Module 5: Final Report 2018-2019

Sikorsky STEM Challenge

Joel Barlow High School

Team Members:

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Advisor: Dr. Katherine Nuzzo, Ph.D.

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Executive Summary

This year's Sikorsky STEM Challenge objective was to design and create a cockpit of the future for a next-generation Sx-18 single-pilot helicopter, using the Arduino kit provided by Sikorsky, and any materials deemed appropriate. The cockpit design must be able to control the roll, pitch, and yaw of the helicopter while adhering to Federal Aviation Administration (FAA) regulations and human factors criteria.

The Joel Barlow Sikorsky STEM team's design is a modified side stick control mounted to a rotational elbow joint. The side stick has a displacement joystick to control the helicopter cyclic, with two digital buttons on the front and the top to control collective pitch. At the elbow is a 60-degree rotational joint that controls the yaw.

This cockpit system improves on traditional designs by centralizing all of the Sx-18's controls to one of the pilot's arms. In doing so, the pilot has a free hand to operate other controls such as weapons, radios, or other in-flight necessities without flight interference. By centralizing all flight controls on one hand, the design's range of motion is reduced. This is problematic during turbulence and when fine adjustments are necessary; however, mitigations have been introduced to reduce the impact of these issues, and solidify the design's improvements over traditional flight control systems.

Statement of Work

In order to baseline our design with existing control systems, the creation process began with fundamental research of cockpit designs in both fixed-wing and rotary wing aircraft. From there, the team brainstormed a wide variety of theoretical helicopter control designs, selecting three from a list of twenty as the best conceptual systems. The development of a trade study, whose weighting was determined using a pairwise comparison, indicated the best of the three proposed designs. A physical full-sized mockup was created around the conceptual design. Risks to the design, ability to meet modern FAA regulations, and appeal to human factor criteria were required in the decision-making process. In the final stages of this challenge, the team made final revisions to meet aircraft standards, including FAA regulations and human factors criteria. Qualification tests checked the aircraft design's real-world practicality and reliability, with a finalized, fully functional physical model being integrated in a flight simulator through the use of an Arduino microcontroller.

The team's work has been centered a unique cockpit design for the Sx-18 helicopter that's capable of controlling the roll, pitch, and yaw of the aircraft. In order to confirm the validity of the design, a physical mockup was required to be fully integrated with Arduino and fly a helicopter in the Prepar3d flight simulator.

Background Research

In the first module, the team researched how current helicopter cockpit controls and pilot interfaces work. The team found that the vertical motion is controlled by the collective . The collective is a lever found on the left-hand side of the pilot which works to maintain rotor RPM while altering amounts of lift. When the lever is pulled upward, the aircraft's thrust from the rotor increases; when lowered, this thrust decreases. To control the yaw, helicopters have pedals located at the pilot's feet; the left pedal results in counterclockwise rotation, and the right pedal clockwise around the z-axis. In modern helicopters, a displacement joystick is used to control the cyclic and collective control; the helicopter moves in the same direction that the joystick is pointed toward. If pushed to the left, for example, the swashplate will be rotated so the helicopter's moves left.

To ensure our control system is safe and meets regulations, the team researched FAA regulations using the Code of Federal Regulations (CFR). [CFR 23.1301] mandates controls to be properly labeled as to their function and to be manufactured in a design that fits their function. Additionally, [14 CFR 23.777(b)] requires that controls be located so the pilot can operate them unrestrictedly without interference from clothing, other controls, or other objects in the aircraft. In addition, the team extensively researched FAA regulations in the CFR related to the learning of new systems. Regulations [CFR 5.1.1.23] and [CFR 5.1.1.24] mandate that a cockpit control system be easy to understand, use, and learn; these regulations played a crucial role in the design process by influencing control placement and direction of movement. Additional research into regulations such as [CFR 5.4.1.5.10.4], which describes a necessity for positive feedback for button controls, allowed us recognize the importance of sensory indications for controls such as the collective pitch in our design.

