Critical Design Review:
Helicopter Payload Stabilization Project

Team Jury
Giacomo Fratus, Sidharth Subbarao, Hieu Nguyen
Seong Hong, Jeremy Wong, Jake Smith, Chiraag
Hebbar
May 10, 2021

Table of Contents

Introduction and Overview (Sidharth, Chiraag)

In this report, we present the progress of our MAE 162E/ECE183E senior design capstone project in the form of a Critical Design Review (CDR). Our goal over the winter and spring quarters was to find and solve a problem of importance using the engineering frameworks given to us by the professors. We aim to design a helicopter evacuation stabilization device that prevents the spin of a litter during hoist operations due to external winds and downwash.

In the following sections, we will first explicate the problem and determine the requirements necessary to solve it. This will make use of various design and analysis methods to determine our primary objectives and restrictions. From this, we will present design specifications for the mechanical, electrical, and controls subsystems. We will then compile these into an integrated system design. Finally, we will present our progress and plans for analysis that validate the effectiveness of our design in satisfying its capabilities. We will also use this CDR to update and refine our scope in comparison to our previous Preliminary Design review and leading up to the Final Design Review (FDR).

Problem Statement (Sidharth)

Explication of Problem

A common occurrence during helicopter rescue missions are helicopter hoisting operations (HHOs). During a HHO, a stationary helicopter at a fixed elevation is positioned directly above the load, which is oftentimes a person in a stretcher. The load is connected to the helicopter through a cable, which is then used to hoist up the load so that it can be stored in the helicopter. During HHOs, downwash, which is defined as the change in direction of air by the aerodynamic action of the helicopter rotor blades, can cause the load to spin out of control[1]. This spinning has the potential to damage the helicopter, hoisting cable, and load itself, which might result in monetary damages and loss of life. Team Jury's proposed solution to this problem would be to build a stabilization device that can prevent spin when a stationary helicopter is hoisting up a load, specifically a stretcher. Below is a picture of the downwash caused by a helicopter during a HHO:

[1] https://en.wikipedia.org/wiki/Downwash


Downwash caused by helicopter during hoisting operation[2]

Problem Positioning and Justification:

The context regarding helicopter hoisting operations (HHOs) is as follows. HHOs occur in rescue scenarios where patients need to be quickly transported to hospitals in order to receive first aid. Scenarios that utilize HHOs are where patients suffer a car accident or critical work related injury, and as a result, would need to be transported to a hospital within 15 minutes in order to save their lives. HHOs can also occur when people who are trapped in remote wilderness locations need to be rescued. Examples of this include having to rescue people on a stranded ship, or having to rescue injured hikers on the side of a mountain[3]. During HHOs involving rescuing people, it is imperative that the person being hoisted does not spin due to downwash. Excessive spin of the load during a HHO can cause nausea, which can lead to drowning if the patient is strapped to a stretcher and cannot control their airways. Furthermore, spin of the load during a HHO can result in a severed hoisting cable, ejection of the patient from the stretcher, or collision of the patient with an external object, all of which are life threatening[4]. Spin of the load during a HHO can cause damage to the load, cable, and helicopter itself, which is why it is imperative to stop load spin during HHOs.

The design and computation aspects of the solution to the described problem are as follows. The solution to this problem requires the design of a device that is capable of exerting a counter torque on the load, or stretcher, in order to prevent it from spinning. The device we chose was ducted fans. The design aspect of this problem would focus on deciding the type, placement, and other electrical and mechanical structures needed to make the ducted fan counter-torque device work as specified. The computational aspects of the problem would include deriving an algorithm to control the selected actuators in order to reduce spin of the load, or stretcher. We decided to use a PID control algorithm for this project. This algorithm would then be tested and refined using analytical and physics based simulations.

The solvability of the problem is described as follows. The scope of the problem is limited to designing a device with an algorithm that is capable of controlling one degree of freedom (spin), on a defined load (stretcher), attached to a stationary helicopter with variable wind conditions. By placing these limitations on the problem, the problem should be solvable within the remaining time we have left.

---

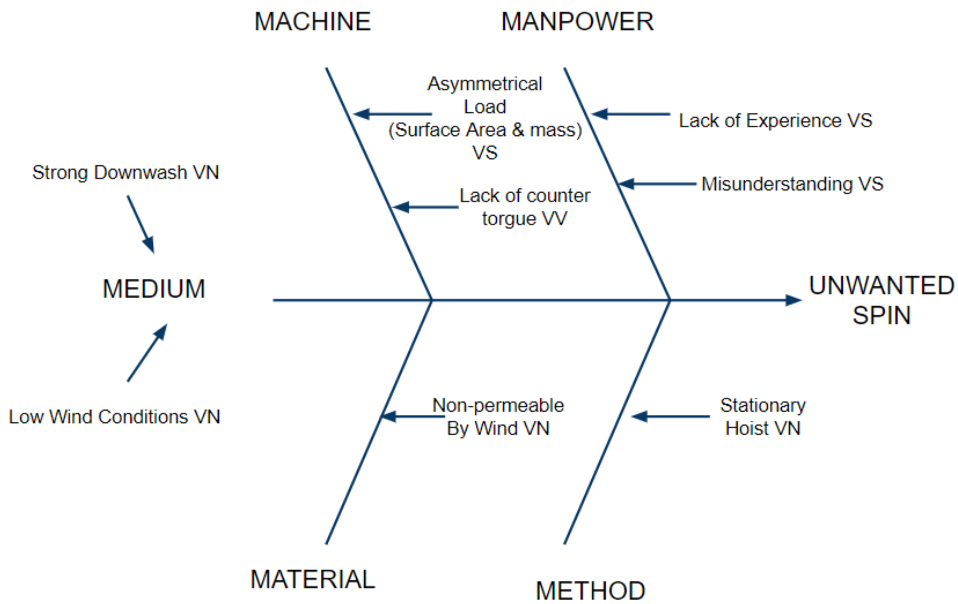
[2] U.S. Navy photo by Photographer's Mate Airman Sarah E. Ard

[3] https://link.springer.com/chapter/10.1007%2F978-3-642-69262-8_80

[4] https://www.airmedandrescue.com/latest/long-read/spinning-avoidance

Root Cause Analysis:

Below is a Fishbone Diagram detailing the root cause of the problem, that being unwanted spin of the load during helicopter hoisting operations (HHOs):



The physical reasons for spin are the downwash caused by the helicopter in low wind conditions. The problem is worsened when the load is surrounded by non-permeable material, which adds to the surface area that wind can act on. On the human side, lack of experience and misunderstanding of how to properly mount the load can cause spin of the load. Therefore, the solution to this problem should be a machine that is able to deal with an asymmetrical load and exerting counter torque on the load in order to prevent spin.

Define Resources:

______Parties that have experienced the problem of unwanted spin during helicopter hoisting operations (HHOs) involve helicopter pilots and rescue workers. Rescue workers include winchmen who are manually deployed in order to prevent spin on the helicopter load, as well as other staff who are responsible for placing the patient in a stretcher and mounting it to the helicopter hoisting cable. Furthermore, the most affected party in this situation is the patient itself, whose safety is predicated on the stretcher not spinning during the HHO.

Examining the literature regarding this problem shows that the most common way to solve the issue of spinning load during HHO is through non-technical solutions. The United States Department of Transportation Federal Aviation Administration released a Safety Alert for Operators, specifying techniques to reduce spin of load during HHO. Furthermore, the Air Med and Rescue magazine aimed at helicopter rescue operators go over specific techniques for preventing spin of load during HHO. The links to the following two sources are posted below:

https://www.faa.gov/other_visit/aviation_industry/airline_operators/airline_safety/safo/all_safos/media/2013/safo13010.pdf
https://www.airmedandrescue.com/latest/long-read/spinning-avoidance

Recently, a private company Vita Inclinata has come up with automated solutions to preventing load spin during HHOs. Vita Inclinata has developed devices that reduce swing,

sway, and vertical pitch of the load during HHOs. Below is a link to the company website, which contains details regarding their various products:
https://vitatech.co/products/

Define Strategies and Methods:

The problem of load spin during helicopter hoisting operations (HHOs) has been addressed in the Air and Med Rescue magazine as well as the private company Vita Inclinata Technologies. The Air and Med Rescue magazine explains to helicopter operators on things that they can personally do to reduce spin on loads during HHOs. Vita Inclinata technologies is a private company which has devised technical solutions to reduce spin and other unwanted motion during HHOs.

The Air and Med Rescue magazine covers various non-technical solutions regarding preventing spin of load during HHOs. One such technique is to manually deploy a winchman to supervise the hoisting operation and manually reduce spin. Another technique specified by the magazine is to travel in the forward direction at a speed of 10 to 15 knots[5]. Travelling at this speed would eliminate downwash, causing the load to stop spinning. The other techniques specified by the Air and Med Rescue magazine involve altering the load so that the center of mass is in line with the hoisting cable, altering the stretcher so that there is less surface area, or hoisting the load in a stretcher with vertical rather than horizontal orientation[6]. While these non-technical solutions are effective in reducing spin in HHO operations, not all of these solutions can be implemented during rescue operations due to external circumstances. In situations where the helicopter must be stationary, where no winchman is available, where the patient needs to be hoisted horizontally, and where no netted stretcher is available, it will be difficult to utilize the aforementioned non-technical solutions to prevent spin due to downwash.

The private company Vita Inclinata has come up with two relevant technical solutions that reduce unnecessary motion of the load during HHO operations. The first solution is the LSS-HR hoist rescue device. This device is autonomous, wirelessly operable, and controls 3 degrees of freedom, being spin, sway, and other oscillatory motion. The LSS-HR hoist rescue device is meant to be easily attachable to any hoisting cable, not stretcher. The LSS-HR hoist rescue device is capable of handling loads up to 750 lbs, controls at a rate of 1.5 periods per swing, and has a control range of around 1000 feet[7]. Below is a picture of the LSS-HR Hoist Rescue device, and a link to the system specification sheet of this device provided by Vita Inclinata:

https://vitatech.co/wp-content/uploads/2020/05/vita-lss-hr-data-sheet-0520.pdf

This product differs from our proposed solution in a number of key areas. The LSS-HR hoist rescue device is meant to be attached to a hoisting cable, while our proposed solution

[5] https://www.airmedandrescue.com/latest/long-read/spinning-avoidance
[6] https://www.airmedandrescue.com/latest/long-read/spinning-avoidance
[7] https://vitatech.co/wp-content/uploads/2020/05/vita-lss-hr-data-sheet-0520.pdf

involves attaching a device to a stretcher. From the datasheet provided by Vita Inclinata, even while the device is autonomous, a winchman is still required to make sure the load, or patient, is properly stabilized[8]. Our solution seeks to eliminate the need for a winchman entirely. While the LSS-HR hoist rescue device is capable of loads up to 750 lbs, our proposed solution only needs to be capable of loads up to 250 lbs, which would be the approximate maximum weight of a person being hoisted in a stretcher. Furthermore, the LSSR-HR hoist rescue device is wirelessly operable, however; as seen in later parts of the PDR, our proposed solution will likely not utilize wireless communication. Most importantly, the LSS-HR device is capable of controlling three degrees of freedom, while our solution at the time being is only concentrated on controlling one degree of freedom, that being spin[9]. Similarities with our proposed solution and Vita Inclinata's proposed solution include the stability specification of being able to handle wind and down wash conditions of around 60 knots, and being lightweight, around 35 lbs[10].

The second technical solution devised by Vita Inclinata is the LSS-LA-litter attachment device. Similar to the LSS-HR hoist rescue device, the LSS-LA litter attachment device is autonomous, wirelessly operable, and controls three degrees of freedom, being spin, sway, and oscillatory motion. The LSS-LA litter attachment device is in the form of a netted stretcher with ducted fans placed underneath. These fans are meant to provide actuation that stabilizes the stretcher. The LSS-LA litter attachment device is capable of handling loads up to 750 lbs, controls at a rate of 1.5 periods per swing, and has a control range of around 1000 feet[11]. Below is a picture of the LSS-LA litter attachment device, alongside link to the system specification sheet provided by Vita Inclinata:

https://vitatech.co/wp-content/uploads/2020/05/vita-lss-la-data-sheet-0520.pdf

This product is similar to our proposed solution as seen later in the PDR report. Our proposed solution is structurally similar to the LSS-LA litter attachment, and seeks to provide actuation in the same way, using ducted fans. Furthermore, as seen from the product description from Vita Inclinata, the LSS-LA litter attachment device does not require a winchman, which is similar to our proposed solution as well. Our proposed solution also seeks to achieve similar stability parameters to the LSS-LA litter attachment, which is capable of stabilizing loads in winds up to 60 knots[12]. Our proposed solution differs from the LSS-LA litter attachment due to the fact that we seek to create a device that can attach to pre-existing stretchers, while the LSS-LA litter attachment product is itself a stretcher with actuators already

[8] https://vitatech.co/wp-content/uploads/2020/05/vita-lss-hr-data-sheet-0520.pdf
[9] https://vitatech.co/wp-content/uploads/2020/05/vita-lss-hr-data-sheet-0520.pdf
[10] https://vitatech.co/wp-content/uploads/2020/05/vita-lss-hr-data-sheet-0520.pdf
[11] https://vitatech.co/wp-content/uploads/2020/05/vita-lss-la-data-sheet-0520.pdf

[12] https://vitatech.co/wp-content/uploads/2020/05/vita-lss-la-data-sheet-0520.pdf

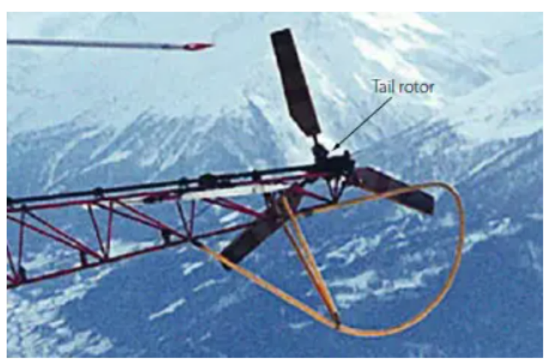
attached to it[13]. While the LSS-LA litter attachment device is capable of loads up to 750 lbs, our proposed solution only needs to be capable of loads up to 250 lbs, which would be the approximate maximum weight of a person being hoisted in a stretcher. Furthermore, the LSS-LA litter attachment device is wirelessly operable, however; as seen in later parts of the PDR, our proposed solution will likely not utilize wireless communication. Most importantly, the LSS-LA litter attachment device is capable of controlling three degrees of freedom, while our solution at the time being is only concentrated on controlling one degree of freedom, that being spin[14].

Background / Related Work / References:

In order to understand the problem and solution, knowledge is required about the forces and torques involved on the load during helicopter hoisting operations, and knowledge for controls and stabilization is required for the design algorithm. Previous work on this issue is covered in the Define Strategies and Methods section. This work includes non-technical solutions to prevent spin on loads as stated in the Air Med and Rescue magazine, or the technical solutions proposed by Vita Inclinata. Below is a link describing the physics behind downwash related spin on loads. There is also a link to a report by NASA about how parameters on ducted fans such as diameter, duct length, number of blades, and motor choice all affect the resultant thrust and lift. Our group will reference these link, alongside other resources in order to come up with the mathematical formulation and algorithm to solve the problem:

https://www.intechopen.com/books/flight-physics-models-techniques-and-technologies/helicopter-flight-physics
https://rotorcraft.arc.nasa.gov/Publications/files/Abrego2_AHS02.pdf

Since our solution involves spin control, or applying opposite torque to the load, other relevant research would be on anti-torque systems found on helicopter rotors. Various anti-torque systems such as tipped blades at variable pitch, or "fan in tail" systems help minimize excessive torque on helicopter rotors[15]. While these solutions regarding helicopter rotors may not be directly applicable to our design, some of the techniques described can be used on the blades of the ducted fans used as actuators for stabilization. Below are pictures demonstrating helicopter rotor stabilization systems, and links regarding sources

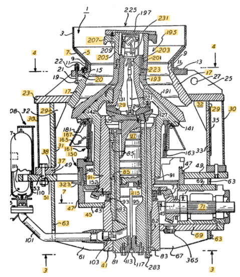


https://www.flight-mechanic.com/helicopter-structures-and-airfoils-anti-torque-systems/
https://www.hindawi.com/journals/ijae/2016/5396876/

[13] https://vitatech.co/wp-content/uploads/2020/05/vita-lss-la-data-sheet-0520.pdf
[14] https://vitatech.co/wp-content/uploads/2020/05/vita-lss-la-data-sheet-0520.pdf

[15] https://www.flight-mechanic.com/helicopter-structures-and-airfoils-anti-torque-systems/

Anti-spin systems have been applied elsewhere as seen in a gyratory crusher system. The picture below shows the design for a mechanism, which through the use of uni-directional valves prevents the spin of the mantle of a crusher unless a certain force is exceeded[16]. While the context of this problem is different from helicopter rescue operations, it is interesting to see a purely mechanical approach to solving issues regarding spin. Below is a link to the patent description of said device:



https://patents.google.com/patent/US4206881A/en

The sub problem defined in the explication section has not been completely solved. The U.S government is still funding Vita Inclinata with 2 million dollars per year, showing that there is still a market for a solution to this problem[17]. Vita Inclinata's anti-spin hoist device is still in development, and the litter attachment is not modular and cannot work with existing stretchers. Our solution is unique in the sense that it can attach to existing stretchers and is relatively lightweight. Furthermore, an automated solution has not yet been standardized as helicopter operators still need to undergo manual procedures to stop spin on loads[18].

Summary of Fundamental Questions:

Below is a compilation of the answers to the fundamental questions listed from the PDR specifications. We included these answers in the CDR for reference.

The overall problem that this project is trying to solve is to reduce excessive load movement caused by downwash in helicopter hoisting operations (HHOs). The subset of the overall problem that our group is trying to solve is to reduce the spin of a hoisted stretcher during a HHO where the helicopter is stationary.

People should care about this problem because spinning loads during HHOs can cause damage to the helicopter, hoisting cable, and load itself, which could result in monetary loss or injury. In the context of our specific sub-problem, excessive spin can cause nausea which could result in drowning if the patient is strapped to a stretcher and cannot control their airways. Excessive spin can also cause the hoisting cable to be severed, the patient to be ejected from the stretcher, or make the stretcher collide with an external object, all of which can be life threatening for the patient. Furthermore, spinning loads can affect small helicopter's center of mass, making helicopter control difficult in low velocity launch situations.

Various non-technical solutions are used in practice to stop load spin during HHOs. These techniques are specified in the Air and Med Rescue magazine article. Furthermore, the private company Vita Inclinata has proposed two relevant technical solutions that help solve this issue.

[16] https://patents.google.com/patent/US4206881A/en
[17] https://vitatech.co/news/vita-receives-us-air-force-contract/
[18] https://www.airmedandrescue.com/latest/long-read/spinning-avoidance

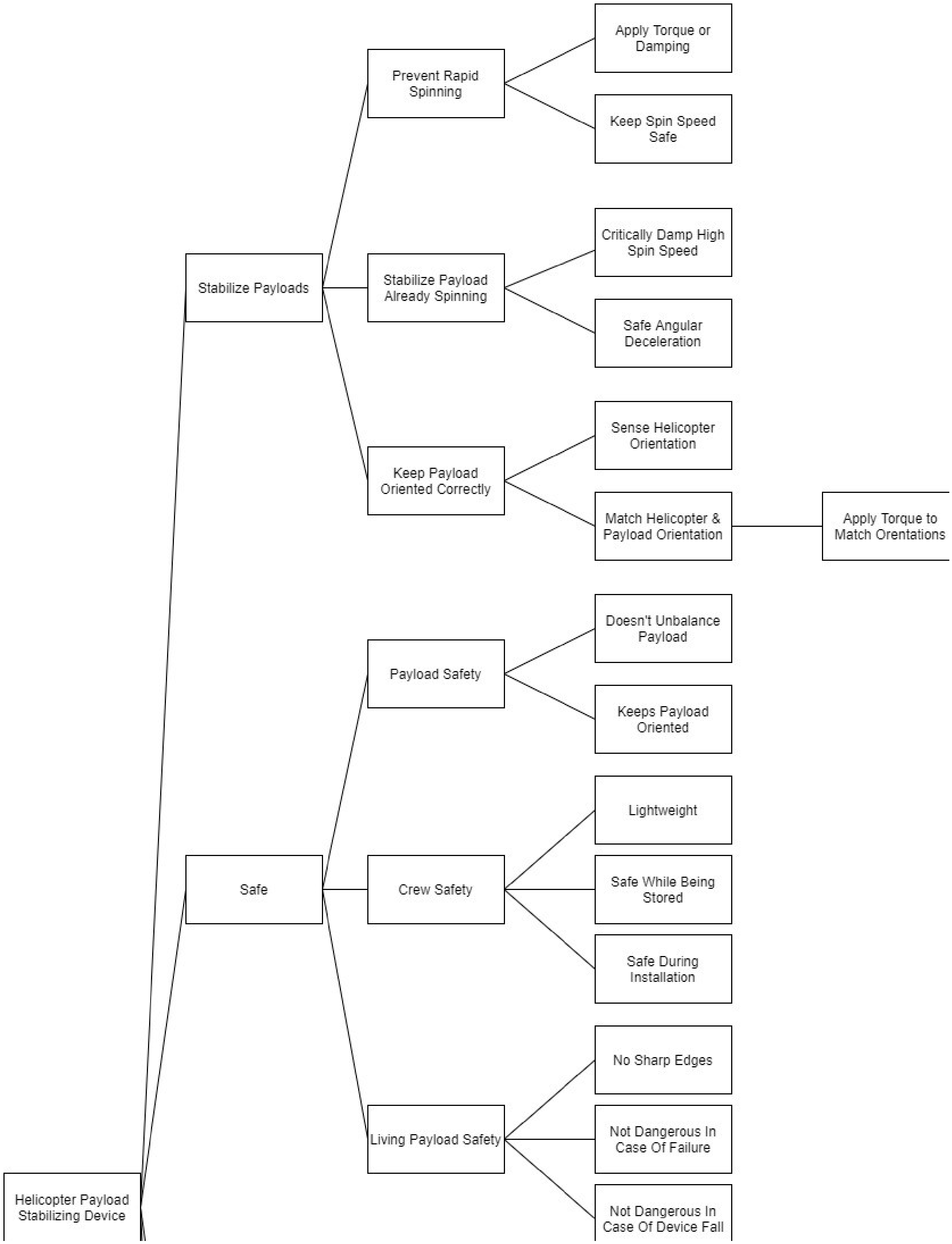
Scope:

The overall problem is to design a device that is capable of regulating excessive load motion during helicopter hoisting operations (HHOs). The subset of this problem our group is trying to solve is to reduce the spin on a hoisted stretcher during a HHO where the helicopter is stationary at fixed elevation. Through solving this sub-problem, hopefully the technology used in this project can be expanded upon to control multiple degrees of freedom, work on other loads, or deal with situations where the helicopter is not stationary. Our group's specific approach to solving this sub problem is to build a modular device capable of attaching to existing stretchers to allow for spin stabilization during HHOs. Our group plans on testing our solution using simulation software such as Solidworks, Webots, and analytical simulations. Using Solidworks, it is possible to conduct structural tests on our device, and perform aerodynamic flow analysis. Through modelling the problem as a controls problem, it is possible to use metrics such as step tracking error, sinusoid tracking error, max overshoot, peak time, and other controls parameters to quantitatively measure the performance of the device. These metrics could be attained through Webots and analytical simulations.

