator.

Table 2: Binary Pairwise Comparison

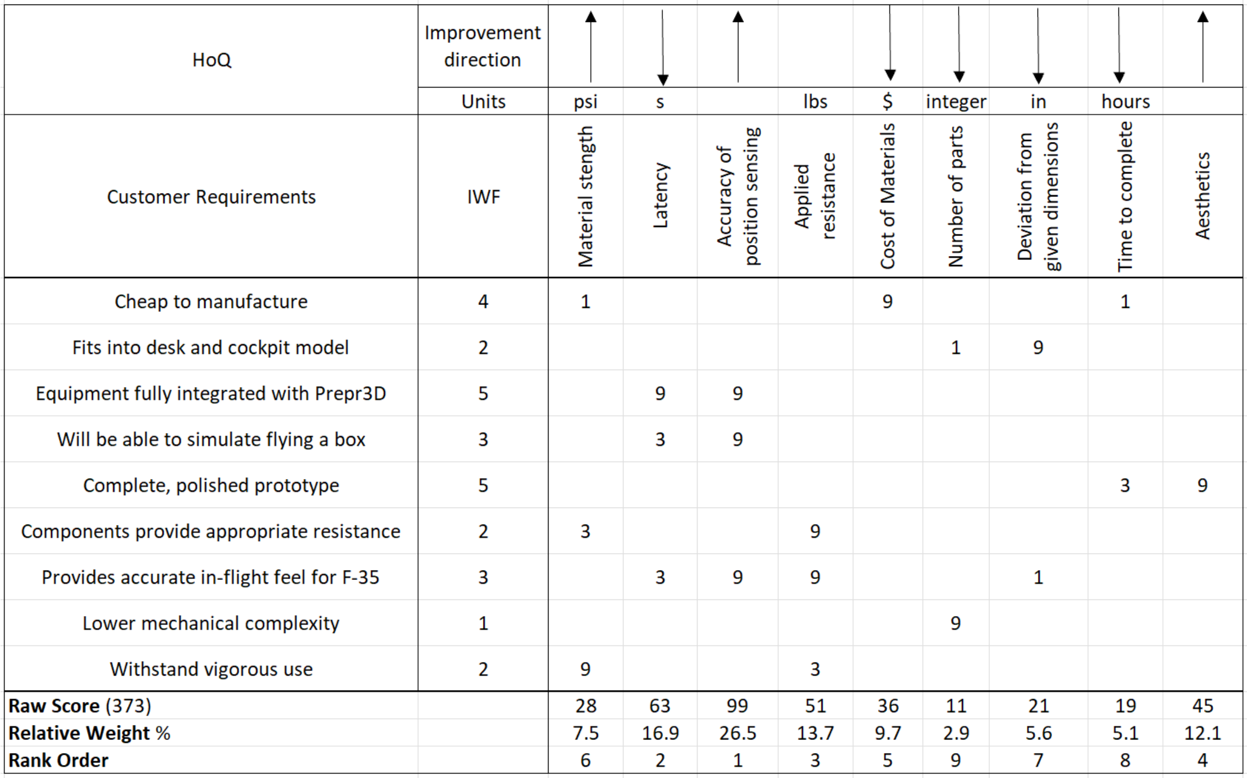
	1	2	3	4	5	6	7	8	9	Total	IWF
1. Cheap to manufacture	-	1	0	1	0	1	0	1	1	5	4
2. Fits into desk and cockpit model	0	-	0	0	0	1	0	1	1	3	2
3. Equipment fully integrated with Prepar3D	1	1	-	1	0	1	1	1	1	7	5
4. Will be able to simulate flying a box	0	1	0	-	0	1	0	1	1	4	3
5. Complete, polished prototype	1	1	1	1	-	1	1	1	1	8	5
6. Components provide appropriate resistance	0	0	0	0	0	-	1	1	0	2	2
7. Provides accurate in-flight feel for F-35	1	1	0	1	0	0	-	1	0	4	3
8. Lower mechanical complexity	0	0	0	0	0	0	0	-	1	1	1
9. Withstand vigorous use	0	0	0	0	0	1	1	0	-	2	2
Total	3	5	1	4	0	6	4	7	6	n-1=8	

Looking at the binary pairwise comparison table, the comparisons on top of the diagonal dashed cells are given priority in the calculation of the Importance Weight Factor (IWF). The IWF is a ranking of the attributes on a scale of 1 to 5 and used next to determine which engineering characteristics are more critical to the success of the simulator. Here, the highest graded attributes are the full integration of equipment to Prepar3D software and the presentation of a complete, polished prototype

1.6.3 Matching Customer Requirements to Engineering Characteristics

To ensure the product being developed meets Lockheed Martin's requirements, physical engineering characteristics are ranked in a house of quality (HOQ). The purpose of using an HOQ is to determine which physical engineering characteristics will determine the overall success of the simulator by meeting Lockheed Martin's needs in an innovative final product. Some of these engineering characteristics are the material strength of the components and the total number of parts in the system. These engineering characteristics have specific values that are associated with them and help guide us to a final design that meets our established targets. The HOQ uses the IWF developed by the binary pairwise comparison in combination with a skewed ranking system that will isolate important engineering characteristics to focus on. For each attribute, every engineering characteristic is given a rating of a 1, 3, or 9 based on how related the characteristic is. Engineering characteristics that have no correlation on an attribute are not scored (rated a zero). The HOQ for the simulator is shown in the table below.

Table 3 - House of Quality



HoQ	Improvement direction	↑	↓	↑		↓	↓	↓	↓	↑
	Units	psi	s		lbs	$	integer	in	hours	
Customer Requirements	IWF	Material stength	Latency	Accuracy of position sensing	Applied resistance	Cost of Materials	Number of parts	Deviation from given dimensions	Time to complete	Aesthetics
Cheap to manufacture	4	1				9			1	
Fits into desk and cockpit model	2						1	9		
Equipment fully integrated with Prepr3D	5		9	9						
Will be able to simulate flying a box	3		3	9						
Complete, polished prototype	5								3	9
Components provide appropriate resistance	2	3			9					
Provides accurate in-flight feel for F-35	3		3	9	9			1		
Lower mechanical complexity	1						9			
Withstand vigorous use	2	9			3					
Raw Score (373)		28	63	99	51	36	11	21	19	45
Relative Weight %		7.5	16.9	26.5	13.7	9.7	2.9	5.6	5.1	12.1
Rank Order		6	2	1	3	5	9	7	8	4

From the HOQ, the three lowest ranking engineering characteristics are eliminated due to their lower correlation to meeting the needs of Lockheed Martin. The highest-ranking physical characteristics have to do with the speed and accuracy of the electrical components selected. The HOQ reveals how important the electrical component selection will be to the success of the project.

