Project D.R.O.V.E.R

Drone Rover Operations on Versatile Extra-hazardous Regions

Final Report

April 30th, 2025

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1 Executive Summary (Elizabeth Beraducci)

This document was prepared for the Critical Design Review (CDR) of Project DROVER, a 2024-2025 capstone design team at Florida Tech. The purpose of the review is to assess the system's compliance with defined requirements, verifying that the design meets the project objectives and will satisfy the mission.

Recently, the use of unmanned aerial vehicles (UAVs) has proven to greatly enhance search and rescue operations by reaching inaccessible areas quickly and safely. The ability of drones to cover vast areas while providing real-time feedback is crucial in search and rescue missions. Nonetheless, the drone's limitations become apparent due to its quickly deteriorating battery life while in flight. Project DROVER will combine the capabilities of a drone and rover into a unified, manually controlled prototype.

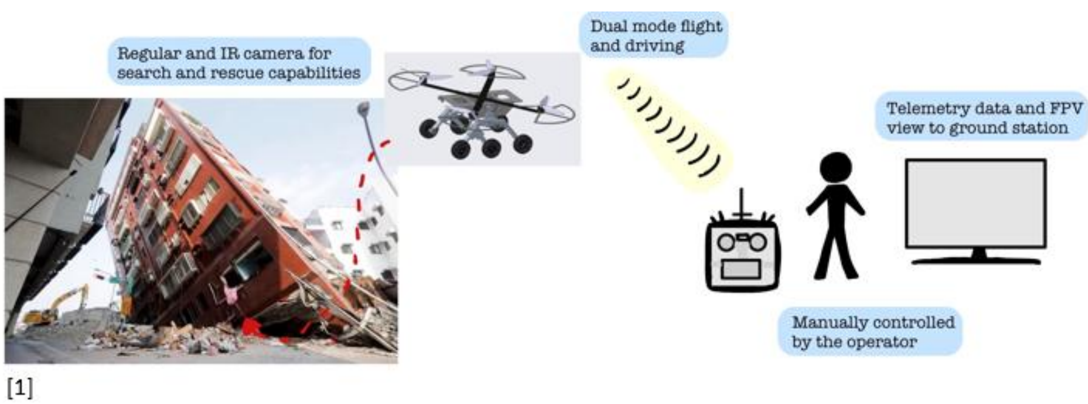


Figure 1: DROVER operations summary [1]

2 PROBLEM STATEMENT AND OBJECTIVES

2.1 Problem Statement (Rhys Wallin, Haylee Fiske)

Natural disasters are a recurrent problem on a global scale, and mitigating the destruction that ensues is crucial to preserving human life. In 2023, there was an earthquake that hit Turkey and Syria, and the lives of over 55,000 people were lost, mostly due to the collapse of infrastructure [50]. Drones are currently used for surveillance to find survivors in immediate danger, and the aftermath of natural disasters often presents collapsed buildings that a normal drone would not be able to access.

The primary objective of Project DROVER is to design, build, and fly a drone-rover hybrid prototype designed to enhance search and rescue operations capable of aerial and terrestrial navigation to locate and assist people in distress. This prototype will demonstrate the unique capability to take flight when traversal via driving is not possible due to obstacles such as steep inclines and impassable debris. This hybrid vehicle holds the potential to revolutionize search and rescue operations by harnessing the energy efficiency of a rover combined with the agile air mobility of a drone.

2.2 Project Objectives (Fabrizio Chigne)

OBJ-01. The team shall design, build, and test a drone-rover hybrid that can drive, fly, and turn in a search-and-rescue environment.

Rationale: A drone-rover hybrid combines the best features of the two vehicles. A search and rescue mission presents numerous challenges, including difficult terrains and hazardous conditions. This hybrid vehicle can navigate both ground and aerial environments, enhancing exploration efficiency by covering larger distances and accessing hard-to-reach areas.

Status: Fully Compliant

OBJ-02. The DROVER shall be able to establish communication with identified targets in support of mission operations.

Rationale: Live video and two-way communication are critical for assessing situations in real time and coordinating rescue efforts. Rescuers must be able to monitor conditions, identify obstacles, and locate individuals needing help.

Status: Fully Compliant

2.3 Deliverables (Marcelo Samaan)

2.3.1 Documentation and Analysis Products

The following list contains all documentation and analysis products that the team has delivered as part of the Capstone design project.

- All documentation required by the Senior Design class (SRR, PDR, CDR, PDR and CDR presentations, Final Report, Showcase Poster)

  Status: Fully Compliant

- Testing Plans and Test Results of each Subsystem

  Status: Fully Compliant

- Flight Checklist/Procedure

  Status: Fully Compliant

- Layout of the obstacle course

  Status: Fully Compliant

2.3.2 Hardware/Software Products

As part of the Capstone design project, the following Hardware/Software products has produced:

- Fully functional DROVER based on systems requirements

Status: Fully Compliant

- Finite Element Model analysis of major structural components
  Status: Fully Compliant
- CFD Analysis of DROVER's propeller blades and airborne aerodynamics
  Status: Fully Compliant
- CAD models and engineering drawings of major subsystem components
  Status: Fully Compliant
- Pixhawk 6X flight controller with ArduPilot installed
  Status: Fully Compliant
- Ground station established for communication with DROVER
  Status: Fully Compliant
- Manual Controller Radio master TX16s MKII
  Status: Fully Compliant

2.4 Broader Impact (Francesco De Luca)

The ever-increasing demand for a safer society is leading the scientific community to experience new and more efficient practices. As a matter of fact, a lot of research has been done on drones and rovers to make them accomplish tasks that would be too dangerous for humans. However, only a modest amount of research has been carried out on technology that merges the two. By merging the capabilities of drones and rovers, the hybrids will have a wider range of applications as compared to the two separate systems which are restrained to earth or air purposes only [54].

The unique dual-mode design of the DROVER opens a new wide range of possibilities for the utilization of technology to positively impact human lives. This project's design is easily interchangeable to accommodate different possible missions. For example, project DROVER can be utilized to assist agriculture, as support for military operations, in search and rescue operations, for security purposes, in the inspection of hazardous areas, or in traffic management in a large city.

- Assisting Agriculture: Robotic dogs are used on the ground for mapping and making a model of a farm that can be later utilized in the analysis of crop health. [2] Drones can also be used to map farms, they can give great insights into the best way to use pieces of land, how to properly irrigate, and efficiently utilize pesticides. Also, fertilizer can be poured from a height by a drone and dusted over the crops by large drones that hold the fertilizer in reservoirs.

Figure 2: Drone used for agricultural purposes [2]

- Military operations: A hybrid between a drone and a rover could also be used in military settings as "Deploying a surveillance drone serves as a strategic imperative to attain comprehensive situational awareness in the operational area" [3]. This is in fact what Elistair surveillance drones can do. This type of aerial reconnaissance improves the security of the teams that utilize this drone and mitigates potential risks thanks to live insights into the surrounding area. In a military setting, the advantages of having a technology with drone and rover capabilities will improve the effectiveness of a given reconnaissance mission as the ability of roving would make the DROVER less prone to identification. Furthermore, the same drone from Elistair can be used for traffic monitoring as this company presents a remote-controlled aircraft that is able to provide real-time information regarding congestions in each area and gathers data about traffic to present an “efficient traffic management plan”. The figure below shows a drone used for military surveillance and aerial reconnaissance able to provide day or night reconnaissance focusing objects located up to 10 km (6 miles) away.

Figure 3: Military Drone from Elistair [3]

- Search and rescue: Additionally, project DROVER can be used for search and rescue operations as it can be easily employed in recovery operations after a disaster such as an earthquake or hurricane. This will allow for safely coordinating teams that are working on the ground to assist them with aerial video in the search and rescue of people after a disaster. An example is the thermal camera drone utilized in the rescue of a 10-year-old girl who went missing near Shreveport, Louisiana on September 14th, 2024. [4]

Figure 4: DJI Matrice 350 RTK used for search and rescue operations. [5]

- Industrial Security and the inspection of hazardous areas: Another application for the DROVER is its use for industrial security. Elistair built a drone capable of giving a complete aerial perspective of an industrial plant during high-risk maneuvers such as the transport of heavy loads, the handling of hazardous or toxic materials, or providing a first look at an unauthorized access to critical infrastructure sites, such as nuclear facilities or other secure zones. Security Drones "can monitor large areas efficiently and quickly. They can perform tedious tasks like inspecting hard-to-reach locations and gather necessary data to assess potentially dangerous situations, without getting tired" [6]. Additionally, another function is mapping and structural assessment in hard-to-reach areas and hazardous areas, such as the situation following the 2011 Fukushima Daiichi Nuclear Power Plant accident where Unmanned Ground Vehicles were utilized for mapping and to complete a structural assessment of buildings in the area hit by the disaster [7].

Figure 5: Hazardous Environment Drone [8]

Project DROVER presents a unique variant as it can be used for all the functions listed above. Particularly, project DROVER will be focused on search and rescue operations, as these missions often struggle with limited accessibility and time constraints and need all the resources possible to save lives. The DROVER will address these issues by providing quick and versatile navigation through both air and land. Through driving, the DROVER will be able to cover ground more efficiently to preserve battery life in situations where flight is unnecessary. Furthermore, in locations where flight isn't an option, the driving mechanism gives the users another transportation option. This version of DROVER targets emergency response units, including fire departments, search and rescue teams, and disaster relief organizations, aiming to improve their operational efficiency and effectiveness in challenging terrains. On February 6th, 2023, the southern Turkish province of Gaziantep was struck by a magnitude 7.8 earthquake that caused 55,000 deaths and injured 107,000 [9]. More than 7,800 people were rescued and many more could have been saved if a technology similar to DROVER had been implemented in the search and rescue efforts [10].

A similar technology has also been utilized in Italy, on August 24th, 2016, as a rover from a European Union FP7-funded initiative was utilized [11]. In this mission, however, the scope was very different than DROVER as the rover that was built by the European Union FP7-funded initiative was tasked to create 3D textured models of two old churches to assess their integrity.

Figure 6: Rover built by the TRADR Project [12]

Given the high versatility of Project DROVER, during search and rescue operations the DROVER could also be used to:

Communicate with people in trouble or find missing individuals or objects: Project DROVER will lay the foundations for future work in rescue operations as a two-way communication will be used to identify and locate stranded people. A regular camera will be used for basic surveillance and as eyes for the operator. A thermal camera capable of identifying heat coming from a body will also be an important feature on the DROVER to further refine rescue operations as studies have been shown that the utilization of thermal cameras presents a simple and very efficient way for tracking down targets during search and rescue operations [13]. Drones that also utilize thermal imagery are DJI Matrice 350 RTK, DJI Matrice 30T, DJI Mavic 3 Thermal, and Autel Robotics EVO Max 4T [5]. Another system on board will be a two-way communication system utilizing a microphone and a speaker in order to talk with anyone in distress that the DROVER may find out in the field.

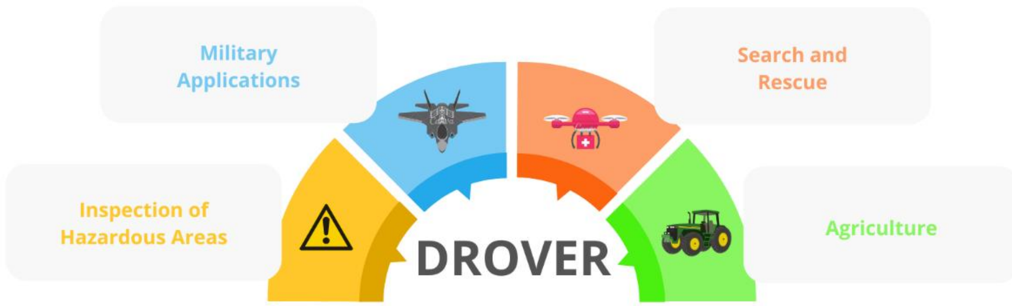


Figure 7: DROVER's multi-use

3 Concept of Operations and External Interfaces

3.1 Concept of Operations (Haylee Fiske)

Figure 8: Functional Flow Block Diagram for DROVER Mission

The DROVER will be tested on Earth terrain to demonstrate its capabilities utilizing one manual controller for driving and flight (Figure 8, 1.0). In this first stage, communication between the DROVER's transmitter and receiver will be set, and a live feed will be established for data analysis. For the following stages after the initial starting point, the DROVER will transmit data to the ground station which will include battery percentage, video, and audio feed. The operator will then initiate the driving functions, where the DROVER will drive straight and turn until an obstacle is encountered (Figure 8, 2.0). Using the data and video feed transmitted to the ground station, the pilot can traverse the terrain by sending inputs from the controller to the DROVER system. With the same controller, the operator will decide to initiate flight over the obstacle (Figure 8, 3.0). Similar to the driving functions, the operator can send flight inputs from the controller to the DROVER while receiving and saving data to the ground station. Further maneuvers in flight, such as turning and altitude adjustments, will be made by the operator to get around the obstacle (Figure 8, 4.0). These adjustments will be made from manual controller inputs by discretion of the operator and their analysis of the ground station data. Finally, the operator will use the controller to safely land the vehicle (Figure 8, 5.0).

3.2 System External Interfaces (Francesca Afruni, Haylee Fiske)

The main external interfaces of Project DROVER include a radio transmitter, an obstacle course, and a ground station. The radio transmitter serves as the primary communication link between the prototype and the ground station. The obstacle course imitates the physical environment of a potential search and rescue situation with which the system will interact. It has been built by the team and has been used to verify and validate the system with the Demo-DROVER and the final design (more information and detailed specifications about this can be found in the testing section 10.1.1.8). It’s also important to note that when operating the DROVER and the obstacle course, weather considerations specify no expectation of rain, emphasizing that the system is optimized for dry and controlled environments. Finally, the ground station is the central control hub that will process and relay commands to the prototype while receiving telemetry data.

Figure 9: Demo-DROVER pictured during Obstacle Course Test

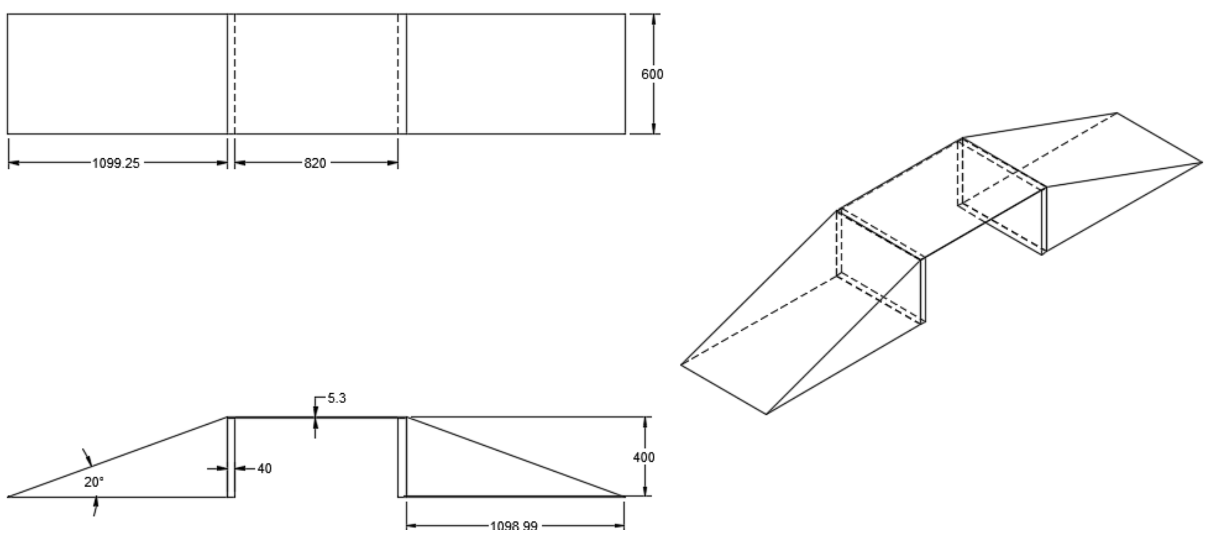


Figure 10: Obstacle Course Schematic

The figure above shows the dimensions of the obstacle course in millimeters. The ramps and table were constructed from laser-cut wood to maintain the correct dimensions. The main highlight of this obstacle course is the twenty-degree inclination of the ramps to help verify the requirements (STR.01) and (STR.02) of landing and driving on the incline.

3.3 Engineering Standards (Francesca Afruni, Haylee Fiske)

To ensure safe operations, several safety standards must be considered when designing, building, and flying the DROVER.

The list of documents is:

- 14 CFR Part 107, Small UAS Rule [18]

  This document covers the aspects of unmanned flights of small aircraft. The requirements in this part detail that the aircraft's weight must be under 55 pounds and flown below 400 feet within the eyesight of a visual observer to ensure proper safety for other aircraft and personnel. The document also refers to the exceptions not to require licensing for the aircraft to be flown. Since the DROVER will be tested outside, proper procedures must be followed to ensure safety.

- 14 CFR 25.303 Factor of Safety [20]

  This document specifies that all aircraft must have a factor safety of a minimum of 1.5 to be applied to the prescribed limit loads (which are considered external loads on the structure).

- MIL-STD-1472H Department of Defense Design Criteria Standard for Human Engineering. [51]

  Section 4.2 states that a product that promotes practical work, safety, health, and sustainability standards must be created.

4 LEVEL 1 SYSTEM REQUIREMENTS (KYLE KINKADE)

Table 1: Level 1 System Requirements

Requirement #	Requirement Text	Requirement Rationale	Verification Method	Verification Strategy	Status	Reference Sections
SYS.01	The DROVER **shall** be capable of flight with a minimum hovering time of at least 20 minutes	The DROVER will need to engage flight for situations where driving is not possiblewhile allowing ample flight time to complete the mission	Test, Demonstration	Takeoff and hover the drone; record the time for the battery to discharge	Not Compliant	10.1.1.17, 10.1.1.18, 12.1
SYS.02	The DROVER **shall** be capable to drive in a straight line and turn	The DROVER will need to navigate via the ground when applicable because it's more energy efficient than flight	Test, Demonstration	Test and demonstrate the drivingcapabilities on rough external terrain	Fully Compliant	10.1.1.15
SYS.03	The DROVER **shall** display live video feed during the entire operation	The live video feed is essential to the user to operate outside the field of view	Demonstration	Utilize the DROVER out of sight from the user	Fully Compliant	10.1.1.4, 10.1.1.9
SYS.04	The DROVER **shall** have two-way verbal communication between operator and the system	To communicate with possiblerescuees	Demonstration	Communicate with a team member from an extended distance	Fully Compliant	10.1.1.5
SYS.05	The DROVER **shall** be controlled manuallyby the pilot	Controlling the DROVER manually allows forthe pilot to look for people	Demonstration	Fly the DROVER with a single controller	Fully Compliant	10.1.1.7, 10.1.1.8, 10.1.1.12-18
SYS.06	The DROVER **shall** adhere to all FAA regulations	Required by the FAA	Analysis	Identify applicable rules and strictlyfollow them	Fully Compliant	7.1, 10.1.1.12-15, 10.1.1.17-18
SYS.07	The DROVER **shall** carry at least a 600 g payload	Provides flexibility for consumers to alter the usage of the DROVER and deliver supplies like, for example, a 0.5L water bottle	Analysis, Test	Analyze the structural and aerodynamicconstraints, successfully complete the obstacle course with the 600 g attached	Fully Compliant	10.1.1.15
SYS.08	The DROVER **shall** be able to fit through a 203 cm tall and 82 cm wide area	The DROVER shall be able to traverse through an American sized door	Inspection	Measure the dimensions of the DROVER	Fully Compliant	10.1.1.15

Project DROVER's entire basis is dependent on the Level 1 Requirements. The primary purpose of the DROVER is to provide an efficient form of navigation with both flight and ground transportation. SYS.01 and SYS.02 discuss the need for the DROVER to be capable of quick and versatile navigation through air and land. As this project aims to introduce dual-mode transportation for real-world use, it is necessary to include these basic requirements. SYS.01 also provides a minimum hover time requirement to ensure ample flight time for the system, as flight will be the critical power draw case. This requirement has a red status as the hovering time tested was just above 15 minutes, which is below the specified 20 minutes. However, the system is able to fly safely for three-quarters of the expected time. This will be explained further in sections 7.1, 7.2, and 10.1.1.18.

To continue, SYS.03 discusses the use of a live video feed. For the DROVER's intended use, there will be many scenarios in which the customer needs to send the drone out of sight to the user. This requirement is fully compliant and further information can be found in 10.1.1.4 and 10.1.1.9. Furthermore, if a person in distress is identified, SYS.04 discusses the use of two-way communication. Two-way communication keeps the user and receiver notified of aid efforts, helps those in need to stay motivated, and lowers their anxiety. It also informs the first responders of the identified personnel's condition. SYS.04 is fully compliant as the team has established two-way verbal communication using a Raspberry Pi 4B coupled with a microphone and speaker set. Further information can be found in Section 10.1.1.5.