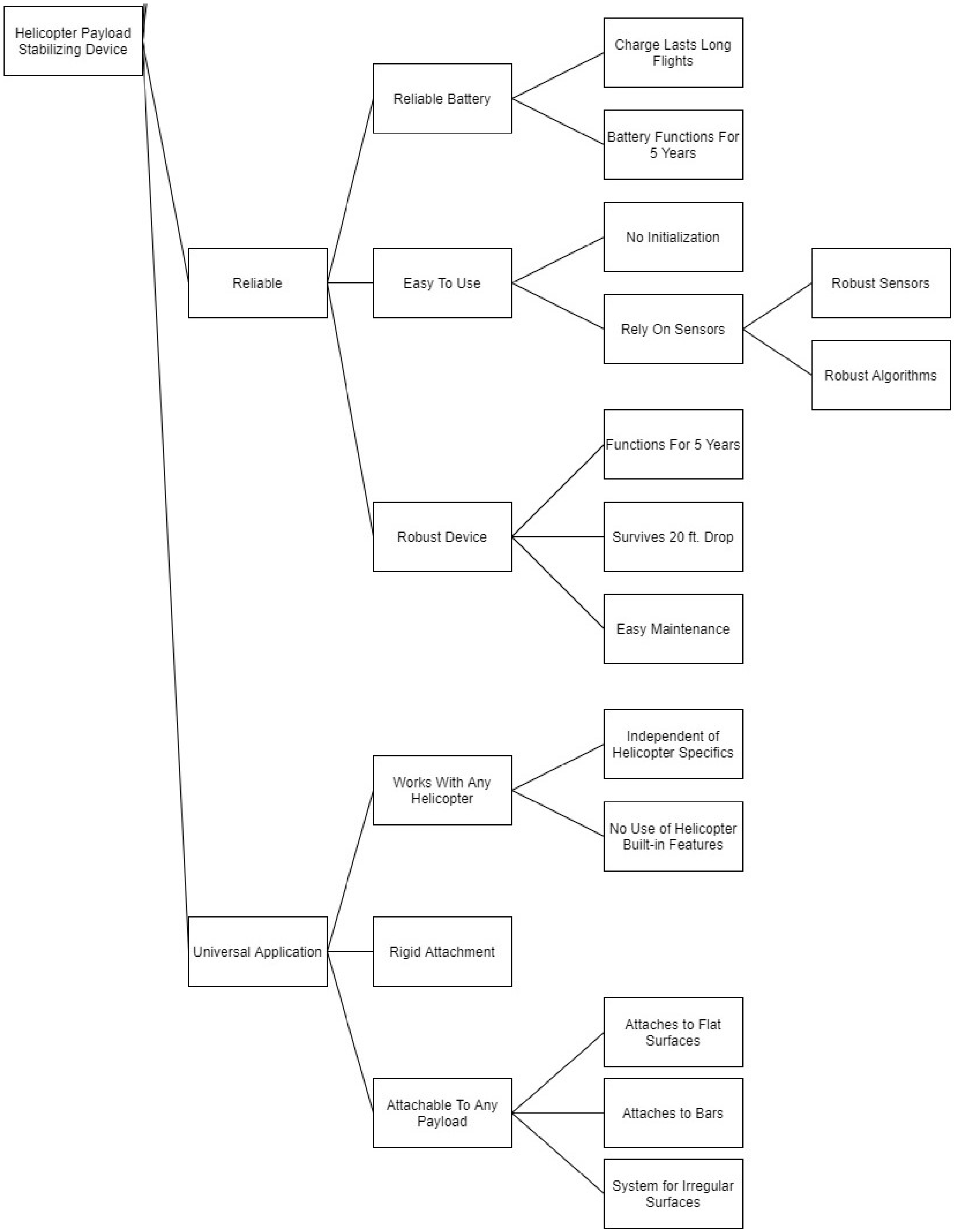
Preliminary Analysis (Jeremy, Chiraag, Jake)

Objective Tree Analysis

The first method of analysis used was the objectives tree. The objectives tree is a way of visualizing what we want a project to be able to do, by ranking the objectives. As the tree gets more branched out, the blocks gradually go from nebulous objectives to actionable design parameters. This way, the whole problem is though through to ensure the stabilizer does everything it needs to. There are four basic objectives for this project. It should stabilize payloads, be safe, be reliable, and have a universal application.



Helicopter Payload Stabilizing Device
Stabilize Payloads
Prevent Rapid Spinning
Apply Torque or Damping
Keep Spin Speed Safe
Stabilize Payload Already Spinning
Critically Damp High Spin Speed
Safe Angular Deceleration
Keep Payload Oriented Correctly
Sense Helicopter Orientation
Match Helicopter & Payload Orientation
Apply Torque to Match Orentations
Safe
Payload Safety
Doesn't Unbalance Payload
Keeps Payload Oriented
Crew Safety
Lightweight
Safe While Being Stored
Safe During Installation
Living Payload Safety
No Sharp Edges
Not Dangerous In Case Of Failure
Not Dangerous In Case Of Device Fall



Helicopter Payload Stabilizing Device
Reliable
Reliable Battery
Charge Lasts Long Flights
Battery Functions For 5 Years
Easy To Use
No Initialization
Rely On Sensors
Robust Sensors
Robust Algorithms
Robust Device
Functions For 5 Years
Survives 20 ft. Drop
Easy Maintenance
Universal Application
Works With Any Helicopter
Independent of Helicopter Specifics
No Use of Helicopter Built-in Features
Rigid Attachment
Attachable To Any Payload
Attaches to Flat Surfaces
Attaches to Bars
System for Irregular Surfaces

Performance Specification Method

The second method of analysis used was the performance specification method. The purpose of the performance specification method is to list performance attributes and weight them so that designs can be compared. Because the solution must fit a problem correctly and not the other way around, we considered different options besides actuators that induce torque via force generation from the side of a payload. Among alternatives considered were landing the helicopter first to remove the need for an HHO, using multiple cables to keep a payload in line, or even foregoing airlifts and using conventional ground transport. All of these alternatives are lacking in some way, and none can compete with the versatility and agility of HHO's. The next step was to determine actuators. The team considered a flywheel whose axis was tipped, passive damping, thrusters, rotors, and turbines.

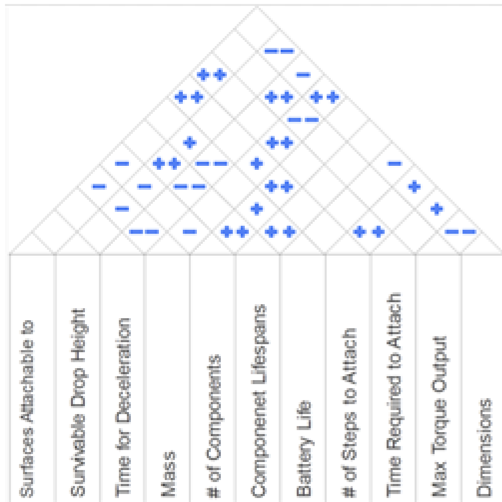
It was determined that the angular payload should not be allowed angular velocity greater than 15 rpm, and a maximum angular acceleration of 30 rpm^2. All assembly and parts must have a factor of safety of 2.5 or higher to keep in line with industry standards, and the device must be effective on a payload of 300 lbs. or more.

Quality Function Deployment Method

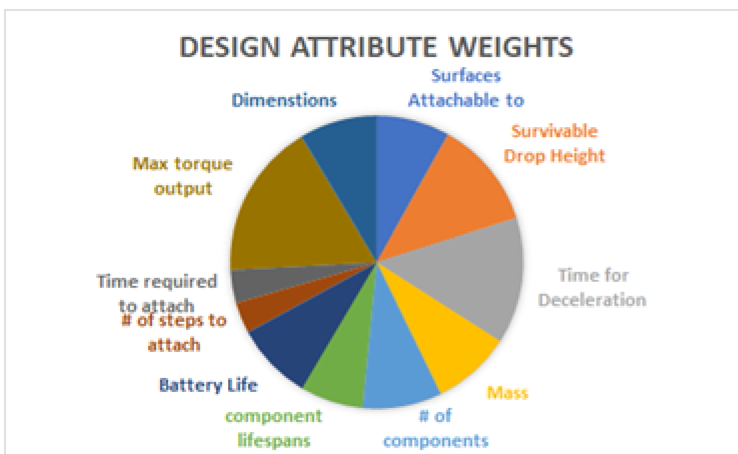
The last method of analysis used was the quality function deployment method, also known as the house of quality. This method uses a complex weighting system to determine what design attributes are the most important to design for.

	Weight (1-10)	% Weight	Surfaces Attachable to	Survivable Drop Height	Time for Deceleration	Mass	# of components	Component Lifespans	Battery Life	# of Steps to attach	Time Required to Attach	Max torque output	Dimenstions
			↑	↑	↓	↓	↓	↑	↑	↓	↓	↑	↓
Stabilize Payload	8	0.296296296											
Safe	9	0.333333333											
Reliable	6	0.222222222											
Easy to Use	4	0.148148148											
		Imputed importance	4	5	6	4	4	3	4	2	2	8	3.9
		Units	#	m	s	kg	#	hr	hr	#	s	Nm	m^3
		Design % Weight	8	12	14	9	9	7	9	3	4	17	8.6

The “roof” on the house of quality is used to visually understand how changing an aspect can affect others.



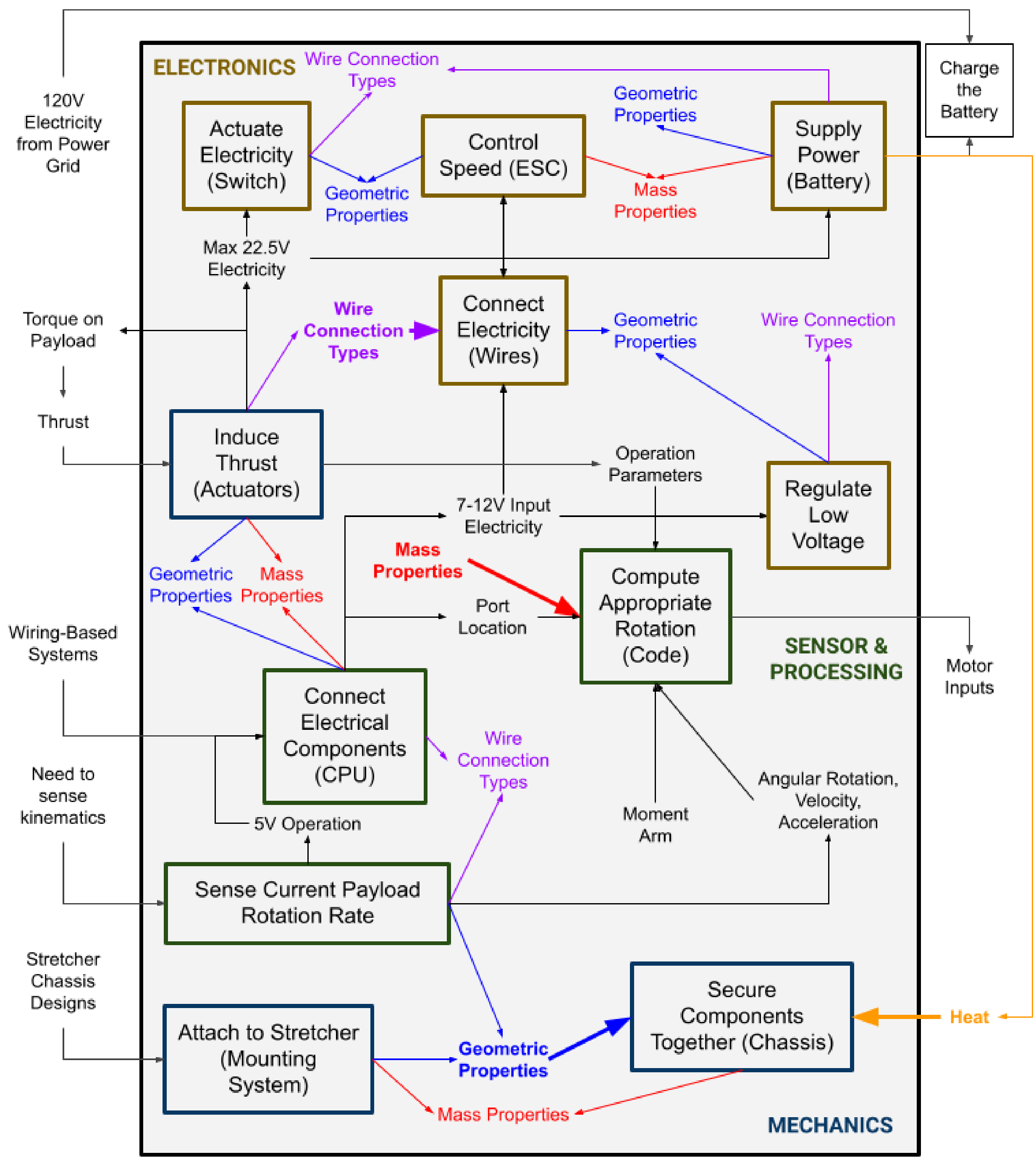
The end result of performing a quality function deployment method analysis is a series of design weights that tell the designers what the most important attributes to design for are.



As is evident in the above figure, maximum torque output is the most important parameter, and the time for deceleration is second most important.

Function Analysis – Transparent Box Model

As was the case in the PDR, the block diagram is defined such that the design decisions that must go into each subsystem and subproblem result in the completion of these specifications to ensure overall project success. The solutions to these design decisions affect the design parameters of the blocks that each subproblem points to, not what parameter is affected by the previous in its function. Some properties do not have arrows pointing to the subproblem specified; in these cases, 'teleport' to the bolded property with the bolded arrow. For example, the geometric properties specified by the "Actuate Electricity (Switch)" show that design decisions about the switch design dictate how components are secured together in the chassis.



There are three types of components given by different colors in the diagram above: electronics (given in gold), sensor and processing (given in green), and mechanics (given in dark blue). Additionally, information each component produces or is dependent on is described below. Three pieces of information (the geometric properties, the wire connections, and the mass properties) have colors associated with them. These components and information in the diagram are discussed in detail below.

Components: Electronics

Supply Power (Battery)

The rechargeable battery supplies 22.2V electricity to each actuator as well as the CPU. The electricity is sent to these devices through wires and regulated through a voltage regulator. The geometric properties of the power supply will be taken into account such that the chassis can hold the battery and prevent movement throughout actuation. Currently, we will need five batteries per actuators, (the number of actuators needed is discussed in Part V). The mass of each battery will also be taken into account when calculating the required thrust. Heat will be produced by the battery and accurate ventilation will be designed to prevent overheating of other elements.

Connect Electricity (Wires)

The wires distribute electricity from the battery throughout the module. The chassis must be designed such that the wires are able to reach the devices they need to supply power. Except for the LED, chassis, and the mounting system, all components use wires to route electricity back and forth; thus, the wire selection is dependent on the connection mechanisms of each device. Additionally, the wires are dependent on the voltage of the electricity that is run through them.

Actuate Electricity (Switch)

The switch will receive an on/off orientation. When on, it will distribute electricity to the voltage regulator. We assume that the mass of the switch is negligible, but include its geometric properties in the design of the chassis. Only one switch is needed, and this switch is located on the main module.

Regulate Voltage (Low)

The voltage regulator receives electricity from the wires from the battery and adjusts the voltage to the correct amount so as not to overheat the electrical components. The sensors and CPU will operate at 7.5V while the actuators, switch, battery will operate at around 22.2V. One type of voltage regulator is needed and is located with the CPU to adequately distribute the adjusted power. The chassis must be designed to ensure that the voltage regulators are held secure.

Components: Sensors and Processing

Central Processing Unit (CPU)

The CPU's purpose is to receive and distribute information such as the moment arm, angular kinematics, and motor inputs to the appropriate devices. Only one CPU is required for this system. The CPU will house the code that computes the appropriate rotation. The types of wires used must be able to connect to the CPU. The CPU determines the electricity we will use throughout the system, which is 7.5V. The chassis must be designed to ensure the safety of the CPU, and its mass properties will be taken into account in the rotation calculation. The appropriate port locations must be taken into account from the Arduino guide.[19]

[19] https://store.arduino.cc/usa/arduino-uno-rev3

Compute Appropriate Rotation (Code)

The code's purpose is to calculate the appropriate amount of thrust for the actuators in motor inputs based on the mass properties of each component and the angular kinematics gathered from the sensors and distributed by the CPU. The code is the only component without a mass, inertial, or geometric property under consideration in this module. The code will be uploaded into the CPU before the CPU is installed. The code must be compatible with the CPU's programming language.[20]

Sense Current Payload Rotation Rate

These sensors determine the current rotation rate of the payload and determine the payload's current angular rotation, velocity, and acceleration. This information is sent to the code via the CPU. The current payload rotation rate is also based on the torque previously applied by the actuators in a negative feedback loop. The sensor locations correspond to the location of the actuators. The mass of the sensors must be taken into account and their geometric properties must be considered in the design of the chassis. The wires connecting the sensors must have adequate connections and the sensors must be able to run 5V electricity.

Components: Mechanics

Secure Components Together (Chassis)

The chassis's purpose is to secure all devices. It must ensure that adequate ventilation is met for devices that produce heat. It must consider the geometric properties of all components except the code. The chassis will be designed into multiple parts, one part for each actuator. Its mass must be considered when calculating the appropriate thrust.

Induce Acceleration (Actuators)

The actuators receive electricity from the power supply via the wires and PWM inputs to produce the appropriate thrust determined by the code in the CPU. The thrust creates a torque on the payload. The electricity we will use is 22.2V based on the 70mm fan we are considering.

Depending on the type of actuator, it will also produce sound that must not exceed the noise level requirements given by the National Institute for Occupational Safety and Health. It is recommended that the sound generation be below 85 dB[21], but we do not anticipate the actuators we use to exceed 60 dB. More on actuators is discussed in Part V, including the type and quantity of each actuator. The chassis must be designed to ensure the proper operation of the actuator, and its mass properties will be taken into account in the rotation calculation.

Attach to Stretcher (Mounting System)

The attachments to the stretcher secure the actuators and CPU to the stretcher such that a force created by the actuators will not cause actuators to fall off. The attachments are designed based on the stretcher chassis designs we will clamp the device to. Ideally, the modules would be able to attach to any stretcher regardless of design. The number of attachment mechanisms correspond to the number of modules needed.These attachments

---

[20] https://www.arduino.cc/en/guide/introduction
[21] https://www.cdc.gov/niosh/topics/noise/infographic-noiselevels.html

must be designed to fit the chassis and its mass properties will be taken into account in the rotation calculation.

Information

Heat

Some heat is generated through the CPU and the sensors, but most heat in our system is generated through the batteries. The chassis must be adequately designed such that the heat is appropriately ventilated away from the device to be sure to not melt any critical components.

Geometric Properties

These properties are required of all physical components so that the chassis can be designed to fit them.

Mass Properties

These properties are required of all non-negligible physical components so that the appropriate and values can be calculated for the thrust. The heavier the actuators, the more thrust the actuators must be able to provide.We assume that the weight of the payload is about 95kg and the mass of the system is expected to be around 35-40lbs (18kg). Maximum load is 250 lbs (113kg). The code uses the mass to calculate the inertial properties of the system.

Wire Connection Types

The wires will have different connection types depending on the device it is connecting to. The wires will be designed depending on these device connections.

Electricity (22.2V, 7.5V, 5V, 120V AC from Power Grid)

The only source of energy used in our design is from our battery. The battery will output electricity for each component through wires. Electricity will be used exclusively to power our system, from the actuators and sensors to the central processing unit (CPU) itself. The electricity will undergo conversion to the appropriate voltage to be sure to power each device appropriately and not blow anything up. The electricity will be distributed through wires from the power supply, which is charged with electricity through a charging port and wire from the electrical grid before use in a helicopter.

Angular Rotation, Velocity, Acceleration

Different angular kinematics are output depending on the type of sensor. The code must be adjusted to convert and manipulate these values into usable quantities.

Moment Arm

We hardcode the value of the moment arm, fed to the code via the PCB and are used along with the mass of the actuators to calculate the appropriate torque on the payload.

Port Location

The code must be compatible with the CPU's ports such that the right signals are sent to the right places using the right commands. The code must be adjusted if a change in CPU or CPU orientation occurs.

Thrust

Thrust is generated from electricity in the actuators that propels the stretcher. Ideally, the thrust will come from two actuators equally at a certain distance apart such that a torque is created on the stretcher with a net force of zero, preventing additional sway from the stretcher.

Morphological Chart

The morphological chart is a rational design method in which we create design blocks that present many alternates for a given feature of the solution. By comparing many possible design decisions, we can explore different combinations of design features and determine which best satisfy the design requirements. Below is our morphological chart, with most viable options listed in bold.

Design Block	Option 1	Option 2	Option 3	Option 4
Actuation	Flywheel	**Turbine**	**Rotor**	Twisting Cable (powered)
Number of Actuators	1	**2**	3	**4+**
Power	**Electric**	Gas	Hybrid	
Device Location	**Edge of payload**	**Under Payload**	Center of mass	Hoist cable replacement
Shape	Basket/Bed	**Box attached to payload**	Cable	
Sensors	IMU	Compass		
Modular vs. Combined	**Modular**	Combined		

For actuation, we found that having a turbine or rotor to enact forces in various directions would be the most simple and reliable way to stabilize the payload system. Rotating flywheels require large power input and complex actuation, and focusing actuation on the cable would only solve anti-spin stabilization and ignore the possibility of anti-sway. In terms of the number of actuations, two actuators is the minimum number needed to counteract spin, and four is the minimum to counteract sway; similarly, an even number of actuators is preferred to maintain symmetry. Finally, we determined that a modular approach is advantageous because it minimizes weight and allows for versatility with existing stretcher models.

Weighted Objective Method

The weighted objectives chart is the second of the rational design methods for this project. This chart is derived from the weighted objective tree, where we assign a weight to each objective at a given layer. This weight is scaled similar to a rank, and is normalized to a factor such that the combined weights at a given layer add up to one. The result is a relative ranking of objectives which we are to address in our design. Below is an example of the calculations involved in the top layer of the objective tree.

Objective	**Weight (scaled)**	Weight (fraction)	Weight (normalized/sum of 1)
Safety	3	3/10	0.3
Universal Application	1	1/10	0.1
Reliability	2	2/10	0.2
Payload Stabilization	4	4/10	0.4

Under each node, its children are similarly weighted and normalized to a sum of one. The total weight of a given node is the multiplication of its weight and that of its parent nodes. We repeat this process for each node in the tree until the third and bottom layer, when we can compare the final weight of each objective and determine which design criteria are the most important to consider. The weight and normalization is based on the total number of sibling nodes. Below is the final weighted objectives chart, with local and total weights shown for each node.

Layer 1	Layer 2	Layer 3
Payload Stabilization (**0.4**)	Prevent Spinning (0.4x0.5)=**0.2**	Apply Torque/Damping (0.2x0.5)=**0.1**
		Safe Spin Speed (0.2x0.5)=**0.1**
	Stabilize Payload already spinning (0.4x0.333)=**0.13**	Damp high spin speed (0.13x0.5)=**0.065**
		Safe deceleration (0.13x0.5)=**0.065**

	Keep Payload Oriented Correctly (0.4x0.167)=**0.07**	Sense Helicopter Orientation (0.07x0.33)=**0.023**
		Match Orientations (0.07x0.66)=**0.046**
Safety (**0.3**)	Payload Safety (0.3x0.167)=**0.05**	Doesn't unbalance payload (0.05x0.66)=**0.033**
		Maintain orientation (0.05x0.33)=**0.017**
	Crew Safety (0.3x0.333)=**0.1**	Portable (0.1x0.33)=**0.033**
		Safe in Storage (0.1x0.17)=**0.017**
		Safe in Installation (0.1x0.5)=**0.05**
	Living Payload Safety (0.3x0.5)=**0.15**	Safe in use (0.15x0.5)=**0.075**
		Safe in structural failure (0.15x0.33)=**0.05**
		Safe when device fails (0.15x0.17)=**0.025**
Reliability (**0.2**)	Reliable Battery (0.2x0.5)=**0.1**	Lasts long flights (0.01x0.66)=**0.066**
		5 Year reliability (0.01x0.33)=**0.033**
	Easy to Use (0.2x0.333)=**0.07**	No Initialization (0.07x0.33)=**0.023**
		Reliable Sensors (0.07x0.66)=**0.046**
	Robust Device (0.2x0.167)=**0.03**	5 Year functionality (0.03x0.167)=**0.005**
		Survives 20 ft. drop (0.03x0.5)=**0.015**
		Minimal Maintenance (0.03x0.33)=**0.01**

Universal Application (**0.1**)	Works with Any Helicopter (0.1x0.5)=**0.07**	Independent of Helicopter specifics (0.07x0.5)=**0.035**
		No use of Helicopter features (0.07x0.5)=**0.035**
	Rigid Attachment (0.1x0.167)=**0.0167**	N/A (**.0167**)
	Attachable to any payload (0.1x0.333)=**0.033**	Attach to flat surface (0.033x0.33)=**0.01**
		Attach to Bars (0.033x0.5)=**0.0165**
		System for irregular surfaces (0.033x0.17)=**0.006**

As we can see from the weighted objectives chart, objectives that have a higher parent such as payload stabilization and safety tend to have higher final weights. In addition, throughout the final layer we see that objectives related to the hoisting/rescue operation and the safety of the patient involved are of higher priority than those relating to long-term reliability or general compatibility. As such, in our design process our priority is to create a product that solves the problem statement by safely stabilizing the system, and compatibility and convenience is an important but secondary objective.

Design Specifications (Hieu, Giacomo, Sidharth, Chiraag, Jake, Jeremy, Seong)

Overview:

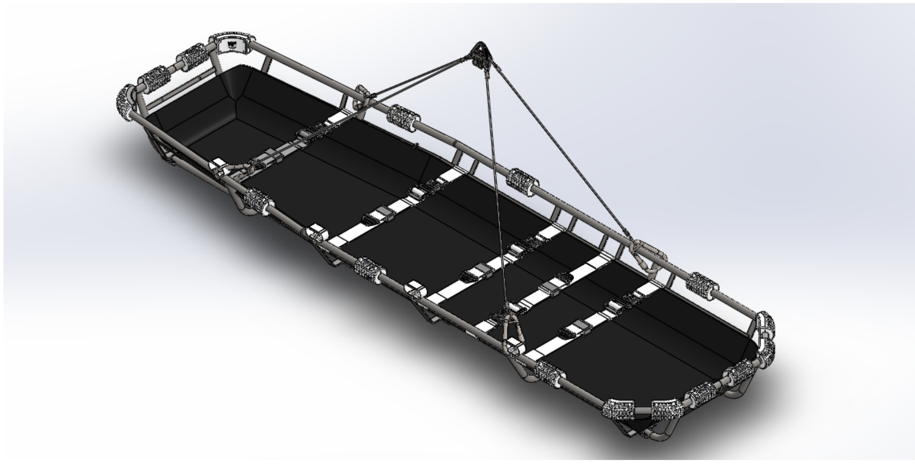
Using the morphological chart and weighted objective method, we determined the best actuators to use are four ducted fans powered by electricity. We also determined that we should place the modules on the sides of the stretcher, and connect them via communication wires. Finally, we determined that a single IMU and CPU placed in one module would be sufficient for closed loop control.