Team Organization

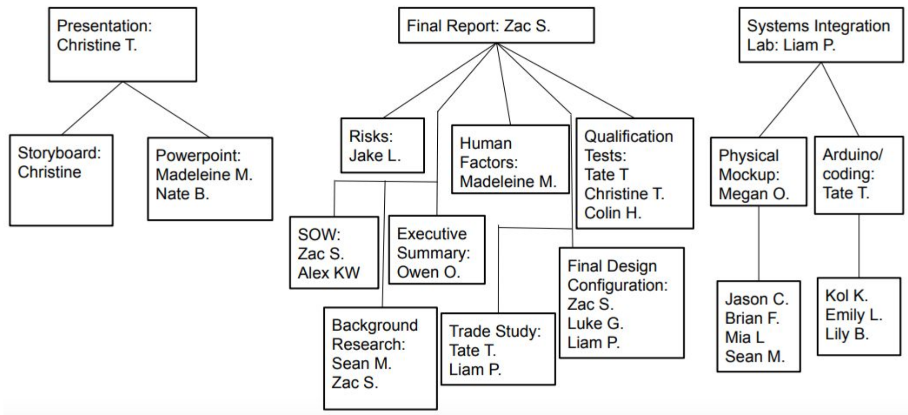


Figure 1: Team Organization Chart

The team had 3 main sub-teams, with a group leader for each as shown in Fig. 1. The group leaders delegated roles in their areas to specific team members based on their previous work throughout the challenge. Some leaders, such as Liam P., divided Arduino into 2 subgroups lead by Tate T. and Megan O., while other leaders such as Zac S. assigned groups of people to each section in the Final Report rather than having subgroups. Some team members were placed into several groups depending on their familiarity with the given topics and their experience in prior modules.

Project Schedule

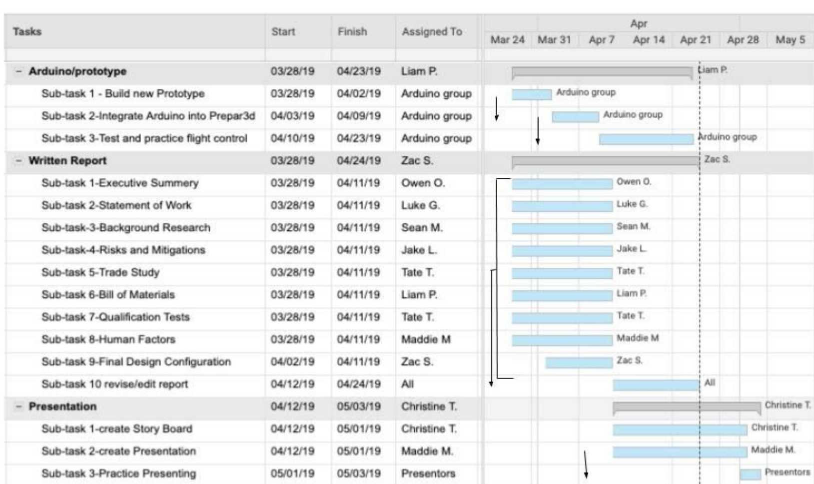
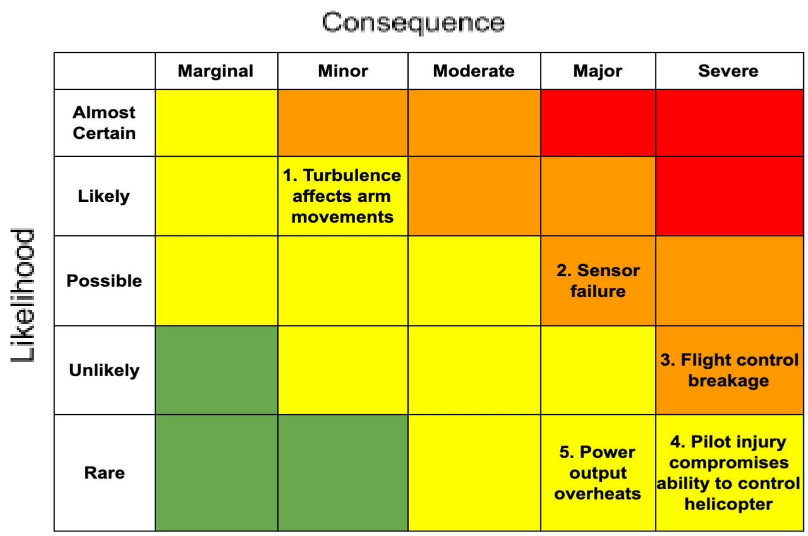


Figure 2: Segmented, Detailed Project Schedule (full schedule in appendix Fig.10)

The team planned around spring break, sports, and standardized testing, all of which decreased attendance. The number of meetings was increased to 2-3 per week, allowing members to attend at least one of the days. This increased productivity and ensured deadlines were met.