As mentioned previously, SYS.05 states that the drone will be manually controlled from the ground, as the team does not have the resources to attack an autonomous drone with the prototype. This requirement is also fully compliant as the team has successfully programmed a TX16S transmitter to control both flying and driving functions.

Furthermore, to allow for any full system test to happen, the drone must adhere to all laws and regulations, specifically the FAA regulations for drones greater than 250 grams (SYS.06) [14]. The team is compliant with this regulation by having the appropriate licensing. SYS.07 provides a 600-gram payload requirement. The main purpose of this requirement is to allow for any minor sensor modifications or an additional external payload to support those in distress. Because the team knows that the DROVER concept has many applications, the excess payload gives the consumer some external weight to adjust the DROVER as they see fit. Furthermore, an excess payload gives the user an opportunity to use the DROVER as transportation for supplies, like a water bottle, which is about 500 grams. The team is compliant with this requirement as the full obstacle course test was completed with the payload. More information about this test can be found in 10.1.1.15.

The final Level 1 requirement is that the DROVER must not exceed 203 cm tall or 82 cm wide. A size constraint needs to be applied to the design to complete the missions in question. Because the team sees the DROVER as a use for damaged building response, the size requirement is based on entering an average-sized American door [15]. This requirement ensures that the DROVER can find an entry into a building for search and rescue purposes. This requirement is fully compliant as the DROVER was driven between the constraints during the obstacle course test (Section 10.1.1.15).

Figure 11: System 8 Requirement -- Size Constraint Reference

As seen in the table above, all requirements are fully compliant with the exception of SYS01, which will be discussed in greater detail in Sections 10.1.1.18 and 12.1.

5 TECHNICAL APPROACH: SYSTEM DESIGN

5.1 System Design Approach and Alternatives Considered (Francesca Afruni, Marcelo Samaan, Fabrizio Chigne)

Figure 12: Full Assembly

The DROVER was designed to be compact and versatile while still being powerful enough to produce a 2:1 thrust-to-weight ratio. For control and simplicity purposes, the team opted for a manually controlled prototype. The DROVER features distinct systems that control driving and flying operations. The rover functions are controlled through an Arduino Nano, while the drone functions are governed by a Pixhawk 6x Flight Controller, which also relays the telemetry coming from the normal camera. The two are then integrated with a Radio Master transmitter. The DROVER also presents a Raspberry Pi, which is used to relay the information coming from the IR camera, the microphone, and the speaker. These foundational decisions guided the team through various design considerations, including selecting the rotorcraft type and the suspension system. Moreover, the DROVER structural assembly is made of different materials, mainly Onyx, Carbon

Fiber, and PLA. These were chosen among other alternatives like aluminum after performing a material analysis (Structures Section 6.1.2).

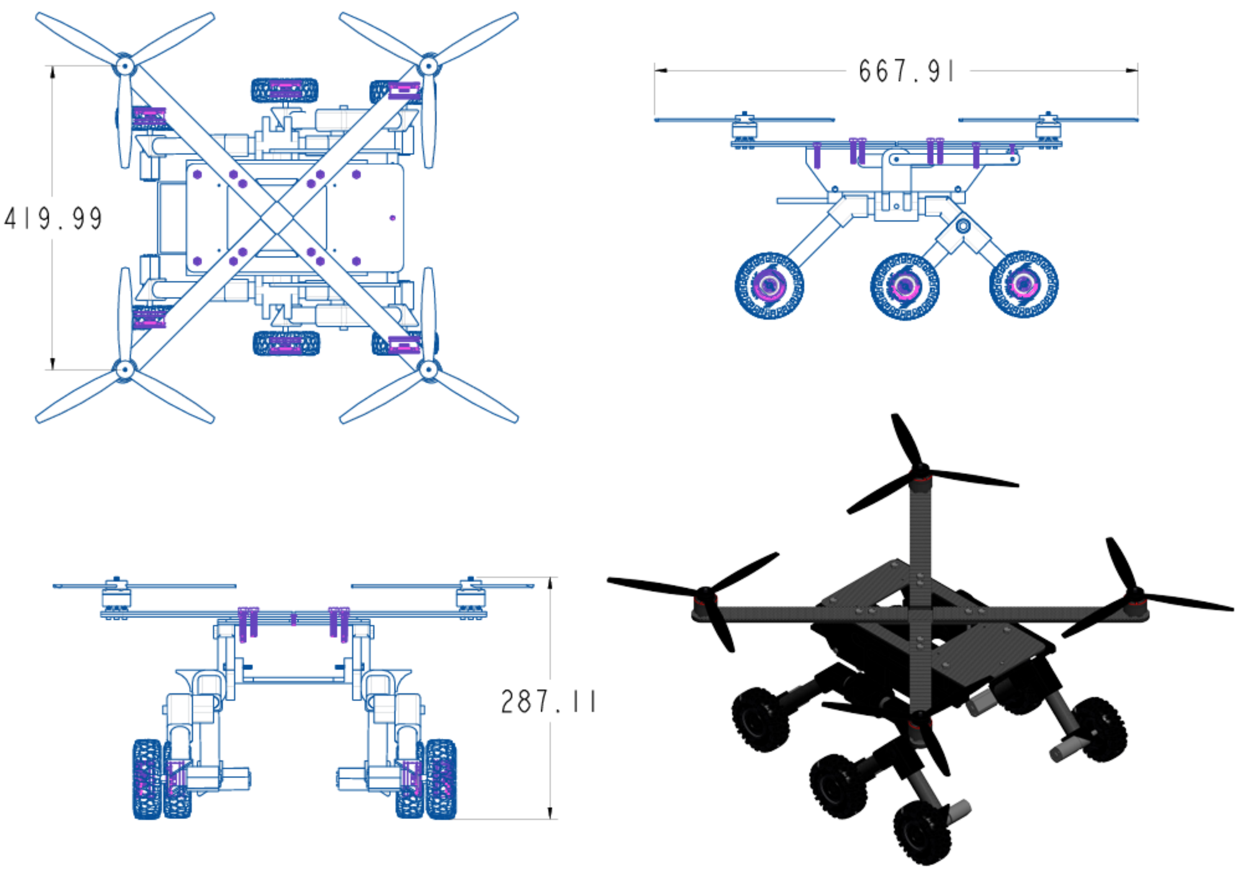


Figure 13: DROVER's Full Assembly Dimensions

The Rotorcraft type was one of the main design choices that helped shape the project in its early stages. Initially, the prototype was meant to traverse and fly on Martian terrain and featured a hexacopter configuration. However, when the scope of the project was modified to serve search and rescue purposes, the complexity and the cost of a hexacopter seemed to outweigh the benefits. The team underwent a series of trade studies, and in the end, the two main solution alternatives considered were quadcopter and hexacopter configurations. The final decision was aided by the use of a Pugh Matrix (*Appendix VIII*) that featured weight, thrust, cost, complexity of design, and size as the main key criteria. As expected, the only real benefit of the hexacopter solution was the greater thrust, so the quadcopter configuration was chosen as the rotorcraft type.

Another main design decision lies in the choice of the Suspension System type of the DROVER, as it will be navigating through difficult terrains that will contain obstacles like rocks and rubble. Consequently, to create an effective DROVER it was imperative to have the capability of driving over obstacles without excessively increasing the weight and complexity of the design. Therefore, the alternatives considered for the suspensions system of DROVER were Rocker-Bogie suspension, tracked vehicle suspension, torsion bar suspension, and independent (spring) suspension. These alternatives were compared using a Pugh Matrix considering the following factors: weight, speed, climbing capacity, terrain adaptability, complexity, and cost. After the analysis, the rocker-bogie suspension was chosen as the design of the suspension system due to its overall better climbing capabilities and reliability (*Appendix II*).

Once the suspension system was chosen, another trade study was performed to compare alternatives for the rocker-bogie leg structure design (*Appendix III*). In this trade study two alternatives were considered: circular tubes and rectangular beams. The criteria to compare these alternatives were: shape properties, weight, cost and complexity of design, and after a thorough analysis the circular tubes were chosen as the main component of the rocker-bogie leg structure design as its advantageous properties surpassed the overall increase in design complexity.

5.1.1 Design Evolution (Francesca Afruni, Marcelo Samaan)

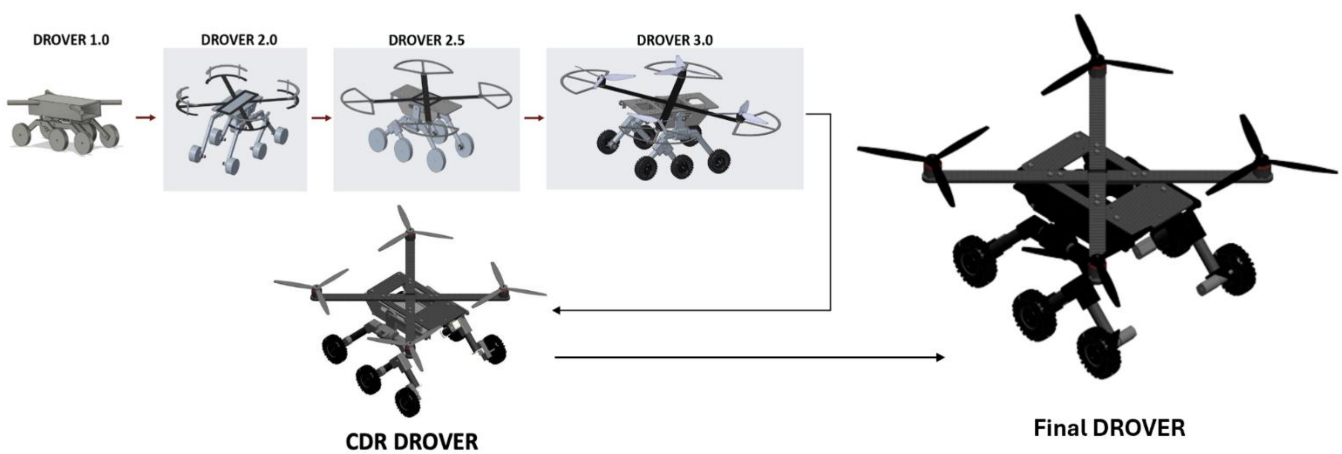


Figure 14: Design Evolution at CDR

The DROVER design evolution starts with DROVER 1.0, which showcased the basic quadcopter design and the rocker-bogie suspension. On the other hand, DROVER 2.0 was the first realistic design with rectangular beams as the legs shape, it also considered the position of the motors and the propellers. DROVER 2.5 improved on the previous design, with many changes coming from structural analysis and trade studies. Finally, DROVER 3.0 shows a fully functional rocker-bogie suspension system with a properly defined drone structure, thus being the PDR design. The CDR DROVER was built upon the PDR design and features multiple improvements that strengthen the effectiveness and reliability of the design. The final DROVER assembled has improved motors and motor mounts, as well as a longer electronics plate.

Figure 13 shows the changes that have been implemented between PDR and CDR which are present on the final assembly. The main basic structure of the DROVER remained unchanged, featuring the quadcopter configuration, the rocker-bogie suspension system, and being manually controlled. However, there have been a few important design changes that came from the start of the iterative manufacturing process (Section 6.1.2, Figure 43).

First, the CDR DROVER does not feature propeller guards anymore, that is mainly because they were an addition to the weight, which was one of the main constraints of the project; Also, due to the nature of DROVER being used for search and rescue purposes and potentially enter unstable buildings the only protection the designed propeller guards gave was in the horizontal direction, leaving the top of the DROVER and its instruments and the top of the propellers exposed to potential damage from falling debris or obstacles above, which could compromise the system's functionality in hazardous environments.

The rocker-bogie has also undergone a few changes, mainly in the onyx attachments; similarly, the drone plate has undergone many changes since PDR; it has been shortened, and the material has changed from Onyx to Carbon Fiber. These changes will be discussed further in the Structures section 6.1.2 (Figure 24).

The arms configuration has also changed since PDR; although hard to notice from Figure 14, the CDR DROVER features a square arms configuration, while the PDR DROVER did not, this change was implemented to help stability during flight.

The electronics box has also changed as the CDR DROVER features an electronics plate. That is because, initially, the team opted to strap the batteries on top of the DROVER while securing all the avionics and electronics instruments in the electronics box. However, due to the ESC and the GPS having to sit on top of the plate, a change was needed, and the batteries were moved to the bottom on a structure that fit them.

Finally, the motor mount design was also changed to fit the new rover motor cases and the rover wheels. The aluminum tie rods featured in the PDR DROVER were also replaced with PLA links and pin joints at the ends of the differential bar, achieving the same rocker-bogie movement results with lower costs and lower complexity (Section 6.1.2).

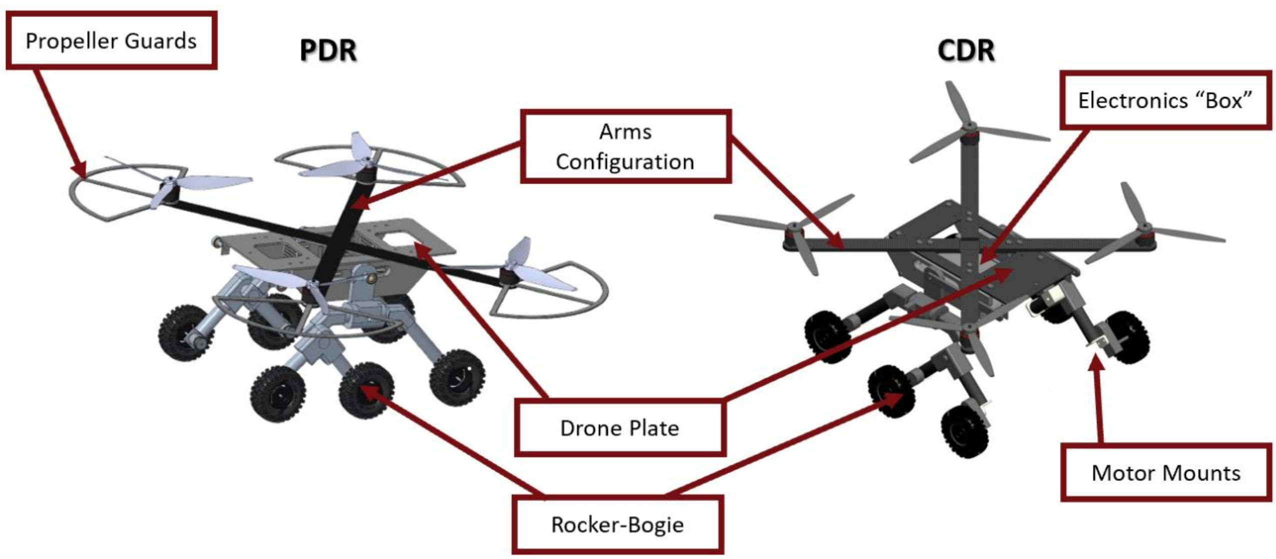


Figure 15: DROVER System Design changes from PDR to CDR

5.1.2 System Design Approach: Demo-DROVER (Francesca Afruni, Francesco De Luca)

An important part of the design process was tied to the iterative manufacturing process (Section 6.1.2, Figure 43) the team had implemented to build the final DROVER design. A great asset in this process was the Demo-DROVER (Figure 15). This prototype mainly showcased the rover portion of the DROVER (the team tested the drone portion separately). The Demo-DROVER was fundamental to test the functionality of the Rocker-Bogie suspension system but also to make sure the whole rover system was working together as intended. This prototype was mainly built out of 3D-printed PLA and wood, all materials that were freely accessible to the team at the Student Design Center.

Also, this first prototype allowed the team to detect early mistakes and opportunities for improvement. The results of this test were needed to support the suspension system requirement STR.03.

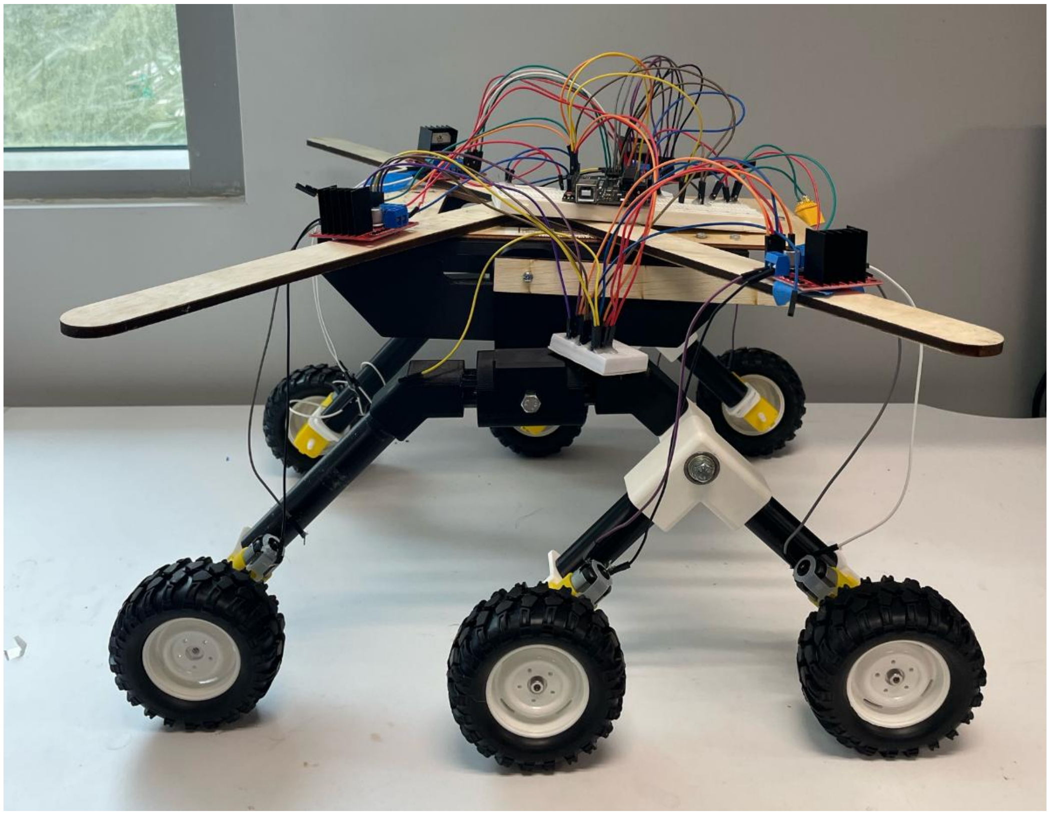


Figure 16: Demo-DROVER

5.2 System Architecture (Francesco De Luca, Fabrizio Chigne)

Project DROVER is subdivided into three main subsystems that are the structures, aerodynamics, and controls subsystems. The main purpose of the structures subsystem was to provide rigidity and strength to the whole DROVER thanks to the use of the DROVER arms, top plate, the suspension system and the attachments. To withstand loads and forces acting on the DROVER, the structures' subsystem was tasked with the goal of designing all the structures components using CAD software and complete finite element analysis (FEA) on these to verify their rigidity and properties. The team extensively used CAD software to design the following elements: the main plate, the drone arms, the attachment parts, the electronics plate, and the suspension system which consists of the rocker-bogie mechanism, the leg configuration, the tie rod, the differential bar, the motor mounts, the shafts and the six wheels. After having designed these parts, the FEA was executed on the suspension system and drone arms.

The main function of the aerodynamics subsystem was to always ensure efficient in-flight maneuverability of the DROVER. The aerodynamic subsystem personnel were tasked with the responsibility of researching and choosing the proper foil for the propellers in addition to executing computational fluid dynamics (CFD) analysis on them. Furthermore, the main purpose of the controls subsystem was to guarantee seamless transition between flight and ground mobility at any moment during operations. The controls subsystem includes the camera system, the flight controller, the microphone system, and the power supply.