Mechanical System:

The mechanical system consists of the stretcher litter, device chassis and subchassis, mounting hardware, and the connective components such as screws, etc. These must also be compatible with our electrical system components.

<u>Stretcher</u>

The primary stretcher litter that we are designing around is the Lifesaving Systems Corp 404 Medevac Stainless Steel Rigid Litter, which is the most common litter used in helicopter rescues[22]. This features a steel frame with a top bar diameter of ¾" and secondary support bars of diameter ½" , which are the primary points of contact for our device. We contacted LSC for a model of their litter for our design process, which they were kind enough to provide. Below is the CAD model of the 404 Medevac Litter.



In order to satisfy our requirement of being compatible with more than one stretcher model, we also found 3 other stretcher models that span the majority of available litter from manufacturers. These are the Junkin JSA-300 Basket Stretcher[23], the CMCPro Stainless Steel Rescue Litter,[24] and the Cascade Rescue Professional Series Litter. [25] We contacted these companies as well but were unable to obtain CAD models. However, we were able to gather common features in all four of our strethers. All stretchers had at least 1 foot of bar at the head and tail of the litter with a top bar diameter of either ¾" or 1", and a slightly varied support bar system. We determined that if we could design our device such that it is compatible with either bar diameter and had a mounting system robust enough to secure despite support bar locations, then our device will be compatible with all these stretchers.

Mounting Hardware

The mount to the horizontal pipes on the stretcher is meant to be rigid and with zero degrees of freedom. It is important that it can accommodate different diameters of pipe. The maximum diameter pipe we found on various stretchers was one inch. For this reason, the maximum allowable pipe diameter on the horizontal mounting hardware is one inch as well. The mount to the "vertical pipes" is meant to fasten onto pipes on the stretcher that are most likely not vertical at all, but for the purpose of this document they are referred to as "vertical pipes".

The horizontal mounts have three requirements. They must be able to mount securely to different diameter pipes (with a maximum diameter of one inch), they must be able to be taken off without opening any parts of the chassis, and they must operate at or preferably above a factor of safety of 2.5 during normal operation of the stabilization device.

[22] https://lifesavingsystems.com/product/medevac-ii-rigid-litter-stainless-steel-with-flotation-kit

[23] https://www.junkinsafety.com/stretchers
[24] https://www.cmcpro.com/equipment/stainless-steel-rescue-litter/#learn_more
[25] https://cascade-rescue.com/cascade-rescue-professional-series-stainless-litters/

The vertical mounts have four requirements. Like the horizontal mounts, they must be able to mount securely to different diameter pipes (with a maximum diameter of one inch), and they must operate at or preferably above a factor of safety of 2.5 during normal operation of the stabilization device. In addition, they must be able to support the weight of the chassis to prevent tipping down, and they must be able to attach to the vertical pipes that are in an unknown position and orientation (each stretcher model is different).

Chassis and Subchassis

The simplest method to manufacture our chassis involves using plastic injection molding with polycarbonate. Since there is no tapping required on the screws, a mold can be designed to hold the actuators, batteries, and CPU. The latter two components must be separated from the actuators so that dirt, water, or oils do not get into the chassis. These components will also require vents such that heat dissipation occurs. The chassis is designed in two main parts, top and bottom, such that easy installation and swapping of inner components is achieved, with adhesive present for loose components. Socket head screws are used to ensure minimal interference with the smoothness of the chassis.

We will design two different chassis configurations, one for each side of the stretcher. Only one chassis (the main chassis) will have the CPU and sensor equipment, while the other chassis (sub-chassis) will not contain these components. The relative sizes of these chassis components will remain the same size relatively due to 1) negligible mass difference of electronics components and 2) needed space to integrate mounting hardware.

Electrical System:

The electrical system consists of the ducted fans (actuators), electronic speed controllers (ESC), central processing unit (CPU), inertial measurement unit (IMU), batteries, voltage regulator, and various wires/connectors. All parts must be compatible and meet our design requirements.

Actuators

Given a moment arm of 1.1m (half length of stretcher), our actuators must produce at least 5.5N each to counteract the 12Nm of external torque seen in the spinning stretcher video. The more thrust our actuators can produce, the better we can counteract external torque. However, increasing actuator power reduces battery life.

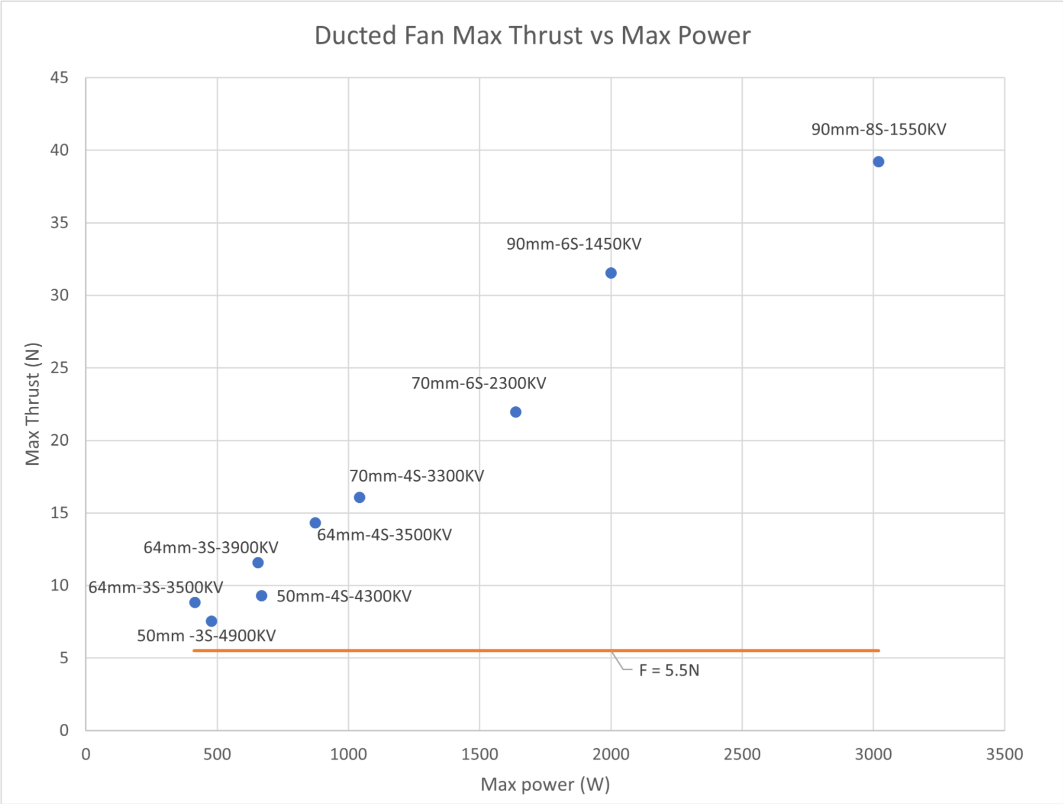


Figure: Actuator power vs thrust comparison

As seen in the figure above, all actuators above 50mm meet the minimum safety requirement of 5.5N. Since we want the maximum actuator thrust to be considerably higher than the minimum thrust requirement, we narrowed the choice to 70mm rotors or greater. Rotors of 90mm have good thrust, but consume over 2000W at max thrust, meaning the device could only operate for a short period. Our final choice is the 70mm-6s-2300KV ducted fans, since they deliver over 4 times the minimum thrust requirement while operating under 2000W.

Electronic speed controllers (ESC)

To keep things simple, we chose the ESCs that were recommended by the ducted fan manufacturers. These are the Skywalker Hobbywing 80A ESCs.

Central processing unit (CPU)

We chose Arduino Uno Rev 3 due to multiple reasons. Arduino IDE is simple to code, there are many code libraries that are available to use, which will be sufficient for our project. This board has 20 I/O pins, and 6 of them are PWM output pins[26], which are enough to command 4 actuators in our project and communicate with the IMU sensor. This board has 3.3V and 5V pins, which can act as voltage supplies for many kinds of sensor.

[26] https://store.arduino.cc/usa/arduino-uno-rev3

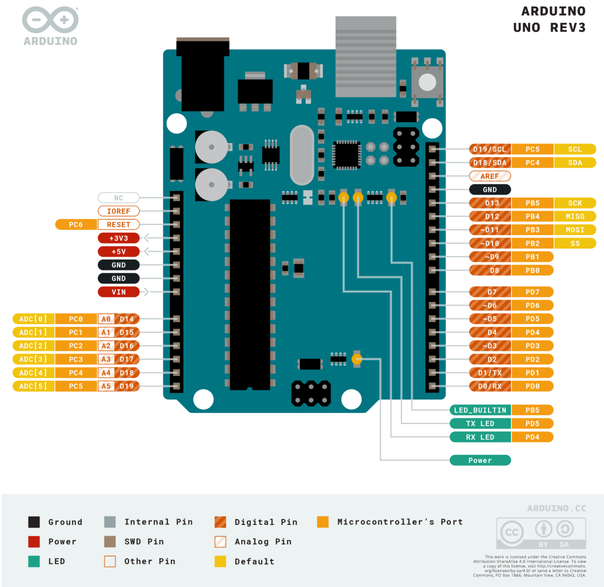


Figure: Arduino Uno Rev3 pin diagram

<u>Inertial measurement unit (IMU)</u>

The IMU that we desired for this project was required to be compatible with our Arduino and had to be capable of measuring angular velocity at a reasonable resolution. The 6 DOF Adafruit ISM330DHCX IMU was the device we chose to use for this project. This IMU is capable of measuring angular velocity at a resolution of 4000 degrees per second at a sample frequency of 6.75kHz[27]. The high resolution and measuring frequency coupled with a low noise margin of 2% error on angular velocity makes this an ideal IMU for this project. Furthermore, this IMU operates on both 3 volt or 5 volt pin from the Arduino, and comes at a relatively cheap price point of $14.95[28].

<u>Batteries</u>

To power the ducted fans, the manufacturer recommends 22.2V/6S - 35C batteries. Given that HHOs typically take at most 13 minutes[29], we wanted our system to last for multiple rescues on one battery charge. Using 10 batteries per model, we can achieve 30 minutes at maximum thrust, which allows us to make 2 consecutive rescues in the worst case scenario.

The batteries will emit enough heat such that ventilation is required. However, the batteries must also be insulated such that no water, dirt, or oils interfere with the battery. Thus, we concluded that a material that is waterproof, has high thermal conductivity, and prevents electrical breakdown will be sufficient for our purposes.

[27] https://www.st.com/resource/en/datasheet/ism330dhcx.pdf
[28] https://www.st.com/resource/en/datasheet/ism330dhcx.pdf
[29] https://www.sciencedirect.com/science/article/pii/S1080603219301140

Voltage regulator

Since our CPU runs on 7-12V, we require a step down regulator to reduce the 22.2V power supply. We also would like to limit the amount of back EMF entering the CPU. Thus, we chose a Pololu 7.5V step down regulator to achieve both these requirements.

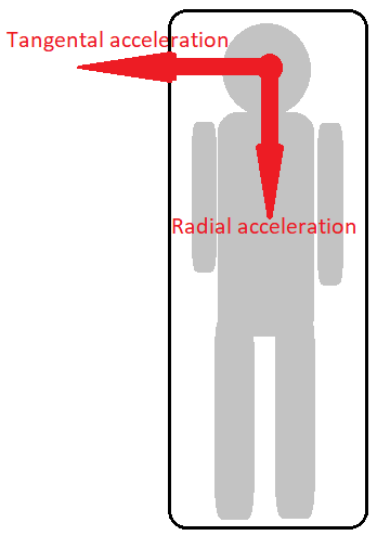
Wires/connectors

We would use physical wires and connectors for any kind of connections in the electrical system.

Control Algorithm:

The goal of the control algorithm is to drive the stretcher angular velocity to zero. While this goal is our number one priority, we have certain safety and comfort criteria that our system must meet. For the safety requirements, we want to limit the acceleration experienced by the patient. For comfort, we will attempt to reduce the jerk experienced by the patient.

Safety



$$a_r = \frac{v^2}{r} = r\omega^2$$

$$a_t = r\alpha$$

a_r: Radial acceleration (m/s^2)
a_t: Tangental acceleration (m/s^2)
v: Tangental velocity (m/s)
ω: Angular velocity (rad/s)
α: Angular acceleration (rad/s^2)
r: radius (m)

Figure: Acceleration experienced by patient on rotating stretcher

Humans can typically survive large accelerations perpendicular to the spine, even up to 10g for 1 minute[30]. However, acceleration along the spine forces blood away or towards the head, causing severe damage in extreme cases. Most people can handle up to 5g along the spine, but our system will most likely be transporting injured patients. Thus, we will attempt to limit the radial acceleration to 0.5g at the patient's head. We chose 0.5g because it is less than the patient would experience while standing upright (1g).

[30] https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/19980223621_1998381731.pdf

Setting our limit to 0.5g ($4.9 m/s^2$) and radius to 1.1m (radius of stretcher) results in a maximum angular velocity of 2.11 (rad/s). This is the worst case scenario, since it assumes the patient's head is located at the tip of the stretcher. Any patient shorter than this height will experience less radial acceleration.

<u>Comfort</u>

Patient comfort is certainly desirable. To maximize patient comfort, we will attempt to limit the jerk experienced by the patient to 0.9 (m/s^3). This is the upper limit of comfort for a seated passenger[31]. Although comfort is desirable, it is not our priority, so exceeding 0.9 (m/s^3) will be acceptable. The total magnitude of jerk is calculated from the following formula:

$$||J(t)|| = r\sqrt{(\omega^3 - \frac{d\alpha}{dt})^2 + (3\alpha\omega)^2}$$

We are working on plotting jerk over time, but haven't finalized the code yet. Our plots in this report only contain the angular velocity limits.

System Design (Hieu, Giacomo, Sidharth, Chiraag, Seong)

System Dynamics

We will limit the stretcher motion to one degree of freedom; rotation about the cable axis.

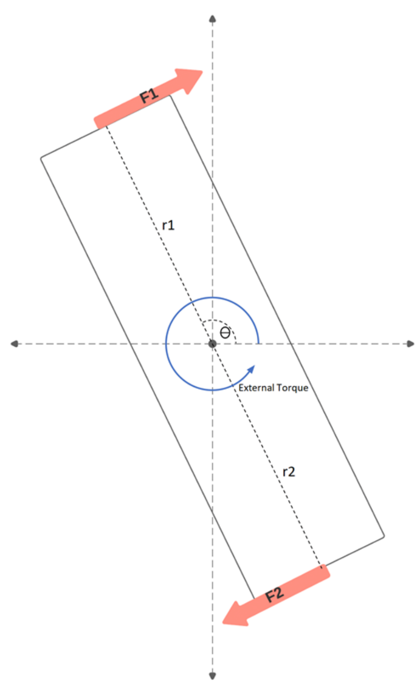


Figure: Stretcher free body diagram

To derive the system dynamics, we will make the following assumptions:

[31] https://www.diva-portal.org/smash/get/diva2:839140/FULLTEXT01.pdf

1. Our four actuators can be reduced down to two forces, since actuators pointing in opposite directions in a given module will never be activated at the same time
2. The torque from the cable, kθ, and torque from wind resistance, cω are negligible
3. All effects due to wind disturbances due to downwash and gusts can be simplified into some time dependent torque on the stretcher, labeled as $\tau_{ext}(t)$. As labeled in the diagram above, torque provided by external forces is opposed to the torque provided by the actuators on the stretcher

   Angular acceleration of stretcher about center:

$$\sum \tau = I\alpha$$

$$\tau_{ext} - (r_1F_1 + r_2F_2) = I\alpha$$

$$\alpha = \frac{\tau_{ext} - (r_1F_1 + r_2F_2)}{I}$$

The forces and torque on the system are time varying, so

Angular acceleration: $\alpha\left(t\right) = \dfrac{\tau_{ext}(t) - (r_1F_1(t) + r_2F_2(t))}{I}$

Angular Velocity: $\omega(t) = \omega_{initial} + \int_0^t \alpha(\tau)d\tau$

Absolute angle: $\theta(t) = \theta_{initial} + \int_0^t \omega(\tau)d\tau$

Using the above equations as a guideline, we derived the discrete time representation of the system as shown below:

State: $x = \begin{bmatrix} \omega \\ \alpha \end{bmatrix}$

Inputs: $u = \begin{bmatrix} F1 \\ F2 \end{bmatrix}$

Disturbance: $w = [\tau_{ext}]$

Outputs: o = $[\omega_{\text{measured}}]$

State Equation:

$$x_t = Ax_{t-1} + Bu_{t-1} + Cw_{t-1}$$

$$\begin{bmatrix} \omega_t \\ \alpha_t \end{bmatrix} = \begin{bmatrix} 1 & 0 \\ 0 & 0 \end{bmatrix} \begin{bmatrix} \omega_{t-1} \\ \alpha_{t-1} \end{bmatrix} - \frac{1}{I} \begin{bmatrix} r_1\,\Delta\,t & r_2\,\Delta\,t \\ r_1 & r_2 \end{bmatrix} \begin{bmatrix} F1 \\ F2 \end{bmatrix} + \begin{bmatrix} \Delta t \\ 1 \end{bmatrix} \frac{1}{I} \tau_{ext}$$

Output Equation:

$$o_t = Dx_{t-1} + N$$

$$\left[\omega_{\text{measured}}\right] = [1 \quad 0] \begin{bmatrix} \omega_t \\ \alpha_t \end{bmatrix} + Noise$$

In our mathematical formulation, our state only consists of angular velocity and angular acceleration. This is because our objective is to stop the stretcher from spinning, which involves driving the angular velocity to zero. We need information on angular acceleration as well because it will be used to determine the safety of the person within the stretcher. The output equation models the angular velocity measured by the IMU. Using information from the IMU system specification chart, noise is modeled as a normal distribution with mean 0 and variance being 2% of actual angular velocity at time t.

Actuator Thrust Model

Typically, a motors RPM is not directly proportional to the input PWM signal. Additionally, RPM to thrust curve for the propellers is also not linear. For example, we can look at other examples of measured motors and propellers.

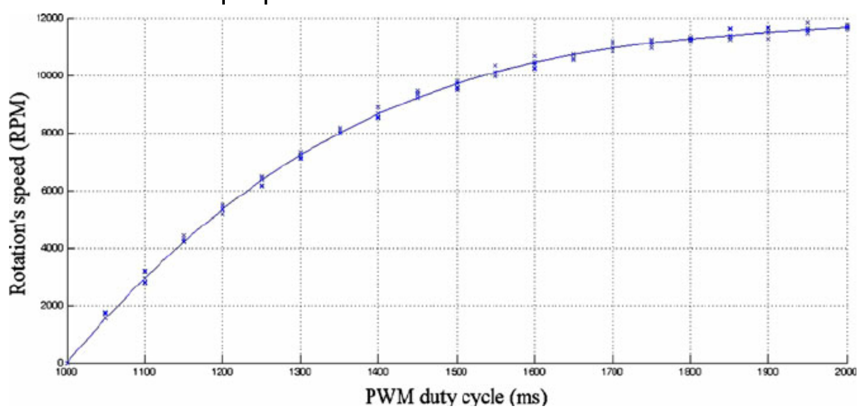


Figure : Measured rotational speed of the motor in various PWMs[32]

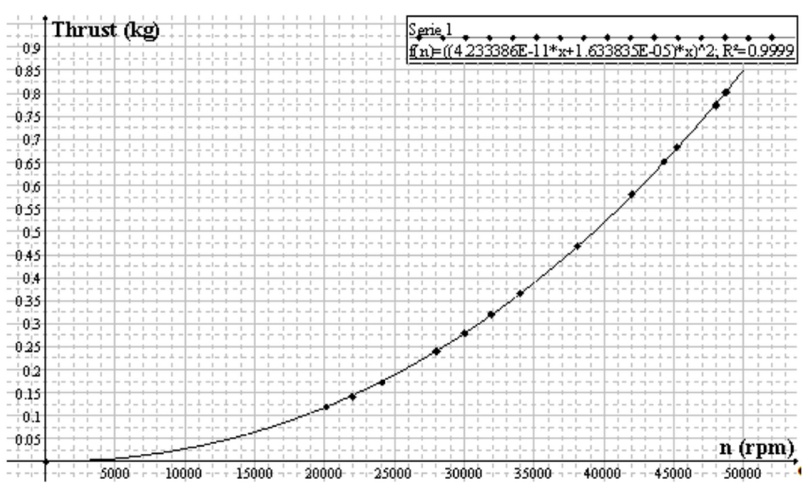


Figure 3: Propeller Thrust (kg) vs. rotational speed (rpm)[33]

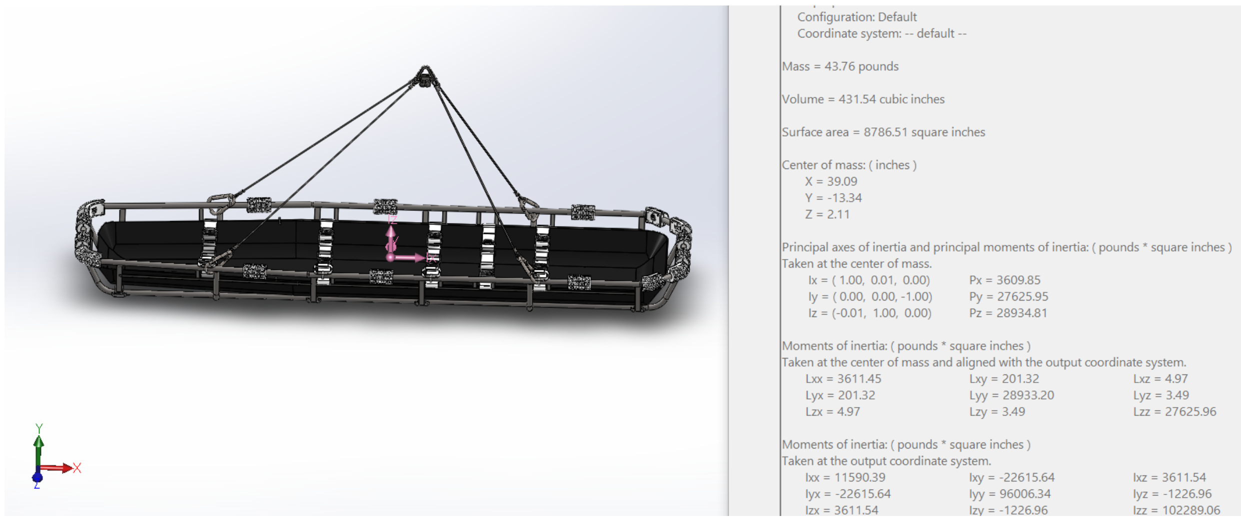
[32] Mohammadi, Mostafa & Mohammad Shahri, Alireza. (2013). Adaptive Nonlinear Stabilization Control for a Quadrotor UAV: Theory, Simulation and Experimentation. Journal of Intelligent and Robotic Systems. 72. 10.1007/s10846-013-9813-y.

[33] Trancossi, Michele & Dumas, Antonio. (2011). A.C.H.E.O.N.: Aerial coanda high efficiency orienting-jet nozzle. SAE Technical Papers.

These examples are for different motors and propellers than the ones we are using. We cannot find data on our specific actuators, so we will go forward assuming the ESCs and/or actuators have been programmed to output thrust that is directly proportional to the inputs.

Rotational Inertia

In determining the rotational inertia of the stretcher system, we used the 3D model provided by Lifesavings Systems Corp. After applying materials to all the necessary components, we were able to get information on the center of mass and the axial moments of inertia. Below is an image showing the center of mass of the stretcher and inertial data.

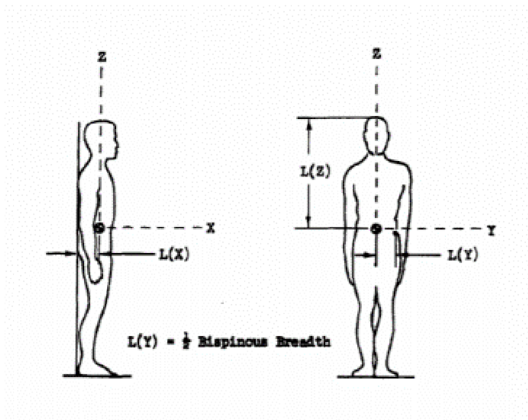


Figure

The coordinate system in pink (created by mass properties feature) is the local coordinate system of the stretcher, which is used to define the directions for the moments of inertia. X is towards the head of the stretcher, Y is toward the side, and Z is towards the sling and the sky. This data is for the stretcher-sling system that connects to the rope. If necessary, we can also obtain inertial data for without the sling system.

We used a paper on anthropometric data and inertia from the Department of Defense to begin modeling a body inside of a stretcher.[34] By taking data concerning the "standing" position and modifying the axes to fit a body laying down, we can approximate the added inertia of a patient in a stretcher. Below is a summary of inertial data for an upright individual, with standard deviations given for a sample size of 66 participants.

[34] Department of Defense Anthropometric Data : https://apps.dtic.mil/dtic/tr/fulltext/u2/410451.pdf



Sample Size 66

Mean Age 33.2 yrs. S.D. Age 7.2 yrs.