A 1-week free period was added to allow for final document revisions and to ensure the document was submitted on time. The Gantt chart has been edited to reflect these changes (Fig. 2).



Risks and Mitigations

Figure 3: Risk Cube

The team identified 5 separate risks that have varying levels of severity and likelihood shown in the risk cube in Fig. 3, with our design properly mitigating all of them. The first risk identified relates to airborne turbulence resulting in unwanted movements to the helicopter flight controls, thereby preventing safe and effective operation. Although a likely risk, the cockpit design mitigates the effect of turbulence through a dead zone on the modified sidestick, along with an adjustable sensitivity dial to dampen the effect of inadvertent flight control movements when necessary. The second risk relates to a failure in one of the sensors that control an axis of movement. As mitigation, redundant sensors with parallel circuits will be used in our design as a backup in case of an individual sensor failure. The third risk identified was physical controls breaking mid-flight. If a crucial component of the design breaks, although unlikely, there could be severe effects on flight capability. The armrest will be made of durable, traditional flight-grade metal materials to reduce the likelihood of breakage during flight. While a prior mitigation included the addition of an auto-hover button, the impracticality of implementing this feature changed the team's perspective. In accordance with the FAA regulation 23.777(b) from the CFR, there will also be no protruding parts, further preventing such a scenario. The fourth risk deals with a pilot injury directly before or during flight. Since the design is one-handed by nature, and is capable of switching sides with the quick release system, the pilot can still operate the aircraft using the opposite arm. The fifth and final risk deals with the power output overheating the system, thereby creating issues in the cockpit environment or controls. To mitigate potential for overheating, proper airflow will be ensured around all sensors, and cooling fans will be placed near high-current wiring.

Trade Study

Weighting was determined using a pairwise comparison (Fig. 9 in appendix), in which each criterion was compared to every other criterion. The team discussed and came to an agreement on which criteria was more important than others. Criteria were either given one point in the cross comparison if a section was deemed more important than another, or the point was split if they were deemed equally important. The weighting factor for each criterion was determined by dividing the point total for each criteria by the total points overall, as shown below.

Criteria	Weighting		Design 1	Design 2	Design 3
Safety	0.29		2	4	2
Manufacturability	0.14		4	3	3
Cost	0.07		4	3	2.5

Human Factors	0.24		4	4	3
Durability	0.19		2.5	4	2.5
Innovation	0.02		1.5	3	4
Precision	0.05		1.5	3.5	3
	Total:		2.96	3.75	2.60

Figure 4: Applied Trade Study Matrix

Final Design Criteria Decisions

Evaluating each solution according to the criteria in the trade study matrix(Fig. 11 in the appendix) and the weighting of each criterion, determined using a pairwise comparison shown in Fig. 9, showed that Design 2 is the best conceptual design (Fig. 4). The design scored a 4 in safety because there are no unmitigated moderate or severe safety concerns based on those identified in Module 2. For example, Design 2 can be operated by either hand through the use of a quick release system on the armrest connection. Even if a pilot's limb is injured before the flight, they can still operate the aircraft assuming they have time to make changes to the cockpit. Aside from such an extreme scenario, a one-handed system allows the pilot to have a hand free while still not risking unwanted movements from turbulence.

This design also scored a 3 in manufacturability. There are relatively few custom components, aside from the pivot joint of the armrest. All other parts, including the displacement joystick and corresponding triggers, can be purchased from stock. The rotational armrest will require some new components, including a system for telescoping so pilots of various sizes can fly the aircraft, but will have a general foundation in preexisting components. Similar reasoning was used to give Design 2 a score of 3 in cost. With relatively few custom components and other items that are already standard in aircraft being duplicated (i.e. triggers, buttons, joysticks), costs should only be slightly more expensive than traditional designs. Design 2 also scored a 4 in human factors. The design, with a telescoping armrest and an ability to be attached on either side through a quick release, compensated for the 95th percentile man and 5th percentile woman in terms of strength and size, as well as dexterity. All buttons and triggers will be concave and have proper necessary frictional forces for safe movements along a full range of motion. All major human factor requirements are fulfilled by the design.