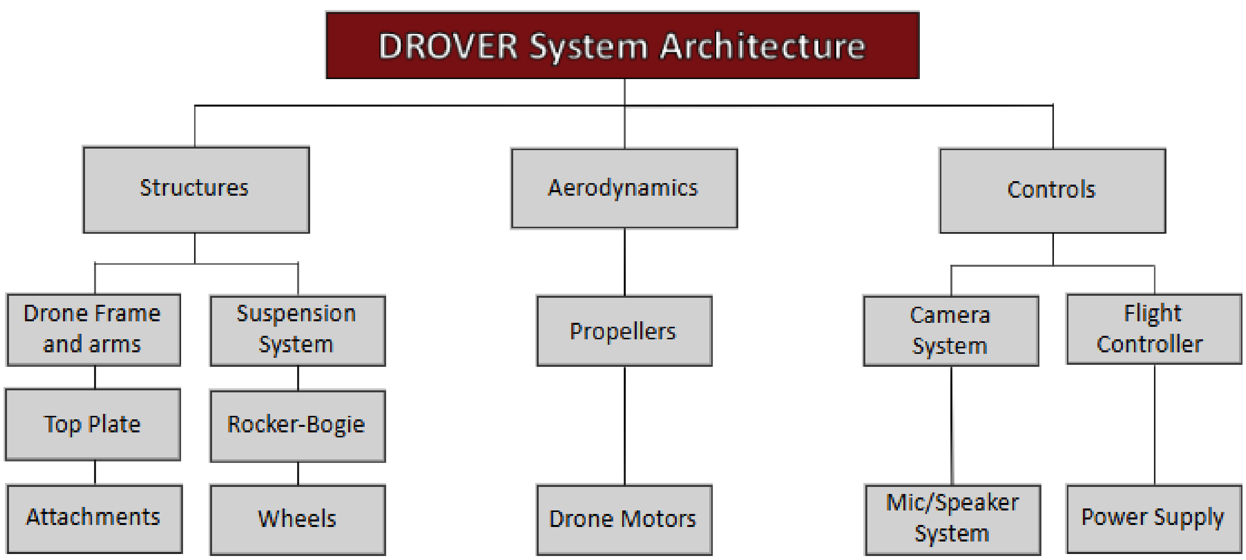


Figure 17: System Architecture

5.3 Engineering Design Specifications (Francesca Afruni, Marcelo Samaan, Haylee Fiske, Kyle Kinkade)

Table 2: Engineering Design Specifications

Metric	***Acceptable Ranges***	***Verification Method***
1.0 Functional Performance		
1.1 Driving		
1.1.1 Speed	Range: 0 – 0.2 m/s	Test, Timer, and Tape Measure
1.1.2 Tilt Surface Drive Angle	Capable of up to 20 degrees	Test, Protractor
1.1.3 Turning Performance	Differential Steering, Turning Radius: 0.15 – 0.35 m	Test
1.2 Flight Performance		
1.2.1 Take-off Weight	6-7 kg total mass	Analysis, Scale
1.2.2 Endurance Performance	Maximum 15 minutes of hover time	Timer
1.2.3 Maximum Altitude	Cannot exceed more than 400 ft	Inspection
1.2.4 Lift Off Velocity	Range: 1-3 m/s	Test
1.2.5 Minimum Thrust-to-Weight Ratio	2	Analysis
1.2.6 Cruising Speed	Range: 5-10 m/s	Test
1.2.7 Turning Performance	360 degrees turning capabilities	Demonstration
1.3 Landing		
1.3.1 Landing Speed	Must not exceed 3 m/s	Analysis
2.0 Design		
2.1 Drone		
2.1.1 Drone Design	Quadcopter Design (4 propellers)	Inspection
2.1.2 Propeller Size	28 cm (11 in)	Tape Measure
2.1.3 Propeller Blades Per Rotor	3	Inspection
2.2 Rover		
2.2.1 Suspension System	Rocker-Bogie Suspension System (6 wheels)	Inspection
2.2.2 Rockers and Bogies	Carbon Fiber, Motor Casings	Inspection
2.2.3 Wheel Design	6 Medium Traction Wheels	Inspection, Test
2.2.4 Wheel Diameter	9 cm	Inspection
2.2.5 Driving Mechanism	All-wheel drive	Inspection

3.0 Control System		
3.1 Flight Controller	Flight Controller suitable for both fly and drive outputs (Pixhawk 6X)	Analysis
3.2 Turning Capabilities	Variable Power Output for Propellers and Wheels	Analysis
3.3 Battery	Lithium Batteries	Inspection
3.4 Cameras	Normal and IR camera capabilities	Inspection
4.0 Safety		
4.1 FAA Regulations	Must adhere to all regulations	Analysis
4.2 Safety Kill Switch	Emergency Landing Capabilities	Inspection, Test
5.0 Cost		
5.1 Overall Cost	Cannot exceed the budget of $1750	Analysis
6.0 Reliability		
6.1 Fail-Safe Design	Driving and Flying are independent systems	Inspection
6.2 Durability	Suspension System must withstand both traversing and landing loads	Analysis
7.0 Operating Environment		
7.1 Wind Limit	Low wind expectation	Analysis
7.2 Temperature Limit	Temperature cannot exceed 70 degrees Celsius	Analysis
7.3 Weather Forecast	No expectation of rain	Analysis
8.0 Ergonomics		
8.1 Ease of Maintenance	Chassis includes access to electronics	Inspection
8.2 Portability	Lightweight Design, Maximum width of 0.82 m	Inspection, Tape Measure
9.0 Manufacturability		
9.1 Cutting means	Laser Cutter, Milling, Water Jet	N/A
9.2 3D Printing	Casings, Connections	N/A
9.3 Off-the-Shelf	Carbon Fiber plates, Wheels, Motors, Propellers	N/A

The numbers provided in the Engineering Specification table provide a comprehensive framework for developing a hybrid drone and rover system. The system's operational capabilities are categorized into functional performance, design, control, safety, cost, reliability, environmental adaptability, ergonomics, and manufacturability. The functional performance includes driving and flight metrics. The driving speeds range from 0 to 0.2 m/s [16], and the inclination angle for the DROVER to drive up to is a maximum of 20 degrees [17]. Flight capabilities emphasize endurance, with a hover time of 15 minutes, a maximum altitude below 400 ft to adhere to FAA regulations [18] and thrust-to-weight ratios of 2. The system emphasizes lightweight and accessible design for portability and maintenance while adhering to a cost cap of $1750. The design accounts for low wind conditions and ensures the system can operate in temperatures up to 70°C, set mainly by the operating life of the batteries [19]. Weather considerations specify no expectation of rain, emphasizing that the system is optimized for dry and controlled environments. The team expects to approach these values as expected goals for the DROVER. Furthermore, the mass expectation comes from a predicted consolidated list of masses for necessary parts of the DROVER, which can be found in Section 7.1 of the document.

6 TECHNICAL APPROACH: SUBSYSTEM REQUIREMENTS AND DESIGN

6.1 Structures Subsystem Requirements and Technical Approach

6.1.1 Structures Subsystem Requirements (Francesca Afruni, Haylee Fiske, Fabrizio Chigne)

Table 3: Structures Subsystem Requirements

Parent	Number	Requirement	Rationale	Verification Method	Verification Strategy	Status	ReferenceSections
SYS.01	STR.01	The DROVER **shall** be able to land at a 20 degree incline	The vehicle must be capable of landing on uneven environments	Test	Create a physical model environment and land the DROVER on a 20 degree incline	Fully Compliant	10.1.1.15
SYS.02	STR.02	The DROVER **shall** be able to drive on a 20 degree incline	The vehicle must be capable of driving over difficult terrain	Test	Create a physical model environment and drive the DROVER on a 20 degree incline	Fully Compliant	10.1.1.15
SYS.02	STR.03	The DROVER **shall** have a suspension system	To navigate rough terrain a suspension system is preferred	Test	Suspension system will be tested in the obstacle course	Fully Compliant	10.1.1.15-16
SYS.02	STR.04	The DROVER wheels **shall** have all-wheel drive	To drive straight effectively on uneven terrains, the DROVER needs all-wheel drive to provide enough torque and allows for use when some wheels aren't in contact with the ground	Inspection	Check if all wheels drive when throttled	Fully Compliant	10.1.1.15-16
SYS.01 SYS.02	STR.05	The DROVER **shall** have a minimum factor of safety of 1.5	The DROVER must withstand the driving and flying loads with added tolerance	Analysis	Safety factor will be determined with proper calculations	Fully Compliant	6.1.2
SYS.06	STR.06	The DROVER **shall** have a takeoff weight less than 55 lbs	FAA 14 CFR 107.3	Inspection	The DROVER will be weighed prior to takeoff	Fully Compliant	7.1

STR.01 and STR.02 concern the slopes of the incline that the DROVER can drive and land on. An inclined landing area is expected due to the nature of disaster areas in which the DROVER would be utilized. For current quadcopter drones, a slope incline of 25 degrees is tough to land on [17]. The ability of the DROVER to stick the landing was investigated by comparing a few different surfaces and their expected static friction coefficient, as shown in *Appendix IV*. A close approximation was found from the static coefficient of friction of rubber on cardboard to have a slope of 26.6 degrees before the rubber slips. The team also considered the geometry of the DROVER to avoid propeller damage as it approaches or lands on an incline. Considering these factors, the team decided on a slope incline of 20 degrees to be reasonable and in coordination with the mission of the DROVER. This limit provides a margin of safety below the theoretical maximum of 26.6 degrees, reducing the risk of slipping or instability upon landing. Moreover, a 20-degree limit aligns with the expected terrain conditions in disaster areas while maintaining a practical balance between landing stability and DROVER's ability to drive on inclines after touchdown. These two requirements are verified using the obstacle course (Figure 118). The team is fully compliant with STR.01 and STR.02.

STR.03 is a key requirement of the project, as it specifies the dual mode of the prototype. The suspension system allows the DROVER to drive over obstacles without causing issues to the other systems attached to the body. The suspension system chosen is the rocker-bogie suspension system and is explained in detail in Section 6.1.2 (Figure 41). The suspension system has been tested in the obstacle course and the team has achieved full compliance in STR.03.

STR.04 indicates that the DROVER shall have an all-wheel drive. This requirement is needed to ensure the DROVER drives straight and effectively through uneven terrains. This requirement has already been compliant by the team as all six wheels drive when throttled. This configuration helps the system provide enough torque and allows for use when some wheels are not in contact with the ground.

Moreover, STR.05 indicates that the DROVER shall have a minimum factor of safety of 1.5. The team has already met this specific requirement through proper calculations and FEA analysis. This requirement states loading requirements that must be sustained by the DROVER. The factor of safety is specified by FAA industry standards for aircraft [20]. The load applied will determine the ability of the DROVER to sustain flight and maintain structural integrity when operating. The final structures requirement STR.06 was determined by Small UAS Rule Part 107 [18]. The official document for part 107 determines that a drone must not exceed 55 pounds in weight to comply with FAA regulations for small drones [18]. Requirement STR.06 is fully compliant.

6.1.2 Structures Subsystem Design

Drone Structure Design (Fabrizio Chigne)

As mentioned in section 5.1, the quadcopter configuration was selected instead of the hexacopter; from that decision, a few different options were considered. The Quanser drone structure was a very interesting option since it is very lightweight and is made with durable materials, including carbon fiber (Figure 17).

Figure 18: Quanser drone structure considered [23]

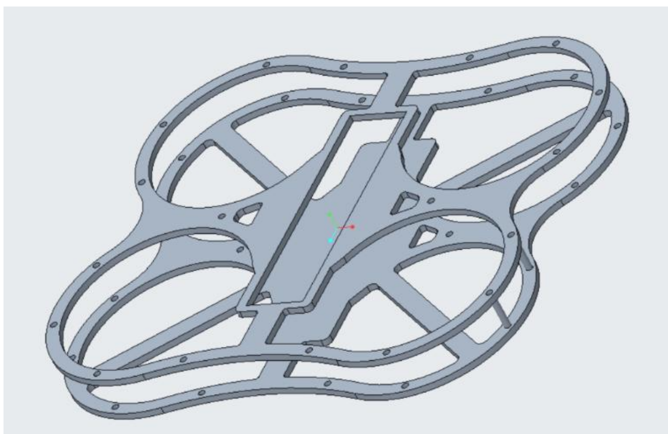


Figure 19: Quanser CAD Drone Structure

However, since the project is not only a drone but also a rover, the team had to consider reducing the mass of this component even more. Therefore, the Quanser design configuration was no longer an option.

Moreover, after making that decision, the team came up with the idea of just making a drone plate with four propeller guards at the end of each one of the arms. See Figure 19.

Figure 20: Drone structure CAD evolution

Nevertheless, the team was still trying to get the drone structure even more lightweight, considering the missing parts. Some of these parts included the rectangular plate, which helps to attach the drone arms to the rest of the structure, the electronics box, differential bar, and the two platform bases. The electronics box was an initial idea to hold the wiring and any other electronics, the platform bases help with the attachment of the suspension system, and the differential bar is needed for the rover part of the vehicle to work. After completing the CAD, the plate was modified, and everything was assembled (Figure 20).

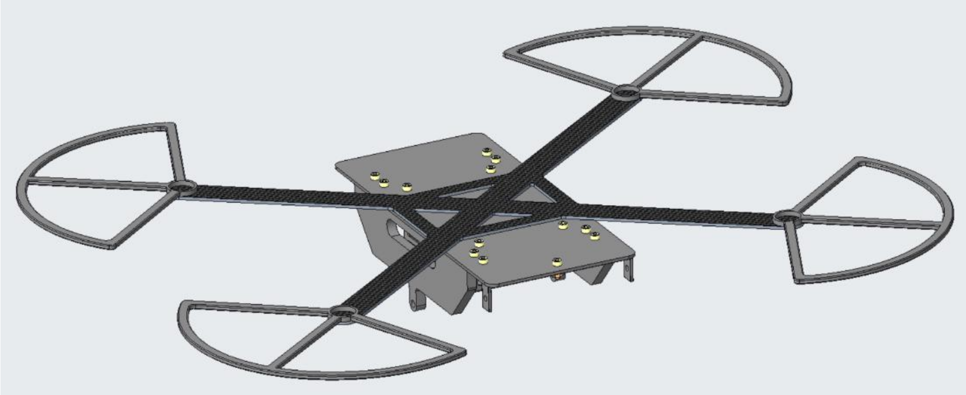


Figure 21: Drone structure CAD evolution

In addition, the square of the drone plate was not necessary; therefore, it was removed.

Figure 20 shows the drone structure assembly for Preliminary Design Review (PDR); however, the team made some important changes for Critical Design Review (CDR). After a finite element analysis (FEA) was performed on ANSYS for the drone arms, the team found that the arms needed to be thicker due to deformation. Because the team had already bought the carbon fiber sheets, the solution was to epoxy two sets of arms. The arms became twice as thick as the original arms (See Figure 21). This, of course, made the weight of the drone structure go up; nevertheless, it was necessary for the safety of the structural components. Moreover, it is important to note that due to the use of carbon fiber, the team had to leave a two-diameter space between the holes (screws for main plate or flight motors) and the edges (See Figure 22).

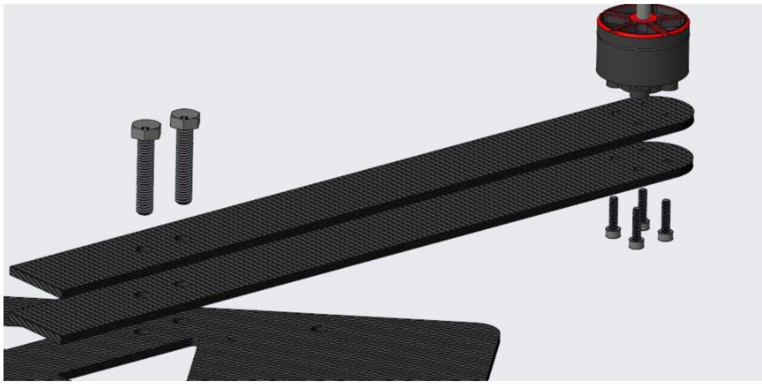


Figure 22: Arm configuration

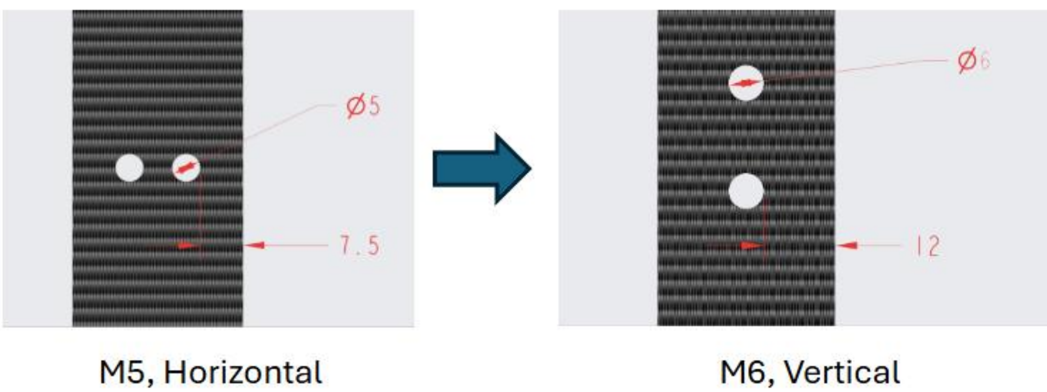


Figure 23: Carbon fiber two-diameter space issue

As can be seen above, the team had to be careful with the position and the size of the screws; therefore, the team decided to go with a vertical configuration and M6 screws. See Figure 23 for a full drawing of the drone arm.

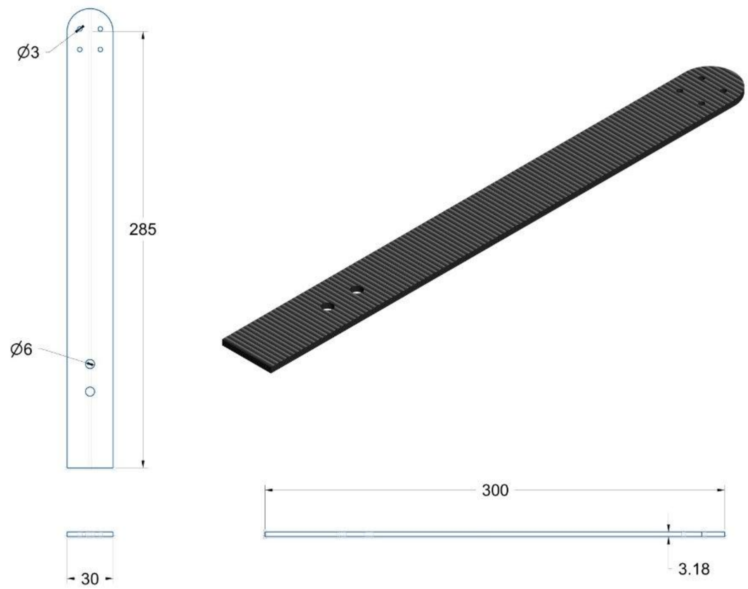


Figure 24: Drone Arm Engineering Drawing (Not to scale) in mm

Next, the main plate is a component the team changed a lot since PDR, and it is now a rectangular plate with a lot of holes for attachment purposes. The material also changed several times. The final material selected for the main plate is carbon fiber; however, other materials such as onyx or even wood were also considered. Onyx was a great option because it was lighter than carbon fiber; nevertheless, carbon fiber is stronger and better in terms of bending. The wood type that was taken into consideration was the hardwood oak, which was about 80 grams lighter than carbon fiber and it is a great option considering shear toughness and strength, but still carbon fiber was a better choice. See Table 4 for a table showing different wood types as materials and their respective mass for this specific part.

Table 4:Wood Types considered for main plate

Wood Types	Density (g/cm^3)	Mass (g)
Bamboo	0.693	85.96
Cork	0.196	24.31
Hardboard	0.917	113.75
Hardwood Oak	0.936	116.12
Hardwood Walnut	0.612	75.92

Plywood	0.748	92.79
Softwood Pine	0.487	60.41

Even though hardwood oak and onyx had interesting properties, carbon fiber was still a better option even though it weighs more. See Figure 24 for an engineering drawing of the main plate.

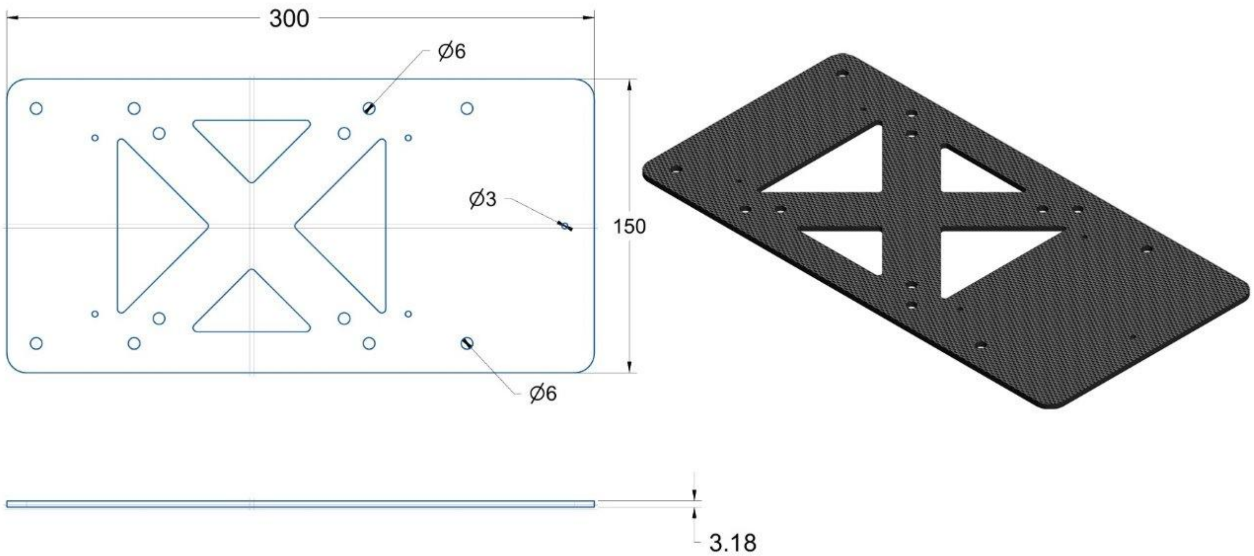


Figure 25: Main Plate Engineering Drawing (Not to scale) in mm

Regarding the attachment of the drone structure to the rover system, the platform bases are the ones responsible for it (See Figure 25). These two bases are made of PLA, and they also have been modified since PDR. For instance, the little notch that connects the legs' main attachment happened to be where it cracked during a flight test that resulted in a hard landing; therefore, the structures team decided to make that specific part bigger so that the bending issue can be avoided.