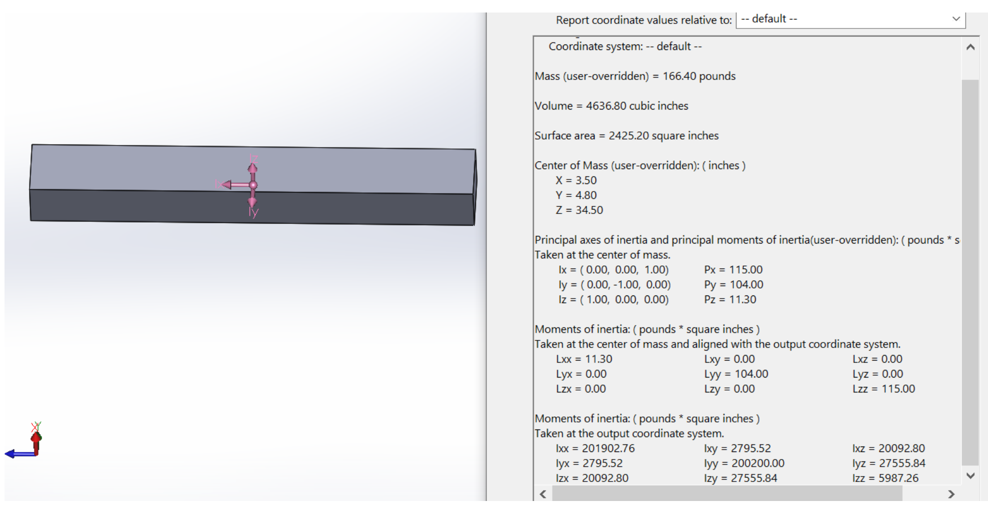
Mean Weight 166.4 lbs. S.D. Weight 19.8 lbs.

Mean Stature 69.4 in. S.D. Stature 2.9 in.

		Axis	Center of Gravity (in.) Mean	S.D.	Moment of Inertia ($lb.in.sec.^2$) Mean	S.D.
1.	Standing	x	3.5	0.20	115.0	19.3
		y	4.8	0.39	103.0	17.9
		z	31.0	1.45	11.3	2.2

Figure:

In Solidworks, we modeled the body as a prism with overridden mass and inertia properties. Since the body will rotate about its center of gravity and is strapped into the stretcher, this is adequate to model in our simulations. Below is a model based on the mean mass and inertia values.



Figure

We also modeled several more bodies that represent 2 standard deviations above and below mean DoD data, as well as extraneous cases of a tall and thin body and a short and stocky body, selected from the sample data. In planning our test cases, we will also vary the locations of the body inside the stretcher rather than strictly lining up the center of masses.

<u>External Torque (Disturbance) Model</u>

While the stretcher is being hoisted, it is subject to downwash from the helicopter, as well as wind from any direction, however, we are not coding a fluid dynamics simulation in python. Our goal is to model wind/downwash as an external torque, with reasonable magnitude and direction over time. We can approximate the bounds of this torque by estimating the maximum force exerted by wind on the stretchers side.

To calculate the force exerted by wind, we will use the following equation,

$$F_{wind} = m_{air} \times V_{air}^2 \times \sin(\theta);$$

$$m_{air} = A_{surface} \times D_{air}$$

which describes the force exerted on a small object for a given wind speed and angle relative to the surface. The maximum wind speed a helicopter can safely operate in is about 90km/hr[35]. Additionally, wind from downwash can travel very quickly as seen from the plot below.

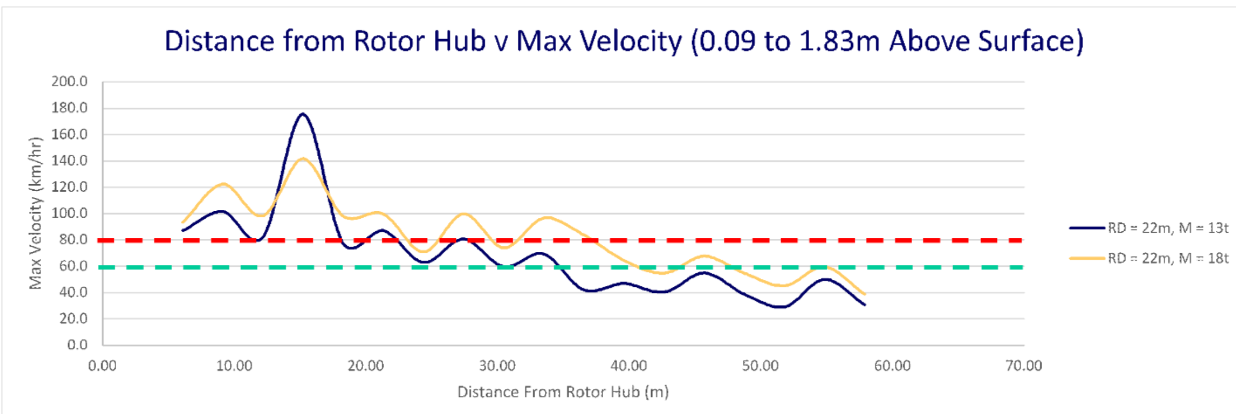


Figure : Distance from rotor hub versus maximum downwash velocity[36]

The wind speed of downwash can range from 40km/hr to 180km/hr depending on distance to rotors. However, it is directed down at the stretcher, and thus the angle at which the air hits the sides of the stretcher is likely low.

Using this information, we can calculate the total force wind or downwash could exert on the stretcher:

---

[35] STARS air ambulance: http://starshorizons.ca/when-is-it-too-windy-to-fly/#:~:text=The%20BK117%2C%20the%20helicopter%20we,rotating%20at%20a%20low%20speed.

[36] JJ Ryan Consulting: https://jjryan.com.au/index.php/helicopter-rotor-downwash-excessive-wind-fod-and-brownouts-what-are-the-risks/

$$F_{wind} = 1.229 \times 0.38 \times 25^2 = 291N$$

$$F_{downwash} = 1.229 \times 0.38 \times 50^2 \times \sin(10^\circ) = 203N$$

Force of wind at 90 km/hr and Force of downwash at 180km/hr and 10°

These numbers look very large, but since this wind is exerted equally across the surface area, there is no torque exerted on the stretcher. Torque is only exerted when there is a difference in pressure along the surface area.

Let us assume the worst-case scenario, in which wind only acts on one side of the stretcher. Then the force exerted by the wind would be 145N spread out across one side. For simplicity, lets us assume that equates to a single force acting at the halfway point between the center of the stretcher and the end. This produces a torque of 78 Nm. Likewise, the maximum torque we would see from downwash would be around 54 Nm. While these numbers are larger than the maximum torque output of our actuators (47 Nm), our solution is not designed to handle extreme scenarios like this. However, we will test all scenarios within this range even if our actuators saturate.

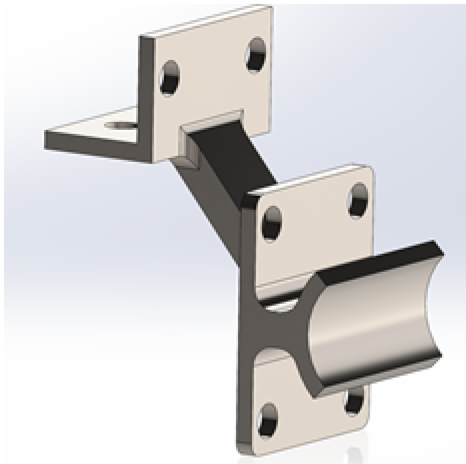
Our goal is to model the external torque over time (disturbance), and design a controller that can reject this disturbance. Since it is very hard to predict what the actual disturbances look like in the real world, we will conduct many tests with many disturbance models between these bounds.

Mechanical Subsystem

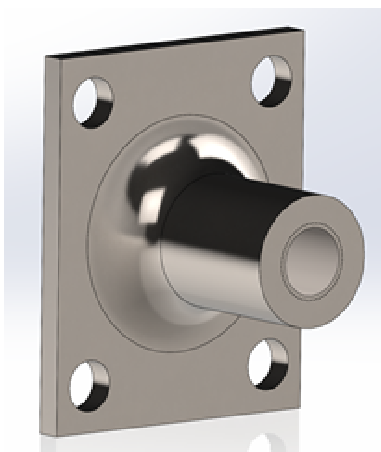
Mounting Hardware

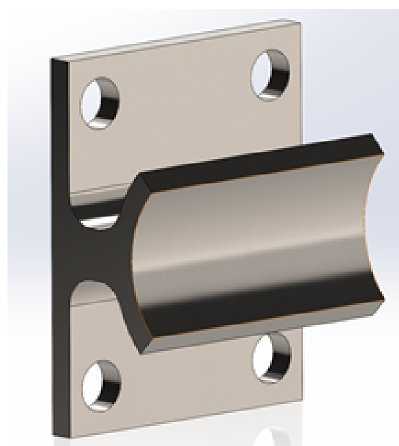
Off the shelf components were chosen when possible to decrease the effort and cost required. They also carry the added benefit of being designed by reputable engineers that have passed scrutiny tests. The horizontal mount uses U-bolts and ¼” – 20 threaded nuts, and washers. The U-bolts were chosen so that a user could tighten the mount around a pipe even if the pipe is smaller than one inch. The same U-bolts, nuts, and washers were also used in the vertical mounts. Other pieces used were a rod end ball joint, an inline ball joint linkage, a ⅜” – 24 threaded rod, and ⅜” – 24 nuts.

The horizontal mount has a custom-made piece named “Pipe Fitting Corner Mount”. It has through holes for ¼” diameter bolts and has a curved section to secure to the horizontal pipes. The other half, seen on the left in both pictures shown below, is the piece that attaches to the chassis, again using ¼” diameter bolts. The reason for the angled piece is to allow a user to unscrew the nuts for the U-bolts while not having to take apart the chassis. Lowering the plate that attaches to the pipe lets the operator use a wrench without interfering with the chassis.

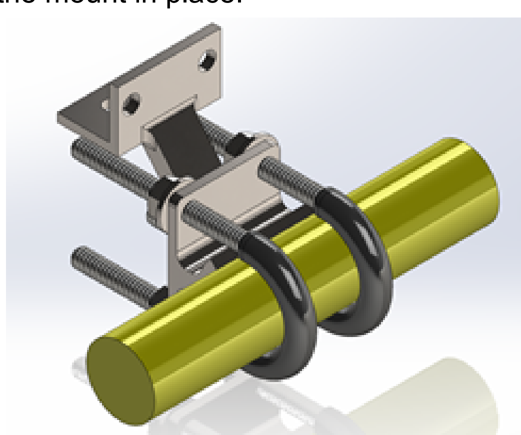


The vertical mounts required two unique pieces, called “Pipe Fitting” and “Pipe Fitting Hole”. Pipe Fitting is used to attach to the vertical pipes, and Pipe Fitting Hole is used to attach the mount to the underside of the chassis and the end of the inline ball joint linkage. The Pipe Fitting is similar to the Pipe Fitting Corner Mount, it was simplified because it did not share the same constraint about removing the U-bolts while in close proximity to the chassis. The Pipe Fitting Hole is simply a plate with a threaded extrusion to accommodate 3/8” – 24 threaded rod.

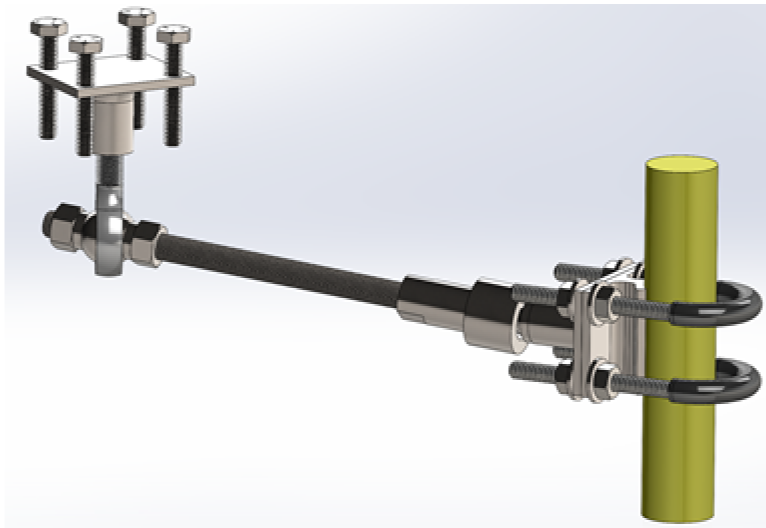




The horizontal bracket is shown below with an example yellow pipe. The operator tightens the nuts to secure the mount in place.



The vertical mount is more complex. First, the Pipe Fitting Hole part is secured to the chassis via four bolts. The rod end ball joint is then threaded into the Pipe Fitting Hole part. A threaded rod is slipped through the ball of the ball joint and held in place by two nuts on either side of the ball. The other end of the threaded rod is threaded into the inline ball joint linkage which is secured to a Pipe Fitting Hole part that is then fastened to the Pipe Fitting part and attached to the vertical pipe of the stretcher.



The rod end ball can be positioned a maximum of 23 degrees from being in plane with the rest of the joint, and the inline ball joint linkage can be positioned a maximum of 7 degrees from it's housing axis.

Electrical Components

______The following electrical component will be stored within the main chassis, separated from the LiPo Batteries and the ESC via an electrical housing; the Arduino CPU, the IMU sensor, the voltage regulator, the CPU DC power socket to 2-pin terminal adapter, and the various wirings and connectors.

The aforementioned components use minimal amounts of power from the battery, and are not a major heat producer of our product. The large majority of our heat is produced from the 22.2V LiPo Batteries and the ESCs. To protect our critical components, a polycarbonate attachment was created to fasten the CPU and IMU and protect them from possible contact with the batteries and ESC. As for the small amounts of heat produced in the components within the housing, the holes that wires are allowed to exit will have slight gaps from being slightly larger than the wires, which will serve as ventilation. As the chassis itself is a competent water and debris-proof casing, the electrical housing will be safe from external threats.

The electrical housing also serves as a convenient way to change and replace batteries and ESC's without intruding the electrical system. For a modular system, an extra layer of protection from debris, water, external forces, and convenience can allow a system to extend its life and use.

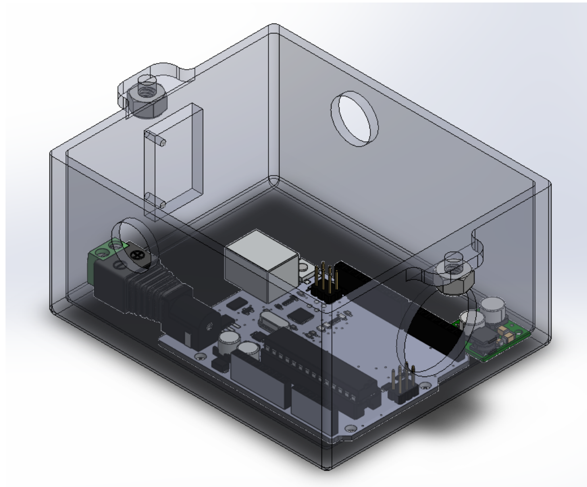


Figure: Electrical housing with electrical components

Battery Integration

After further research, the product we concluded would meet our design specifications for the battery foam was the Tflex™ B200, a reliable compliant thermal material offering good thermal performance. It has high dielectric insulation which works to prevent dielectric breakdown and is made of ceramic filled silicone, a waterproof material. Placing this material in between the vent and the battery allows us to properly vent the heat from the batteries while keeping unwanted water, dirt, and oils outside. The foam also has a tacky side, used to attach to the battery, ESC, and the chassis to hold them together structurally.

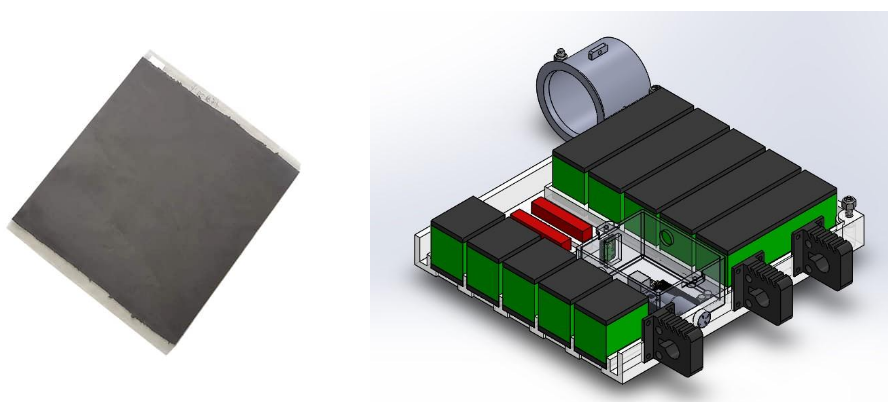


Figure: Tflex™ B200 from Digikey (left) on the batteries in chassis (right)

Chassis and Subchassis

______The figure below shows the final chassis design after numerous iterations. The two top and bottom components are very similar, allowing for easy revisions and updates.

The base was first extruded long enough to include the components within the chassis, including the batteries, ESC's, and other electronics. The holes were then created in the walled components, with room for ¼" socket head screws. The fan holders were then extruded out with their own screw holes to hold them in place. Cuts and wiring holes were created to ensure that the fan would be able to fit.

Once the fans were created, the ribs inside the chassis were created to hold the batteries, ESC's, and foam together without falling apart. The vents for these components were then created. Mounts were also attached to the corner of the chassis and the bottom of the chassis, with ¼" hex screws to keep the mounts in place. Finally, the electronic components were placed with the power button, ensuring that the CPU would remain separate from the batteries and ESC's and allow for easier exchange of parts.

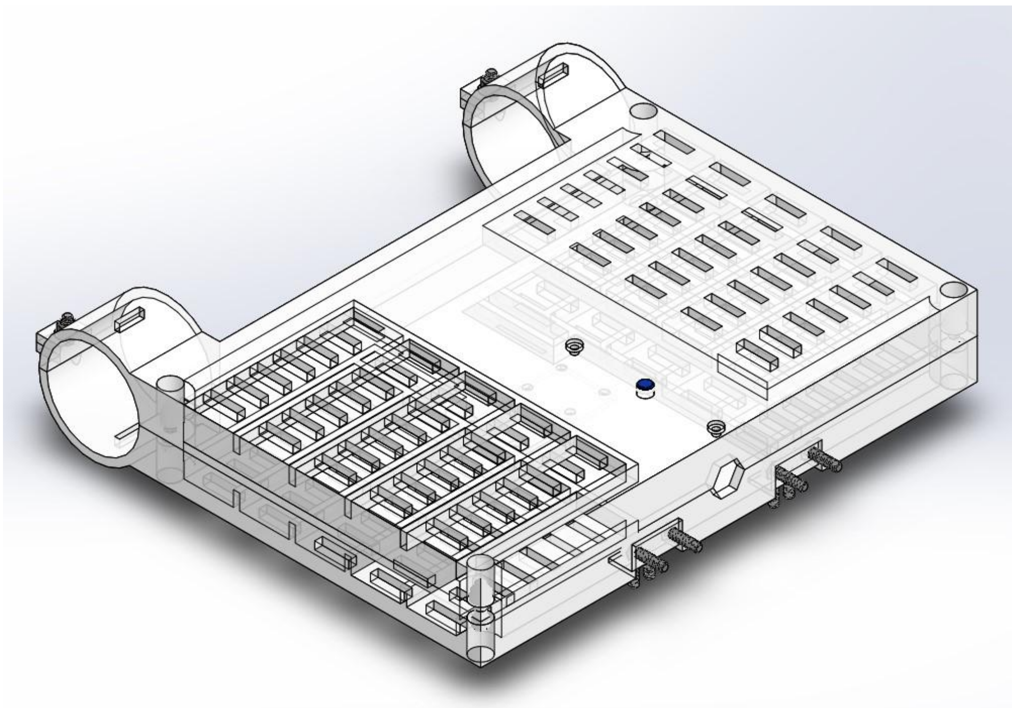


Figure: Chassis for main module. The subsystem chassis has similar properties.

The sub-chassis followed a similar iteration process with some final design modifications. Since this module is connected to the other module via wire, unnecessary electrical components were eliminated. Other than these changes, the sub-chassis remains the same as the main chassis.

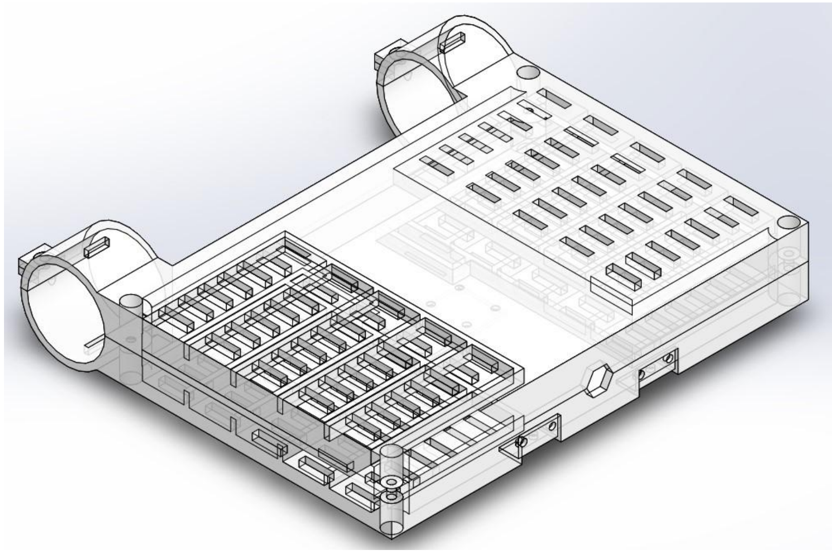


Figure: Chassis for sub-module.

Assembly

The assembly of all components was fairly simple to integrate given the comprehensive design of the chassis. The figure of the main assembly shows the final assembly's configuration which will be attached to the stretcher as shown in the figure following:

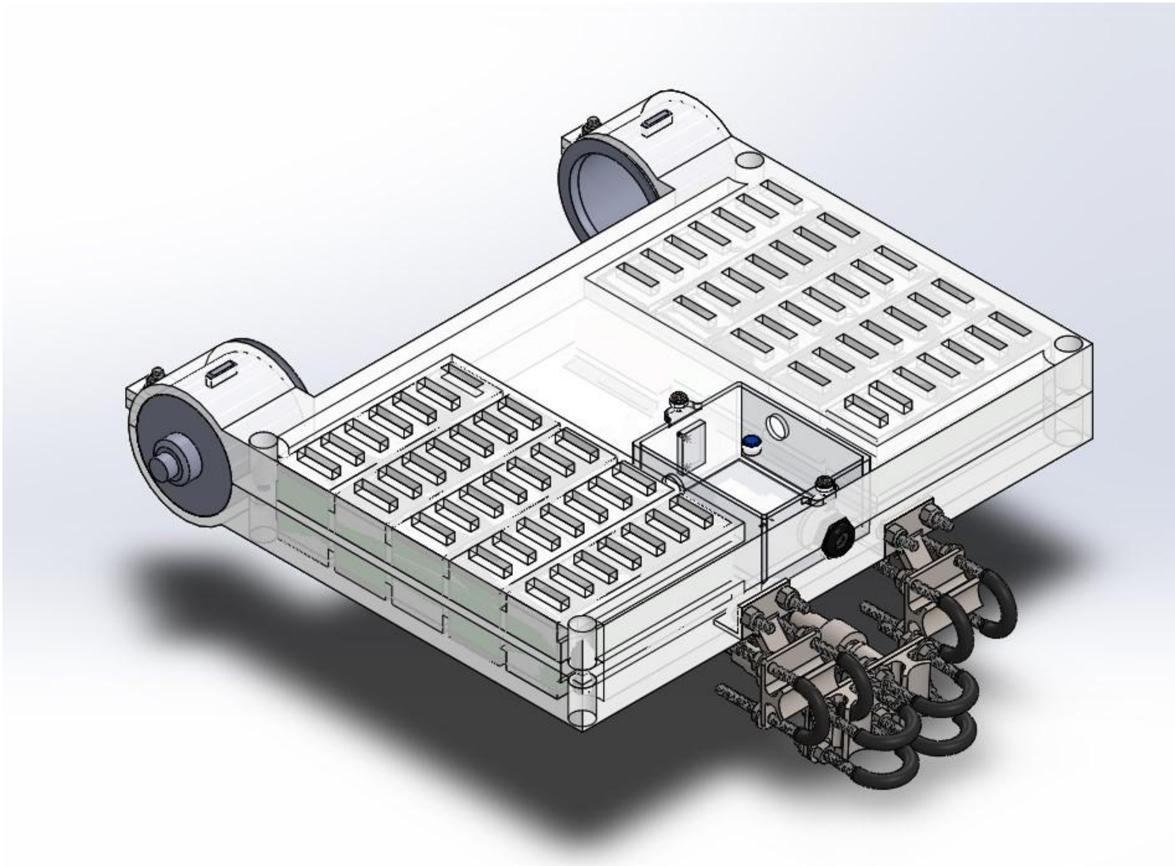


Figure: Main assembly including chassis, fans, mounts, electronics, and batteries.

The final chosen configuration was a device horizontal to the ground in parallel with the stretcher, offset from the stretcher itself. This configuration was chosen to avoid receiving the weight of the stretcher at the bottom, which may crush the modules when the patient is placed on the stretcher. We believe that the mounting system is strong enough with enough points of contact such that the device will not slip, rotate, or translate around the stretcher bars. This is yet to be confirmed through testing.