1.6.4 Applying Engineering Characteristics to High Fidelity Concepts

To whittle down the best concepts for the start of prototyping, the HOQ provided the most important characteristics to consider. For direct comparison, each idea was compared to each respective engineering category in a Pugh Chart for the purposes of eliminating the weaker ideas.

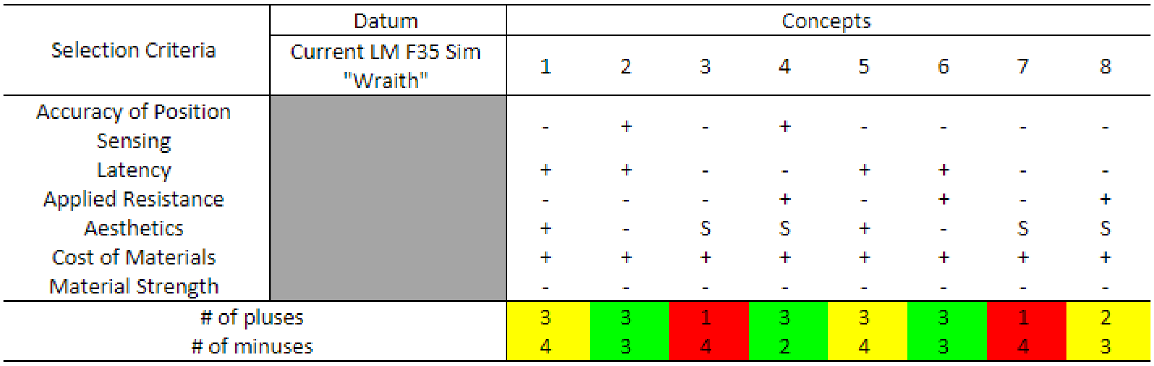
The top 8 concepts are as follows.

Table 4: Top 8 Concepts

	electrical	throttle	joystick	rps
1	hall & individual	single	ball	use existing
2	hall & individual	single	gimbal	use existing
3	hall & common	single	ball	use existing
4	hall & common	multi	gimbal	use existing
5	pot & individual	single	gimbal	use existing
6	pot & individual	multi	gimbal	use existing
7	pot & common	single	gimbal	use existing
8	pot & common	multi	gimbal	use existing

Multiple Pugh Charts were used to compare ideas against different datums. Each datum is a current system on the market that Lockheed Martin could potentially outsource instead of our design, and how each of our design concepts will match up against them. In the first Pugh Chart, we compared our eight best ideas to the RPS assembly and HOTAS which Lockheed Martin currently uses, made by Wraith Systems.

Table 5: Pugh Chart 1



Selection Criteria	Datum	Concepts							
	Current LM F35 Sim "Wraith"	1	2	3	4	5	6	7	8
Accuracy of Position Sensing		-	+	-	+	-	-	-	-
Latency		+	+	-	-	+	+	-	-
Applied Resistance		-	-	-	+	-	+	-	+
Aesthetics		+	-	S	S	+	-	S	S
Cost of Materials		+	+	+	+	+	+	+	+
Material Strength		-	-	-	-	-	-	-	-
# of pluses		3	3	1	3	3	3	1	2
# of minuses		4	3	4	2	4	3	4	3

When looking across the Pugh Chart, each symbol in the respective column is that concept compared to the original Wraith systems datum. Each "+" signifies that our concept should out-perform the current system, and each "-" denotes that the concept will not measure up. Our third and seventh ideas were clearly inferior to the current design and newer concepts, and thus removed. To further simplify, the next datum was the previous Senior Design Teams' prototype.

Table 6: Pugh Chart 2

Selection Criteria	Datum	Concepts					
	Past year projects	1	2	4	5	6	8
Accuracy of Position Sensing		-	+	+	+	+	+
Latency		+	+	+	+	+	+
Applied Resistance		S	+	+	+	+	+
Aesthetics		-	-	+	-	-	+
Cost of Materials		-	-	-	-	-	-
Material Strength		+	+	+	+	+	+
# of pluses		2	4	5	4	4	5
# of minuses		3	2	1	2	2	1

When looking at the previous HOTAS system and rudder assembly, implementing a ball design for the stick assembly ended up not being feasible. Consequently, it is reflected in the Pugh Chart, having fewer positives than negatives. Finally, the last comparison was to the closest competitor of Wraith Systems, Logitech Pro Flight Systems. The final five concepts are whittled down to three here.

Table 7: Final Pugh Chart

Selection Criteria	Datum	Concepts				
	Logitech pro flight	2	4	5	6	8
Accuracy of Position Sensing		+	+	S	S	S
Latency		S	-	S	S	-
Applied Resistance		+	+	+	+	+
Aesthetics		S	+	S	S	+
Cost of Materials		-	-	+	S	S
Material Strength		-	-	-	-	-
# of pluses		2	3	2	1	2
# of minuses		2	3	1	1	2

Concept 4 was eliminated because it had the highest number of minuses, and concept 6 was eliminated for having the lowest number of pluses. From this, the top three, and therefore high fidelity concepts, are concepts 2, 5, and 8.

1.6.5 Analytical Hierarchy Process

The analytical hierarchy process (AHP) is a logical and mathematical way to make design decisions based on many criteria. The process is started by creating a matrix to compare all the criteria for the designs. The criteria are weighed against each other based on a scale using odd numbers from 1-9, with 1 being that the two criteria are equal and 9 meaning that one is way more important than the other. The opposite of these ratings is put into the chart on the opposing triangle. Then, the sum of each column is calculated. The chart is called [C] and is shown below.