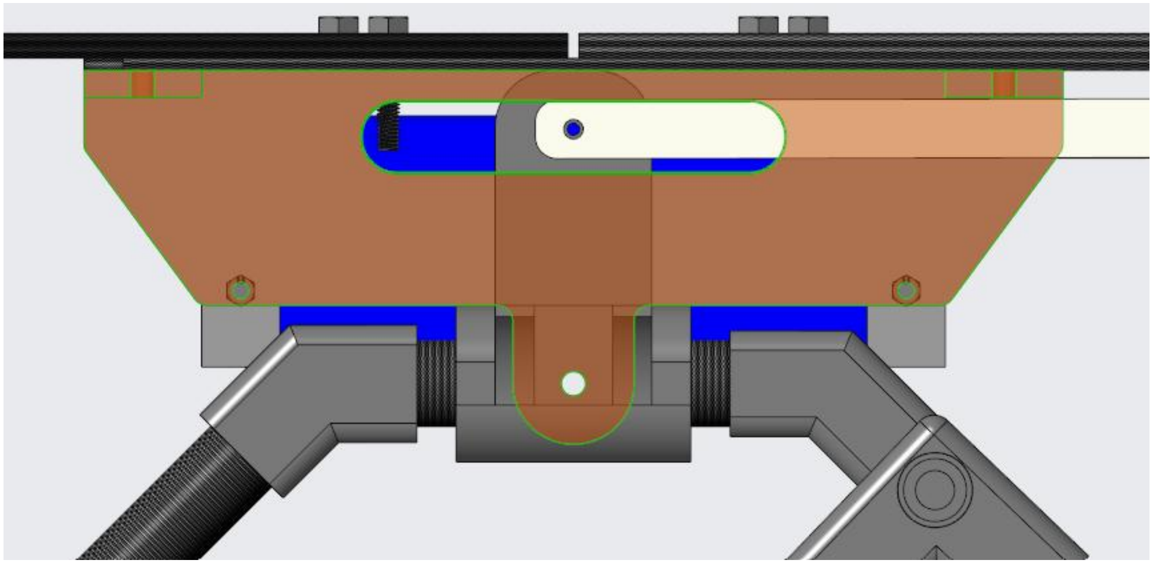


Figure 26: Platform Base (connection between drone and suspension system)

The placement of the batteries also changed from PDR, as the team decided that the best way to attach them is under the main plate. Before, the team designed an electronics box that really was not made for any electronics specifically; therefore, the design has changed to an electronics plate that perfectly fits the two batteries needed to perform the mission operations (See Figures 26 and 27). This new design also features two big holes that help attach the batteries using zip ties.

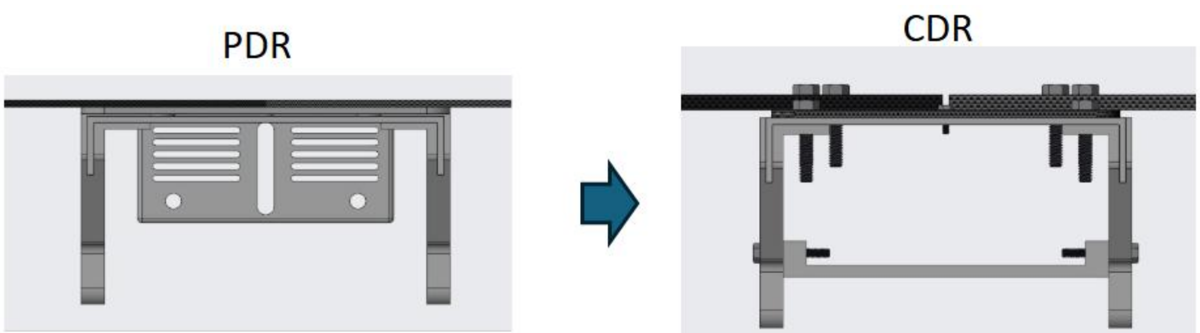


Figure 27: Change of electronics box to electronics plate

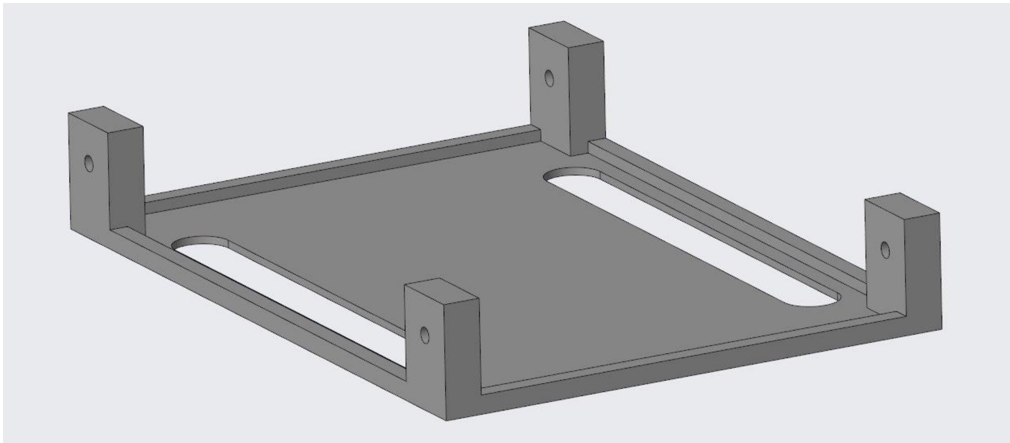


Figure 28: CAD Design of Electronics Plate

An important decision was made in the past months as the team removed the propeller guards from the final product. The team understands the risks involved with keeping the propellers without some type of protection; however, the design was not useful enough as it only covered the guards horizontally but not vertically. Also, the mass added by the thicker arms and bigger bases made the team realize that weight was starting to become an issue and that the team had to make a choice. That choice was to remove the guards and leave that concept for the future of this product.

The upper structure consists of five parts: the arms, the main plate, the platform bases, the differential bar, which will be explained in detail in Section 6.1.2 (Figure 56), and the electronics plate. The electronics plate had a final modification, in which the team added an extra See Figure 28 for an isometric view and Figure 29 for an exploded view of this structure. The mass adds up to 998 grams (See Table 5).

Figure 29: Isometric View of the Drone Structure

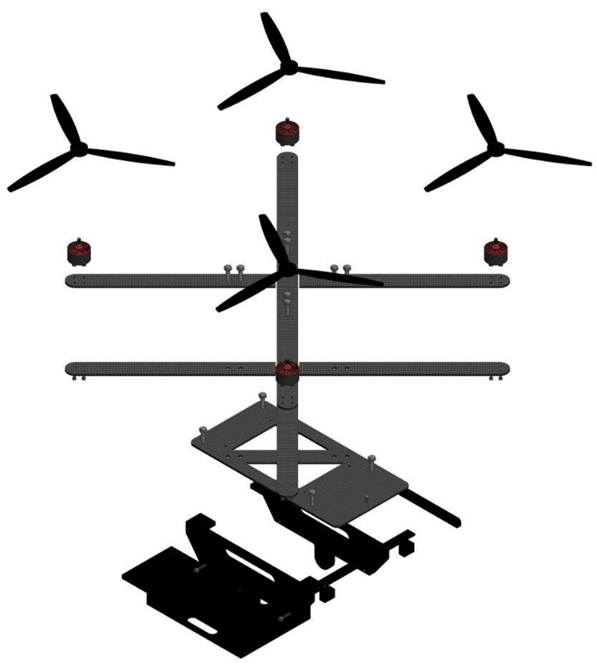


Figure 30: Exploded View of the Drone Structure

The dimensions of the drone structure are about 57 x 67 cm (See Figure 30). All the dimensions were influenced by the blade's size and the thickness of the plate due to budget and mass purposes.

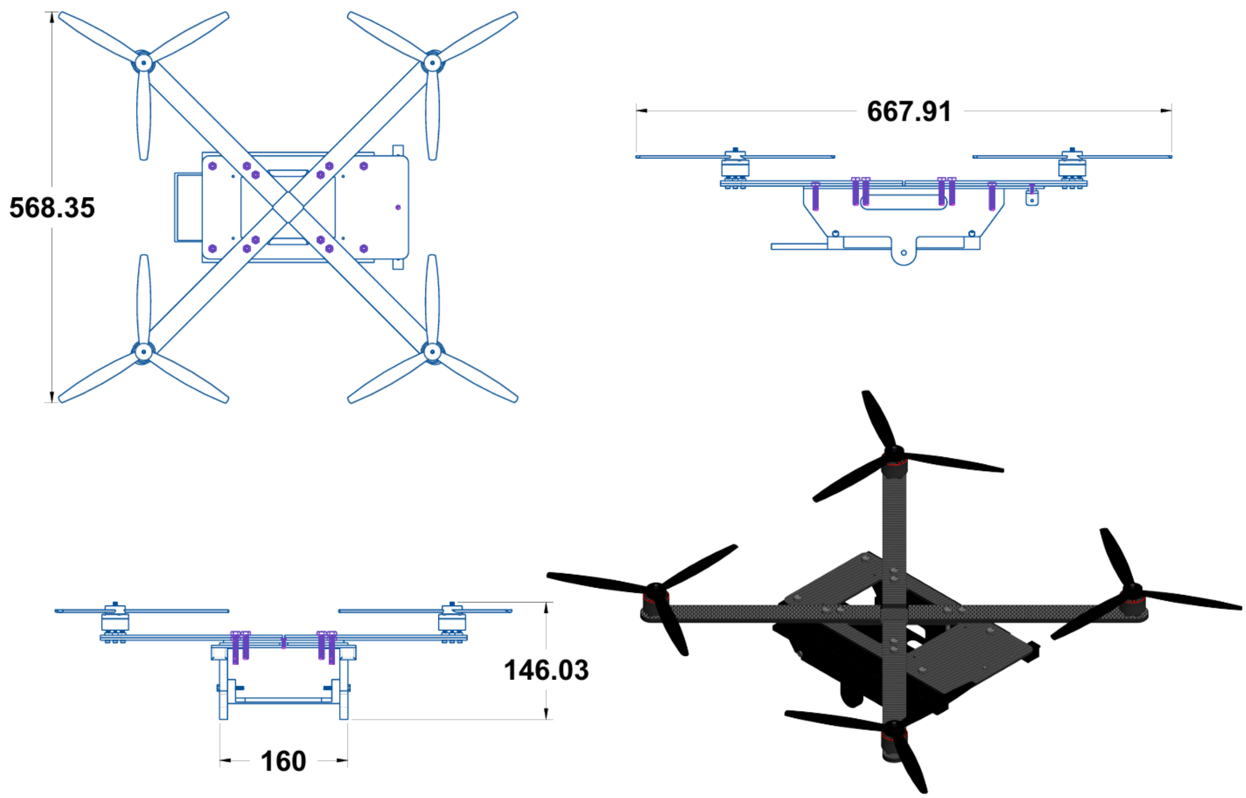


Figure 31: Drone Structure Engineering Drawing (Not to scale) in mm

Table 5: Drone Structure Mass

CAD Part Name	Material Assigned	Density (g/cm^3)	Mass (g)	Qty	Total Mass (g)
Arm	Carbon Fiber	1.57	43.96	8	351.67
Plate	Carbon Fiber	1.57	189.22	1	189.22
Electronics Plate	PLA	1.25	112.46	1	112.46
Differential Bar	PLA	1.25	20.57	1	20.57
Platform Base	PLA	1.25	171.11	2	342.23

Carbon Fiber Drone Structure Finite Element Analysis (Kyle Kinkade)

As mentioned in the previous section, the drone plate is made from carbon fiber because that's where the expected loads of the drone structure are. The plate must withstand the thrust force the motors and propellers generate at maximum power. A basic FEA analysis was completed for the drone structure to confirm the design geometry and the carbon fiber material's capability. This drone arm design differs from the PDR geometry as the new arm geometry introduces two epoxied carbon fiber plates and connects the full assembly to the bottom drone plate with fasteners. This change was made to lower the total deformation of the drone arm to ensure structural (1.5 FS) and aerodynamic stability. Below are the PDR and updated CDR geometries.

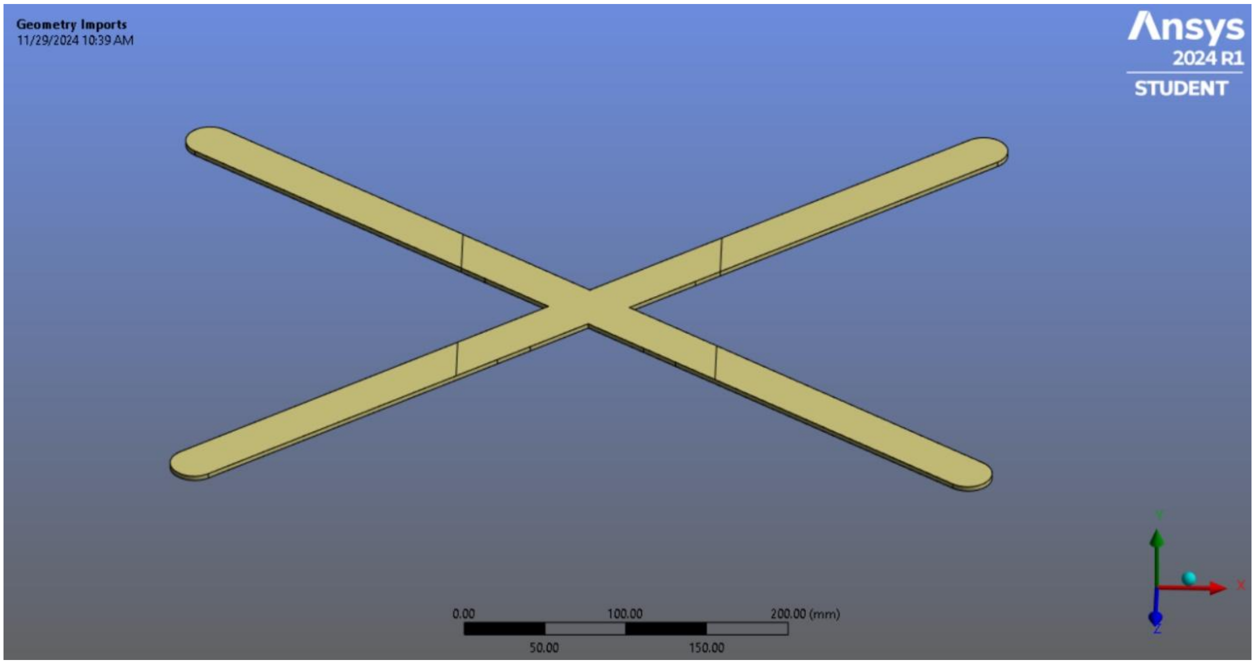


Figure 32: PDR Geometry

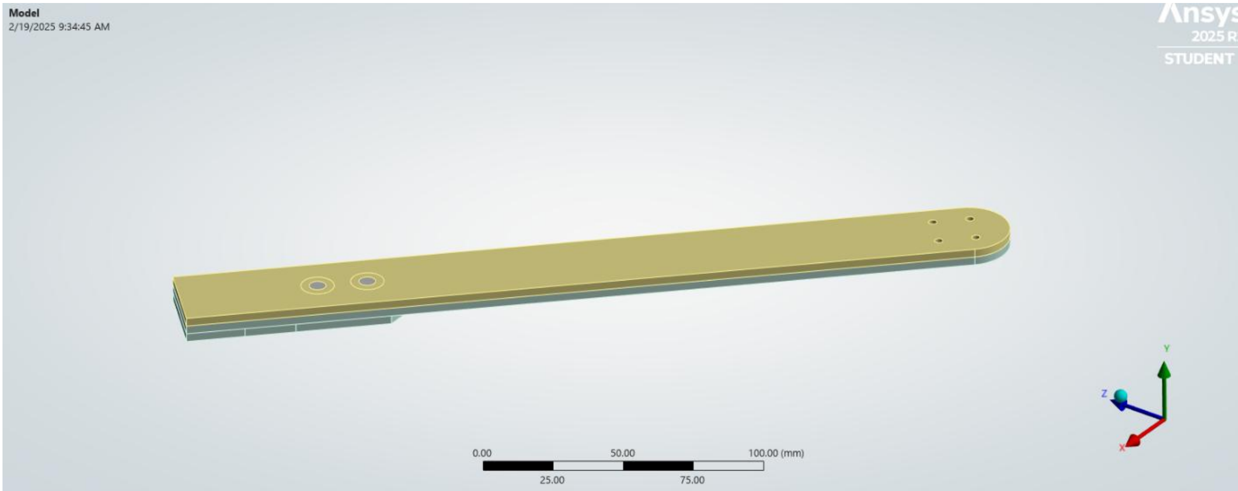


Figure 33: CDR Geometry (1 Drone Arm)

Assumptions:

- The carbon fiber plate is perfectly fixed to the onyx bottom plate.
- 4 kg of thrust per motor.
- All carbon fiber is cut in the fiber direction to achieve the listed properties provided by McMaster-Carr [21].

Objectives:

- Confirm a greater than 1.5 FS for maximum and minimum principal stresses (STR.05).
- Determine the max deflection of the arms is <= 1 mm for aerodynamic and structural stability (AERO.03).

Hand Calculations (Simplified Cantilever Beam)

$$F = m * g = 4\ kg * 9.81 \frac{m}{s^2} = 39.24\ N\ (Thrust\ Per\ Motor)$$

This thrust exceeds the expected need for thrust for the DROVER (assuming max weight is 6500 g) by 750 grams per motor. This comes from the 2:1 Thrust-to-Weight requirement. Also, assuming the same weight, the hover thrust per motor is 2375 grams less than the 4 kg assumed in this analysis. This provides the team with a built-in factor of safety.