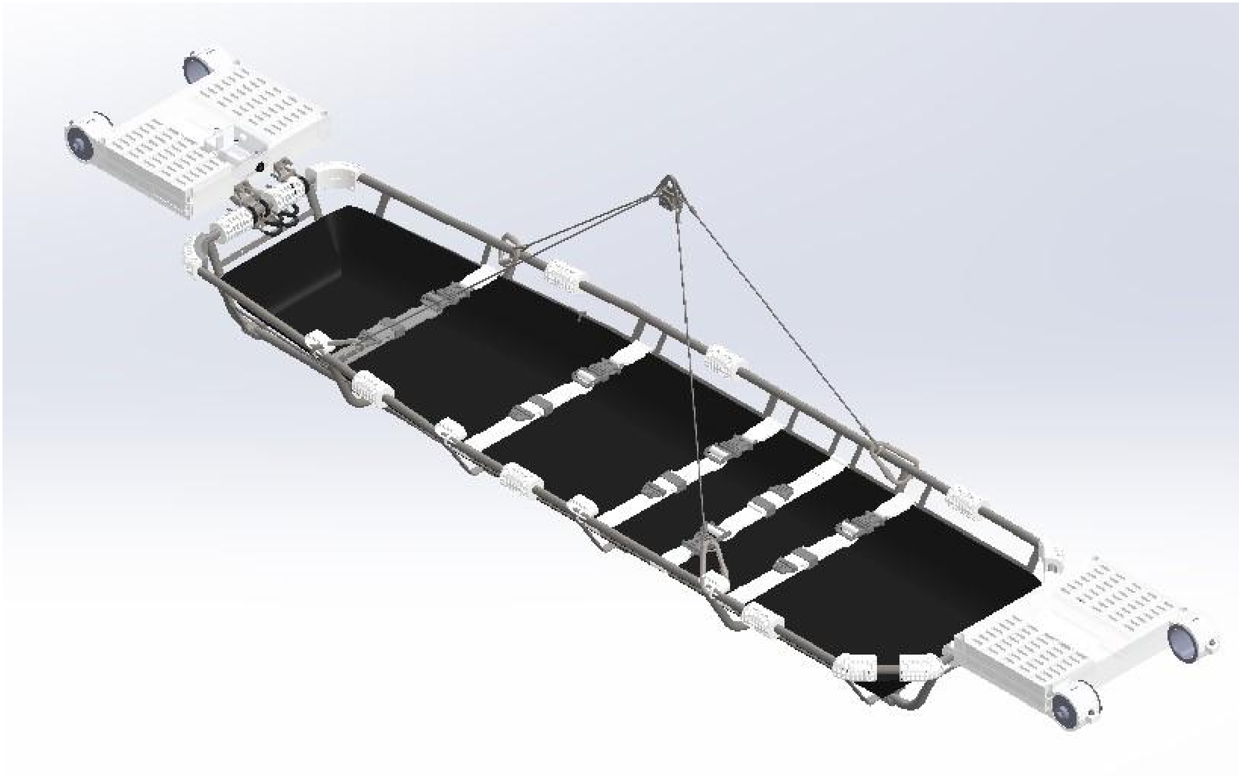


Figure: Assembly of the stretcher with the main and sub-modules.

The assembly is designed to be able to fit in this formation on any stretcher. Though we have only been given one CAD model stretcher, we have been given drawings of other stretchers to be able to confirm this assumption.

Electrical Subsystem

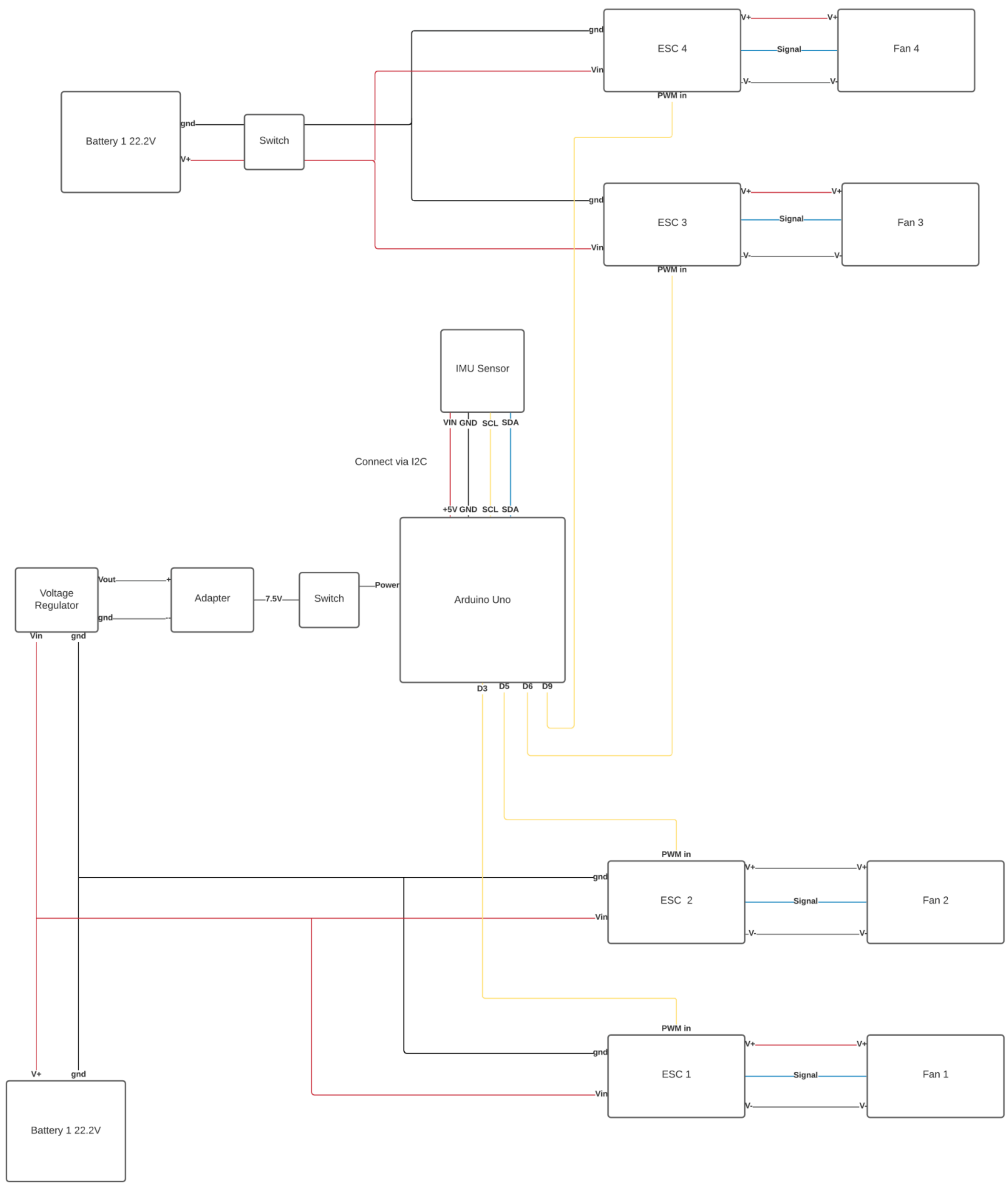


Figure: Electrical Schematic

We would use colored wire cables to connect between pins so it would be easy to debug if the connections were suspected to be wrongly wired. This would make the manufacturing process more smooth since the flaws that related to the electrical subsystem could be found in an easy way. The colors of used wires should match with the colors in the above schematic except for the two wires connected between CPU and ESC3,4 since we would use 2-conductors-cable.

For each battery in the Electrical Schematic, we design it by connecting 10 22.2V/6S - 35C batteries in parallel as shown in the figure (battery housing). We would use combinations of XT 60 male Connectors and 12 AWG Stranded Copper Wire Cables for the wiring connection since the 22.2V/6S - 35C battery goes with XT 60 female connector and 12 AWG wire cable fits with the connector[37].

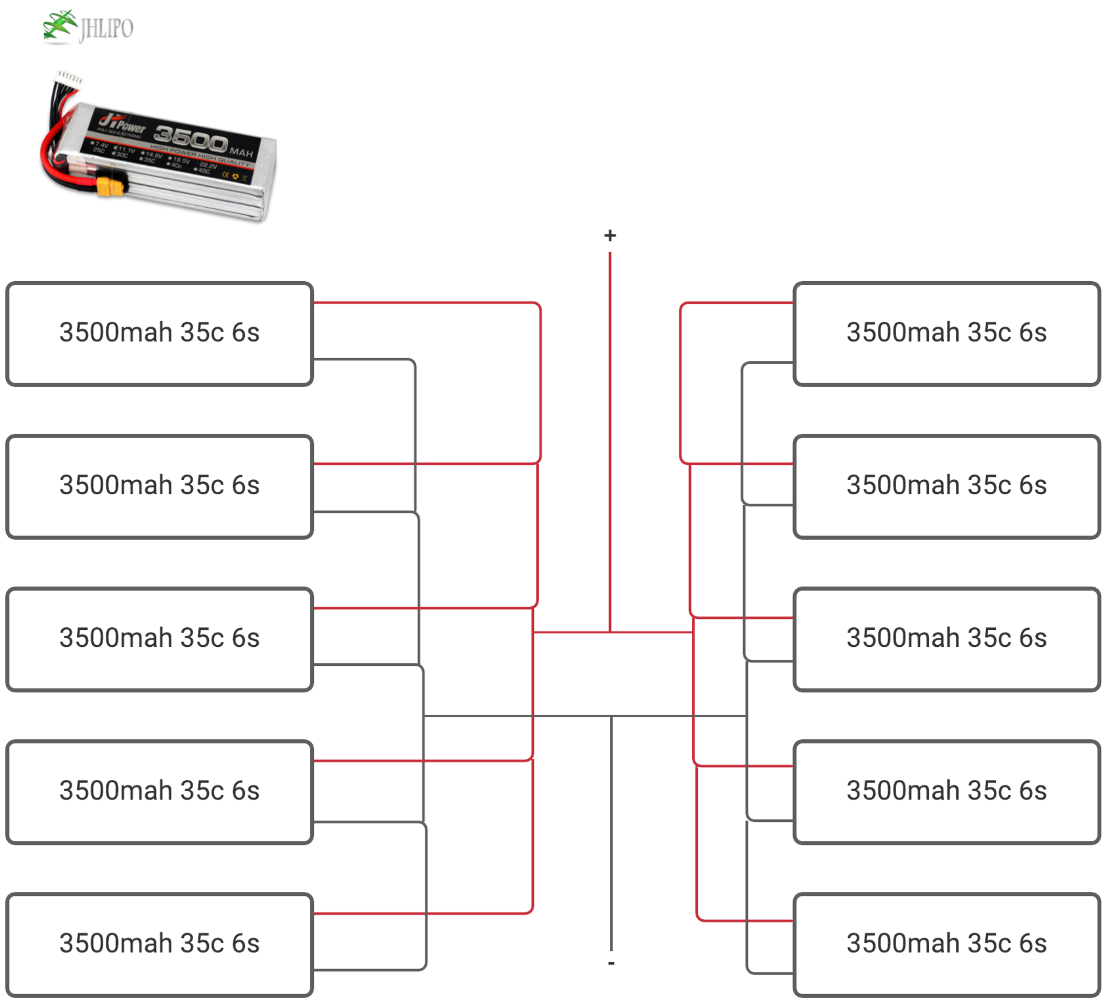


Figure: Battery Housing Schematic

The communication between CPU and IMU sensor is crucial for our autonomous system since the controlled actuators react on the angular velocity of the stretcher around its center of mass. We would connect them via I2C interface by using 30 AWG electric wire cables, which provide good connectivity and excellent uniformity for easy processing, stripping, and terminating. We would do the following instructions to connect the Arduino Board with the IMU sensor[38].

---

37 https://www.amazon.com/Connectors-Replace-Battery-Builder-Hobbyist/dp/B07L3JMZPJ/ref=sr_1_1_sspa?dchild=1&keywords=xt60%2Bconnectors&qid=1617845094&sr=8-1-spons&spLa=ZW5jcnlwdGVkUXVhbGlmaWVyPUFEVkdRREEwNUI4WDkmZW5jcnlwdGVkSWQ9QTA5Mjc5MDUySzVaVjNCMUpZUzVNJmVuY3J5cHRlZEFkSWQ9QTA2MDQxODYxVFo2QkNSTjdIQzlEJndpZGdldE5hbWU9c3BfYXRmJmFjdGlvbj1jbGlja1JlZGlyZWN0JmRvTm90TG9nQ2xpY2s9dHJ1ZQ&th=1

38 https://learn.adafruit.com/lsm6dsox-and-ism330dhc-6-dof-imu/arduino

- Connect IMU board VIN (red wire) to Arduino 5V
- Connect IMU board GND (black wire) to Arduino GND
- Connect IMU board SCL (yellow wire) to Arduino SCL
- Connect IMU board SDA (blue wire) to Arduino SDA

By following the wiring instruction, the wires would be connected like the figure below.

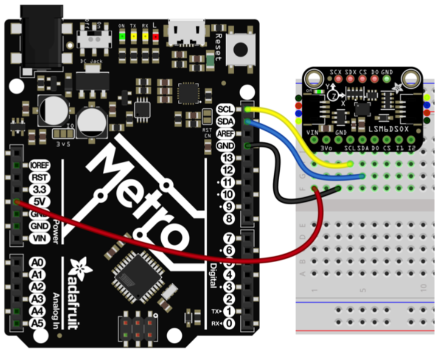


Figure: I2C Wiring with Arduino[39]

Since the Arduino Board is not in the same module as ESC 3 and ESC 4 from Electrical Schematic. We would use 22 AWG-2 conductors-BELDEN B8442MN, which is covered by PVC Jacket. We picked this wire cable because PVC is known as resilient and durable to abrasion[40].

For the connector, we picked a Gxilee IP68 3 PIN DIN Female/Male Screw-on Solder connector[41]. The females will be installed into the main chassis and the sub-chassis, on each side facing the stretcher. The male parts of the connector will be soldered to each side of the BELDEN 22 AWG wire. This connection from the CPU in the main chassis, to the 3 pin female, to the 3 pin male, through the BELDEN WIRE, and to the 3 pin female on the sub-chassis, will directly send the information from the CPU to the sub-chassis ESC.

This connector was chosen for several reasons. The nylon PA66 body and the silicon sealing element allows this connector to survive the harsh conditions of this product; it is waterproof grade, fireproof, debris-proof, and is resistant to corrosion. The screw-on connection also secures the fastening of the wire, preventing slight tugs from a person or object to sever the connection. The screw system also allows ease of deliberate detachment, making it a great choice for a modular, versatile device that still requires a strong wired connection between its parts.

A concern with the wired connection between the two chassis is its vulnerability to external forces, such as tugging, severing, cuts, and being caught. The wire will run inside the stretcher, which eliminates many of these problems, as we assume that the operating conditions make sure that all payloads in the system are relatively safe. The screw connections provide resistance to unintentionally tugging or tripping of the wires. A second protection is added by using a Safcord Cord protector; a 6 foot nylon sleeve that encapsulates the wire. Velcro is lined

[39] https://learn.adafruit.com/lsm6dsox-and-ism330dhc-6-dof-imu/arduino
[40] https://www.digilaptopx.com/index.php?main_page=product_info&products_id=810484
[41]
https://www.elandcables.com/the-cable-lab/faqs/faq-what-are-the-benefits-of-pvc-insulated-cables#:~:text=Cable%20with%20a%20PVC%20insulation,durable%20and%20resistant%20to%20abrasion.

on both sides of the sleeve, and users may secure velcro on the stretcher and the sleeve to guarantee security. All in all, with these two measures, the wire and connection is as safe from the outside as the payload within the stretcher, which we will assume is not in significant danger.

Software Architecture

To rapidly test our control algorithm, we created an analytical simulator which simulates the system dynamics given an external torque, moment arm, and actuator thrust. The advantage of the analytical simulator is that it runs simulations very quickly, and does not require a 3D model of the system. However, the analytical simulator assumes ideal actuator dynamics, and does not provide any visual representation of the system. Thus, we also simulate the system in WeBots to provide a more realistic physics and sensor simulation, as well as a visual representation of the system in action.

Since we are using both python and WeBots to run simulations, we will use the following software architecture that includes a simulation layer, interface layer, and algorithm layer.

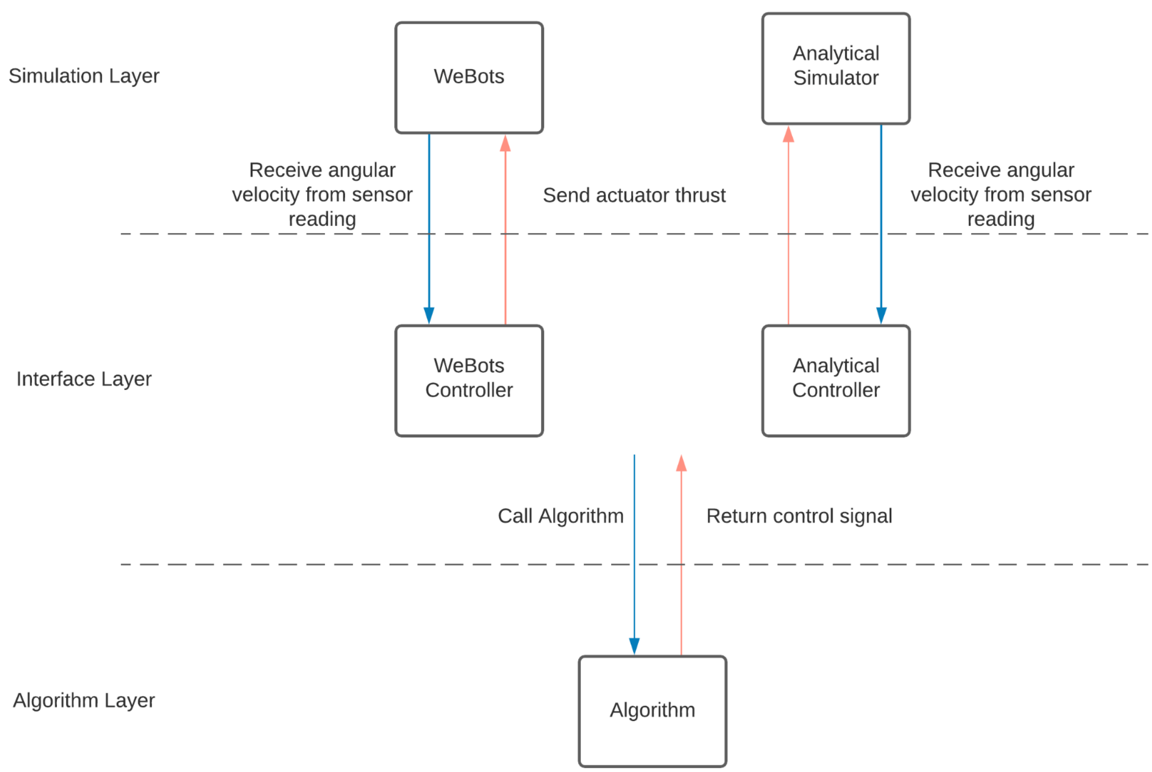


Figure: Software architecture block diagram

This architecture allows us to maintain a consistent control algorithm, and makes switching between simulations easy. Currently, our testing has mostly been done in the analytical simulation. However, as the mechanical model reaches completion, our focus will shift towards WeBots.

Algorithm

Our goal is to drive the stretcher's angular velocity to zero, which requires us to reject any wind disturbance. PID controller is the best candidate to solve the problem. Our job is to define appropriate proportional gain kp, integral gain ki and derivative gain kd[42] such that our requirements are met.

Pseudo-code for Arduino IDE:

While IMU *is available*

Requesting data from IMU
Call PID controller with IMU data as parameter
Compute output from PID controller to get PWM values
Command ducted fans with PWM values

Libraries that is needed for this algorithm are Servo[43] and Adafruit LSM6DS[44]. We would have to install Adafruit LSM6DS since it is not a default library.

Analysis (Giacomo, Hieu, Sidharth, Jake, Chiraag, Seong)

Overview

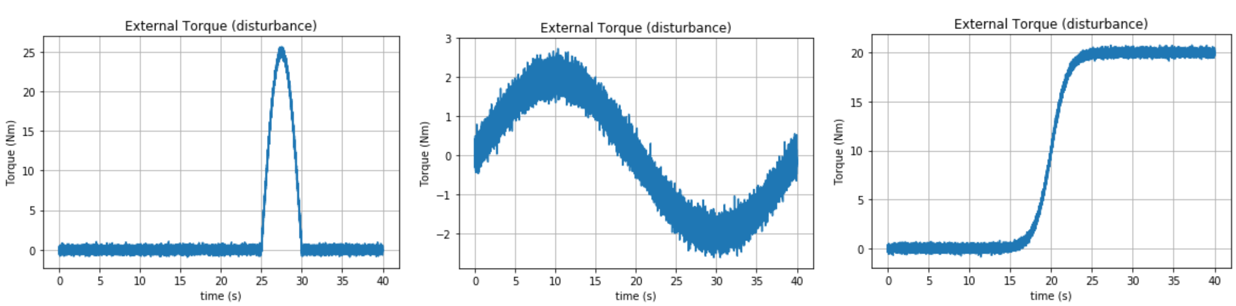
We will analyze the effectiveness of our system by evaluating the control algorithm performance in both simulation types, as well as the mechanical robustness. In order to test our control algorithm, we must test it on different wind disturbance scenarios and different payloads.

Formulation of Test Scenarios

To make sure our control algorithm is robust, we are testing it thoroughly in many different conditions. The unknowns we can test it on include the wind disturbance, differences in stretchers (payload), and differences in body position within the stretcher.

<u>Wind disturbance modeling</u>

In order to build a library of disturbance models, we created a wind disturbance toolbox. This toolbox includes a set of basis durbances that can be added quickly into the overall disturbance model. So far, we have gusts, sinusoids, and step disturbances.



(a) (b) (c)

[42]https://web.archive.org/web/20150421081758/http://saba.kntu.ac.ir/eecd/pcl/download/PIDtutorial.pdf
[43] https://www.arduino.cc/reference/en/libraries/servo/
[44] https://learn.adafruit.com/lsm6dsox-and-ism330dhc-6-dof-imu/arduino

Figure: a) 25Nm gust, b) Low frequency sinusoid, c) 20Nm step

By combining these basis disturbances, we can come up with many unique test scenarios. As defined in our system dynamics, the maximum external torque we expect to see is 78Nm. Below are examples of disturbances that fall within these bounds.

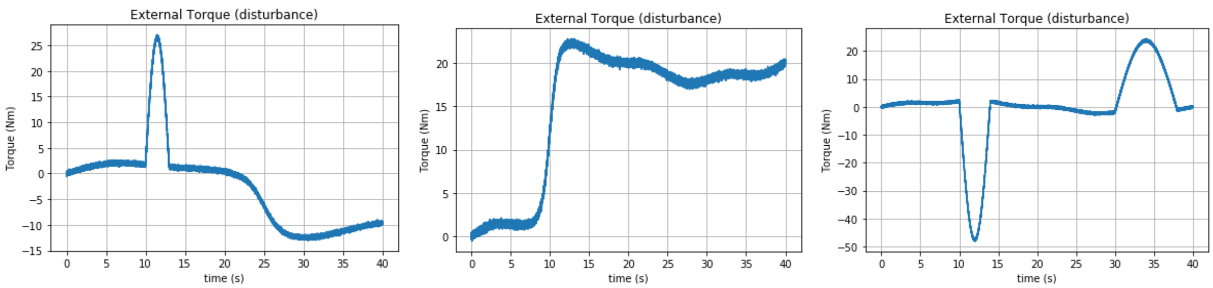


Figure: Various disturbance models created with toolbox

Payload variance

We plan on varying the payload of our stretcher device by swapping out our modeled patient body with the 5 total body models as mentioned in the System Dynamics section. This represents a wide range for the possible payloads that our system can control for. In the numerical simulation, we can calculate the total rotational inertia after swapping out our body model. In Webots, we can simply replace the body model with a different one and change the mass and inertia properties accordingly.

Payload positioning

We will also vary the position of the payload inside the stretcher to account for non-perfect alignments of the body and stretcher centers of mass. We can perform a similar mathematical adjustment to the total rotational inertia for the numerical simulation, and move the location of the body in the stretcher in Webots.

Numerical Simulation

Since the rotational inertia of the payload (stretcher and human) is unknown to the controller, we have estimated a few different rotational inertia due to the information of rotational inertia that we have obtained in the System Dynamics session.

Rotational Inertia of human: 115 lb.in.sec^2 = 13 kg.m^2
Standard deviation: 19.3 lb in sec^2
Minimum: 115 - 19.3*3 = 57.1 lb.in.sec^2 = 6.5 kg.m^2
Maximum: 115 + 19.3*3 = 172.9 lb.in.sec^2 = 19.5 kg.m^2
Rotational inertia of stretcher: 115 lb.in.sec^2 = 13 kg.m^2

Total Rotational inertia:

- Average: 26 kg.m^2

- Minimum: 19 $kg.m^2$
- Maximum: 32 $kg.m^2$
- Empty stretcher: 13 $kg.m^2$

Taking advantage of the Control System Toolbox in Matlab, we used the PID auto tuner to tune our controller with the average rotational inertia (26 $kg.m^2$). The table below contains controller gains, performance and robustness. The performance is superior to the baseline PI controller that Matlab automatically designs for the defined plant. Especially, with 6.92% overshoot, we might be able to avoid the case of angular velocity crossing over the safety threshold (2.1 rad/s).