Table 8: Criteria Matrix [C]

[C]	Accuracy of Position Sensing	Latency	Applied Resistance	Aesthetics	Cost of Materials	Material Strength	Deviation from Given Dimensions
Accuracy of Position Sensing	1.000	1.000	5.000	3.000	3.000	7.000	9.000
Latency	1.000	1.000	3.000	3.000	1.000	5.000	5.000
Applied Resistance	0.200	0.333	1.000	1.000	1.000	5.000	7.000
Aesthetics	0.333	0.333	1.000	1.000	1.000	5.000	5.000
Cost of Materials	0.333	1.000	1.000	1.000	1.000	5.000	7.000
Material Strength	0.143	0.200	0.200	0.200	0.200	1.000	1.000
Deviation from Given Dimensions	0.111	0.200	0.143	0.200	0.143	1.000	1.000
Sum	3.121	4.067	11.343	9.400	7.343	29.000	35.000

The next step in the AHP is to normalize the above matrix. To do this each element in the chart must be divided by the sum of the column that it is in. The success of this normalizing is checked by then calculating the sum of each column again, and the result should be 1. From this chart the criteria wrights, {W}, can be calculated. The weight of each criteria is the average of the normalized value in the criteria's corresponding row. A higher criteria weight corresponds to a more important criteria. The resulting Norm[C] chart is shown below.

Table 9: Normalized Criteria Matrix

Norm[C]	Accuracy of Position Sensing	Latency	Applied Resistance	Aesthetics	Cost of Materials	Material Strength	Deviation from Given Dimensions	Critera Weights {W}
Accuracy of Position Sensing	0.320	0.246	0.441	0.319	0.409	0.241	0.257	0.319
Latency	0.320	0.246	0.264	0.319	0.136	0.172	0.143	0.229
Applied Resistance	0.064	0.082	0.088	0.106	0.136	0.172	0.200	0.121
Aesthetics	0.107	0.082	0.088	0.106	0.136	0.172	0.143	0.119
Cost of Materials	0.107	0.246	0.088	0.106	0.136	0.172	0.200	0.151
Material Strength	0.046	0.049	0.018	0.021	0.027	0.034	0.029	0.032
Deviation from Given Dimensions	0.036	0.049	0.013	0.021	0.019	0.034	0.029	0.029
Sum	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000

This chart shows that the previously 5th ranked criteria, Cost of Materials, is now ranked third by this process. This makes sense because the cost of the final product is a major concern to the sponsor for Lockheed Martin and is pivotal in the success of the project. Once the weights are calculated, the consistency of the process must be checked. This is done by first calculating the weighted sum vector, {Ws}, which is the product of the matrix [C] and the vector {W}. This vector is then divided, element by element, by the vector {W} to achieve the consistency vector. The average of all values in the consistency vector gives the variable λ. The resulting vectors are shown below.

Table 10: Consistency Check

Consistency Check		
Weighted Sum Vector {Ws}	Criteria Weights {W}	Consistency Vector {Ws}./{W}
2.447	0.319	7.671
1.724	0.229	7.537
0.893	0.121	7.359
0.878	0.119	7.361
1.088	0.151	7.212
0.230	0.032	7.194
0.205	0.029	7.123
		λ= 7.351

The calculation for the consistency index and consistency ratio used the following equations.

Table 11: Consistency Equations

$CI=\frac{\lambda-n}{n-1}$	$CR=\frac{CI}{RI}$	n= 7

The results of these calculations are as follows: CI=0.058, RI=random index=1.35 for 7 elements, and CR=0.043. A consistency ratio of less than 0.1 means that the results are consistent and therefore unbiased. So, the criteria rankings are consistent.

The AHP process was repeated for the three high fidelity concepts chosen from the results of the Pugh chart. The concepts were ranked against each other using the top three criteria of the original AHP. Those criteria were accuracy of position sensing, latency, and cost of materials. The following charts were generated for the three concepts based on accuracy of position sensing.

Table 12: AHP for Accuracy of Position Sensing

[C]	2	5	8
2	1.00	5.00	5.00
5	0.20	1.00	1.00
8	0.20	1.00	1.00
Sum	1.40	7.00	7.00

Norm[C]	2	5	8	Criteria Weights {W}
2	0.714	0.714	0.714	0.714
5	0.143	0.143	0.143	0.143
8	0.143	0.143	0.143	0.143
Sum	1.000	1.000	1.000	1.000

Consistency Check		
Weighted Sum Vector {Ws}	Weights {W}	Consistency Vector {Ws}./{W}
2.14	0.71	3.00
0.43	0.14	3.00
0.43	0.14	3.00
		λ= 3.00

The resulting CR was 0, meaning these results were consistent. The top concept based on this criteria was Concept 2: Hall sensor, individual USB with a single rail.

The second iteration uses the Latency of the system to rank the concepts the resulting charts are as follows.

Table 13: AHP for Latency

[C]	2	5	8
2	1.00	0.33	7.00
5	3.00	1.00	7.00
8	0.14	0.14	1.00
Sum	4.14	1.48	15.00

Norm[C]	2	5	8	{W}
2	0.241	0.226	0.467	0.311
5	0.724	0.677	0.467	0.623
8	0.034	0.097	0.067	0.066
Sum	1.000	1.000	1.000	1.000

Consistency Check		
{Ws}	{W}	{Ws}./{W}
0.981	0.311	3.150
2.018	0.623	3.241
0.199	0.066	3.022
	λ=	3.138

From this process, the CR value was 0.13, which is slightly above recommended, but not by much, so these results are still viable. The highest ranked concept from latency was concept five.

The final iteration of AHP based on the cost of materials resulted in the following charts.

Table 14: AHP for Cost of Materials

[C]	2	5	8
2	1.00	0.14	0.20
5	7.00	1.00	3.00
8	5.00	0.33	1.00
Sum	13.00	1.48	4.20

Norm[C]	2	5	8	{W}
2	0.077	0.097	0.048	0.074
5	0.538	0.677	0.714	0.643
8	0.385	0.226	0.238	0.283
Sum	1.000	1.000	1.000	1.000

Check		
{Ws}	{W}	{Ws}./{W}
0.222	0.074	3.013
2.008	0.643	3.121
0.866	0.283	3.062
	λ=	3.066

The resulting CR of this process was 0.06, so results were consistent. Again, the highest-ranking concept was concept 5.

From the weights obtained for each concept, the average was calculated across all three criteria to determine a final concept that should outperform the rest based on the most important criteria. The resulting chart is shown below.

Table 15: Final Concept Rankings

final ranking			
	Concept		
	2	5	8
Accuracy	0.714	0.143	0.143
Latency	0.311	0.623	0.066
Cost	0.074	0.643	0.283
Average	0.366	0.470	0.164

The results of this chart prove that the concept that will be selected for the final design is concept 5. Concept 5 uses a potentiometer to sense the position of each element, a USB for each of the three components, a single square rail to slide the throttle on, a gimbal joint for the joystick and the existing RPS system.