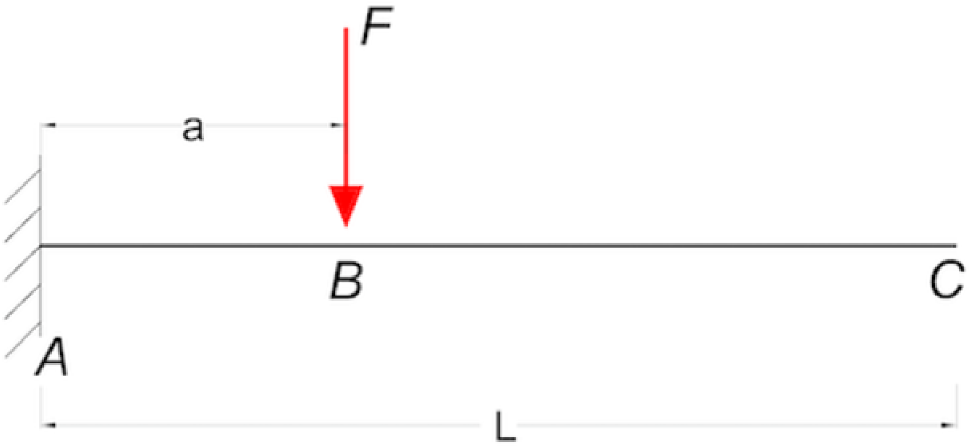


Figure 34: Used Simplified Cantilever Beam Model [22]

Known values

$$I = 6.4 * 10^{-9}\ m^4$$
$$L = 0.232\ m$$
$$a = 0.212\ m$$
$$E = 228 * 10^{9}\ Pa$$
$$F = 39.24\ N$$
$$y = 3.175 * 10^{-3}\ m$$

Max Deflection (Deflection at point C) [22]

$$\delta_c = \left(\frac{Fa^3}{3EI}\right) * \left(1 + \frac{3(L-a)}{2a}\right)$$
$$= \left(\frac{39.24\ N * (0.212\ m)^3}{3 * 228 * 10^9\ Pa * 6.4 * 10^{-9}\ m^4}\right) * \left(1 + \frac{3(0.232\ m - 0.212\ m)}{2 * 0.212\ m}\right)$$
$$= 0.00097\ m = \mathbf{0.97\ mm}$$

Carbon Fiber	
Structural	
Isotropic Elasticity	
Derive from	Young's Modulus and Poisson's Ratio
Young's Modulus	2.28e+05 MPa
Poisson's Ratio	0.3
Bulk Modulus	1.9e+05 MPa
Shear Modulus	87692 MPa

Figure 35: Carbon Fiber Properties

The material properties imaged above were applied to the entire structure shown. These properties match the lowest given properties provided by McMaster-Carr when cutting in the fiber direction. [21]

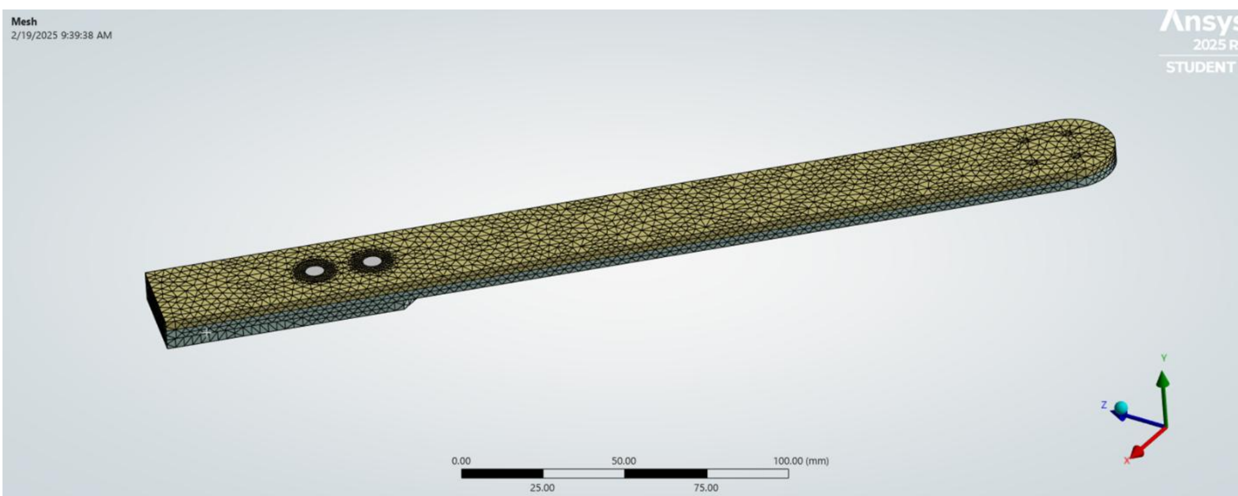


Figure 36: Mesh Applied to Drone Arms

Statistics	
Nodes	61199
Elements	34942

Figure 37: Statistics of Mesh

The number of nodes and elements applied to this structure should be more than enough to produce valid results.

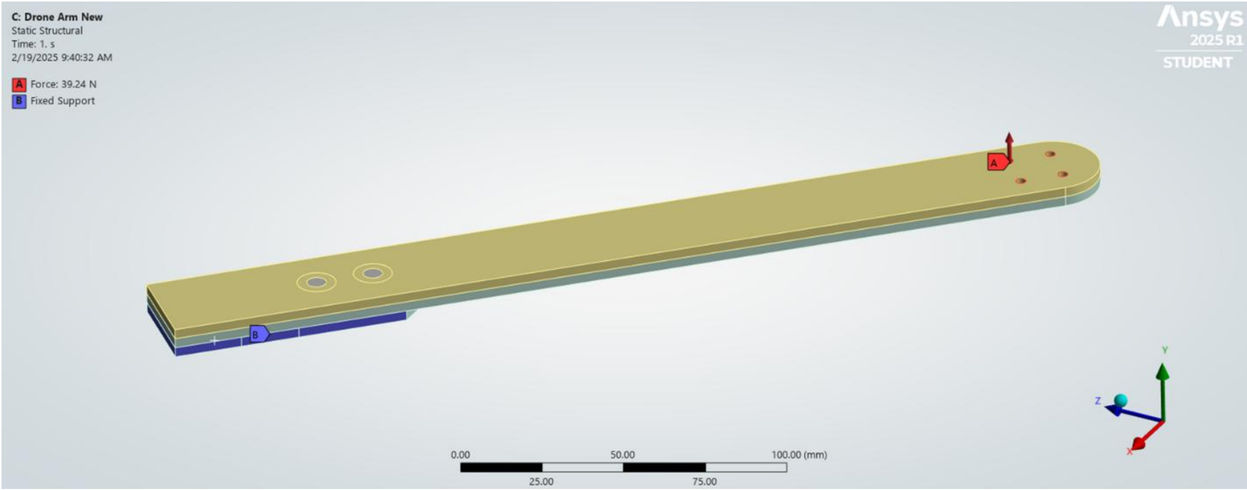


Figure 38: Loads and Boundary Conditions

The double stacked carbon fiber arms are assumed fixed together with epoxy. These parts have already been manufactured, so this assumption can be considered accurate. Furthermore, the arms are fixed to the carbon fiber plate with two M6 fasteners that are located near the end of the rods. These fasteners are modeled using beam elements and applied to both sides of the surfaces with the assumption that washers are used. The blue-filled area represents that area that is expected to be fixed (Drone plate).

Results:

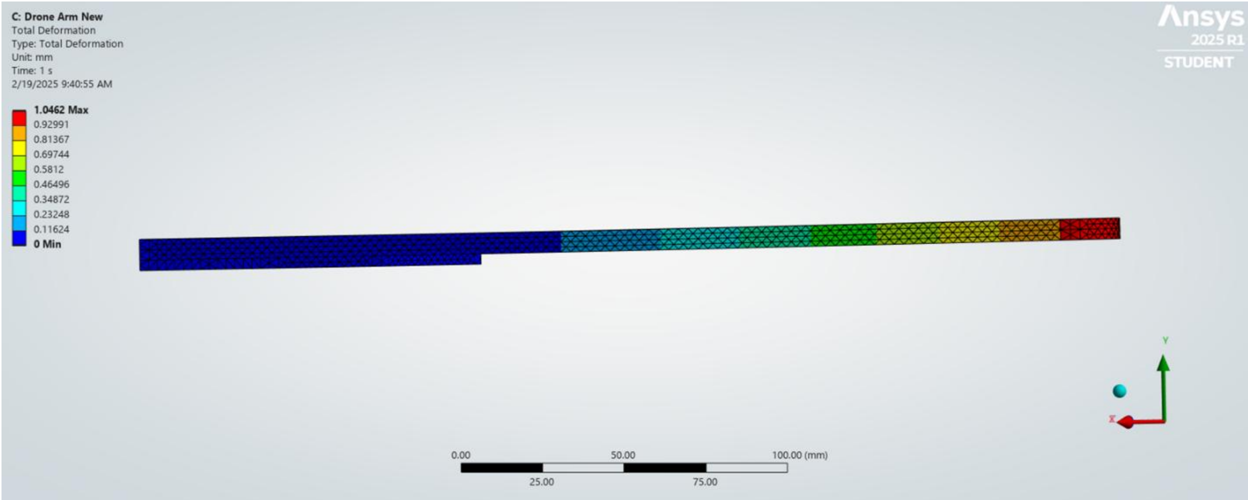


Figure 39: Deformation Results

From the model, a max deformation of 1.04 mm was found. This is slightly above the 1 mm goal; however, because the team underestimates the carbon fiber properties and overestimates the force applied by the drone motors, the team feels that this deformation is acceptable.

This result gives a 6.7% error with the hand calculation, this supports the model's efficacy.

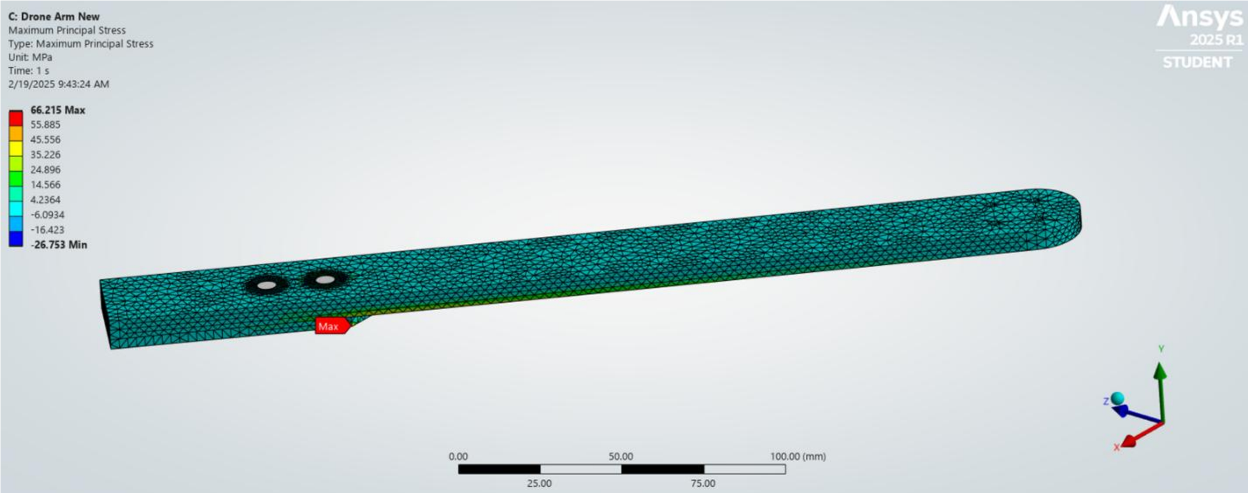


Figure 40: Tension Results

The maximum principal stress of 66 MPa can be found at the bolt's connection with the onyx plate.

Ultimate Tensile Strength = 120000 PSI [21] = 827 MPa

$$FS = \frac{827\ MPa}{66\ MPa} = 12.5$$

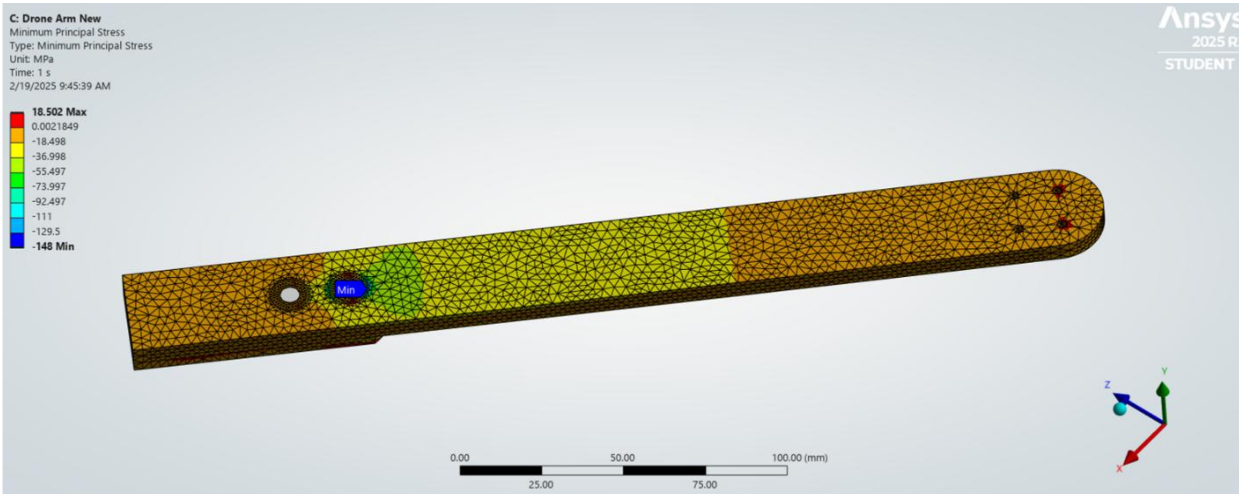


Figure 41: Compression Results

The minimum principal stress is found on the compressive side of the arm, close to the first fastener. This stress was found to be 148 MPa.

Ultimate Compressive Strength = 75000 PSI [21] = 517 MPa

$$FS = \frac{517MPa}{148\ MPa} = 3.5$$

These factors of safety satisfy the minimum structural requirement of 1.5 FS (STR.05) and the deformation results support the aerodynamic stability requirement (AERO.03).

Rocker-Bogie Suspension System Design (Marcelo Samaan)

The rocker-bogie suspension system is a crucial part of DROVER, as it allows it to climb reliably, and stably over obstacles. The final rocker-bogie suspension system features multiple design improvements and solves diverse issues that the PDR design had.

Figure 42: Rocker-Bogie Suspension System

The materials used in the rocker-bogie suspension system have not changed from PDR and CDR. Onyx 3D printed attachments and carbon fiber rods are the main components of the design (*Appendix VI)*. A table containing all components and their materials can be found in this structures section (Table 7). The following drawing contains the most important dimensions of the rocker-bogie suspension system, and all the components directly involved with its operation, and thus it does not feature the drone structure.

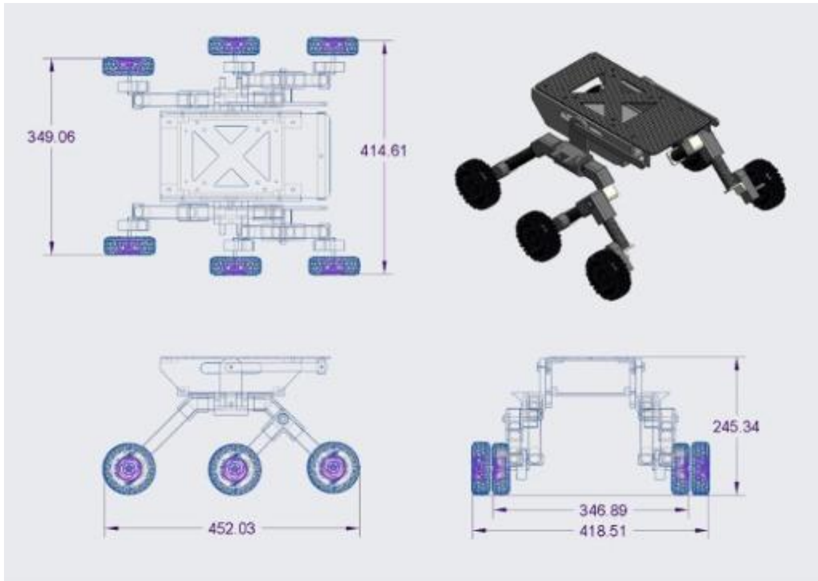


Figure 43: Rocker-Bogie Drawing (all units in mm)

The design reasoning after PDR mainly involved design for manufacturing, FEA improvements, the re-design of crucial attachments, the proper definition of pin connections, motor mounts, and differential bar improvements. All these improvements and design choices will be thoroughly explained in this structures section, and they contribute to the fulfillment of the suspension system requirement (STR.03). Furthermore, it is crucial to mention that the design improvements were found from the iterative design and manufacturing process explained in the following subsection.

Design & Manufacturing Process Flow (Marcelo Samaan)

The design and manufacturing process of DROVER was iterative, and thus it involved analysis, and testing of each design component (Figure 43). This thorough process had the objective of recognizing improvement opportunities in the DROVER design before its final assembly, and consequently, multiple design changes from PDR to CDR were aimed to solve the issues found through this process flow.

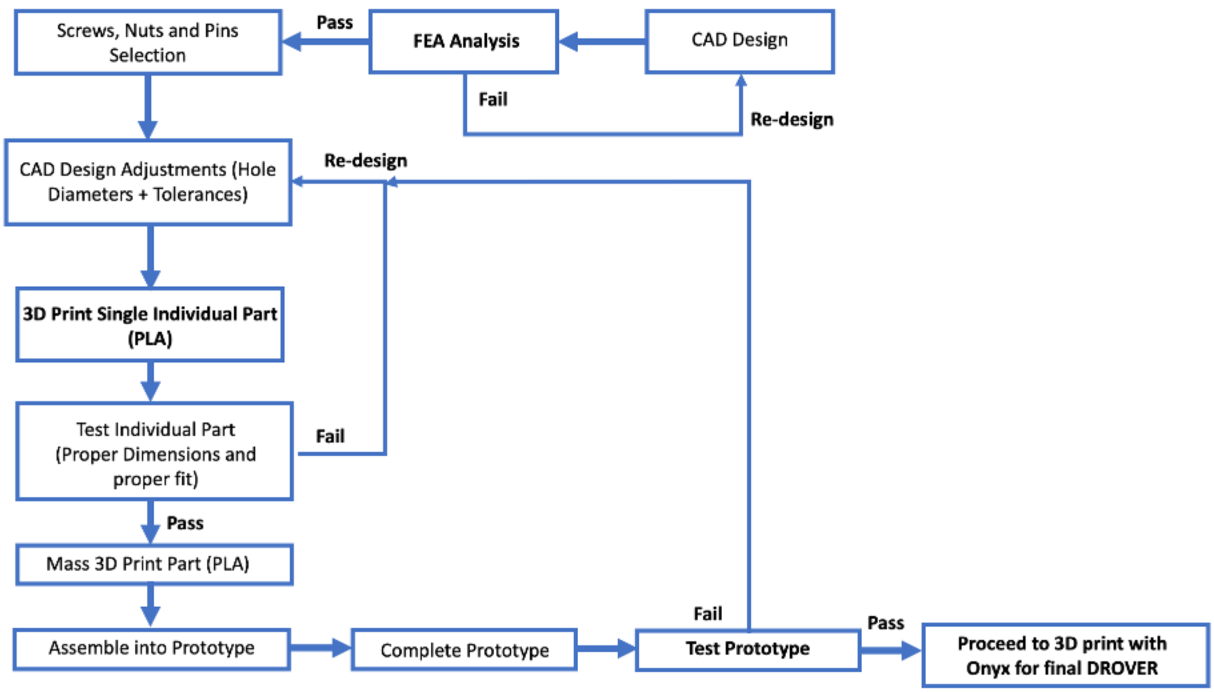


Figure 44: Design and Manufacturing Process Flow

As seen above, the design and manufacturing process begins with the original CAD design from PDR. This CAD design was then analyzed iteratively with FEA in order to ensure that the model reached the desired factor of safety as specified by STR05. Afterwards, the CAD model was prepared for manufacturing, and thus tolerancing and design for manufacturing improvements were made. Then all design components were 3D printed with PLA and tested separately and iteratively to ensure that each component had the proper dimensions and that they worked as intended in the CAD model.

Once all components were successfully inspected, a Rocker-bogie prototype was assembled. This prototype underwent an extensive testing phase which resulted in the multiple design improvements shown in the structures section of this report. Furthermore, this prototype did not only yield design improvements, but it provided the controls team with the opportunity to test the driving code of the DROVER.

Rocker-Bogie Design Improvements (Marcelo Samaan)

1. Design for Manufacturing

All Onyx attachments were redesigned to take into consideration tolerances and the layer of epoxy required to attach them to the carbon fiber rod, and thus the diameter of the attachments is now bigger than the diameter of the carbon fiber rods. The purpose of this change was to guarantee a proper tight fit at the time of assembly. The following table contains information about the diameters of the attachments.

Table 6: Holes and Diameters

Type of hole	Diameter increases	Details
Screw/Pin Holes	+0.2 mm	Easy fit for screws and pins, and thus not threading the Onyx
Hole for Carbon Fiber Rods	+0.4 mm	Tight fit plus a thin epoxy layer

An example of this changes is also shown below:

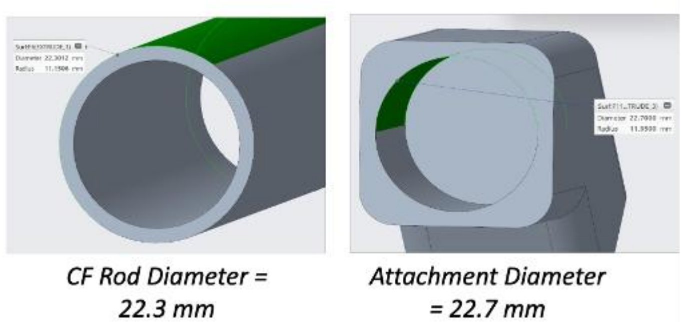


Figure 45: CF rod diameter and attachment diameter for tight fit

Another important design for manufacturing change involved the depth of each onyx attachment. Proper geometry is essential for the correct operation of the rocker-bogie mechanism and to have all wheels touching the ground in alignment. Consequently, there is a specific depth measurement that each carbon fiber rod must be inserted into to maintain accurate geometry. Nevertheless, the PDR design featured completely hollow attachments which increased the possibility of human errors as it would require taking measurements during the assembly process. This changed, and, in the final assembly each onyx attachment has the required depth for proper geometry at the expense of a slight increase in weight.

2. Pin Connection

The bogie pin connection was completely re-designed and improved after testing. A comparison between PDR and final pin connections is shown below.