Controller Parameters

	Tuned	Baseline
Kp	82.2192	25.5118
Ki	26.5457	5.0149
Kd	2.6546	n/a
Tf	n/a	n/a

Performance and Robustness

	Tuned	Baseline
Rise time	0.604 seconds	1.57 seconds
Settling time	5.84 seconds	12.6 seconds
Overshoot	6.92 %	11.6 %
Peak	1.07	1.12
Gain margin	-Inf dB @ 0 rad/s	-Inf dB @ 0 rad/s
Phase margin	90 deg @ 3.16 rad/s	78.9 deg @ 1 rad/s
Closed-loop stability	Stable	Stable

After figuring out the initial PID parameters, we tested this controller with different rotational inertia with step disturbance in the range of 12Nm-20Nm, which is the average range for external torque shown in the Guardian News video[45]. The figure below shows the simulink model that we used to test these cases.

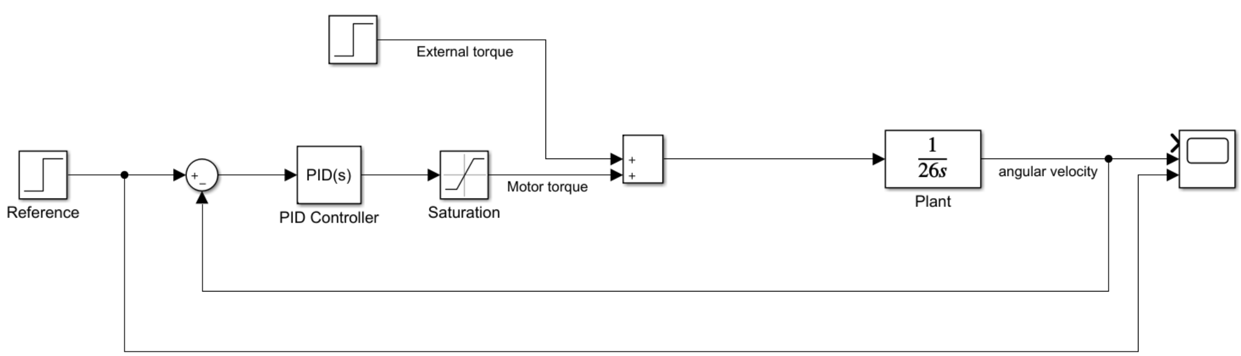


Figure: Simulink Model for Closed-Feedback Loop

[45] https://www.youtube.com/watch?v=yhKZCy41g5w

Here is the detailed-level block diagram for the PID controller that we used for the helicopter payload self stabilizer system. The filter coefficient was set to be 100.

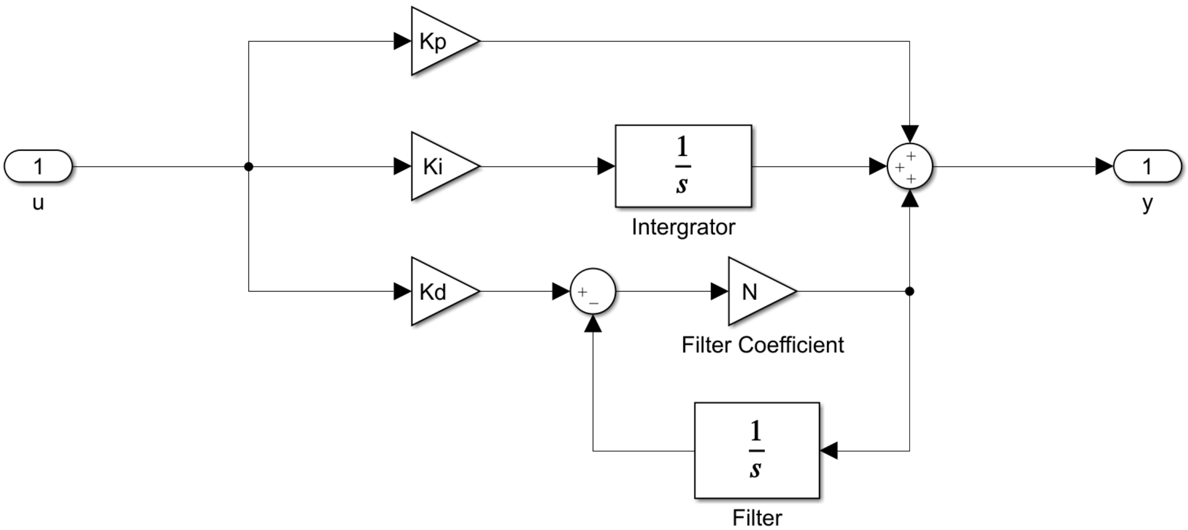


Figure: PID Controller Model

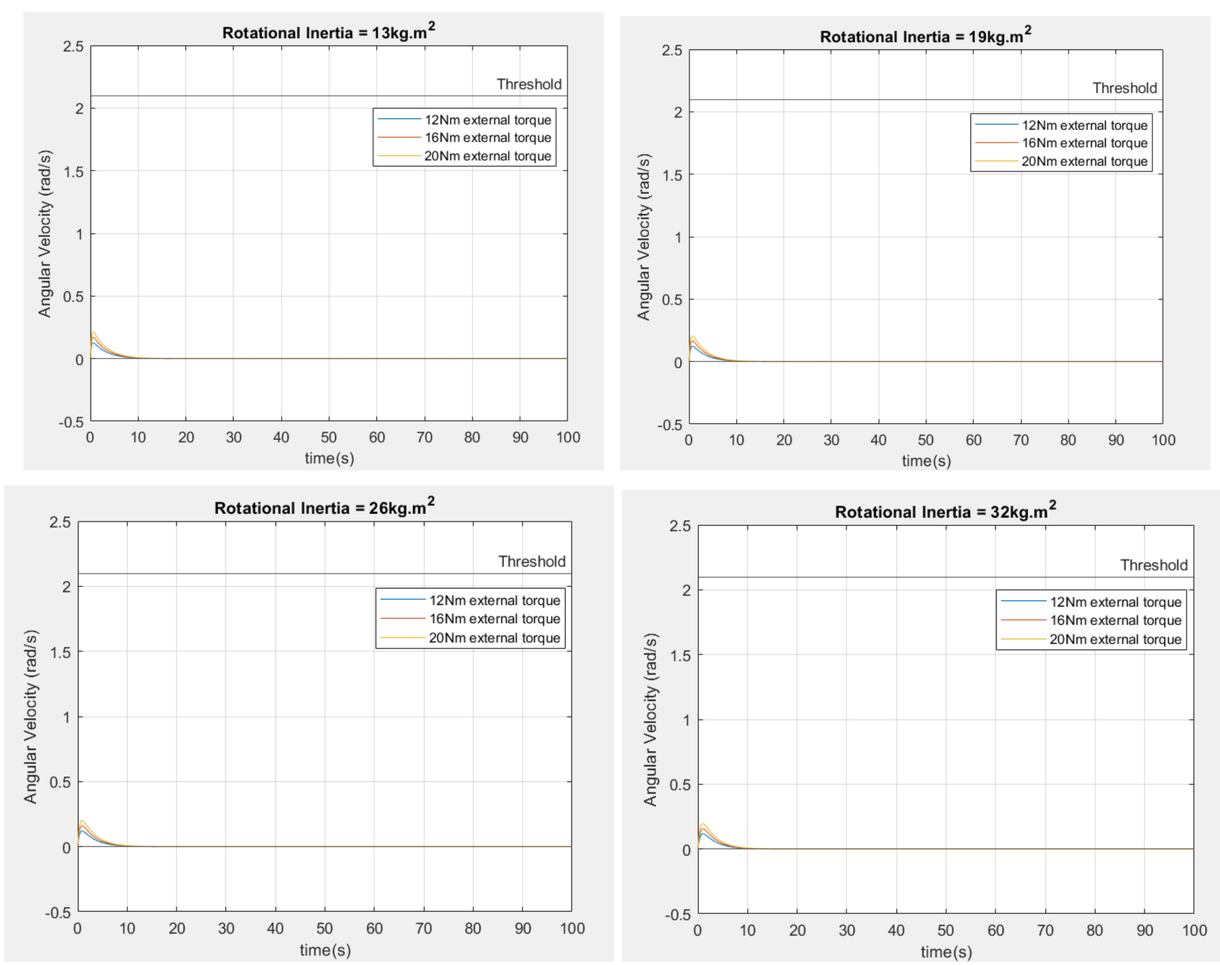
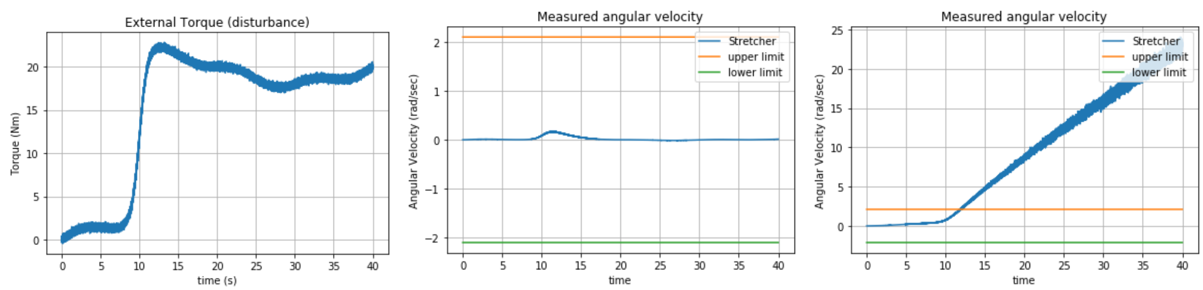


Figure: Test Runs with Rotational Inertia Variance and External Torque Variance

According to the results shown in the above figure, the angular velocity never crosses the threshold line (2.1 rad/s) which we define to be the upper limit that the person can handle during hoisting operation. Therefore, we decided to keep the parameters for the PID controller and we would test the controller with more complicated disturbance in the Physics base simulator to evaluate and optimize the controller by following the safety measure that we defined.

<u>Preliminary Results</u>

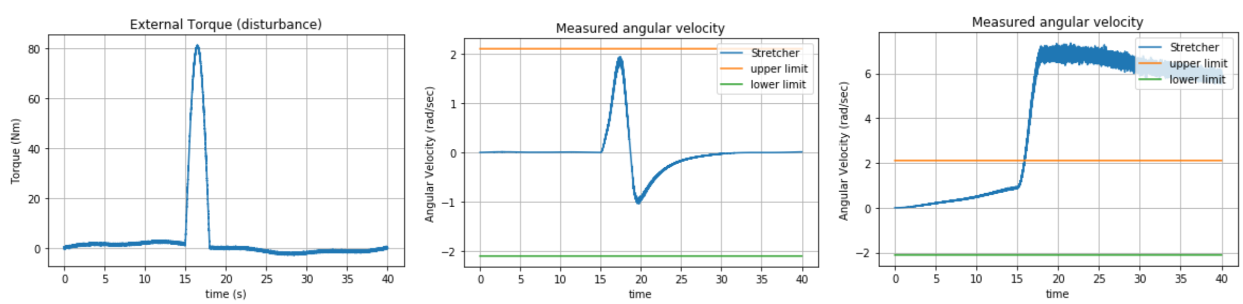
To make sure the control algorithm is working as expected, we have run several simulations using the average rotational inertia of 26 kg m^2.



(a) (b) (c)

Figure: a) Disturbance, b) Compensated c) Uncompensated

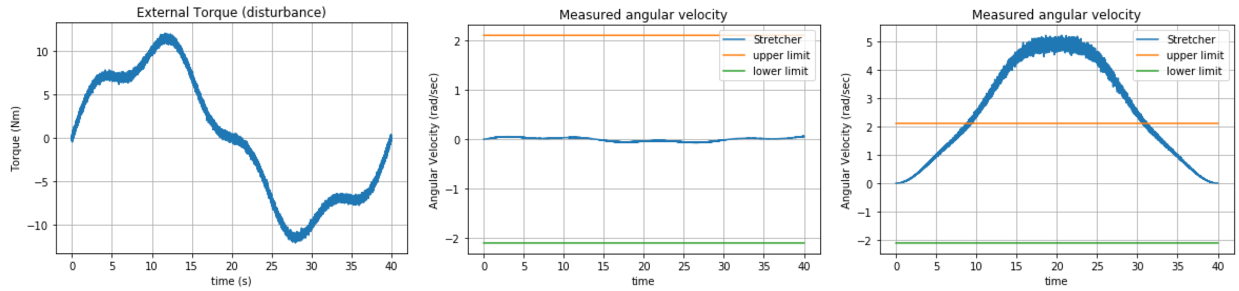
In the above figure, the disturbance is less than our maximum actuator output, and the stretcher's angular velocity stays well within the limits. In this case, the uncompensated stretcher goes very far above the safety limits. In the next scenario, we tested our algorithm on a three second gust of 80Nm.



(a) (b) (c)

Figure: a) Disturbance, b) Compensated c) Uncompensated

Again, the compensated stretcher manages to stay within the bounds even when the external torque exceeds the maximum actuator output. However, a longer duration gust of this magnitude would force the stretcher into the unsafe zone. Next, we test the control algorithm on a sinusoidal disturbance.



(a) (b) (c)

Figure: a) Disturbance, b) Compensated c) Uncompensated

The compensated stretcher has some difficulty rejecting the sinusoid, but does much better than the uncompensated stretcher. We will continue to test and improve our control algorithm as we shift our focus to the mechanical simulation

Mechanical Simulation

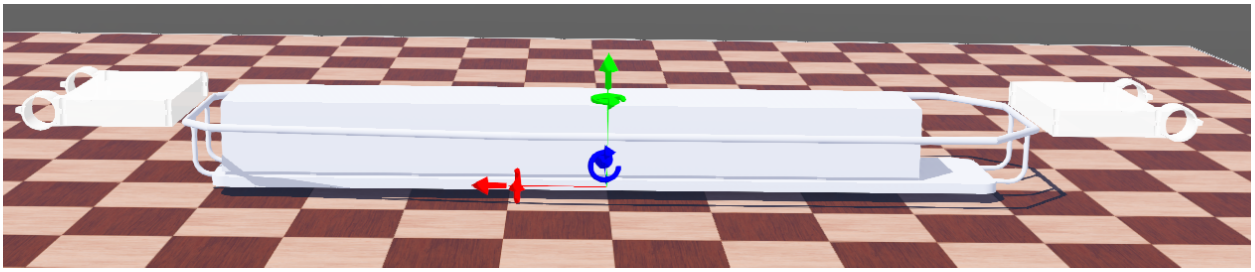
<u>Webots</u>

In order to validate our system design and numerical simulation, we also modeled our stretcher-body-device system in Webots. Webots is an open-source physics and robot simulator from Cyberbotics LTD that allows us to accurately model the kinematics of our system. Through this software, we can model the bodies, sensors, and controllers necessary to recreate and match the results of the numerical simulation.

To model our components in the Webots environment, we imported the solidworks models of our stretcher in VRML format as 3D objects. Due to the complex nature of our stretcher and device models used in the design process, we created simplified models with approximate geometries to use in Webots. By specifying the components' mass and inertia values to be the same as determined by our final solidworks design, the models are accurate for our simulation purposes.

In order for our Webots simulation to match the kinematics numerical simulation, we made use of various webots structures and simulation parameters to apply our design and test restrictions to the environment. The Connector structure locks the location and orientation of two models, which we used to "strap in" our body model to the stretcher as well as attach our stabilization devices to either end in the correct location. Similarly, a HingeJoint modeled at the base of our stretcher restricts the movement to a one degree-of-freedom spin. The external inputs on the system are modeled through the Supervisor node of our robot as a torque on the body, similar to our numerical solution. Our rotors are modeled using the Propellor node, which allows our robot to input a specific fan speed that results in a corresponding thrust force. The IMU in our device is modeled as a Gyro to track angular velocity and placed in its corresponding location in the chassis. The controller mimics that of the numerical solution and our system PID algorithm, receiving angular velocity inputs from the chassis and actuating the fans accordingly to stabilize the system.

Currently, we are in the process of constructing the Webots environment; Below is a preliminary model of our Webots environment.



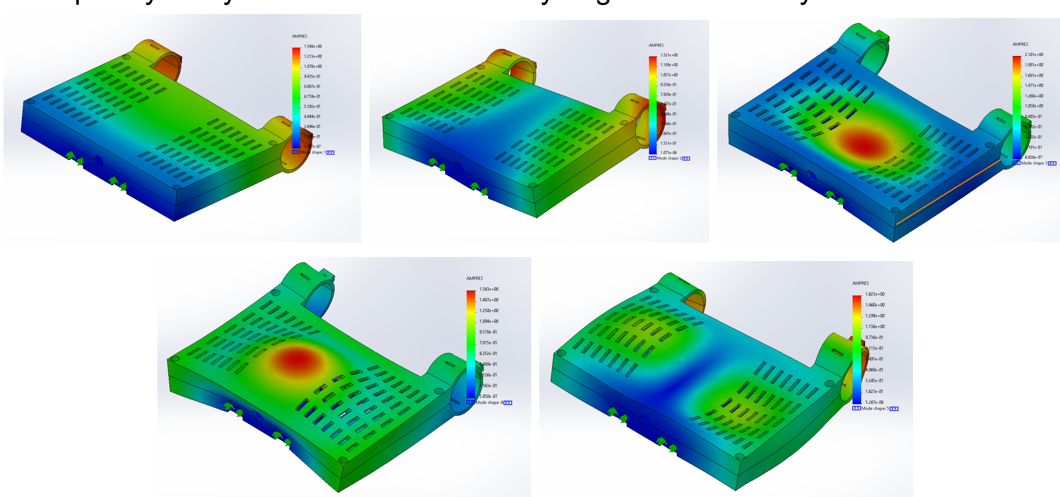
Stretcher, Body, and Stabilization Device Modeled in Webots

We will also recreate our formulated test scenarios in Webots. Different wind disturbances such as gusts, step, and sinusoidal will be controlled by set torque data from the Supervisor node. Payload variance will be achieved by swapping the body model in the stretcher with that of our anthropometric data. We can also vary the payload positioning in Webots by initializing the location of the body and its connector at different locations in the stretcher. Together, these give us a variety of test scenarios to validate our system design in Webots.

Frequency Analysis

FEA Frequency analysis was conducted in Solidworks, using the frequency studies in SolidWorks Simulations.

The sub-chassis was used as a baseline for frequency analysis; the electrical housing of the same material as the chassis provides protection to critical parts of the electrical system, however frequency analysis will still be necessary to guarantee safety.



Mode No.	Frequency(Rad/sec)	Frequency(Hertz)	Period(Seconds)
1	325.56	51.815	0.019299
2	611.45	97.315	0.010276
3	1,155	183.83	0.0054399
4	1,448.6	230.56	0.0043373
5	1,609.9	256.22	0.0039029

Figure: Natural Frequency Analysis results; Modes 1 ~ 5 with Resonant Frequencies

The Powerfun 70mm EDFs have a maximum RPM as standard max EDF RPMs, which is 52000 RPM. This converts to 866 Hz, which is our assumed max frequency applied onto the chassis.

Under this limit, 5 mode frequencies were found when the sub-chassis was meshed and conducted through natural frequency analysis. The controller can be modified to intentionally avoid the following 5 frequencies; 51, 97, 183, 230, and 256 Hz. The mode shapes suggest that Mode 3 and 4 may directly affect the location where the electrical components are stationed; although there is an electrical housing that will provide protection, other measures may need to be made if mode 3 and 4 natural frequencies are in range of common operation frequencies for our system.

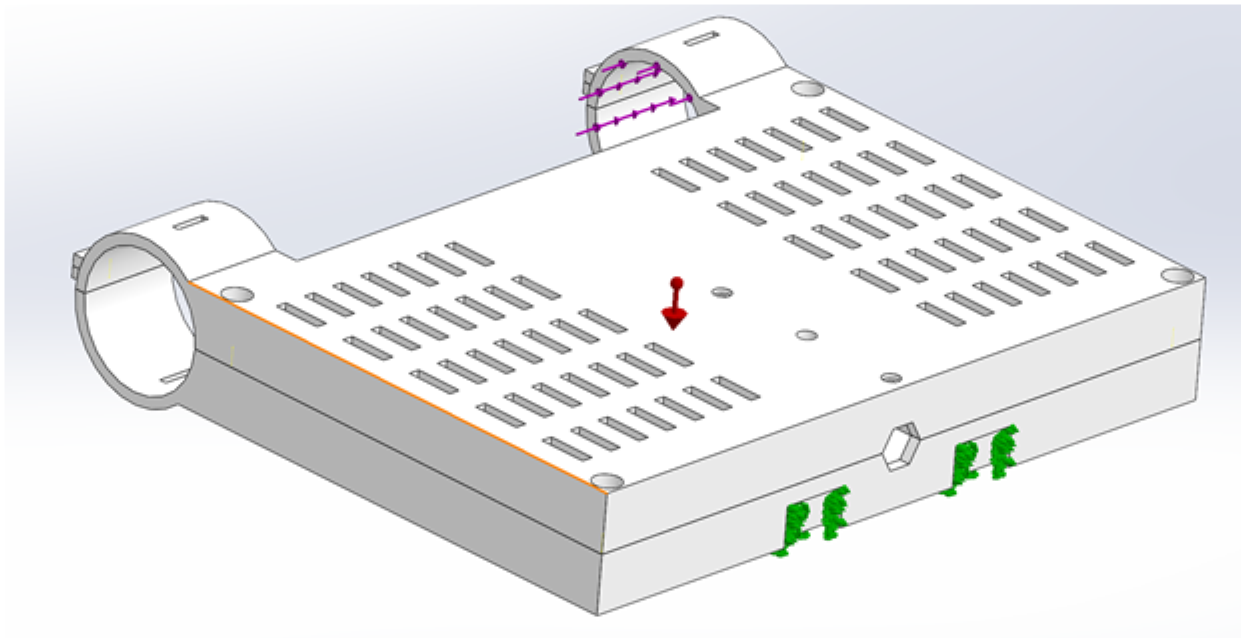
Due to the recent changes to our orientation and chassis, several re-tests with new external loads and gravity considerations are necessary. FEA will be continued for the next two weeks.

<u>Load Tests</u>

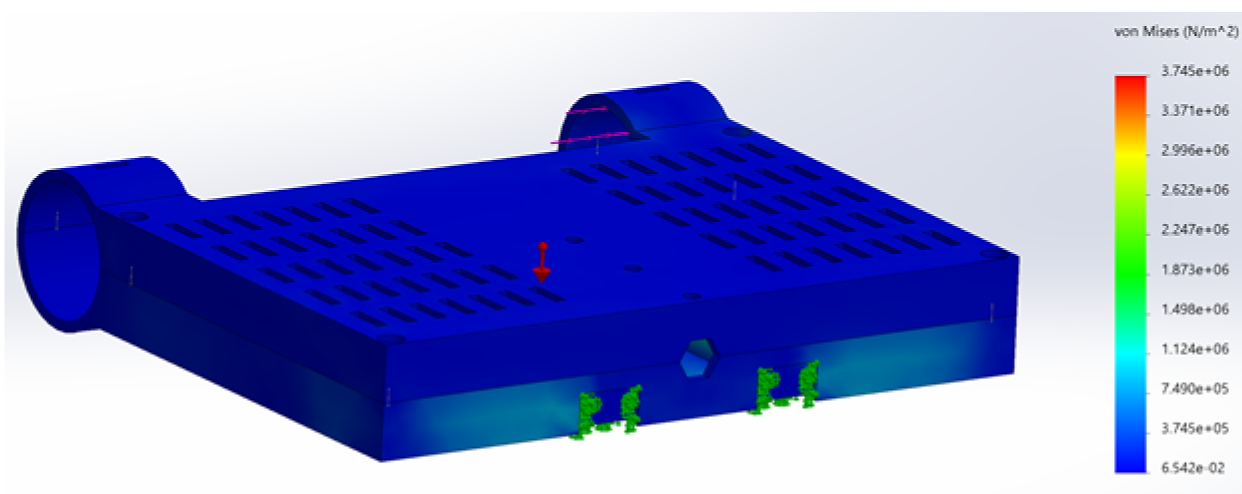
Load testing is done entirely in Solidworks, a professional grade CAD software. All CAD parts and assemblies were also made with Solidworks, making it the de facto choice for simulations. Running simulations is a tedious task that uses a good deal of computing power. For this reason, and others stated below, only the chassis and mounting hardware assemblies have had load tests applied so far.

The purpose of a load test is to determine where stresses are concentrated on a part, to what extent the parts/assemblies are deformed, and to inform on whether or not any pieces fail. It is also critical to know that components' stresses are within our factor of safety during the most rigorous testing scenarios. The components that face the most difficult challenges in a load test are the mounting hardware and the chassis. The other components simply need to be kept in their places to be operational.

The first assembly to undergo a static load test was the bottom and top of the chassis in contact with each other using bolts. The mounting brackets on the side were fixed and the maximum actuator output was simulated from one of the actuator casings. Gravity was also applied to increase the realism of the simulation.