Design 2 also received a 4 in durability. Because the design has comparatively fewer moving parts, there are relatively few points that risk breakage compared to traditional designs. In addition, all sensors have been designed with room for dual redundancies, and similar joysticks are often used in traditional aircraft. Long term use poses no clear risks to flight controls. All mechanical controls are relatively simple and don’t have particular areas of high pressure that could risk damage to flight mechanics. All electronics are similar to those used in standard aircraft, with the exception of slight modifications and placement changes, and should thereby match modern aircraft electronics’ durability.

In terms of innovation, the design loosely reflects traditional side-stick controls but also has many newly added properties for easier use. In other words, Design 2 has the foundation of modern cockpit designs but is sufficiently different in other regards to earn a 3 in innovation. Finally, Design 2 was given a 3.5 in precision. With triggers responsible for aircraft control, there are minor concerns about a limited range of motion, but these concerns are not major enough to merit a full points deduction for this criteria, and can likely be mitigated with wider adjustments to the joystick’s top controls. Design 2 had an average rating of 3.75 within the given criteria, which is substantially higher than the other two designs.

Bill of Material

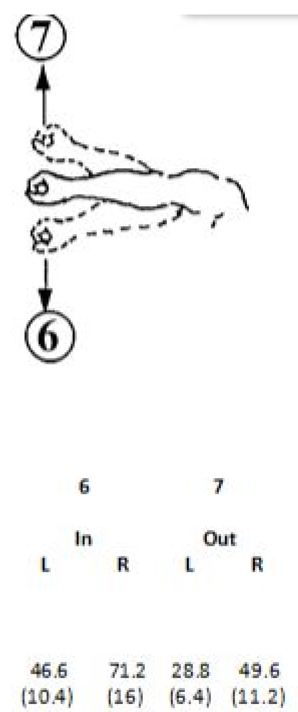
Component	*Estimated Price (USD)*
Arduino Uno	$30.00
2-Axis Joystick	$5.00
Small Digital Button (x2)	$5.00
Rotational Potentiometer	$3.00
Industrial Strength Hoop & Loop Tape (Velcro)	$3.00
Custom Double Pivoting Armrest	$20.00
Wood (¼”)	$10.00
Bolts and Nuts (⅛”)	$2.00
3D Printed Joystick, button extensions, case	$8.00
	Total Price: $86.00

Qualification Testing

Test	Requirements of Test	Testing Apparatus/Tools
Static Load	A load of 0.5 times the weight of a 95th percentile male's arm, or 25 Newtons(N), will be placed on the control system. 10N of weight will be added every 5 minutes until 1.5 times the arm weight of 75N is reached, which will be maintained for 10 hours.	Various sized weights
Shock Test	Impulses at a starting value of 75N, lasting 0.5 seconds, will be delivered to the control system and incremented by 50N until the controls break to test the design's ability to handle large forces.	Various sized weights
Humidity	The design will be placed in a container with a humidity of 85% and 85 degrees Celsius for 96 hours. This will test the design's ability to operate to extreme humidity.	Hygrometer in a closed container
Arduino Reliability	The design will fly 1000 simulated take-offs and landings. This will test the electronics' reliability after extended use and multiple flight cycles.	Prepar3d flight simulator with Arduino control system
Vibration	The design will be placed on a vibration plate, at maximum intensity, for five cycles of one hour at a time. This will test the design's ability to resist damage during turbulence.	Vibration Plate

Human Factors Evaluation

The armrest design effectively allows for a wide range of pilots to comfortably and easily operate the aircraft. To accommodate left and right-handed pilots with different sized arms, the design is adjustable with a telescoping system to change the length and quick mounting system to switch between left and right sides (CFR 5.12.4). Because pedals are not used, the required space for actuation of the pedals is not required. Human Factor (CFR5.4.1.1.3.9) regarding the accommodation for handwear is followed by having pronounced buttons with diameters of approximately 15mm. This also accounts for the difference in hand size among pilots. In line with human factor (CFR 5.4.1.1.6.1), the pilot will need to overcome some friction when controlling yaw. The friction prevents accidental and turbulence related movements, but is not strong enough to exhaust the pilot during flight.