1.7 Fall Project Plan

Milestones	**Tasks**	**Subtasks**		**Assignee**
Code of Conduct (9/9)				**All**
	Create document			All
	Write subtitles			All
	Fill in information			All
	Review information			Emelia
	Sign document			Branden
	Submit document			Laiken
Work Break Down Structure (9/16)				**All**
	List Milestones			Branden
	List Tasks			Laiken
	List Sub-tasks			Laiken
	Assign milestones/tasks			Emelia
	Write report			All
	Submit			Laiken
Project Scope (9/23)				**Emelia Branden Will**
	Describe the overall project in > 3 sentences			Branden

	Define key goals by describing what we will *do*			
		Quantify Deliverables		Emelia
			Research associated standards of deliverable	Branden
	Identify primary and secondary markets through research on product use			Emelia
	Identify assumptions necessary to fit project within the scope			Emelia
	Identify stakeholders			Will
	Write report			Will
	Submit report			Branden
Customer Needs (9/30)				**Laiken** **Francisco** **Jonah**
	Draft questions to ask sponsor			All
	Meet with sponsor			All
	Record sponsor responses			Laiken
	Interpret responses and identify needs/wants			Laiken
	Write report			Branden
	Submit report			Laiken
Functional Decomposition (10/7)				**Laiken** **Emelia** **Branden**

	Break up project into smaller parts (major functions and minor functions) that describe physical action (what does it do) and describe outcomes			Emelia
	Create flow chart/graphic			Laiken
	Write report			Branden
	Submit report			Emelia
Targets (10/28)				**Branden Francisco Will**
	include at least one target/metric (which is a number with units) for each function			Francisco
	Identify the critical targets and metrics			Branden Francisco Will
		include specific testing/ validation for the critical targets/ metrics		Branden
	Include discussion of how the targets were determined and reasoning behind selection of critical targets			Branden
	Determine resources needed to validate targets			Will
	Write summary and include a table in the evidence manual "Targets" chapter			Will

	Prepare complete target catalog for the appendix			Will
	Submit milestone			Will
Concept Generation (11/4)				**All**
	Generate 100 concepts using concept generation tools			Branden
	Write report			Emelia
	Add information to evidence manual			Branden
	Submit report			Emelia
Concept Selection (11/4)				**Jonah** **Francisco** **Will**
	House of quality			Francisco
	Pugh charts			Branden
	AHP			Francisco
	Select final concept and indicate how the above methods led to its selection			All
	Add the charts to the evidence manual			Branden
	Submit evidence manual			Branden
Risk Assessment (11/18)				**Emelia** **Laiken**
	Complete safety expectations document			Emelia
	Complete project hazard assessment			Laiken
	Complete project control document			Emelia
	Submit all 3 forms			Emelia
Bill of Materials (11/28)				**Jonah**

	Line items			Jonah
	Order needs			Jonah
	Parts list			All
	Vendors identified			Jonah
	Method for identifying the completeness of a line item			Jonah
	Method for identifying the completeness of the project			Jonah
	Method for identifying the project's cost			Jonah
	Method for identifying unit cost			Jonah
	Method for identfying the labor cost			Jonah
Spring Project Plan (12/2)				**Laiken Emelia**
	Make a timeline for spring semester to include milestones and deliverables			Emelia
	Write report			Laiken
	Submit report			Emelia

Chapter Two: EML 4552C

2.1 Spring Plan

Project Plan.

The plan for the spring semester was divided into various categories to ensure we hit our original targets. The project was divided into the Joystick, the throttle, and the Rudder Pedal

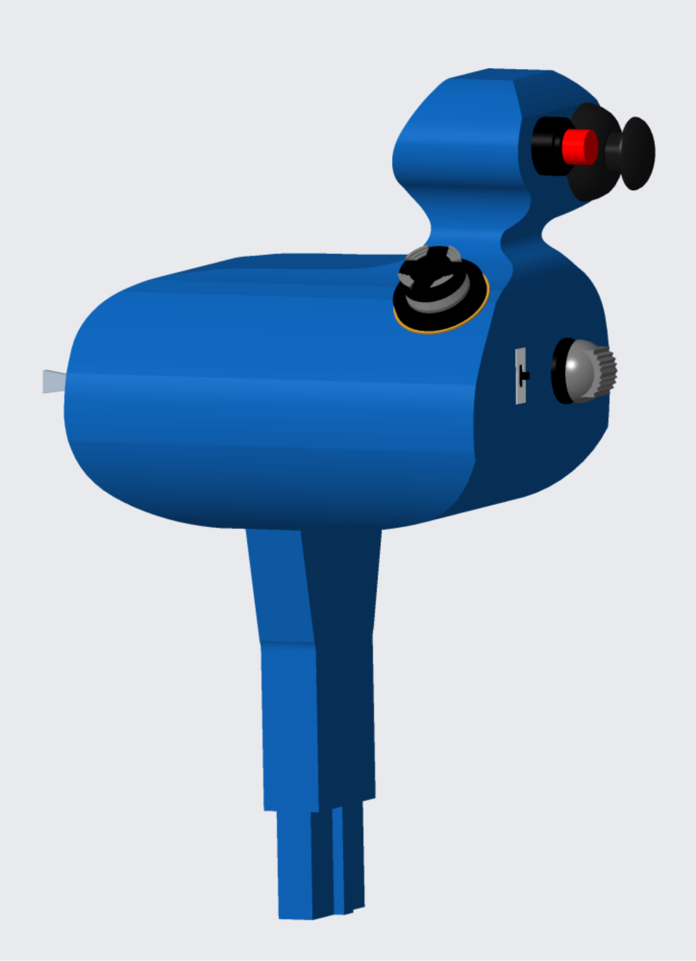
System (RPS). On the joystick we decided to stick to a multi-plane gimbal, with a ball joint. The throttle was going to translate in one direction using a rack and pinion and a single rail with a belt system. For the RPS we were going to upgrade the electronics, more specifically the circuit board which needed to be redesigned completely.