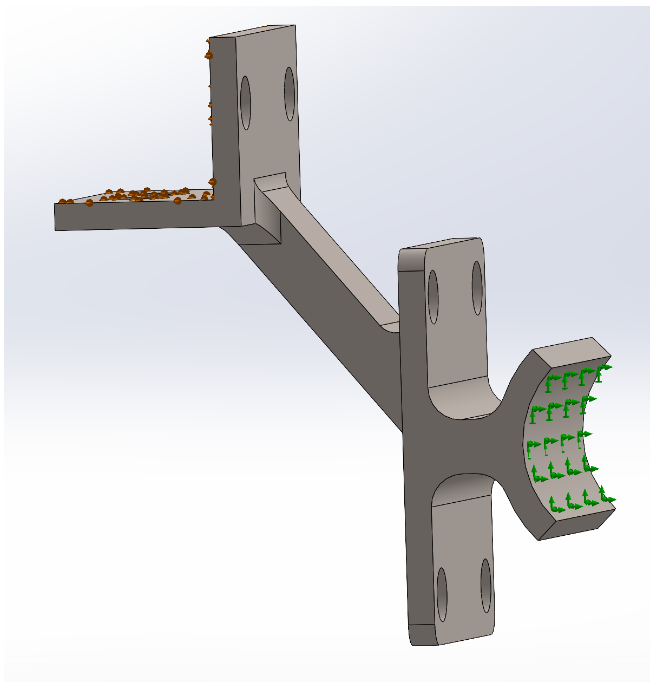


The resulting Von Mises stresses in the part are shown below:

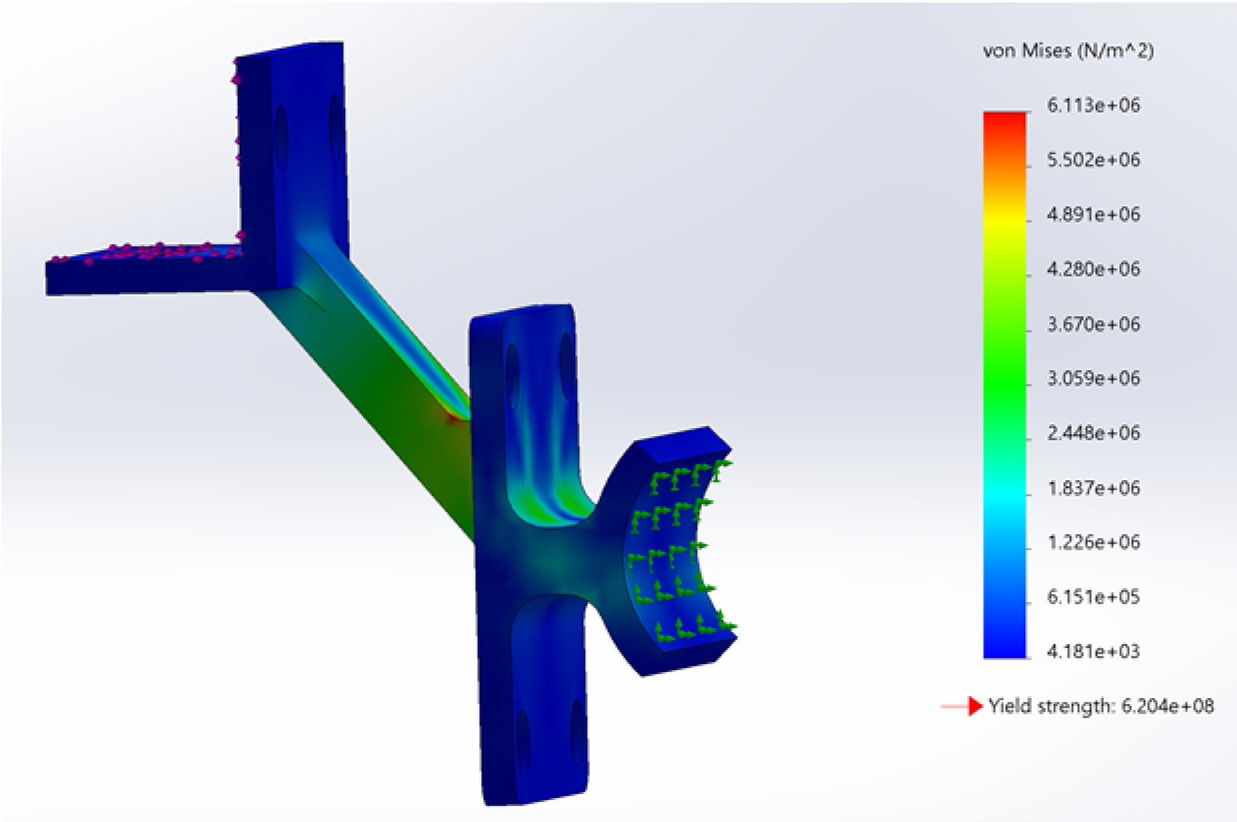


The stresses in this part do not exceed 1.5e+6 N/m^2. The top and bottom halves of the assembly are made of PC High Viscosity plastic, which (according to Solidworks) has a tensile strength of 6.27e+7 N/m^2. While factors of safety are normally calculated using the yield strength of materials, plastics behave differently than metals and so the yield strength is not a parameter that is used. Regardless, the maximum stresses experienced in the chassis due to maximum output by an actuator is far below the threshold for material failure. If we use tensile strength to calculate the factor of safety, this chassis assembly has a factor of safety of over 40.

The next component to be simulated was the “Pipe Fitting Corner Mount” part. This component is made of alloy steel, and was tested by applying a shear force equal to the maximum output by the actuator. This simulation is more extreme than the operating conditions, and while this test is not helpful if the part fails, if it passes this test then it is safe to assume it will pass the real scenario as well. This simulation was done by fixing the area that comes into contact with the pipe.



The stress results of the Pipe Fitting Corner Mount part are shown below:



From the simulation, the part is in no danger of being stressed beyond the yield strength. The maximum simulated stress is 6.113e+6 N/m^2, while the yield strength is 6.204e+8 N/m^2. The factor of safety on this part in this particular simulation is 98.8.

The mounting brackets that attach to the bottom of the chassis and the vertical pipes on the stretcher have ball joints, and more research will need to be done to simulate them correctly. However, if the results of the static simulation on the Pipe Fitting Corner Mount are any indicator, we do not expect to have to redesign the vertical mounts.

The next steps to determine the structural integrity of the device is to perform a static load simulation with the entire assembly with all 189 components. Once this has been done and if the results are favorable, then we can confidently say that our design is structurally robust, and that as long as the frequency simulations are passable then the CAD model for the device is finished.

Unknowns and Concerns (Seong, Jeremy)

Many of our unknowns and concerns have been solved and answered throughout the project duration. The technical questions we have had on our project design and creation were helped by TA and professor help, as well as personal research on the topic. We predict that most of our concerns and unknown in the future will also be technical; we will continue getting direct help from our TAs, professors, and resources. No significant concerns threaten our ability to meet capabilities and requirements of our product.

One aspect of concern that may affect our end product is the lack of experience and knowledge of appropriate test cases. There are many simulations possible given the software we have access to and much research has been done to determine what other designers and engineers test for in their designs. However, specific and relevant cases to our work are few and far between given our product's niche, since we could only find one company to compete with. Established data and research on unmanned aerial vehicles (UAV) and drones provide useful information, however are not generally applicable to our product, which is an attachment and not an autonomous system. As such, there is not a lot of data to compare with nor test cases specific to our design to find. Essentially, we are not sure what we are missing in our simulation test cases, and we do not know what we do not know. One solution may involve a lot of brainstorming, but all the possible test cases are unknown to us at the moment given the resources we have on hand. We will be looking for advice and recommendations in the future.

Refinement of Scope and Future Work (Chiraag, Seong)

Looking towards the next few weeks and the Final Design Review, we are not making any major changes to the scope of our project, which is creating a helicopter evacuation litter stabilization device for rotation about the hoist cable axis. We believe that we will be able to present a final design and multifaceted analysis that supports our capabilities and design requirements.

Though we are making good progress, we decided to revise our schedules to better reflect the current state of our project and future tasks. One issue with our previous Gannt chart was that we set many tasks to start all at the same date and extend for a large period of time (>1 month) despite those tasks realistically needing less time to complete. This was especially true for the latter half of our Gannt chart after week 5, as we left a large buffer time and did not necessarily intend or were able to start certain tasks. For example, load testing was given 4 weeks to complete according to the original chart, but due to finalization and updates to our chassis we did not start it at the intended date. We still felt we were on time in completing our work for the quarter, but the Gannt chart did not reflect that indicated that we were severely behind. Another major update to our Gannt chart is the addition of Week 10; Our initial chart mistakenly only extended to week 9 and had all of our project finishing by then. This revision gives us a more accurate schedule and space to plan our goals to the end of the quarter. Our updated Gannt chart is available in Appendix 3.

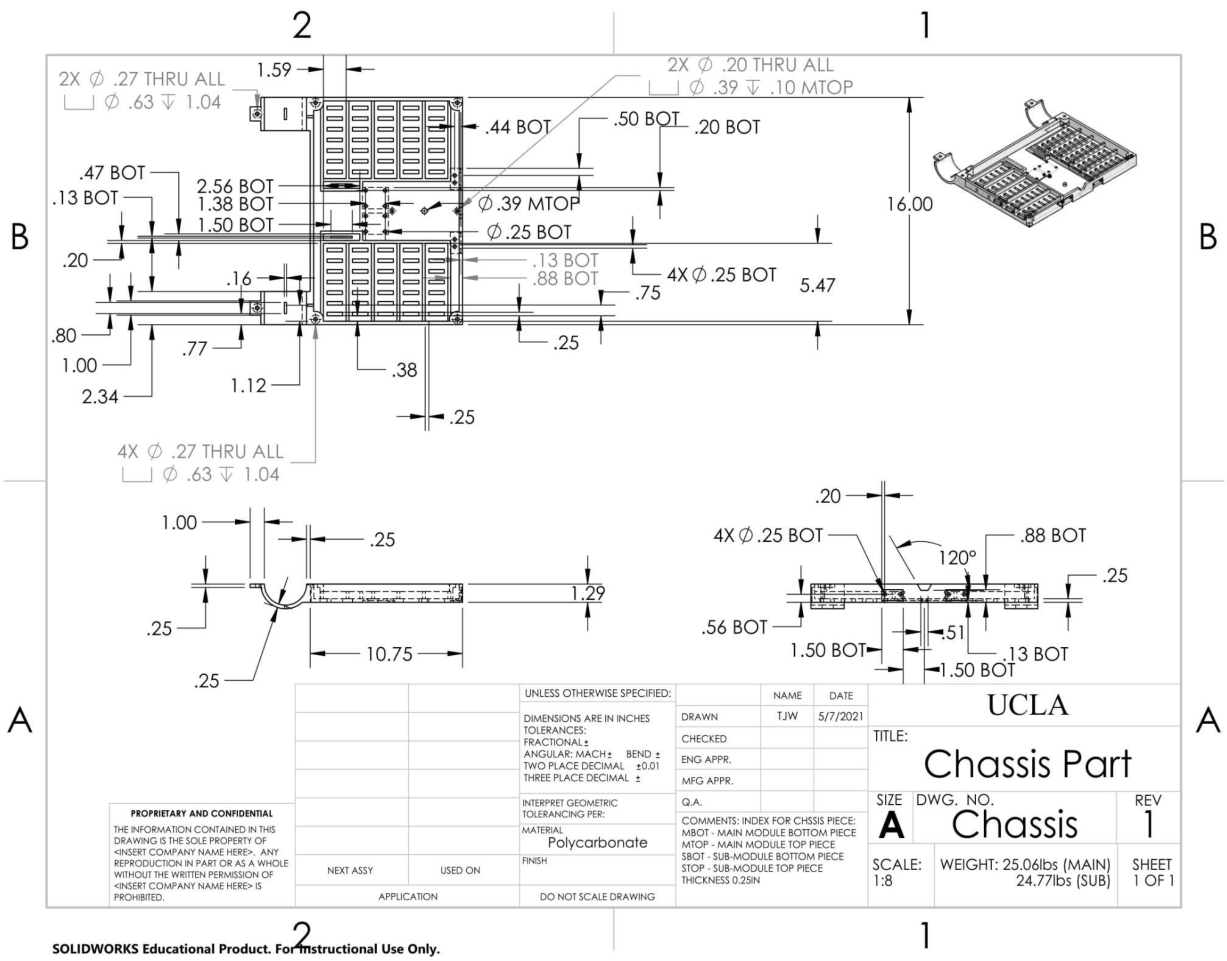
The GANTT chart firstly added staggers to many of the tasks to more accurately represent the allocation of time on certain tasks. Payload variance and positioning was pushed back to start in week 8 and extend to week 10. Secondly, many of the tasks were extended to week 10, to compensate for our initial mistake. Thirdly, the simulation and mechanical analysis portions were extended to match the slight delay due to the mounting hardware and chassis updates. Lastly, some tasks were shortened to more accurately represent actual necessary time needed. The revisions to the GANTT chart and milestones do not change the fact that our scope has stayed consistent, and that we are still on a great trajectory to finish in time.

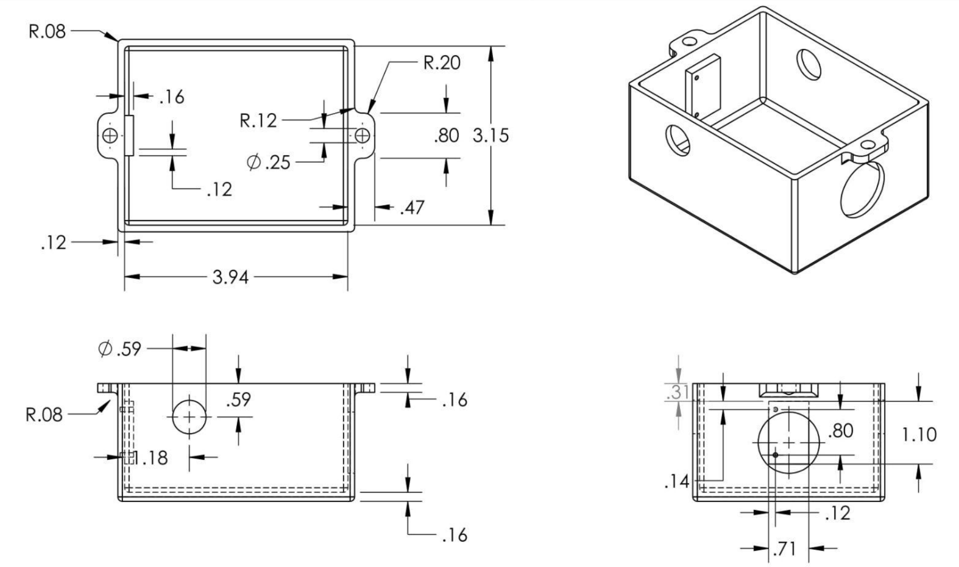
We also made minor revisions to our weekly milestones for weeks 7-10. Although we were on track with a majority of our milestones, As mentioned earlier, we were one week behind on a few milestones such as simulations. We edited weeks 7-8 to match our current progress and plans, but found that weeks 9-10 were compatible with our updated schedule and left it as-is. We also removed CDR content from week 7 (already completed) and FDR content from week 9 to better match with our due dates for the quarter. Our updated milestones chart will also be available in Appendix 3.

Appendix 1 - Technical Drawings

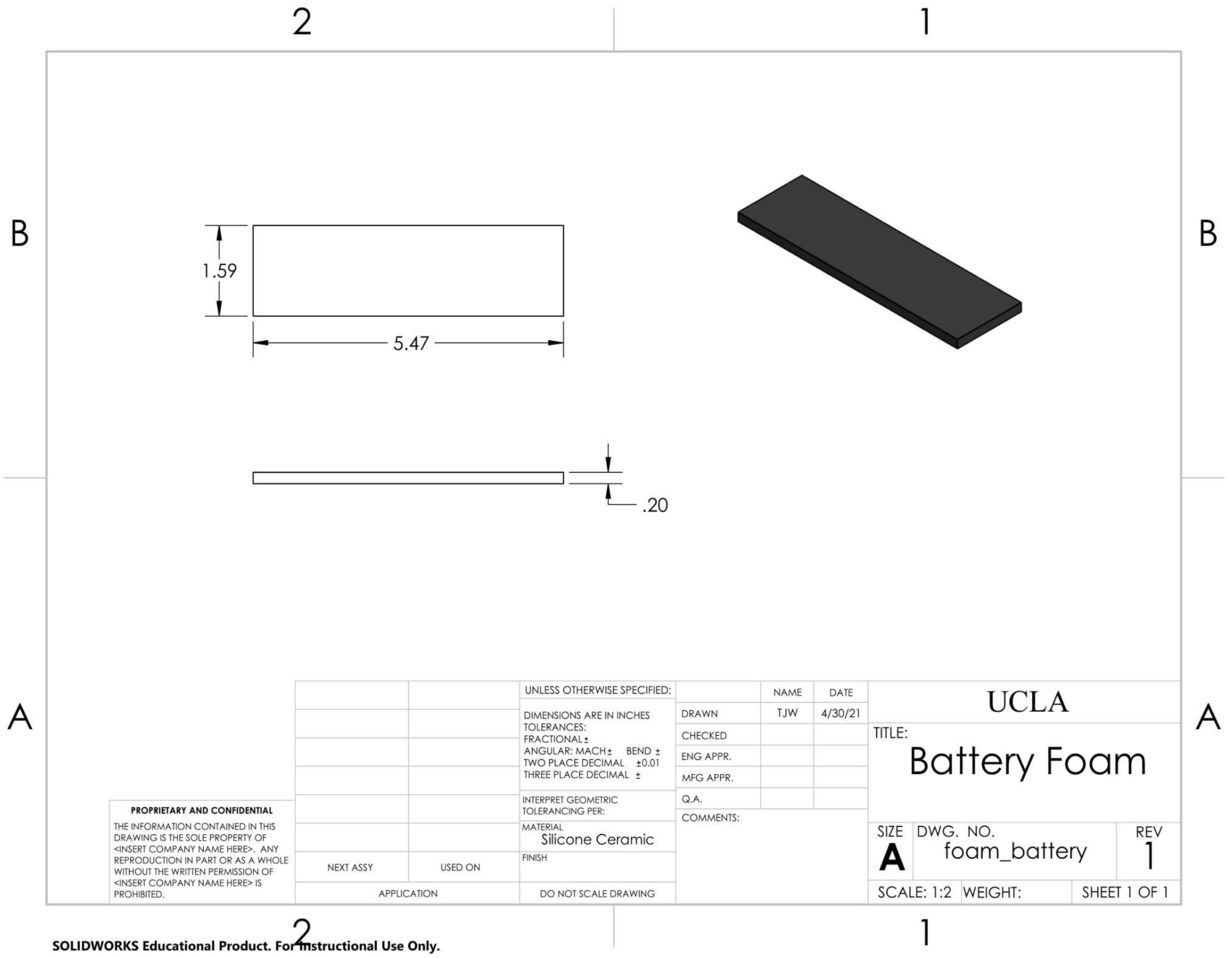
Part Drawings

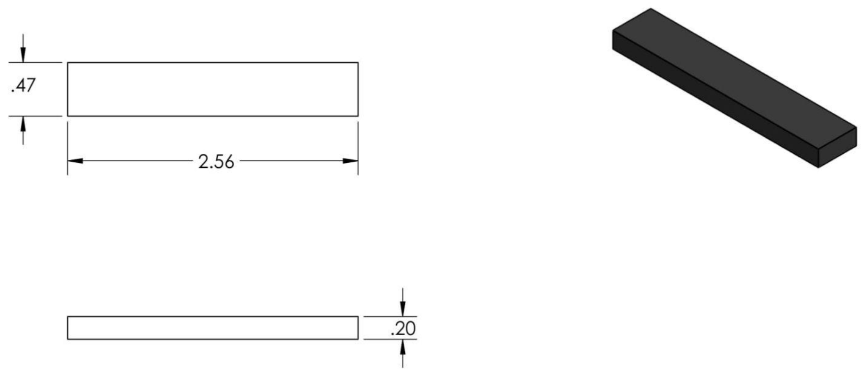
Below are the drawings for each part we created, excluding catalog parts. Assembly and subassembly drawings are in progress.





		UNLESS OTHERWISE SPECIFIED:		NAME	DATE	UCLA
		DIMENSIONS ARE IN INCHES TOLERANCES: FRACTIONAL ± ANGULAR: MACH ± BEND ± TWO PLACE DECIMAL ±0.01 THREE PLACE DECIMAL ±	DRAWN	TJW	5/4/21	TITLE: CPU Housing
			CHECKED			
			ENG APPR.			
			MFG APPR.			
		INTERPRET GEOMETRIC TOLERANCING PER:	Q.A.			
		MATERIAL Polycarbonate	COMMENTS:			SIZE A DWG. NO. CPU Housing REV 1
NEXT ASSY	USED ON	FINISH				
APPLICATION		DO NOT SCALE DRAWING				SCALE: 1:2 WEIGHT: 0.24lbs SHEET 1 OF 1


2
1
B
A
1.59
5.47
.20
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL±
ANGULAR: MACH± BEND ±
TWO PLACE DECIMAL ±0.01
THREE PLACE DECIMAL ±
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
Silicone Ceramic
FINISH
DO NOT SCALE DRAWING
NAME
DATE
DRAWN
TJW
4/30/21
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
UCLA
TITLE:
Battery Foam
SIZE
A
DWG. NO.
foam_battery
REV
1
SCALE: 1:2
WEIGHT:
SHEET 1 OF 1
NEXT ASSY
USED ON
APPLICATION
PROPRIETARY AND CONFIDENTIAL
THE INFORMATION CONTAINED IN THIS DRAWING IS THE SOLE PROPERTY OF <INSERT COMPANY NAME HERE>. ANY REPRODUCTION IN PART OR AS A WHOLE WITHOUT THE WRITTEN PERMISSION OF <INSERT COMPANY NAME HERE> IS PROHIBITED.
SOLIDWORKS Educational Product. For Instructional Use Only.



UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±0.01
THREE PLACE DECIMAL ±

INTERPRET GEOMETRIC TOLERANCING PER:

MATERIAL
Silicone Ceramic

FINISH

DO NOT SCALE DRAWING

	NAME	DATE
DRAWN	TJW	4/30/21
CHECKED		
ENG APPR.		
MFG APPR.		
Q.A.		