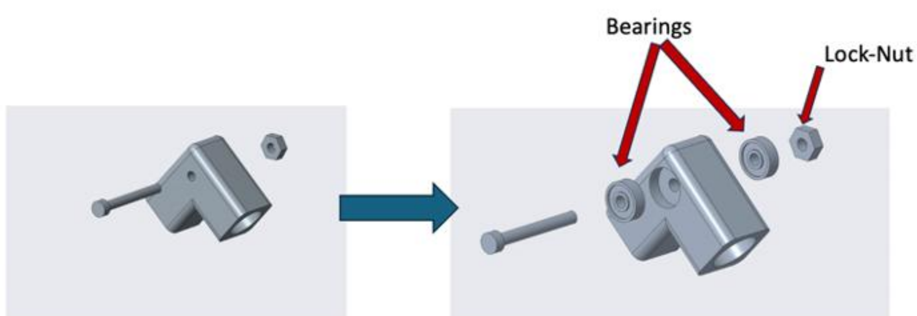


Figure 46: DROVER pin connection

The PDR design presented two main issues: the attachment struggled to rotate, and the nut would progressively loosen with time and use. On the other hand, the final pin connection presents two bearings, which solve the rotating issue, and a lock nut, which ensures that the nut stays in place even after prolonged usage.

Another crucial aspect to mention regards the ease of movement of this pin connection. Essentially, the pin connection needs to be smooth enough to be able to rotate when climbing obstacles, but stiff enough to stay in place during flight as wiggling motion could affect flight performance. The lock nuts solve this issue as depending on how much it's tightened it guarantees stiffness of the pin connection in flight while at the same time being smooth enough to rotate when climbing the necessary obstacles. This new pin connection was tested successfully on the prototype and thus used in the final DROVER assembly.

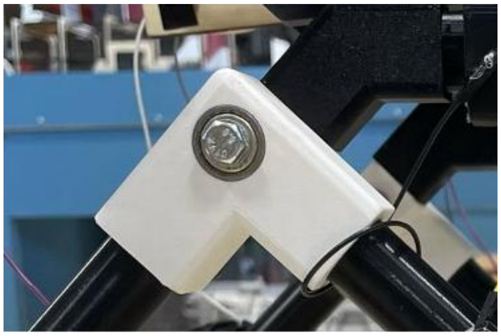


Figure 47: CDR Pin connections on the Prototype

3. Legs Connection – Instability, Torque and Alignment problems
   The figure below shows the improvements made in the leg connection.

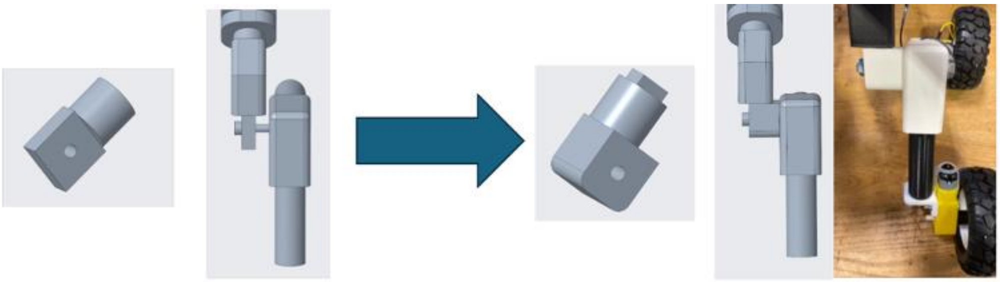


Figure 48: Final Leg Connection Design

The PDR design proved to be unstable, as the pin was not effectively secured, and would easily move and wiggle in a direction perpendicular to the pin shaft. The solution for this instability problem was to extend the leg connection attachment to contact the pin attachment as seen in the figure. The team moved on with this new design as it was tested successfully on the prototype, and proved to be effective on the final DROVER assembly.

Nevertheless, there were also other issues that were solved with this new leg connection, mainly torque and alignment problems. The force from the wheels generates a moment arm and thus a torque in the attachment which tends to rotate it (Figure 48). This design did not only put a lot of pressure in the epoxy layer but, during the prototype assembly, it was nearly impossible to guarantee the proper 90-degree alignment between this connection and the shaft coming from the pin attachment.

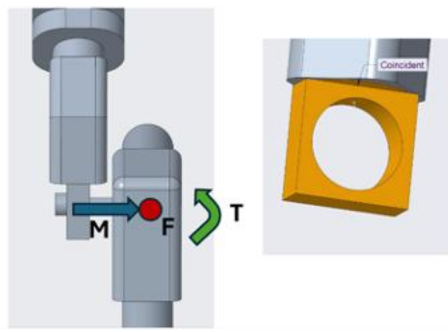


Figure 49: Torque and Alignment issues in Leg Connection

The tested solution for these problems was to distribute the torque effects to a bigger area and to guarantee alignment by modifying both attachments as seen in the figure below.

Figure 50: CDR Leg connection attachments

The left attachment now features a rectangular section intended to perfectly connect to the hollow rectangular section of the attachment to the right. Therefore, the crucial 90-degree alignment is now guaranteed, and the torque effects are now diminished as instead of tending to rotate only the leg connection attachment now it would have to rotate the assembly of these two attachments.

4. FEA Feedback improvements

Most of the attachments were thickened in order to achieve the required factor of safety of at least 1.5 (STR.05). FEA analysis of the rocker-bogie will be thoroughly described in the following sections of this report. One of these thickness modifications is shown below, where the attachments which had equal thickness in the PDR design have now different values between each other, as one of them experienced increased loads and deformations.

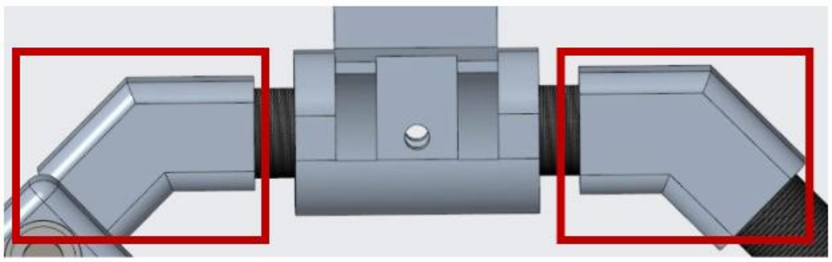


Figure 51: Attachments with modified thickness

The left attachment presents a thickness of 2.15 mm, which is enough to achieve the factor of safety of 1.5 during impact. However, the right attachment went from that 2.15 mm to 3.65 mm (a 70% increase) to effectively handle its increased loads and deformations.

5. Motor Mounts:

The position of the motor changed, and the motor mounts were completely re-designed in order to properly fit the motors bought.

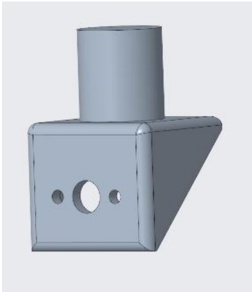


Figure 52: Final motor mounts

Therefore, the motors are now placed perpendicular to the carbon fiber rods instead of parallel. The triangular shape adds stiffness in the motor mounts and thus prevents bending deformations.

6. Propeller Protection:

Propeller protection was added in this rocker-bogie design. After testing there was a small probability of the pin connections rotating fully up, and thus hitting the back propellers, as seen in the picture below.

Figure 53: Pin connection rotating fully upwards

To completely mitigate this risk, the main attachment of the rocker-bogie was modified to now include a limit to how much the wheel can go up. A limit of approximately

14 centimeters. This does not affect the operations of the rocker-bogie as it is not expected to climb obstacles of that size.

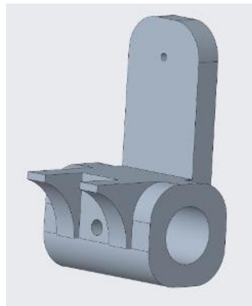


Figure 54: Propeller protection added to main attachment

Furthermore, this modification proved useful in the final assembly of the DROVER as it served as the platform for the communication speakers.

7. Differential Bar and Links Improvements.

The differential bar is a crucial component of the rocker-bogie assembly, as it holds and stabilizes the entire structure of the DROVER. The differential bar rotates on its own axis allowing the opposite movement of the right and left legs via the links which connect them.

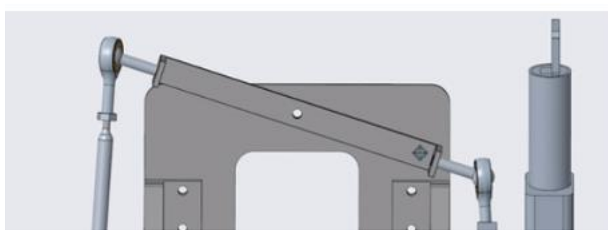


Figure 55: Differential Bar Rotation

One of the first decisions after PDR was to replace the tie rod links with simple PLA links due to the complexity of design and availability.

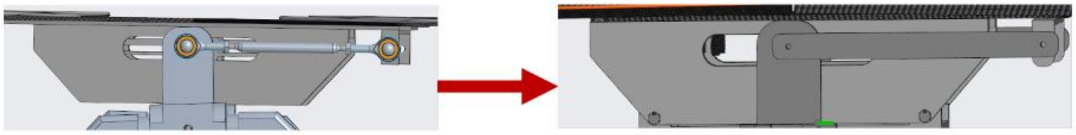


Figure 56: DROVER Links

Therefore, to compensate for the circular movement of the differential bar without the degrees of freedom offered by the tie rod, improvements had to be made to the differential bar. Mainly, the differential bar was made longer, and pin blocks were attached to the ends of the differential bar. This was highly beneficial for the design as it allowed the links to behave similarly to the tie rods and increase the length of the links' back and forth trajectory.

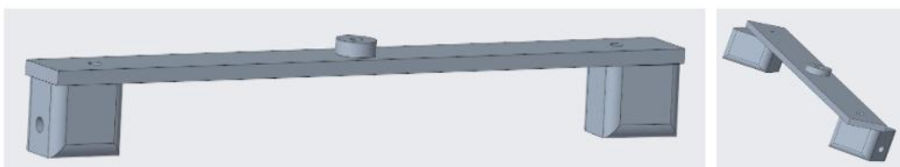


Figure 57: New differential bar with pin blocks (pin blocks are free to rotate)

As part of the iterative process multiple configurations of the differential bar were tested, and this mentioned differential bar proved to work on the final assembly exactly as intended in the prototype, as the differential bar rotated smoothly and thus the links and legs also moved accordingly. The following figures show the new differential bar mechanism on the prototype.

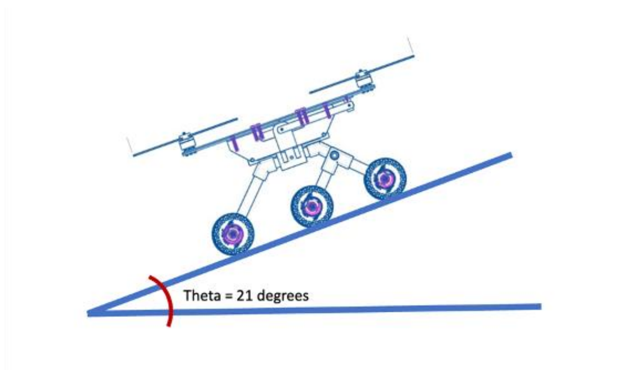
Figure 58: New differential bar, pin blocks and links on prototype

Figure 59: Rocker-bogie mechanism (one wheel up and the opposite down as intended)

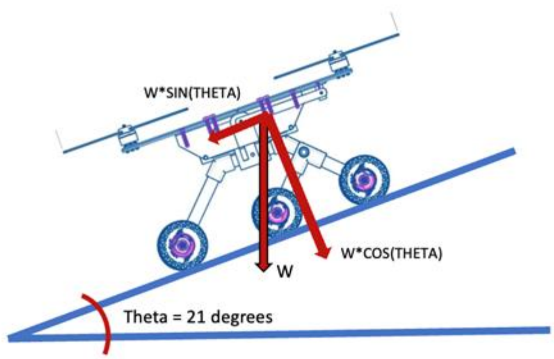
8. Driving Motors

To determine the driving motor needed for the rocker-bogie, torque calculations were performed. The following assumptions were made:

- Even weight distribution (Not true during incline, but does not affect these calculations as the weight only shifts to the back wheels, however, due to traction losses, calculations with the assumption of only 4 wheels were also performed)
- All six wheels have contact on the ground.
- Constant Climbing Velocity.
- Total Mass of DROVER = 8 kg (Higher than estimated total mass of 6.3 kg, as a safety factor)
- Incline angle 21 degrees (20 degrees required, 20.2 degrees at obstacle course)



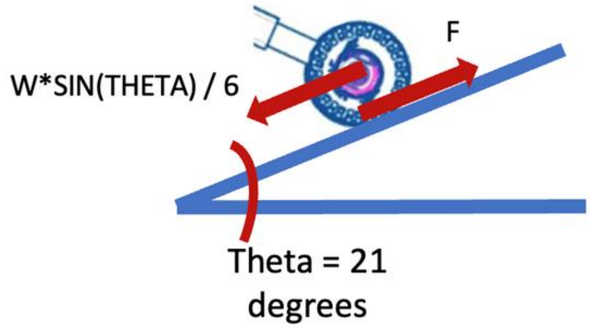
$$Total\ Weight = mg = 8 * 9.81 = 78.48\ N$$



$$Parallel\ Force = mg * \sin(theta) = 78.48 * \sin(22) = 29.4\ \text{N}$$

$$Parallel\ Force\ per\ Wheel = 29.4/6$$

$$Parallel\ Force\ per\ Wheel = 4.9\ \text{N}$$



Torque provided from motor should equal or be greater than that value

$$Torque_{Required} = Force\ per\ Wheel * \mathrm{R}$$

$$Torque_{Required} = 4.9 * 0.045$$

$$\boldsymbol{Torque_{Required} = 0.2205\ Nm}$$

<u>If only the four back wheels are touching the ground:</u>

$$Parallel\ Force\ per\ Wheel = 29.4/4$$

$$Parallel\ Force\ per\ Wheel = 7.35\ \mathrm{N}$$

$$Torque\_Required = 7.35 * 0.045$$

$$\boldsymbol{Torque\_Required = 0.33\ Nm}$$

<u>Maximum friction force:</u>

$$Normal\ Force = mg * \cos(theta) = 61.803 * \cos(22)$$

$$Normal\ Force = 57.3\ N$$

$$\text{Normal Force per Wheel} = 57.3/4$$

$$\text{Normal Force per Wheel} = 14.32\ N$$

$$\text{Friction force\_max} = 14.32 * friction\ coefficient$$

Assuming: mu = 0.7

$$\text{Friction force\_max} = 14.35 * 0.7 = 10\ N$$

Therefore wheels should not slip

Consequently, after these calculations, the following 20mm Metal Gear Motor Model NFP-GM20-180 with a 195:1 gear ratio was chosen. Therefore, this new motor provides 0.490 N·m of torque, which is 48.5% more than the required minimum torque.

Rocker-Bogie Final Leg Design (Marcelo Samaan)

The final leg design and its components are shown in the figures below. The legs' cylindrical shape rational can be found in *Appendix III*.

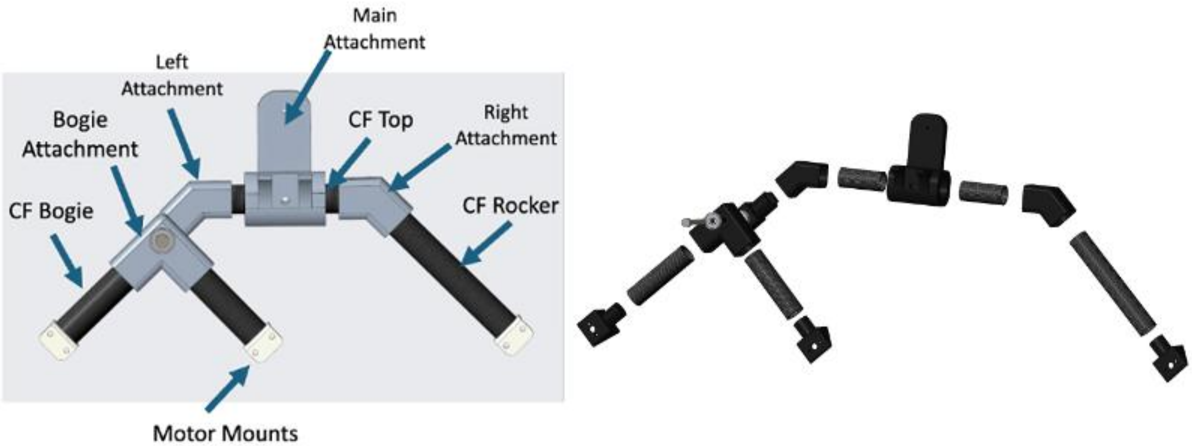


Figure 60: Final Leg Design Components

The following drawing contains all the important dimensions of this leg design, and it includes the 90 mm diameter wheels.

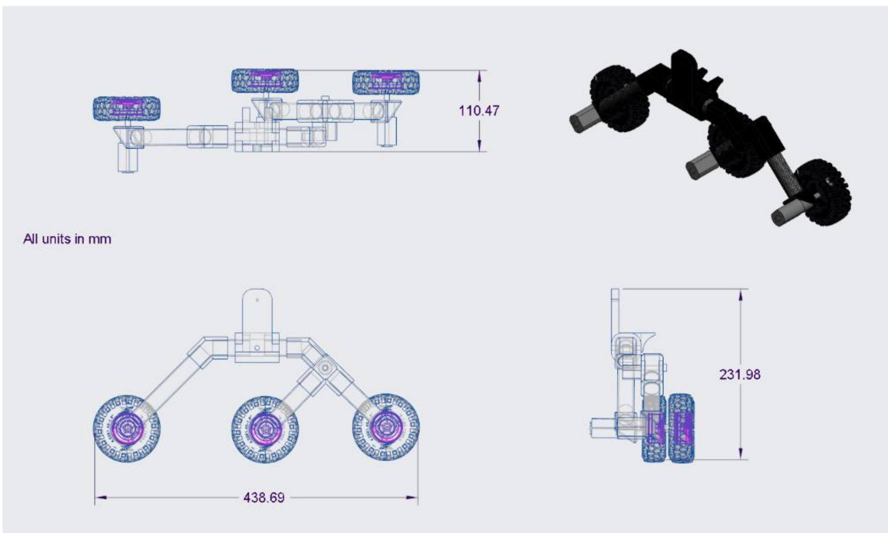


Figure 61: Leg design drawing with 90 mm diameter wheels

Furthermore, this leg design was tested on the prototype, as can be seen in the picture below.

Figure 62: Leg assembly in prototype

The final leg design followed the prototype design with the only modification being the new motor mounts.

Figure 63: Final DROVER Leg Design

The following table contains the mass values of the final leg structure

Table 7: Material and Components of Leg Assembly

Item	Quantity	Individual Mass (g)	Total Mass (g)
CF Rocker	1	22	22
CF Top	2	8.3	16.6

CF Bogie	2	13.6	27.2
Onyx Main Attachment	1	110	110
Onyx Right Attachment	1	36	36
Onyx Left Attachment	1	23.2	23.2
Onyx Connector	1	27.7	27.7
Onyx Bogie Attachment	1	58	58
Onyx Motor Mounts	3	14.9	44.7
Total Mass			**365.4**
2 Sets of Legs in Structure			**730.8**

Therefore, it can be seen that the total mass for the two sets of legs is approximately 731 grams. This is an addition of 120 grams when compared to the PDR design, mostly caused by the design improvements mentioned in the sections above.

Rocker-Bogie Suspension Operating Principles (Marcelo Samaan)

The rocker-bogie suspension design works by connecting the two sets of legs together through links and a differential bar. This connection relates the angular movement of one rocker to the other, and thus, when one rocker moves up, the other tends to move down, as shown in the following figure.

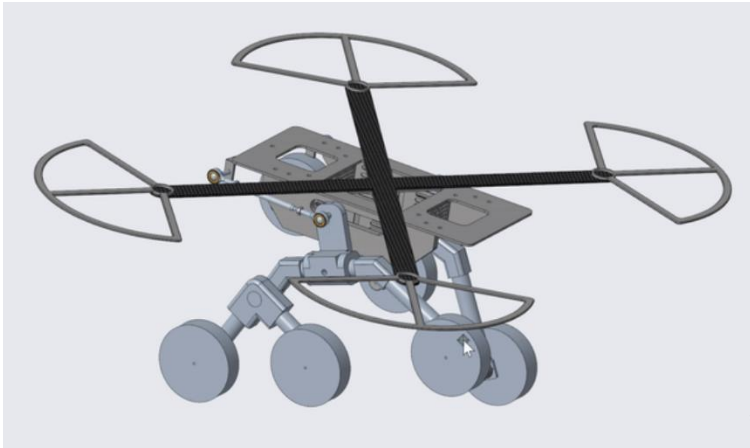


Figure 64: Rocker Connected Movement

The differential bar is a pin connection allowing it to freely rotate and relate the movements of the rockers, as seen in the following figure.