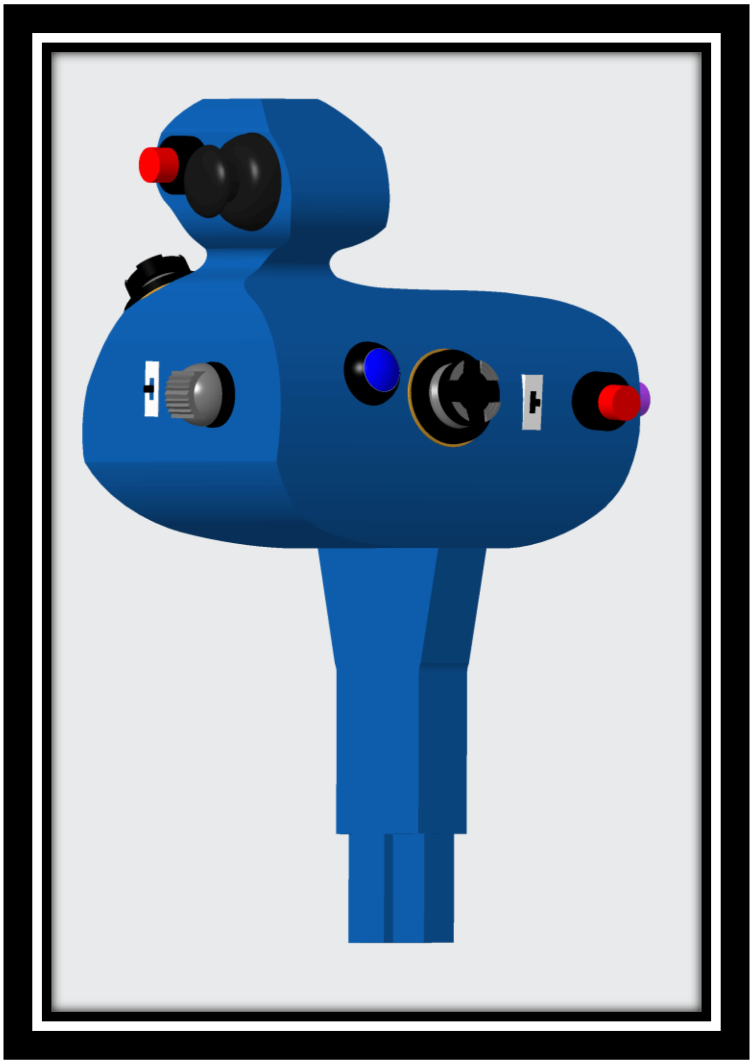
2.2 Build Plan.

The Computer Aided Designs (CAD) had to be completed by the end of February. Those were the top priorities in our project, redesigning the HOTAS completely. The past senior design team had troubles fitting the buttons and making the HOTAS communicate with the Prepar3D program, so our first goals were to create a bigger and ergonomic design and create a custom-made circuit board. New attachments to the joystick and throttle handles needed to be created, so a new joint mechanism needed to be created for both.

2.3 Results

The final design of our HOTAS and RPS systems were able to meet all our targets and metrics that were set at the beginning of the fall semester. In the HOTAS, the final assembly was divided into two components: the joystick and the throttle. The joystick and throttle were redesigned to fit the pilot height requirements of the air force. Meaning the handles could be comfortably held by people ranging from 5.3ft to 6.4ft. The joystick was made slimmer and had a hand and thumb rest on the sides so the user could comfortably grab the handle and reach all the buttons set on it. The joystick was attached to a multi-plane gimbal with rotary sensors to detect movement and a custom USB microcontroller. Modular connectors were used to connect each of its buttons to the printed circuit board. This enables the user to replace buttons without having to solder any connections. The throttle handle was redesigned with the intent to give it a wide grip that was aesthetically pleasing to the user, allowing it to store all the necessary buttons to fly an F-35 plane, meanwhile giving a smooth feel to the pilot. The throttle was attached using a linear square rail to allow a single plane translation, accompanied by a rack and pinion with a rotary sensor that was attached to a custom USB microcontroller. For the RPS the electronics were upgraded by connecting the system to a custom USB microcontroller that had a rotary sensor in the middle. Some mechanical parts were removed to make it less bulky and allow a smoother transition of the pedals. Below are some images of the final assembly.





Finally, the project's cost was $1987.54, considering the cost of assembly and shipping. This cost was under the sponsor's $2000, meaning we were able to efficiently manage the budget for our project.

2.4 Discussion

Keeping Manufacturing costs low:

As stated at the beginning of our project, our goal was to keep each of the subcomponents below $1000 each. The two subcomponents were the throttle and the joystick. In the end, we met this goal, and the total cost of the joystick was $835.68, and the throttle was $436.61. This total amounted to $1272.69, and the rest of the budget was divided into the electrical components, the hardware, and the shipping fees.

Fits and ergonomics:

The new HOTAS design fitted the height standards of the air force pilots. To ensure that we had an ergonomic design that was aesthetically pleasing to the user and allowed a high maneuverability to reach the desired buttons when flying the aircraft. The physical prototypes were tested among all the members in our group, and everyone was able to comfortably use the HOTAS without issue.

Integration in to Prepar3D:

The HOTAS and RPS systems successfully integrated into Prepa3D and were flight tested by our members.

Appendices

Appendix A: Code of Conduct

Mission Statement

Our mission is to design a flight control system to be deployed across the F-35 Training Enterprise that will reduce the cost and complexity of the current flight controls while integrating previous projects, which, comprise the throttle and rudder controls.

Outside Obligations

I. Branden:
i.Interning ~30 hrs/week but available after 5pm and weekends.
ii.Specific dates: Out-of-state March 13-18th
iii.I prefer to have Sunday mornings free
II. Emelia:
i.Circus obligations ~ weekly practices: Monday 5:30, Wednesday 9:30, and Friday 2:30 for half an hour each.
v.13 Jan: Mandatory cast meeting at 5pm
vi.10 Feb: Mandatory cast meeting at 6pm
vii.24-26 Feb: Out of town
viii.28 & 30 Mar: show rehearsals at 5:30pm
ix.3 & 5 Apr: show rehearsals at 5:30pm
x.7-8, 14-16, & 21-22 Apr: Circus home shows
ii.I would prefer to have Sunday morning and Wednesday evenings off
iii.Work ~ I work on the weekends occasionally, I will know way ahead of time.
III. Laiken:
i.~~22-23 Sep: Elton John Concert in ATL~~
ii.~~7-10 Oct: Women in Uniform Conference in NC~~
iii.~~22 Oct: marching in FAMU Homecoming parade~~
iv.~~29 Oct: working the Clemson game for ROTC~~
v.~~11 Nov: out all day for Veterans Day parade and Marine Corps birthday ball~~
vi.~~19 Nov: FSU Military appreciation game~~
i.Religious obligations ~~at 7:30pm Wednesdays and~~ 10:00am Sundays
ii.Jan 28: Mandatory NROTC Event
iii.17-19 February: ROTC Tulane Drill Meet
IV. Francisco:
i.AME research: I work 11 hours a week
ii.COE library: I work here 9 hours a week
iii.Rather meet on weekends since I am pretty busy Monday to Friday
V. Will:
i.ROTC
i.~~16 Sep: Air Force Ball~~
ii.~~17-21 Oct: Military Flight Physical at Wright-Patterson AFB Ohio~~
iii.~~Football Home Games: I work the ticketing gates for a fundraiser~~
i.Wednesdays I am not available from 5 to 8:30 pm