The amount of frictional force when moving the armrest toward one's body will be 25N and the frictional force for moving away from one's body will be 20 N to account for the 5th percentile female and 95th percentile male in accordance with human factor (CFR 5.4.1.5.16.1) and the table shown in Fig. 5. In accordance with human factor (CFR 5.4.1.1.6.1) controls shall be designed and located so that they are not susceptible to being moved accidentally or inadvertently, particularly critical controls where such operation might cause equipment damage, personal injury, or system performance degradation. The pilot needs to be able to comfortably grip the joystick in a resting position as described in human factor (CFR 5.4.12.1). This is accounted for by allowing the pilot to adjust the length of their armrest before taking off— a key feature of our design.

Figure 5: Arm Strength(N)

Final Design Solution

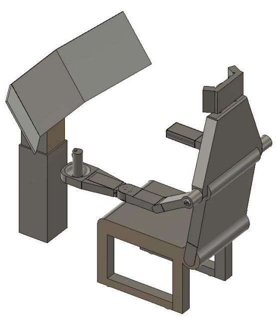


Figure 6: CAD of Completed Design

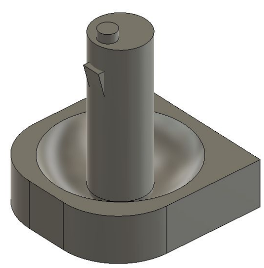


Figure 7: Modified Side Stick

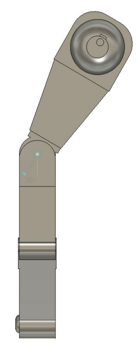


Figure 8: Rotational Elbow Joint

The final design uses a rotating armrest and a modified side stick to control a helicopter with one hand. Fig. 6 shows the completed assembly of the design. To allow for use by either hand, the armrest uses a quick release system that would allow a pilot to switch between operation on left and right hands. The front half of the armrest swings left and right with a total range of motion of 60 degrees. Swinging the armrest right, as depicted in Fig. 8, rotates the helicopter clockwise. A left swing rotates the helicopter counterclockwise. For both, larger movements command an increased rate of rotation, making the helicopter turn faster.

The armrest uses industrial-grade loop and hook tape (i.e. Velcro) to secure the pilots arm to the armrest, allowing him/her to control yaw. The armrest is operated on a telescoping system that allows for use by the 95th percentile man and 5th percentile woman in regards to size. At the end of the armrest is a joystick, as shown in Fig. 7. This joystick component controls the movement of the cyclic; left and right movements of the joystick change the roll of the helicopter in the respective direction, while forward and backward movements of the joystick affect the aircraft pitch. On the front and top of the joystick are digital buttons. Both of these components result in changes in the collective pitch. The front button and top button increases and decreases the collective of the helicopter respectively. In addition, the nature of this design, with separate armrest and joystick components, allows it to be modular and thereby customized. The armrest length, seat distance from flight controls, and trigger range of motion will all be adjustable for comfort. The side-stick's form is also shaped to improve ergonomics and meet industry standards for accessibility. An added sensitivity dial and joystick dead zone also allow for varied control precision which is especially useful during turbulence.

In our mock-up, the Arduino acts as the control interface unit. The Arduino receives six inputs from our design. Four inputs are analog: two from potentiometers, which control the yaw of the aircraft and control sensitivity, and two from a joystick for roll and pitch functionality. The Arduino also receives two digital inputs from buttons, which signal for an increase or decrease in throttle. All signals from the Arduino are independently exported as controller inputs using the UnoJoy Windows Game Controller Arduino converter. The values processed and exported by Arduino are then assigned to control surfaces in the flight simulator, translating to helicopter movements.

This design is easy to learn and operate. Whereas traditional designs require the use of pedals and both hands, this design condenses controls so only one arm is used. With a free hand, the pilot has easier access to flight instruments at all times, especially in the case of emergencies. A free hand makes standard flight tasks, like communicating through radio and adjusting environmental conditions, significantly easier. This cockpit design is perfect for the advanced Sx-18 helicopter.