COMMENTS:

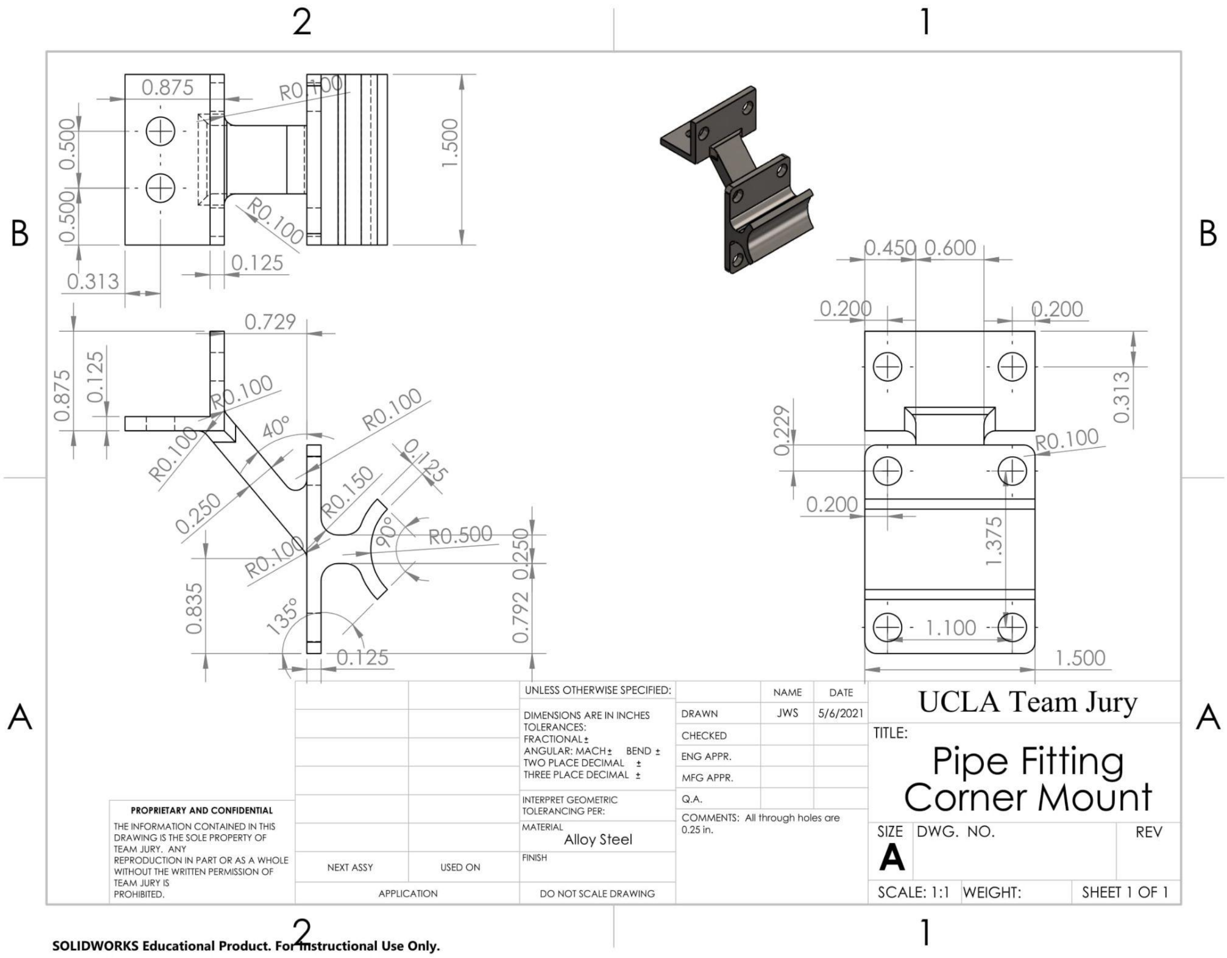
UCLA

TITLE:
ESC Foam

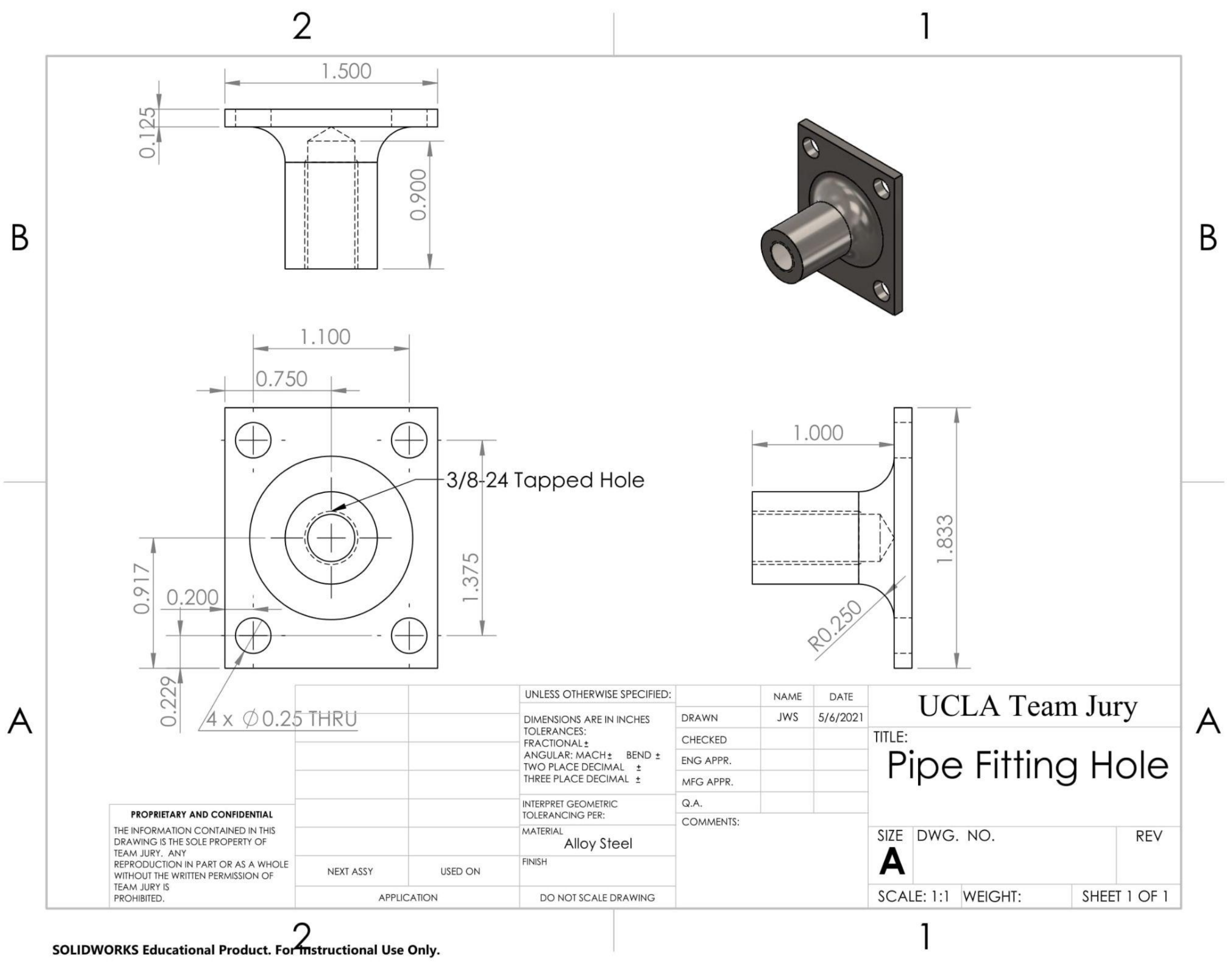
SIZE A | DWG. NO. foam_ESC | REV 1

SCALE: 1:1 WEIGHT: SHEET 1 OF 1

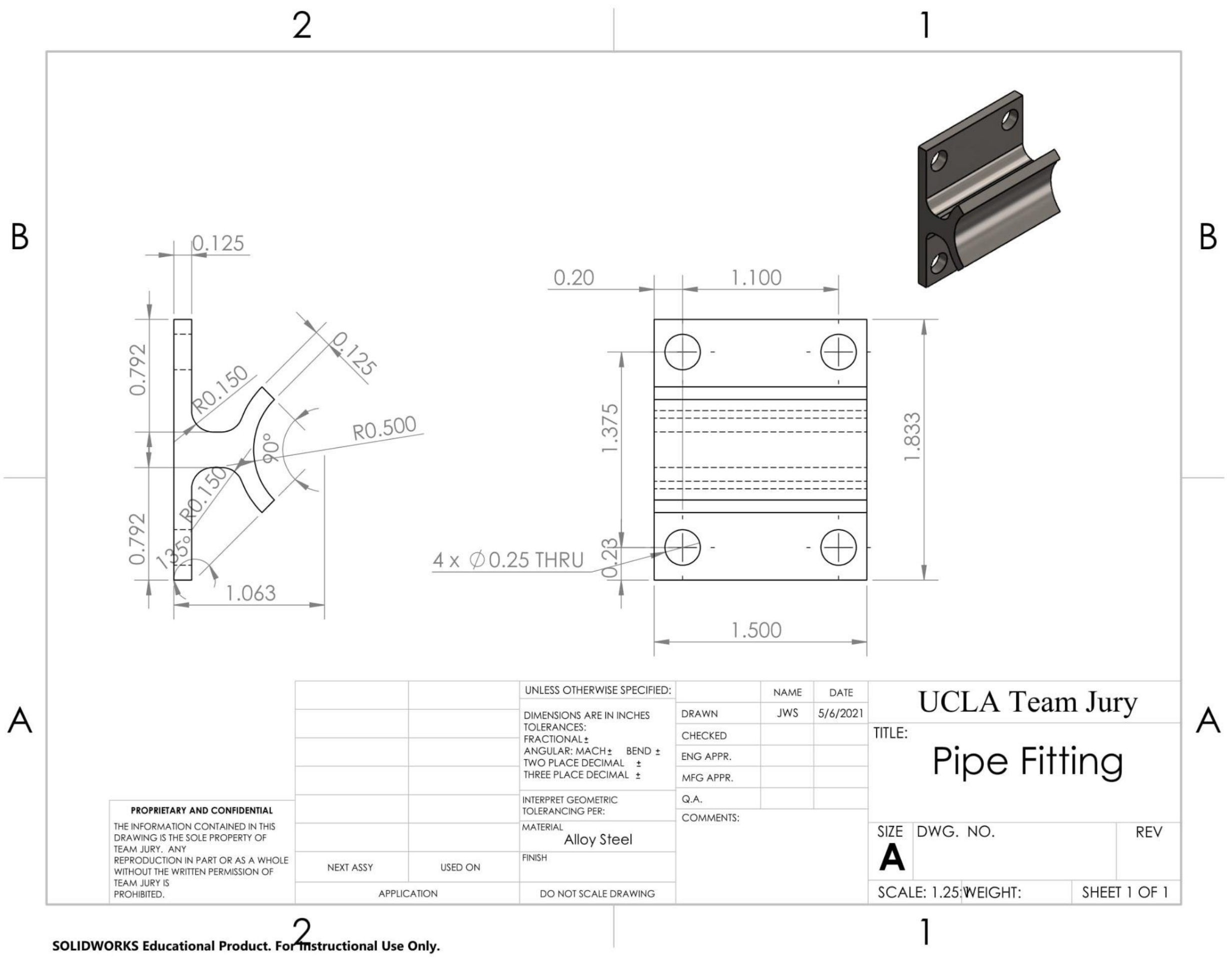
NEXT ASSY | USED ON
APPLICATION



2
1
B
A
0.875
R0.100
0.500
0.500
R0.100
1.500
0.313
0.125
0.729
0.875
0.125
R0.100
R0.100
R0.100
40°
0.250
R0.150
0.125
90°
R0.500
R0.100
0.250
0.835
135°
0.792
0.125
0.450 0.600
0.200
0.200
0.313
0.229
R0.100
0.200
1.375
1.100
1.500
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL±
ANGULAR: MACH± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
Alloy Steel
FINISH
DO NOT SCALE DRAWING
NAME
DATE
DRAWN
JWS
5/6/2021
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS: All through holes are 0.25 in.
UCLA Team Jury
TITLE:
Pipe Fitting Corner Mount
SIZE
A
DWG. NO.
REV
SCALE: 1:1
WEIGHT:
SHEET 1 OF 1
NEXT ASSY
USED ON
APPLICATION
PROPRIETARY AND CONFIDENTIAL
THE INFORMATION CONTAINED IN THIS DRAWING IS THE SOLE PROPERTY OF TEAM JURY. ANY REPRODUCTION IN PART OR AS A WHOLE WITHOUT THE WRITTEN PERMISSION OF TEAM JURY IS PROHIBITED.
SOLIDWORKS Educational Product. For Instructional Use Only.



1.500
0.125
0.900
1.100
0.750
3/8-24 Tapped Hole
0.917
0.200
1.375
0.229
4 x ∅0.25 THRU
1.000
1.833
R0.250
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
Alloy Steel
FINISH
DO NOT SCALE DRAWING
NAME
DATE
DRAWN
JWS
5/6/2021
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
UCLA Team Jury
TITLE:
Pipe Fitting Hole
SIZE
A
DWG. NO.
REV
SCALE: 1:1
WEIGHT:
SHEET 1 OF 1
PROPRIETARY AND CONFIDENTIAL
THE INFORMATION CONTAINED IN THIS DRAWING IS THE SOLE PROPERTY OF TEAM JURY. ANY REPRODUCTION IN PART OR AS A WHOLE WITHOUT THE WRITTEN PERMISSION OF TEAM JURY IS PROHIBITED.
NEXT ASSY
USED ON
APPLICATION
SOLIDWORKS Educational Product. For Instructional Use Only.


0.125
0.792
R0.150
0.125
R0.500
90°
R0.150
0.792
135°
1.063
0.20
1.100
1.375
1.833
4 x ∅0.25 THRU
0.23
1.500
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL±
ANGULAR: MACH± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
Alloy Steel
FINISH
DO NOT SCALE DRAWING
NEXT ASSY
USED ON
APPLICATION
NAME
DATE
DRAWN
JWS
5/6/2021
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
UCLA Team Jury
TITLE:
Pipe Fitting
SIZE
A
DWG. NO.
REV
SCALE: 1.25:1
WEIGHT:
SHEET 1 OF 1
PROPRIETARY AND CONFIDENTIAL
THE INFORMATION CONTAINED IN THIS DRAWING IS THE SOLE PROPERTY OF TEAM JURY. ANY REPRODUCTION IN PART OR AS A WHOLE WITHOUT THE WRITTEN PERMISSION OF TEAM JURY IS PROHIBITED.
SOLIDWORKS Educational Product. For Instructional Use Only.

Appendix 2 - Bills of Materials

Category	Component	Vendor	Description	Qty.	Unit Price($)	Total Price($)
Actuators	Ducted Fans	Powerfun	70mm Ducted Fans	4	43.27	173.08
Actuators	ESC	Skywalker Hobbywing	80A ESC	4	45.99	183.96
CPU	Arduino Uno Rev3	Arduino	MCU with pin I/Os	1	23	23
Sensor	Adafruit ISM330DHCX	Adafruit	6DOF IMU	1	14.95	14.95
Power Supply	Voltage Regulator D24V22F7	Pololu	7.5V step down regulator	1	9.95	9.95
Power Supply	LiPo Battery	JHLIPO	Pack of 10 22.2V/6S 3500mAh 35C	2	136.9	273.8
Wiring	ESC Connector (10pcs)	HONBAY	male/female servo extension	1	6.79	6.79
Wiring	30 AWG Wires	Striveday	30 AWG Electric Wire Cable	1	10.99	10.99
Wiring	XT60 Connector (20pcs)	Assemble enthusianst	Battery-battery-ESC connecters (male/female)	1	14.99	14.99
Wiring	Adapter (Used for Arduino)	CableWholesale	DC Power Socket to 2-Pin Screw Terminal Adapter	1	0.77	0.77
Wiring	Power Wires (Used for batteries)	BNTECHGO	12 AWG Stranded Copper Wire	1	9.48	9.48
Wiring	Communication Cable	Belden	2 22 AWG wires cable set (8ft)	1	4.96	4.96
Wiring	Cord Protector	Willbond	Cable Grip Strip 4”Width x 10’Length	1	8.85	8.85
Connector	Pin Connector	Gxilee	3 Pin DIN Female/Male Solder Connectors(pack of 3)	1	11.99	11.99
Switch	On/Off Button	Adafruit	Mini Illuminated Momentary Pushbutton - Blue Power Symbol	1	1.95	1.95
Fasteners	Rubber Cushioned U-Bolt 1/4"-20	McMaster	30555T31_RUBBER-CUSHIONED U-BOLT.SLDPRT	16	5.06	80.96
Fasteners	Steel Rod	McMaster	3313N769_ HIGH STRENGTH	4	10.52	42.08

	3/8"-24		STEEL THREADED ROD.SLDPRT			
Fasteners	Swivel Ball Joint Rod End 3/8-24"	McMaster	6960T610_SUPER-SWIVEL BALL JOINT ROD END.SLDPRT	4	10.68	42.72
Fasteners	Cap Screw 1/4"-20	McMaster	91309A542_LOW-STRENGTH ZINC-PLATED STEEL CAP SCREW.SLDPRT	16	0.0746	1.1936
Fasteners	Nylon Insert #10-24	McMaster	91831A011_TYPE 18-8 STAINLESS STL NYLON-INSERT LOCKNUT.SLDPRT	2	0.057	0.114
Fasteners	Nylon Insert 1/4"-20	McMaster	91831A029_TYPE 18-8 STAINLESS STL NYLON-INSERT LOCKNUT.SLDPRT	44	0.0902	3.9688
Fasteners	Flat Washer 1/4"	McMaster	92141A029_TYPE 18-8 STAINLESS STEEL FLAT WASHER.SLDPRT	48	0.0347	1.6656
Fasteners	Socket Head Screw #10-24	McMaster	92196A242_18-8 STAINLESS STEEL SOCKET HEAD SCREW.SLDPRT	2	0.081	0.162
Fasteners	Socket Head Screw 1/4"-20	McMaster	92196A542_18-8 STAINLESS STEEL SOCKET HEAD SCREW.SLDPRT	28	0.3214	8.9992
Fasteners	Hex Nut 1/4"-20	McMaster	95462A029_GRADE 5 STEEL HEX NUT.SLDPRT	48	0.0529	2.5392
Fasteners	Hex Nut 3/8"-24	McMaster	95505A613_GRADE 5 STEEL HEX NUT.SLDPRT	8	0.0552	0.4416
Fasteners	Inline Ball Joint Linkage 3/8"-24	McMaster	8412K460_HEAVY DUTY INLINE BOOTED BALL JOINT LINKAGE	4	13.47	53.88
Chassis	Main Chassis Bottom		Polycarbonate Chassis Part	1	250	250
Chassis	Main Chassis Top		Polycarbonate Chassis Part	1	250	250
Chassis	Sub Chassis Bottom		Polycarbonate Chassis Part	1	250	250
Chassis	Sub Chassis Top		Polycarbonate Chassis Part	1	250	250
Foam	Thermal Foam	DigiKey	A17916-20 Thermal Materials	2	25.63	51.26
Attachment	CPU Housing		Polycarbonate Attachment Part	1	250	250

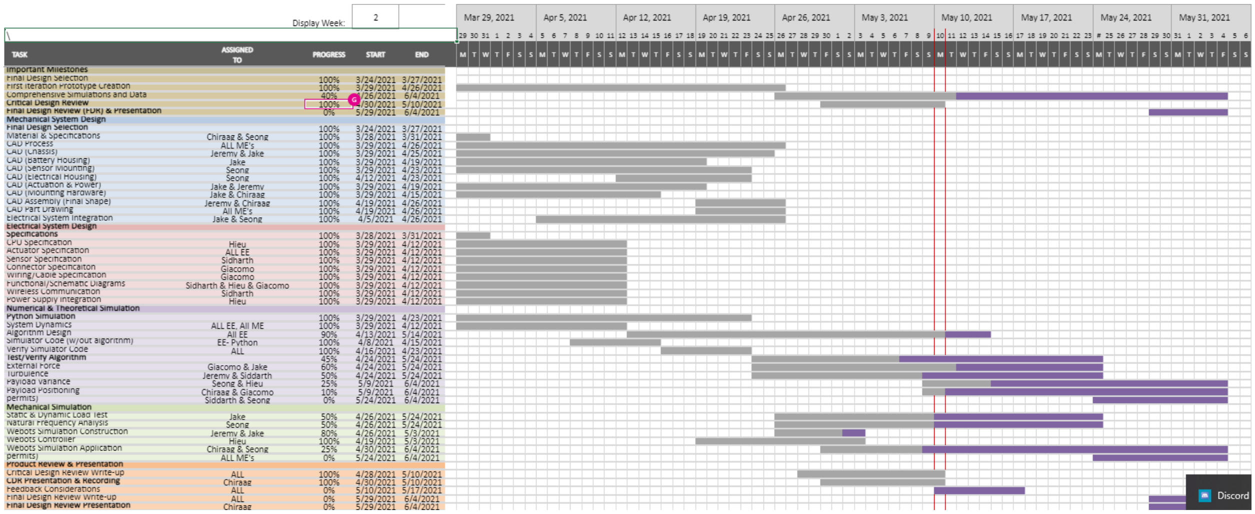
s						
Attachments	Pipe Fitting Corner Mount		Alloy Steel Corner Mount	4	100	400
Attachments	Pipe Fitting Hole		Alloy Steel Pipe Fitting Component	8	100	800
Attachments	Pipe Fitting		Alloy Steel Mount	4	100	400
					Total ($):	3889.494

[46]

46 https://docs.google.com/spreadsheets/d/138dd7lbjPwX1WmmNe60787xIiHYSfB33Vb63n5hpm-4/edit#gid=0

Appendix 3 - GANTT Chart

Following is the visual of our GANTT Chart progress. Grey portions indicate percentage of task designated as finished. Full link to GANNT Chart is included.[47]



TASK	ASSIGNED TO	PROGRESS	START	END
Important Milestones				
Final Design Selection		100%	3/24/2021	3/27/2021
First Iteration Prototype Creation		100%	3/29/2021	4/26/2021
Comprehensive Simulations and Data		40%	4/26/2021	6/4/2021
Critical Design Review		100%	4/30/2021	5/10/2021
Final Design Review (FDR) & Presentation		0%	5/29/2021	6/4/2021
Mechanical System Design				
Final Design Selection		100%	3/24/2021	3/27/2021
Material & Specifications	Chiraag & Seong	100%	3/28/2021	3/31/2021
CAD Process	ALL ME's	100%	3/29/2021	4/26/2021
CAD (Chassis)	Jeremy & Jake	100%	3/29/2021	4/25/2021
CAD (Battery Housing)	Jake	100%	3/29/2021	4/19/2021
CAD (Sensor Mounting)	Seong	100%	3/29/2021	4/23/2021
CAD (Electrical Housing)	Seong	100%	4/12/2021	4/23/2021
CAD (Actuation & Power)	Jake & Jeremy	100%	3/29/2021	4/19/2021

[47] https://onedrive.live.com/view.aspx?resid=2874586556B007FF!3122&ithint=file%2cxlsx&authkey=!APBwyR9iaN0HeTk

CAD (Mounting Hardware)	Jake & Chiraag	100%	3/29/2021	4/15/2021
CAD Assembly (Final Shape)	Jeremy & Chiraag	100%	4/19/2021	4/26/2021
CAD Part Drawing	All ME's	100%	4/19/2021	4/26/2021
Electrical System Integration	Jake & Seong	100%	4/5/2021	4/26/2021
Electrical System Design				
Specifications		100%	3/28/2021	3/31/2021
CPU Specification	Hieu	100%	3/29/2021	4/12/2021
Actuator Specification	ALL EE	100%	3/29/2021	4/12/2021
Sensor Specification	Sidharth	100%	3/29/2021	4/12/2021
Connector Specificaiton	Giacomo	100%	3/29/2021	4/12/2021
Wiring/Cable Specification	Giacomo	100%	3/29/2021	4/12/2021
Functional/Schematic Diagrams	Sidharth & Hieu & Giacomo	100%	3/29/2021	4/12/2021
Wireless Communication	Sidharth	100%	3/29/2021	4/12/2021
Power Supply Integration	Hieu	100%	3/29/2021	4/12/2021
Numerical & Theoretical Simulation				
Python Simulation		100%	3/29/2021	4/23/2021
System Dynamics	ALL EE, All ME	100%	3/29/2021	4/12/2021
Algorithm Design	All EE	90%	4/13/2021	5/14/2021
Simulator Code (w/out algorithm)	EE- Python	100%	4/8/2021	4/15/2021
Verify Simulator Code	ALL	100%	4/16/2021	4/23/2021
Test/Verify Algorithm		45%	4/24/2021	5/24/2021
External Force	Giacomo & Jake	60%	4/24/2021	5/24/2021
Turbulence	Jeremy & Siddarth	50%	4/24/2021	5/24/2021
Payload Variance	Seong & Hieu	25%	5/9/2021	6/4/2021
Payload Positioning	Chiraag & Giacomo	10%	5/9/2021	6/4/2021
Other Simulation Scenarios (If time permits)	Siddarth & Seong	0%	5/24/2021	6/4/2021
Mechanical Simulation				
Static & Dynamic Load Test	Jake	50%	4/26/2021	5/24/2021
Natural Frequency Analysis	Seong	50%	4/26/2021	5/24/2021
Webots Simulation Construction	Jeremy & Jake	80%	4/26/2021	5/3/2021

Webots Controller	Hieu	100%	4/19/2021	5/3/2021
Webots Simulation Application	Chiraag & Seong	25%	4/30/2021	6/4/2021
Additional Simulations Post-CDR (If time permits)	ALL ME's	0%	5/24/2021	6/4/2021
Product Review & Presentation				
Critical Design Review Write-up	ALL	100%	4/28/2021	5/10/2021
CDR Presentation & Recording	Chiraag	100%	4/30/2021	5/10/2021
Feedback Considerations	ALL	0%	5/10/2021	5/17/2021
Final Design Review Write-up	ALL	0%	5/29/2021	6/4/2021
Final Design Review Presentation	Chiraag	0%	5/29/2021	6/4/2021

Updated Milestones Chart

7					
	Data Collection (for algorithm evaluation)	3	Preliminary Graphs and Charts		
				Run Wind Disturbance Modeling trials	Giacomo
				Run Payload Variance Environment trials	Seong
				Run Payload Positioning Modeling trials	Chiraag
				Extraneous test scenarios	Jake
	Webots Simulation	4	Complete Webots Model of System and Disturbances		
				Begin trials of Webots as per test cases	see above
	Mechanical simulation and robustness of testing	3	Webots Environment setup and Results of Load Test and Frequency Analysis		
				Complete robot setup of Webots	Chiraag
				Complete Load Tests on parts	Jake
				Complete Natural Frequency Analysis	Seong
8					

	Optimized Algorithm	2	Algorithm comparison using data anlysis.		
				Evaluate algorithm on test scenarios and tune/optimize it	Hieu
	Data Colletion (for new alogirhtm evaluation)	5	Preliminary Graphs and Charts		
				Run Wind Disturbance Modeling trials	Giacomo
				Run Payload Variance Environment trials	Seong
				Run Payload Positioning Modeling trials	Chiraag
				Extraneous test scenarios	Jake
	Analyze Data from Simulation Results	3	Code that Reads and Analyzes data		
				Write code compatible with algorithm	Jeremy
9					
	Finalized algorithm	2	Algorithm comparison using data analysis.		
				Evaluate algorithm on test scenarios and tune/optimize it	Hieu
	Evaluation of final algorithm	4	Progress of Completed trials		
				Run Wind Disturbance Modeling trials	Giacomo
				Run Payload Variance Environment trials	Seong
				Run Payload Positioning Modeling trials	Chiraag
				Extraneous test scenarios	Jake
	Statistical analysis of Simulation Results (in progress)	2	Partial Analysis of Output Data		
				Begin Data Analysis	Sidharth
10					
	Complete statistical analysis of Simulation	4	Completed Data Analysis of Test Scenario Ouputs		

	Results				
				Write Ouput	Hieu
				Plot Output	Sidharth
				Apply Statistical Analysis	Giacomo
	FDR Preparation	6	Final Design Review		
				Compile Final Design Review Report	Chiraag
				Convert Solidworks Simulation results to FDR	Jake
				Convert Webots Data Analsys to FDR	Seong
				Convert CDR information to FDR	Jeremy