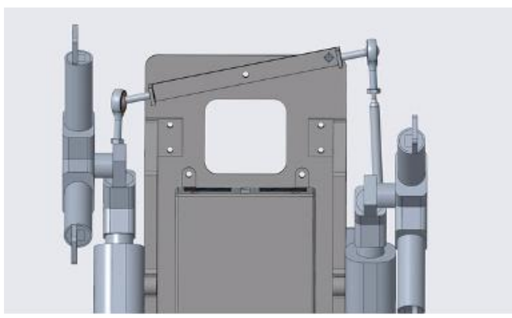


Figure 65: Differential Bar Rotation

The working principle of the rocker-bogie is that when an obstacle is encountered by one of the legs, the force experienced by the rocker trying to climb that obstacle is transferred to the other wheels via the differential bar and pin connections, guaranteeing stability as the force is better distributed among the wheels.

Figure 66: Pin Connection climbing 4.5 cm obstacle

Furthermore, because of that, the chassis tends to maintain the average pitch angle of both rockers, thus minimizing the DROVER's tilt angle and improving its stability [30]. This is one of the main advantages of the rocker-bogie compared to other suspension systems. This is because the minimization of the chassis' tilt angle increases the overall stability, as the center of gravity position does not shift abruptly when an obstacle is being climbed. This principle was observed in the prototype, as shown in the following picture where the chassis does not tilt excessively even when climbing tall obstacles.

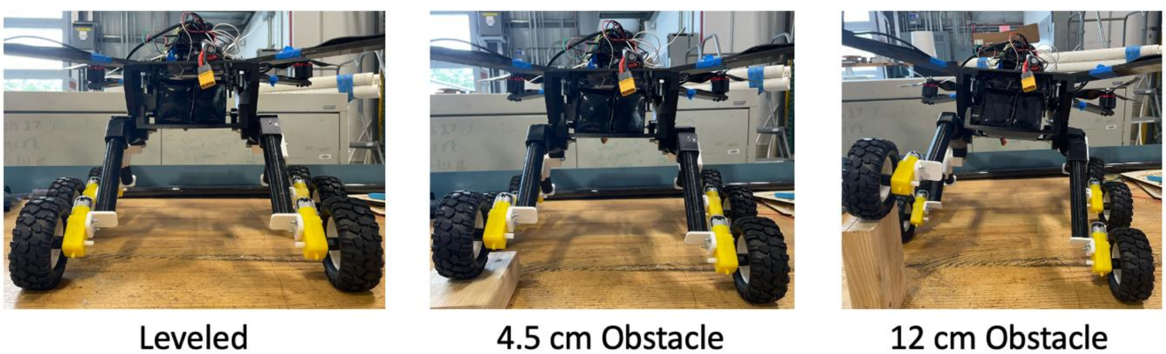


Figure 67: Chassis Movement

On the other hand, other suspension systems will tend to tilt the chassis extensively when one wheel is elevated, or, as in a spring independent suspension, it will depend on how much the spring can compress before transmitting the force to the chassis. On the rocker-bogie, tilting of the chassis will mainly occur when all wheels of one side climb an obstacle, as seen in the following figure.

Figure 68: Chassis when one side completely lifted up

Nevertheless, this configuration's stability will depend on the height of the obstacle being climbed, as the center of gravity shifts towards the opposite side. In the picture, the obstacle is 8 centimeters, and this number would be the recommended maximum limit in order to avoid the risk of the DROVER falling over.

Rocker-Bogie Leg Structure Driving Loads (Kyle Kinkade)

Assumptions:

- Half the total system's mass is applied at the connecting pin joint.
- Normal and braking force applied to the center of the motor mount.
- Braking force is applied equally across all six wheels of the full system.

Objectives:

- Initial leg structure analysis to ensure a large margin of safety for normal driving operations.
- Check major stress locations.

Braking Force Calculation:

Known/Estimated Values

$$m = 3.5\ kg$$
$$v = 1\frac{m}{s}$$
$$d\ (stopping\ distance) = 0.1\ m$$

$$F_{brake,per\ wheel} = \frac{\frac{1}{2}mv^2}{d} * \frac{1}{3} = \frac{\frac{1}{2} * 3.5\ kg * \left(1\frac{m}{s}\right)^2}{0.1\ m} * \frac{1}{3} = 5.8\ N$$
$$W = m * g = 3.5\ kg * 9.81 = 34.3\ N$$
$$N_{per\ wheel} = \frac{34.3\ N}{3} = 11.45\ N$$

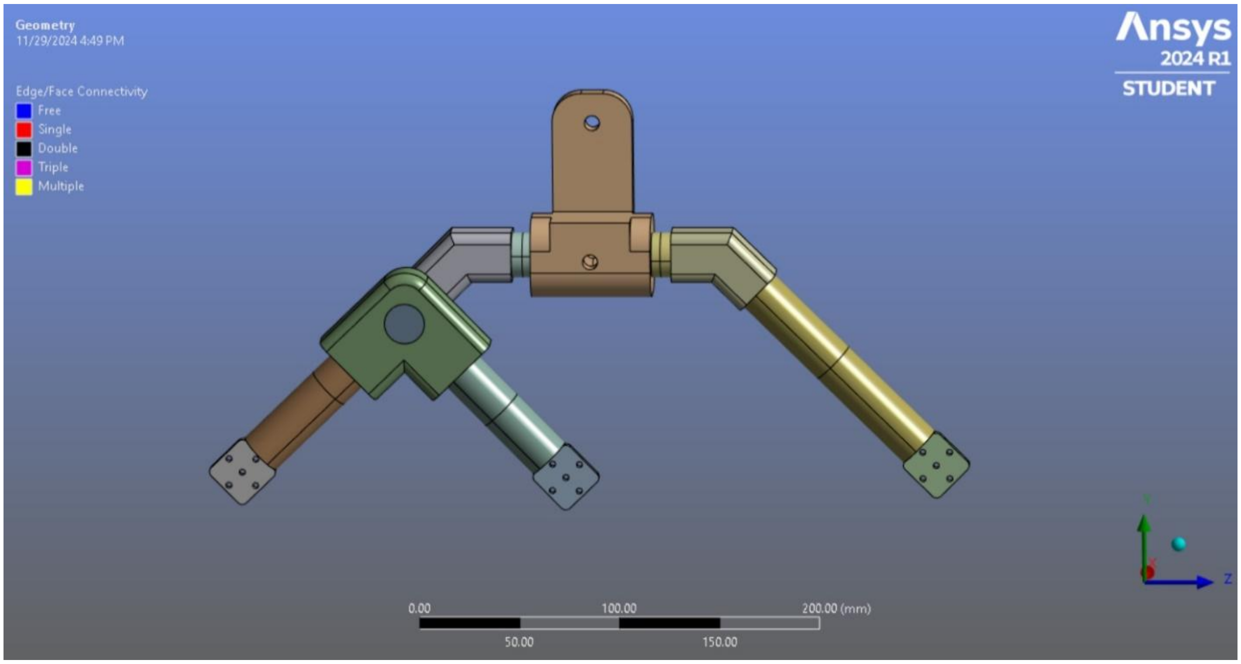


Figure 69: Rocker Bogie Structure Imported into Ansys

Onyx

Density	1.2e-06 kg/mm³
Structural	
Isotropic Elasticity	
Derive from	Young's Modulus and Poisson's Ratio
Young's Modulus	2400 MPa
Poisson's Ratio	0.43
Bulk Modulus	5714.3 MPa
Shear Modulus	839.16 MPa

Figure 70: Onyx Material Properties

Carbon Fiber

Density	1.6e-06 kg/mm³
Structural	
Isotropic Elasticity	
Derive from	Young's Modulus and Poisson's Ratio
Young's Modulus	2.28e+05 MPa
Poisson's Ratio	0.3
Bulk Modulus	1.9e+05 MPa
Shear Modulus	87692 MPa

Figure 71: Carbon Fiber Material Properties

As said previously, the carbon fiber material was applied to the tubes of the structure, while the attachments (complex geometries) are onyx. Both the onyx and carbon fiber properties are assumed to be isotropic. The carbon fiber properties are from McMaster-Carr [21]. Onyx's Young's Modulus comes from Markforged [31], and the Poisson ratio is from other external research [32].

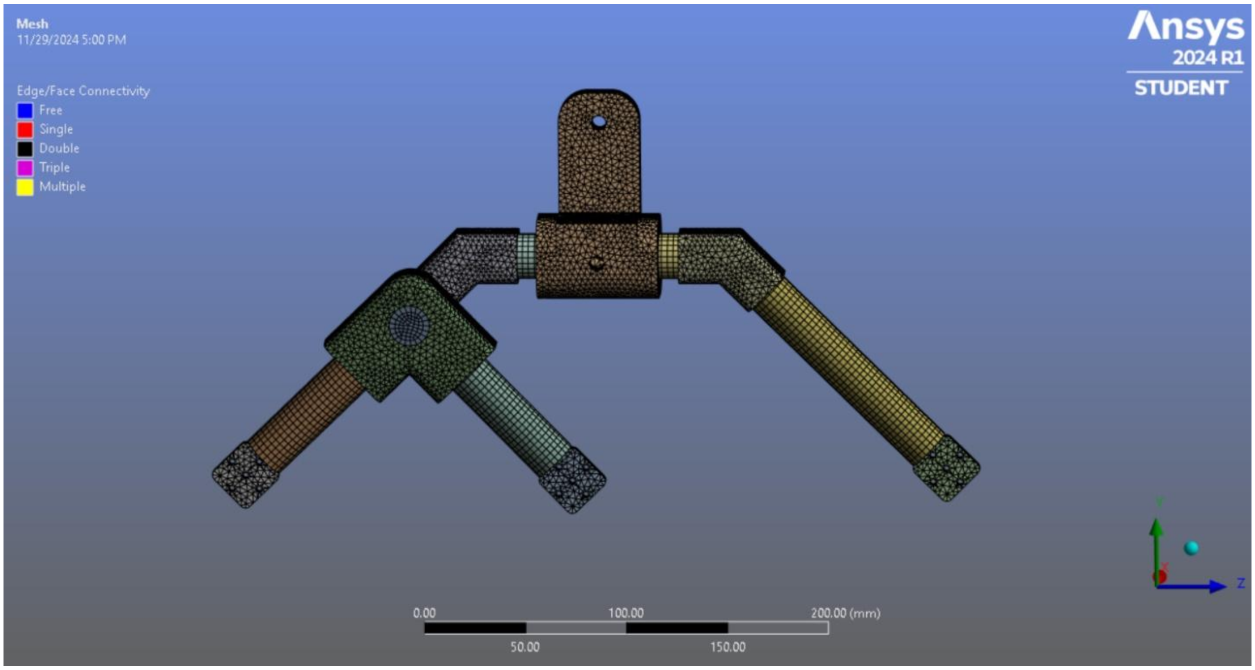


Figure 72: Mesh Applied to Structure

Statistics	
Nodes	98368
Elements	40946

Figure 73: Mesh Statistics

The mesh applied to the structure was close to the maximum number of nodes allowed to be solved in the student edition of Ansys.

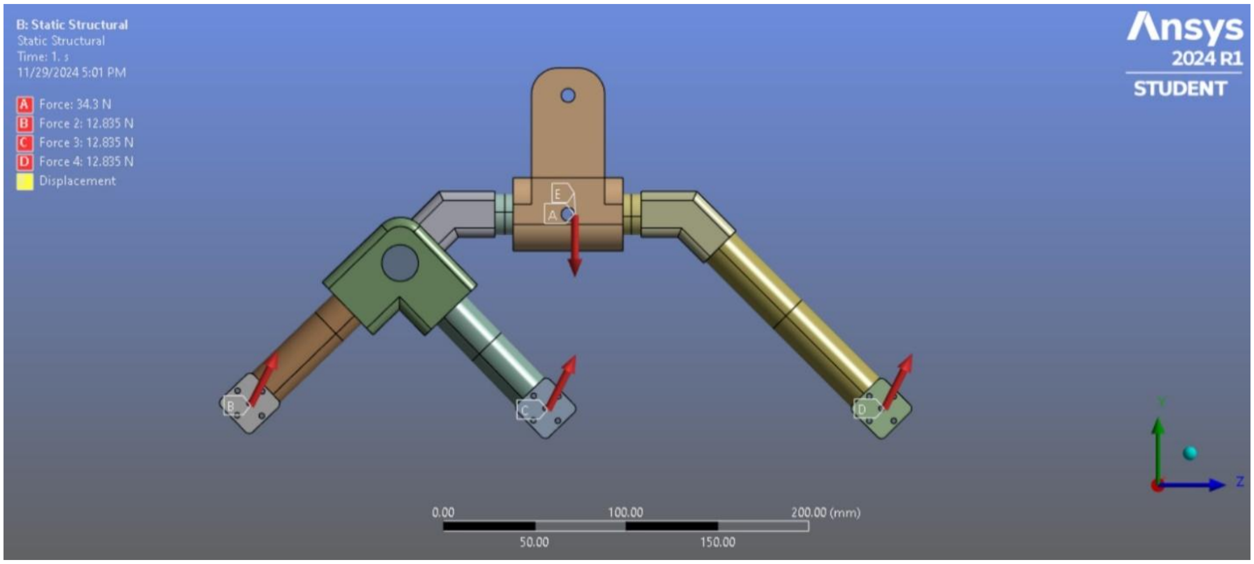


Figure 74: Loads and Boundary Conditions

In the setup, the displacement constraint is set to zero for x-y-z. All other forces that are applied follow as described above in assumptions.

Results:

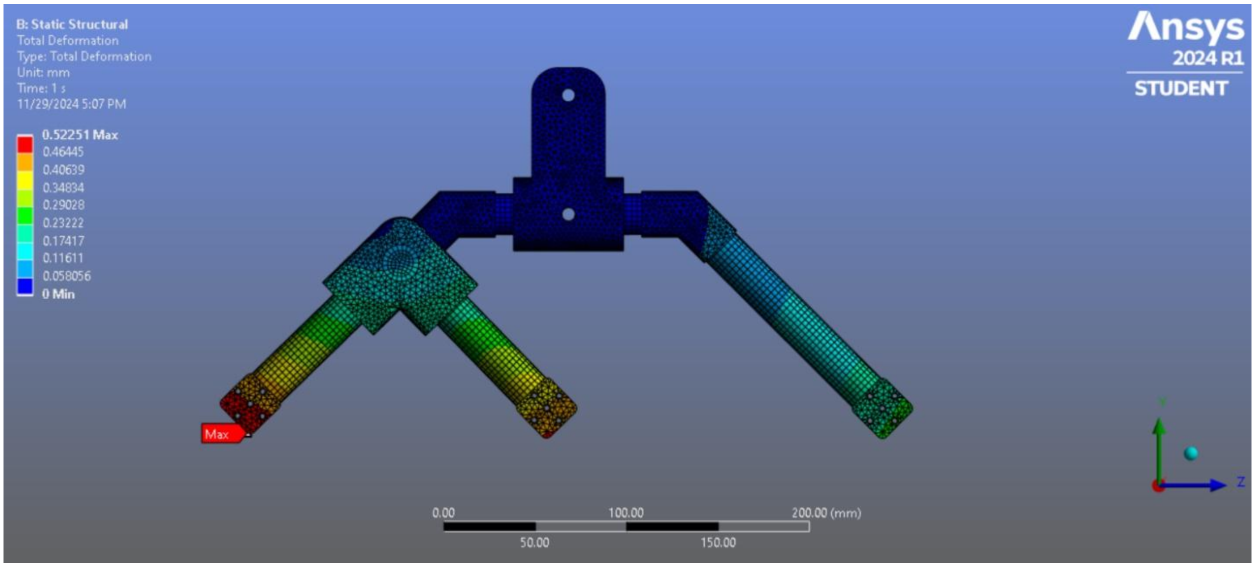


Figure 75: Deformation Results

There is a max deflection of 0.5 mm. The team believes that this max deflection is not critical.

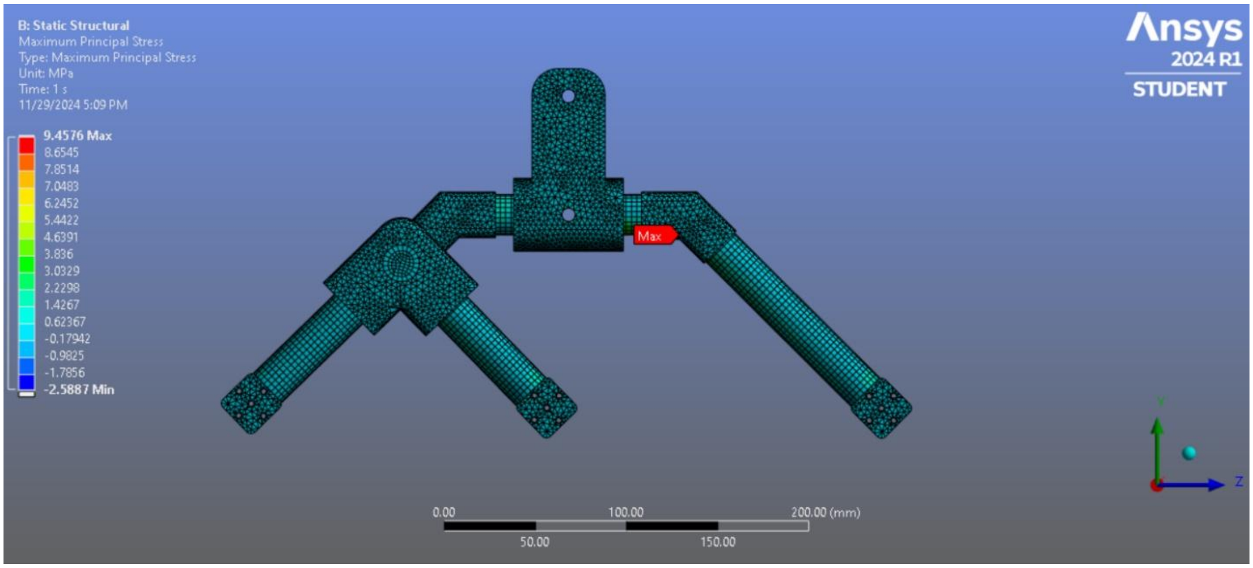


Figure 76: Tension Results

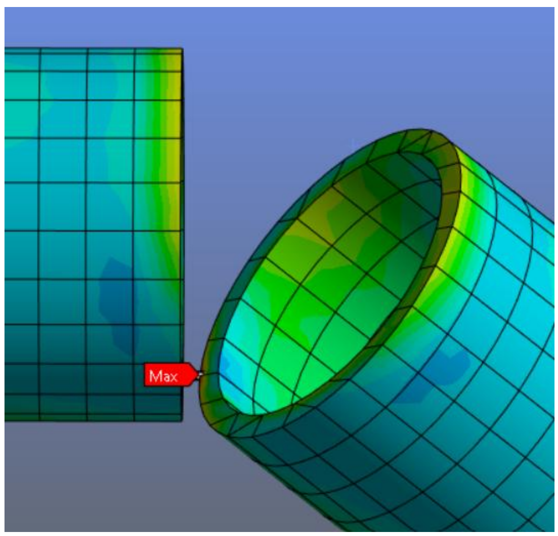


Figure 77: Location of Maximum Tension

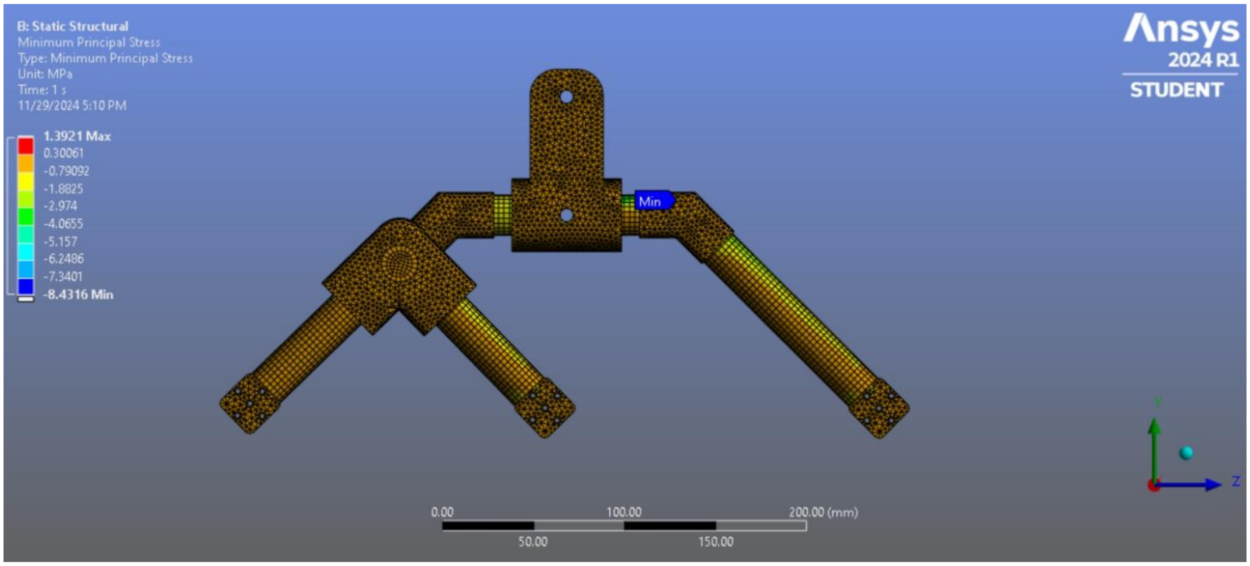


Figure 78: Compression Results

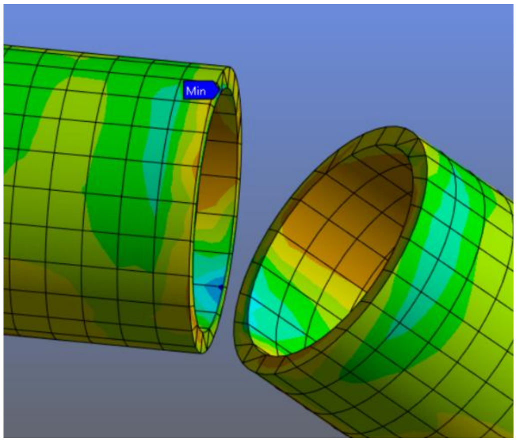


Figure 79: Location of Max Compression

The maximum and minimum principal stresses are 9.5 MPa and -8.4 MPa, respectively. As shown in the images above, these max stresses are applied to the carbon fiber tubes. This is what the team was hoping to achieve due to carbon fiber's superior properties to onyx. It was important to ensure that the onyx attachments underwent minor loads as the max stress for this material is only 37 MPa [31]. Fortunately, the onyx parts underwent very minor loading with nothing approaching the loads that the carbon fiber parts undergo. This structure is more than capable of withstanding normal driving loads.