References

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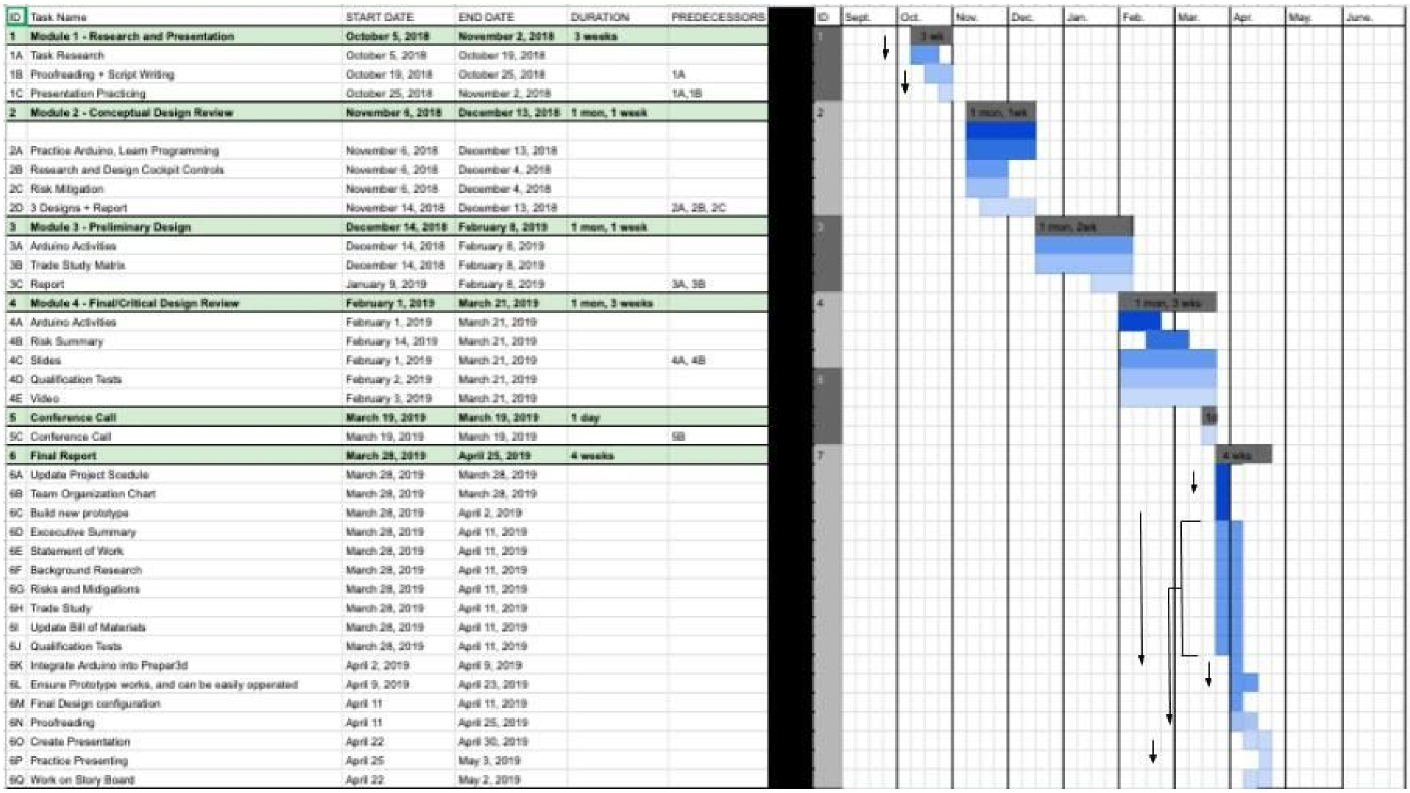
Appendix

Trade Study Weighting

Pairwise Comparison											
	S	M	C	HF	D	I	P		Criteria	Points	Weighting
Safety (S)		S	S	S	S	S	S		Safety	6	28.6%
Manufacturability (M)			M	HF	D	M	M		Manufacturability	3	14.3%
Cost (C)				HF	D	C	P & C		Cost	1.5	7.1%
Human Factors (HF)					HF	HF	HF		Human Factors	5	23.8%
Durability (D)						D	D		Durability	4	19.0%
Innovative (I)							P & I		Innovative	0.5	2.4%
Precision (P)									Precision	1	4.8%
									Sum	21	100.0%