        ii.Sundays I am not available from 5:30 until midnight~~to 8:30 pm~~

    ii.I am up most days at or before 6 am, so I *can* meet if absolutely necessary, but would prefer not to meet past 10 pm.

    iii.I will not be available from 9 to 11:30 on Sundays due to Church

VI. Jonah

    i.Full time job 8am-5pm

    ii. April 7-10th travel

    iii. January 27-29th travel

Team Roles

~~Test & Analytical Engineer~~ Project Manager: Laiken Kinsey
~~Control Systems Engineer~~Computer Aided Designer: Francisco Lopez
Electrical Engineer: Jonah Gibbons
Mechatronics: William Rickles
Web Design: Branden Pacer
Purchasing~~roject~~ Manager and Researcher: Emelia Rodriguez
~~Note Keeper: Laiken Kinsey~~

Other duties will be assigned to members of the team on a volunteer basis. Members of the team with specific expertise or available time are expected to offer the time to the team as we work to share the burden of responsibilities with each other.

Dress Code

Dress for professional presentations will be suits for males. For females, attire includes closed toe flats, dress shoes, or heels; dress pants or skirt; blazers or business appropriate dresses. For meetings with project stakeholders, attire will be business casual to include polo shirts or button-down shirts with some nice dress pants.

Attendance Policy

Team meetings will not extend past 8pm. Meetings can be in person or via Zoom if feasible. Attendance is mandatory at all meetings, unless otherwise previously reported to group members at least 24 in advance of the scheduling conflict. Attendance will be kept for every meeting in the engineering notebook of the appointed note keeper. If a group member misses 3 all hands meetings, even with notification, a team discussion will be conducted. Meeting minutes will be sent to all team members after each meeting via email no later than 24 hours after the meeting occurs.

How to Notify Group and Other Communications

The primary mode of team communication to include updates on project status will be sent via email. File sharing will done on the Microsoft Teams page. All team members will be copied emails that go to the sponsor or to Dr. McConomy. Reminders and easy questions or discussion will be conducted in the GroupMe chat. Members will commit to responding to messages within 24 hours.

A professional tone will be upheld in all meetings with the sponsor or Dr. McConomy. Stakeholders will be addressed using their title. Members of Team 514 will remember to speak to others with respect.

If three members, either separately or corporately, have addressed an issue with another member without resolution (e.g. multiple offenses), outside involvement shall be required. Dr. McConomy will intervene in response to the severity of the situation.

Statement of Understanding

As a member of SD Team 514, I agree to meet all deadlines for any task submission. I have read the above team code of conduct, and I agree to its terms and conditions. I acknowledge that I have had the opportunity to provide my input and ask questions. I agree that all suggested amendments to this document must be presented to the entire group, with good reason, and be agreed upon by the majority of the group.

x Jonah Gibbons

Jonah Gibbons

x Laiken Kinsey

Laiken Kinsey

x Francisco Lopez

x Branden Pacer

Branden Pacer

x William Rickles

Will Rickles

x Emelia Rodriguez

Graduation year

Appendix B: Functional Decomposition

Appendix C: Target Catalog

Functions	Targets	Metrics
Conform to military standards	11 in foot length	Average male foot size
Low cost	Under $2,000	Material budget we need to stay under
Give pilots in-flight feel	Realistic ergonomics	Design must allow the pedals to fit under the desk, be spaced appropriately and allow the pilot to have enough space to move freely
Rudder pedals provide resistance	15 lbf	The force the pilot needs to exert on the rudder pedals should not be more than 15lbf
Receive input signal	Analog, physical displacements and deflections are converted into digital signals.	Rudder pedal system inputs and joystick inputs will be converted to electrical signals that will be sent to the controller
Easy to transport	Each component should not exceed 35lb	Device can be carried easily from one facility to another

Send input signal	Input signal communicates with the simulation software	Input transducer reliably and accurately communicates with the program
Smooth transitions	Smooth bearings that allow pilots to adjust the desired throttle	The bearings should facilitate the translation of the throttle pedal making the pilot feel less resistance and allow the stick to be moved to the desired position faster
Duration of connection with Prepar3d	Connected and functioning for 1 hour without problem	The HOTAS and RPS should be able to run smoothly without issues for over an hour
Little to no latency	20 milliseconds of input delay	The pilots should be able to obtain real flight experience with the least amount of delay possible
Replicate a cockpit	Should be able to fit in an area of 6ft x 2ft x 2ft	This is the area of a standard cockpit
Position awareness	Return the joystick to the initial position	When no force is applied, the joystick should return to its

		original position in the 0-degree datum.
Realistic throttle travel	9 in.	The throttle travels back and forth in a 9-inch span
Rudder pedal displacement	18 in.	The displacement of the rudder pedals should not be more than 18 inches
Realistic joystick operation	6 degrees of deflection in all directions	The angular displacement of the joystick should be 6 degrees in all directions.
Realistic joystick operation	7.5lbf	No more than 7.5lbf required by the pilot to deflect the joystick
Safety	No-slip components	Components handle max expected displacement and deflection forces provided by user without the base slipping

Appendix D: Concept Generation

1. Single spring adjustment, rectangular prism slider, linear adjustment of foot pedal springs, individual microcontrollers to process signals and send to another main controller
2. Single spring adjustment, rectangular prism slider, linear adjustment of foot pedal springs, individual microcontrollers to process signal and send to computer over USB
3. Single spring adjustment, rectangular prism slider, linear adjustment of foot pedal springs, no microcontroller, sensors wired to separate controller
4. Single spring adjustment, rectangular prism slider, linear adjustment of foot pedal springs, no microcontroller, Bluetooth communicators
5. Single spring adjustment, rectangular prism slider, shorter springs for toe brakes to add braking resistance, individual microcontrollers to process signals and send to another main controller
6. Single spring adjustment, rectangular prism slider, hydraulic foot pedal tracks for dampening, individual microcontrollers to process signals and send to another main controller
7. Single spring adjustment, rectangular prism slider, rubber bands instead of current springs, individual microcontrollers to process signals and send to another main controller
8. Single spring adjustment, rectangular prism slider, magnets like Disney monorail, individual microcontrollers to process signals and send to another main controller
9. Single spring adjustment, double cylinder slider, linear adjustment of foot pedal springs, individual microcontrollers to process signals and send to another main controller
10. Single spring adjustment, Potentiometer to measure linear displacement, linear adjustment of foot pedal springs, individual microcontrollers to process signals and send to another main controller
11. Single spring adjustment, detents to “lock” into place, linear adjustment of foot pedal springs, individual microcontrollers to process signals and send to another main controller
12. Single spring adjustment, Liquid pool base with fins attached to bottom of throttle stick that can be twisted to affect resistance while being displaced. (Like using a paddle while canoeing), linear adjustment of foot pedal springs, individual microcontrollers to process signals and send to another main controller
13. Dual spring adjustment controlled by 2 switches, rectangular prism slider, linear adjustment of foot pedal springs, individual microcontrollers to process signals and send to another main controller
14. Ball socket linkage, rectangular prism slider, linear adjustment of foot pedal springs, individual microcontrollers to process signals and send to another main controller

15. Double swivel design, rectangular prism slider, linear adjustment of foot pedal springs, individual microcontrollers to process signals and send to another main controller
16. Dual spring adjustment by unscrewing base plate and switching out springs, rectangular prism slider, linear adjustment of foot pedal springs, individual microcontrollers to process signals and send to another main controller
17. Handle mold attached over a cylinder, rectangular prism slider, linear adjustment of foot pedal springs, individual microcontrollers to process signals and send to another main controller
18. Mold for handle makes up entire joystick, rectangular prism slider, linear adjustment of foot pedal springs, individual microcontrollers to process signals and send to another main controller
19. Dual spring adjustment controlled by 2 switches, Double cylinder slider, shorter springs for toe brakes to add braking resistance, Individual microcontrollers to process signal and send to computer over USB
20. Ball socket linkage, Potentiometer to measure linear displacement, Hydraulic foot pedal tracks for dampening, no microcontroller, sensors wired to separate controller
21. Double swivel design, Detents to "lock" into place, Rubber bands instead of current springs, Bluetooth communicators
22. Dual spring adjustment controlled by 2 switches, potentiometer to measure linear displacement, shorter springs for toe brakes to add braking resistance, individual microcontrollers to process signal and send to computer over USB
23. Dual spring adjustment controlled by 2 switches, potentiometer to measure linear displacement, shorter springs for toe brakes to add braking resistance, individual microcontrollers to process signal and send to computer over USB
24. Dual spring adjustment controlled by 2 switches, detents to "lock" into place, shorter springs for toe brakes to add braking resistance, individual microcontrollers to process signal and send to computer over USB
25. Dual spring adjustment controlled by 2 switches, Liquid pool base with fins attached to bottom of throttle stick that can be twisted to affect resistance while being displaced. (Like using a paddle while canoeing), shorter springs for toe brakes to add braking resistance, individual microcontrollers to process signal and send to computer over USB
26. Handle mold attached over a cylinder, double cylinder slider, shorter springs for toe brakes to add braking resistance, individual microcontrollers to process signal and send to computer over USB
27. Handle mold attached over a cylinder, potentiometer to measure linear displacement, hydraulic foot pedal tracks for dampening, no microcontroller, sensors wired to separate controller
28. Handle mold attached over a cylinder, detents to "lock" into place, rubber bands instead of current springs, Bluetooth communicators

29. Mold for handle makes up entire joystick, double cylinder slider, shorter springs for toe brakes to add braking resistance, individual microcontrollers to process signal and send to computer over USB
30. Mold for handle makes up entire joystick, potentiometer to measure linear displacement, hydraulic foot pedal tracks for dampening, no microcontroller, sensors wired to separate controller
31. Mold for handle makes up entire joystick, detents to “lock” into place, rubber bands instead of current springs, Bluetooth communicators
32. Ball socket linkage, double cylinder slider, shorter springs for toe brakes to add braking resistance, Individual microcontrollers to process signal and send to computer over USB
33. Ball socket linkage, detents to “lock” into place, rubber bands instead of current springs, Bluetooth communicators
34. Single spring adjustment, double cylinder slider, hydraulic foot pedal tracks for dampening, Bluetooth communicators
35. Dual spring adjustment controlled by 2 switches, potentiometer to measure linear displacement, rubber bands instead of current springs, individual microcontrollers to process signals and send to another main controller
36. Ball socket linkage, detents to “lock” into place, Magnets like Disney monorail, Individual microcontrollers to process signals and send to another main controller
37. Dual spring adjustment by unscrewing base plate and switching out springs, Detents to “lock” into place, hydraulic foot pedal tracks for dampening, individual microcontrollers to process signal and send to computer over USB
38. Handle mold attached over a cylinder, liquid pool base with fins attached to bottom of throttle stick that can be twisted to affect resistance while being displaced. (Like using a paddle while canoeing)
39. Single spring adjustment, double cylinder slider, hydraulic foot pedal tracks for dampening, no microcontroller, sensors wired to separate controller
40. Single spring adjustment, double cylinder slider, hydraulic foot pedal tracks for dampening, no microcontroller, individual microcontrollers to process signal and send to computer over USB
41. Single spring adjustment, double cylinder slider, hydraulic foot pedal tracks for dampening, no microcontroller, individual microcontrollers to process signals and send to another main controller
42. Dual spring adjustment controlled by 2 switches, potentiometer to measure linear displacement, rubber bands instead of current springs, individual microcontrollers to process signal and send to computer over USB
43. Dual spring adjustment controlled by 2 switches, potentiometer to measure linear displacement, rubber bands instead of current springs, no microcontroller, sensors wired to separate controller