Figure 9: Pairwise Comparison to determine weighting



ID	Task Name	START DATE	END DATE	DURATION	PREDECESSORS
1	**Module 1 - Research and Presentation**	**October 5, 2018**	**November 2, 2018**	**3 weeks**	
1A	Task Research	October 5, 2018	October 19, 2018		
1B	Proofreading + Script Writing	October 19, 2018	October 25, 2018		1A
1C	Presentation Practicing	October 25, 2018	November 2, 2018		1A,1B
2	**Module 2 - Conceptual Design Review**	**November 6, 2018**	**December 13, 2018**	**1 mon, 1 week**	
2A	Practice Arduino, Learn Programming	November 6, 2018	December 13, 2018		
2B	Research and Design Cockpit Controls	November 6, 2018	December 4, 2018		
2C	Risk Mitigation	November 6, 2018	December 4, 2018		
2D	3 Designs + Report	November 14, 2018	December 13, 2018		2A, 2B, 2C
3	**Module 3 - Preliminary Design**	**December 14, 2018**	**February 8, 2019**	**1 mon, 1 week**	
3A	Arduino Activities	December 14, 2018	February 8, 2019		
3B	Trade Study Matrix	December 14, 2018	February 8, 2019		
3C	Report	January 9, 2019	February 8, 2019		3A, 3B
4	**Module 4 - Final/Critical Design Review**	**February 1, 2019**	**March 21, 2019**	**1 mon, 3 weeks**	
4A	Arduino Activities	February 1, 2019	March 21, 2019		
4B	Risk Summary	February 14, 2019	March 21, 2019		
4C	Slides	February 1, 2019	March 21, 2019		4A, 4B
4D	Qualification Tests	February 2, 2019	March 21, 2019		
4E	Video	February 3, 2019	March 21, 2019		
5	**Conference Call**	**March 19, 2019**	**March 19, 2019**	**1 day**	
5C	Conference Call	March 19, 2019	March 19, 2019		5B
6	**Final Report**	**March 28, 2019**	**April 25, 2019**	**4 weeks**	
6A	Update Project Scedule	March 28, 2019	March 28, 2019		
6B	Team Organization Chart	March 28, 2019	March 28, 2019		
6C	Build new prototype	March 28, 2019	April 2, 2019		
6D	Excecutive Summary	March 28, 2019	April 11, 2019		
6E	Statement of Work	March 28, 2019	April 11, 2019		
6F	Background Research	March 28, 2019	April 11, 2019		
6G	Risks and Midigations	March 28, 2019	April 11, 2019		
6H	Trade Study	March 28, 2019	April 11, 2019		
6I	Update Bill of Materials	March 28, 2019	April 11, 2019		
6J	Qualification Tests	March 28, 2019	April 11, 2019		
6K	Integrate Arduino into Prepar3d	April 2, 2019	April 9, 2019		
6L	Ensure Prototype works, and can be easily opperated	April 9, 2019	April 23, 2019		
6M	Final Design configuration	April 11	April 11, 2019		
6N	Proofreading	April 11	April 25, 2019		
6O	Create Presentation	April 22	April 30, 2019		
6P	Practice Presenting	April 25	May 3, 2019		
6Q	Work on Story Board	April 22	May 2, 2019		

Figure 10: Full Challenge Gantt Chart

Criteria	Safety	Manufacturability	Cost	Human Factors	Durability	Innovation	Precision
Points							
4	Design has no unmitigated safety concerns	All parts can be easily manufactured with little effort and time	Design is much less expensive than standard modern designs	Easily controlled by 95th percentile men and 5th percentile women in regards to strength and size	Control system withstands rigorous and prolonged use	Design is effective and extremely unique relative to standard modern designs	Design allows for minute adjustments of controls
3	Design has one or more unmitigated minor safety concerns	Most parts can be easily manufactured	Design is similar in cost to standard modern designs	Can be controlled with little difficulty by 95th percentile men and 5th percentile women in regards to strength and size	Control system is slightly susceptible to damage with rigorous and prolonged use	Design is effective and has some differences from standard modern designs	Design allows for relatively minor adjustments of controls
2	Design has one or more unmitigated moderate safety concerns	Parts take substantial time and effort, to manufacture	Design is more expensive than standard modern designs	Can be controlled with difficulty by 95th percentile men and 5th percentile women with regards to strength and size	Control system is noticeably susceptible to moderate use	Design is effective but resembles designs currently used	Design allows for general adjustments in the use of controls, with some restrictions
1	Design has one or more unmitigated major safety concerns	Manufacturing parts will be extremely complex and time consuming	Design is too expensive to get proper funding	Design does not allow for the 95th percentile man and the 5th percentile woman to control in regards to strength and size	Control system breaks under moderate to light use	Design is effective but is very similar to current designs	Design does not allow for precise adjustments to control the aircraft

Figure 11: Trade Study Criteria