44. Dual spring adjustment controlled by 2 switches, potentiometer to measure linear displacement, rubber bands instead of current springs, no microcontroller, Bluetooth communicators
45. Ball socket linkage, detents to "lock" into place, Magnets like Disney monorail, individual microcontrollers to process signal and send to computer over USB
46. Ball socket linkage, detents to "lock" into place, Magnets like Disney monorail, no microcontroller, sensors wired to separate controller
47. Ball socket linkage, detents to "lock" into place, Magnets like Disney monorail, no microcontroller, Bluetooth communicators
48. Dual spring adjustment by unscrewing base plate and switching out springs, Detents to "lock" into place, hydraulic foot pedal tracks for dampening, individual microcontrollers to process signals and send to another main controller
49. Dual spring adjustment by unscrewing base plate and switching out springs, Detents to "lock" into place, hydraulic foot pedal tracks for dampening, no microcontroller, sensors wired to separate controller
50. Dual spring adjustment by unscrewing base plate and switching out springs, Detents to "lock" into place, hydraulic foot pedal tracks for dampening, no microcontroller, Bluetooth communicators
51. Potentiometers used to sense stick axes positions
52. Hall effect sensors used to sense positions
53. Buttons wired to Individual GPIO ports
54. Buttons combined and wired with resistors to analog ports with thresholds for processing
55. Rubber stubs (Think bottom of MacBook)
56. Glue a bunch of mouse pads to the bottom of base
57. Combined rubber and metal pokies (Think the leg spokes on a kick drum of drum set)
58. Suction cup like you would have for shower accessories
59. Design parts for force fits
60. Utilize rubber bearings between pins to prevent slip
61. Make bases for HOTAS completely out of rubber to increase durability and lower cost
62. Teflon used as burner material in bearings for throttle
63. Have bases for HOTAS system be as small as possible and have wire management attached to the side of the bases
64. Attach hook and loop fastener pads to the base of all three components and have the other side of the fastener
65. Hire a penguin to pluck keys on a keyboard when you want to move the model in Prepar3d (Biomimicry baby!)
66. Disassemble a video game controller to modify the thumb stick component for the joystick.
67. Use an IR sensor at the base of the throttle to sense distance; this could reduce risk of maintenance under misuse of controls

68. Purchase/outsource pre-made gimbals for the stick to skip that design phase
69. Buy premade HOTAS from x-box flight simulator and obtain model
70. Use rubber to protect the sensors from damage
71. Utilize gaming setup for reference of the pilot cockpit
72. Design a basic stick figure and use a silicon mold that adapts to pilots' hands
73. Use 144 Hz monitor to help reduce lag perceived by pilot
74. Buy premade HOTAS base
75. Utilize MGN15 as new base design for the Throttle to allow smooth transition
76. Use opposing cables to help the traction of the RPS to be smoother allowing us to save parts
77. RPS pedals/throttle are constrained to a linear motion by housing it within a rectangular “box” and slides on numerous small bearings placed on the inside bottom surface of the box between the surface of the box and the base of the component.
78. Utilize raspberry pi’s to allow communication between the components in the system
79. Have mini bread boards inside HOTAS and throttle to ensure neatness in the wiring
80. Allow the HOTAS to have some yaw in the joystick to ensure smoother movement
81. Utilize power sensor to allow us to measure the amount of throttle the plane is producing
82. Use absolute encoders to record the original position and make sure the joystick returns to its original position every time the program is run
83. Utilize potentiometers to measure how much force the pilot is imputing in the rudder pedals
84. Simulate the trajectory of the joystick in Simulink to track the distances it travels and make a more fitted base
85. Use electromagnets to move the control surfaces back to original position when activated
86. Order the components used in F-35 to implement dynamic simulator systems.
87. Use bicycle pedals to replicate the movement a person makes to measure the force a pilot would exert and be able to build a pedal system that would withstand it
88. Implement infrared sensors in a similar fashion to Wii remotes to locate the position of the control surfaces.
89. Incorporate a spring-loaded *triangular* detent to help secure throttle
90. Incorporate a spring-loaded *cylindrical* detent to help secure throttle
91. Place areas of increased friction to act as detents without affecting geometry of track
92. Implement four-bar crank slider mechanism for linear movement of control surfaces
93. Use a cam-follower to allow jaw at the throttle stick
94. Connect systems through ROS to allow components to run at the same frequency and be allowed to stop at the same time
95. Use Watt’s triple rocker linkage for straight line motion.
96. Install kill switch in the throttle to immediately stop the simulation in case anything turns out wrong

97. Linear movement achieved through “rolling pin” design and the control surfaces mount to rolling pin by the sides of the pin
98. VR glasses to ensure the pilot has a more inflight feel
99. Make the rudder pedals in two different pedals that are allowed to be disassembled easily
100. Make the throttle stick with silicon mold to allow malleability into the pilot's hand

Appendix E: APA Headings (delete)

Heading 1 is Centered, Boldface, Uppercase and Lowercase Heading

Heading 2 is Flush Left, Boldface, Uppercase and Lowercase Heading

Heading 3 is indented, boldface lowercase paragraph heading ending with a period.

Heading 4 is indented, boldface, italicized, lowercase paragraph heading ending with a period.

Heading 5 is indented, italicized, lowercase paragraph heading ending with a period.

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Appendix B Figures and Tables (delete)

The text above the cation always introduces the reference material such as a figure or table. You should never show reference material then present the discussion. You can split the discussion around the reference material, but you should always introduce the reference material in your text first then show the information. If you look at the Figure 5 below the caption has a period after the figure number and is left justified whereas the figure itself is centered.

Figure 5. Flush left, normal font settings, sentence case, and ends with a period.

In addition, table captions are placed above the table and have a return after the table number. The second line of the caption provided the description. Note, there is a difference between a return and enter. A return is accomplished with the shortcut key shift + enter. Last, unlike the caption for a figure, a table caption does not end with a period, nor is there a period after the table number.

Table 16

The Word Table and the Table Number are Normal Font and Flush Left. The Caption is Flush Left, Italicized, Uppercase and Lowercase

Level of heading	Format
1	**Centered, Boldface, Uppercase and Lowercase Heading**
2	**Flush Left, Boldface, Uppercase and Lowercase**
3	***Indented, boldface lowercase paragraph heading ending with a period***
4	***Indented, boldface, italicized, lowercase paragraph heading ending with a period.***
5	*Indented, italicized, lowercase paragraph heading ending with a period.*

References

There are no sources in the current document.