Rocker-Bogie Leg Structure Impact Loads (Kyle Kinkade)

Assumptions:

- The highest velocity of impact will be 3 m/s.
- No impact force is absorbed by wheels or motor shaft.
- All 3 wheels do not land simultaneously.
- Half of the total system's weight is applied to the pin joint.

The impact speed assumption is based on the maximum descent speed given by other drone manufacturers. The descent speeds that are given do not represent the final impact as they tend to slow down even more when approaching the ground; however, these numbers are the best publicly available numbers of impact speeds. The 3 m/s number comes from DJI and is specified for one of their flagship drones [55]. Heavy lift drones generally have slightly slower descent speeds to avoid larger loads, for example the SwellPro Fisherman Max has a max descent speed of 2 m/s [56]. Overall, a 3 m/s assumption is slightly overstated, but provides a good max estimation for safety.

Objectives:

- The goal is to check the structural integrity due to a higher velocity landing impact (FS 1.5, STR.05).

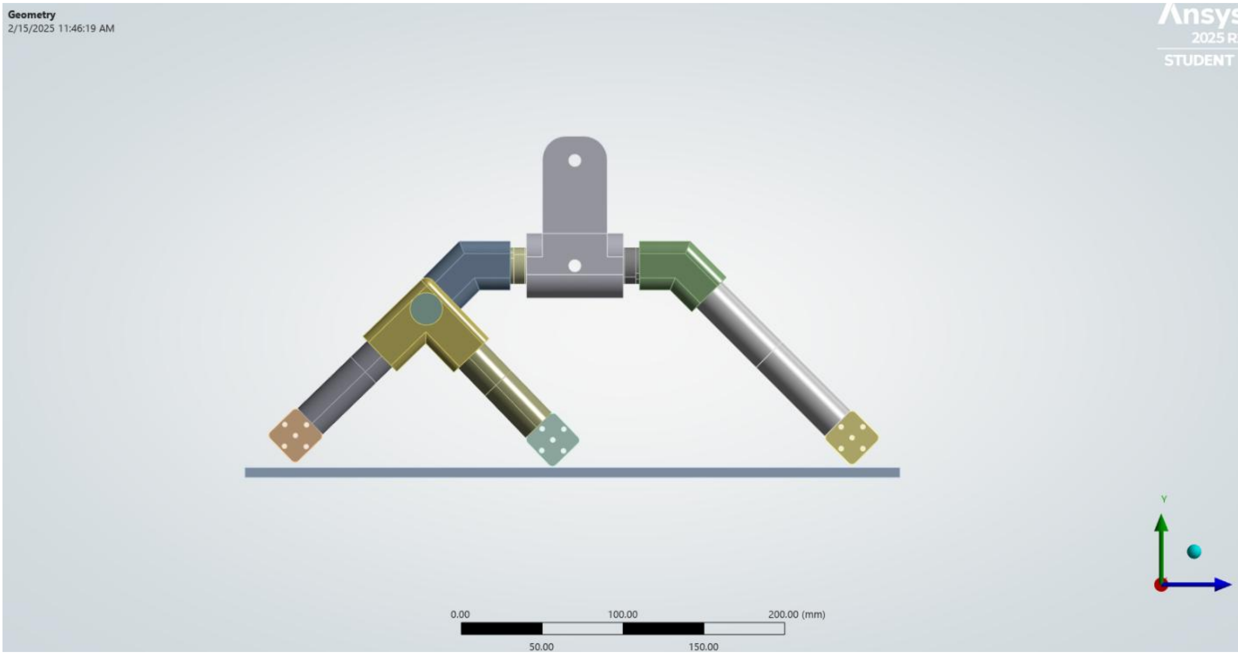


Figure 80: Geometry Used in Impact Analysis

This geometry differs slightly from the geometry used previously in the driving analysis. This is due to the need to thicken some of the Onyx attachment parts as a result of early iterations of this FEA model. The differences between the geometries of these two models only resulted in a more sound structure, meaning that there is no need to repeat the driving model analysis.

Carbon Fiber

Density	1.6e-06 kg/mm³
Structural	
Isotropic Elasticity	
Derive from	Young's Modulus and Poisson's Ratio
Young's Modulus	2.28e+05 MPa
Poisson's Ratio	0.3
Bulk Modulus	1.9e+05 MPa
Shear Modulus	87692 MPa

Figure 81: Carbon Fiber Material Properties [21]

Onyx	
Density	1.2e-06 kg/mm³
Structural	
Isotropic Elasticity	
Derive from	Young's Modulus and Poisson's Ratio
Young's Modulus	2400 MPa
Poisson's Ratio	0.43
Bulk Modulus	5714.3 MPa
Shear Modulus	839.16 MPa

Figure 82: Onyx Material Properties [31, 32]

Similar to other models, these materials are assumed to be isotropic, and the properties are the low-end properties provided by their respective manufacturers.

Mesh:

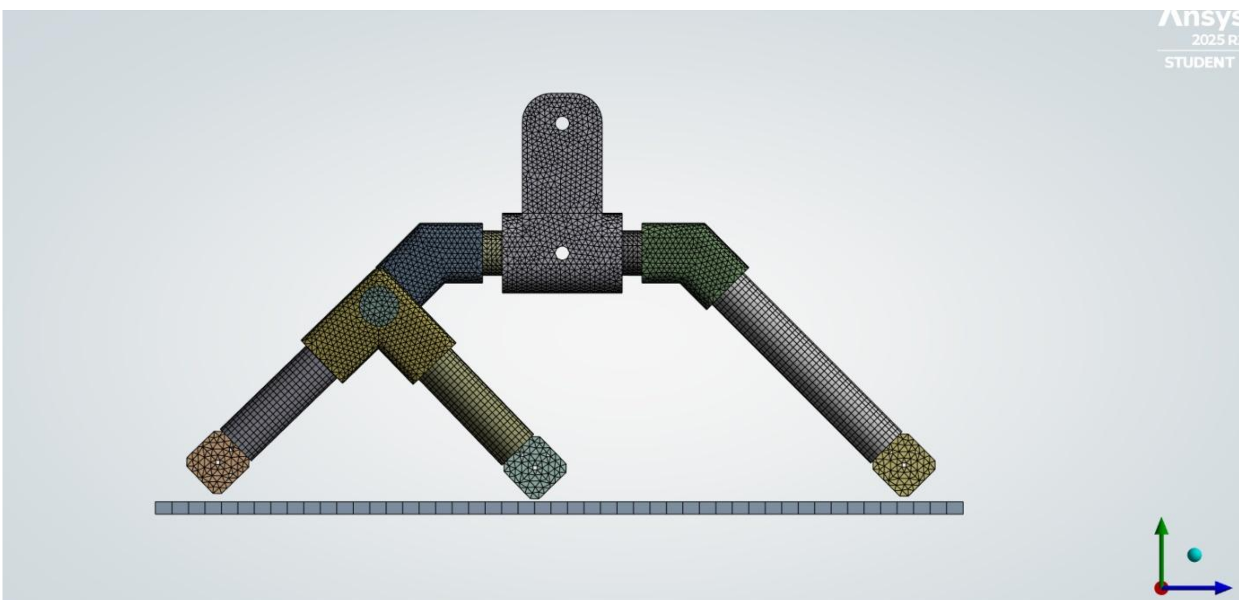


Figure 83: Impact Analysis Mesh

Statistics	
Nodes	27326
Elements	83354

Figure 84: Mesh Statistics

With 83000 elements, this should be a fine enough mesh to run in this analysis.

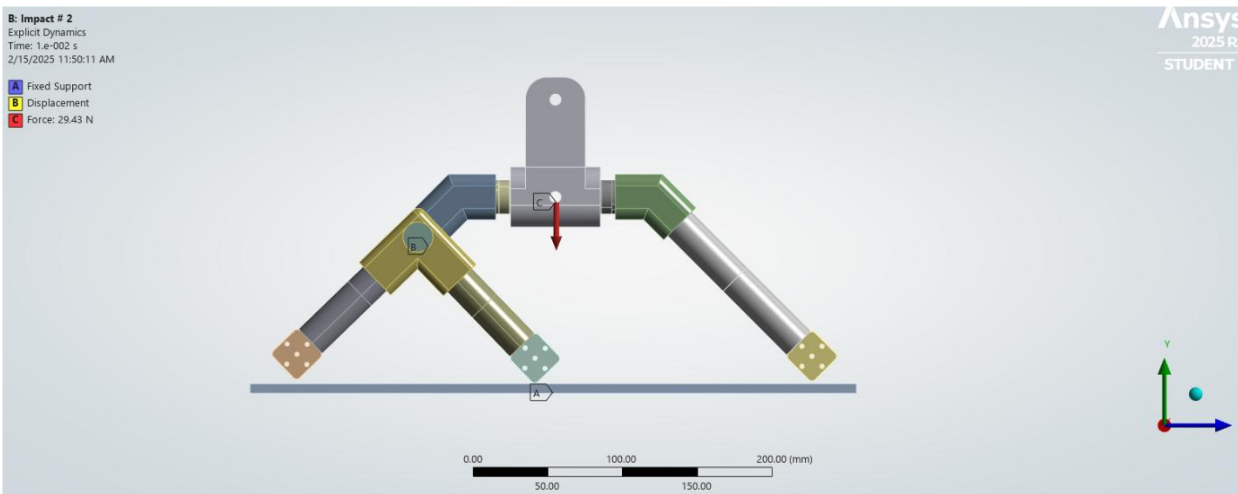


Figure 85: Impact Analysis Setup

The body also undergoes an initial velocity of 3 m/s in the negative y-direction. This analysis was set to run for 0.01 s, which is more than enough time for impact.

Results:

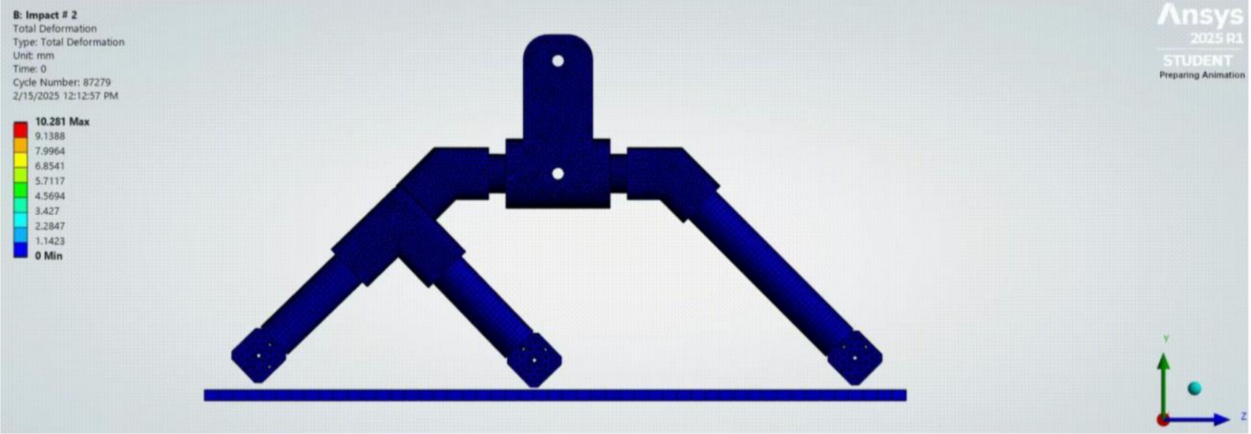


Figure 86: Impact Deformation Results

These results note that the max deformation is 10 mm. However, after closer analysis, the max deformation does not occur until after the initial impact. Because the model does not account for gravity, there is a bounce after the impact. The max deformation due to the impact is 6.2 mm.

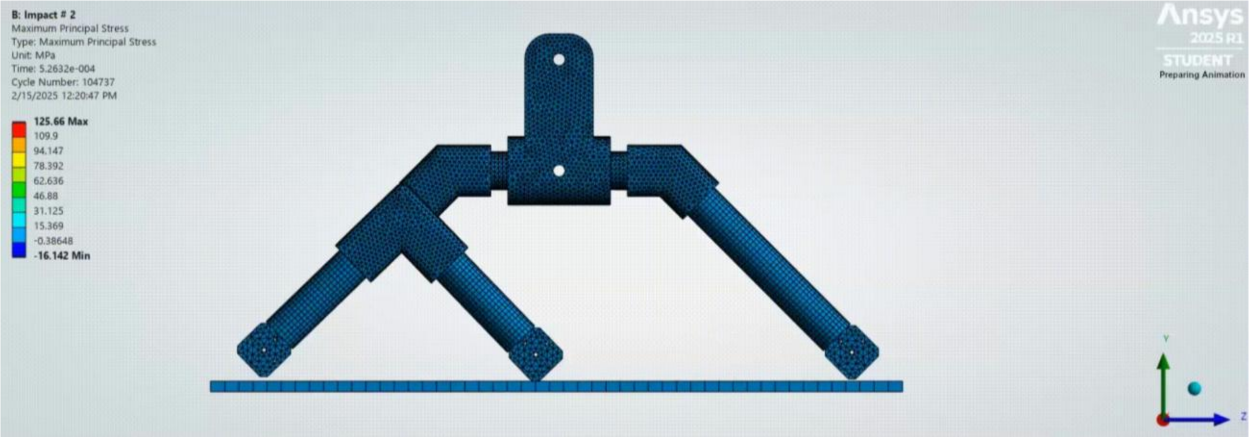


Figure 87: Impact Tension Results

The maximum tension stress shown above is 125 MPa. This stress is applied to the carbon fiber tubing and based on the carbon fiber properties supplied by McMaster-Carr [21], this stress is nothing to worry about. What the team was more concerned about was the Onyx attachment parts. Throughout the whole impact, these attachment parts undergo a maximum tensile stress of 24 MPa. Onyx has an ultimate stress of 37 MPa [31]. Because Onyx is a brittle material, it’s safe to assume that the yield stress and ultimate stress are similar, meaning that no permanent deformation is expected in the rocker-bogie structure.

$$\text{Tension FS Onyx Connections} = \frac{37\ MPa}{24\ MPa} = 1.54$$

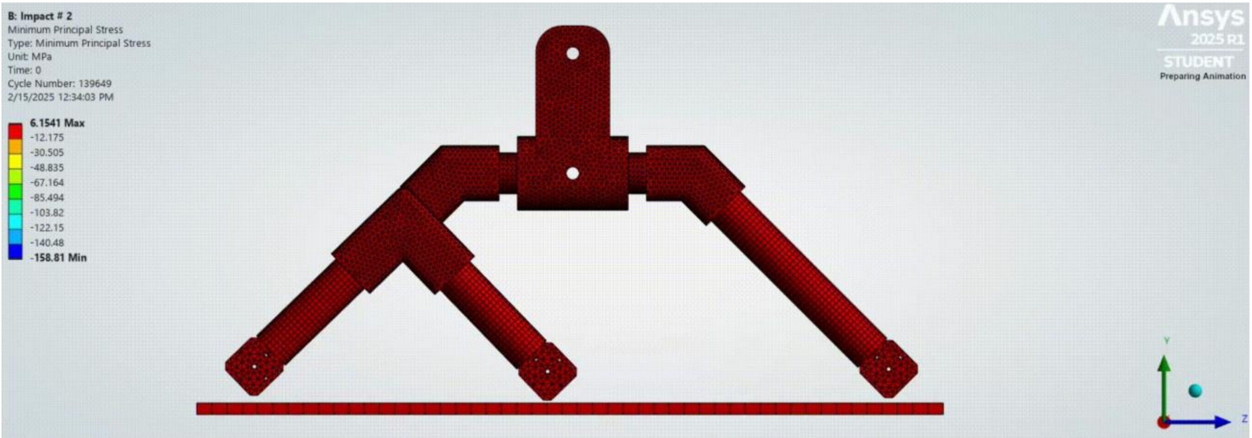


Figure 88: Impact Compression Results

Similarly, the max compression stress shown from the model is applied to the carbon fiber tubing. The Onyx attachments undergo a max stress of 15 MPa. Providing a solid factor of safety for the stress results.

$$\text{Compression FS Onyx Connections} = \frac{37\ MPa}{15\ MPa} = 2.47$$

The last thing to note is that further analysis was complete to identify which attachment part would yield first and at what impact speed that would occur. From the model it was identified that the bogie attachment (connects the two bottom CF tubing) would fail first at an impact speed of 4.5 m/s – 5 m/s. Overall, the impact analysis coupled with the driving and drone arm analysis support and verify the 1.5 factor of safety requirement (STR.05) for the DROVER's major components.

6.2 Aerodynamics Subsystem Requirements (Kyle Kinkade, Francesca Afruni)

Table 8: Aerodynamics Subsystem Requirements

Parent	Number	Requirement Text	Requirement Rationale	Verification Method	Verification Strategy	Status	Reference Sections
SYS.01	AERO.01	The DROVER **shall** produce enough lift for at least a 2:1 thrust to weight ratio	To takeoff quickly and maneuver the drone a 2:1 thrust to weight ratio is necessary	Analysis	Based on thrust values of the propellers and weight of the total DROVER, a thrust ratio can be calculated	Fully Compliant	7.1, 10.1.1.1
SYS.01	AERO.02	The DROVER **shall** be capable of roll-pitch-yaw maneuvers	Maneuverability of the DROVER is necessary to ensure mission completion	Demonstration	Demonstrate the maneuverability of the DROVER in flight	Fully Compliant	10.1.1.15, 10.1.1.18
SYS.01	AERO.03	The DROVER **shall** maintain stable flight during hover	To efficiently manually control the drone stable flight is essential for the user	Demonstration	Demonstrate the stable flight capabilities	Fully Compliant	10.1.1.18
SYS.06	AERO.04	The DROVER **shall** not fly above 400 feet from ground level	FAA 14 CFR 107.51(b)	Inspection	The DROVER will not exceed 400 ft	Fully Compliant	10.1.1.14

The Aerodynamic Subsystem begins with a requirement for the DROVER to exceed a 2:1 thrust-to-weight ratio (T:W). For most drones, a 2:1 thrust-to-weight ratio is a minimum in order to efficiently take off and maneuver [33]. Lowering the T:W ratio can result in significant throttle usage for even basic maneuvers, which could drastically lower the flight time due to increased battery discharge. Overall, a 2:1 T:W ratio is a good rule of thumb for drones. This requirement is fully compliant.

AERO.02 requires the DROVER to have roll-yaw-pitch capabilities. These capabilities are essential to use the drone effectively. The project's purpose is to allow dual-mode transportation, and for flight use, the maneuverability from roll-pitch-yaw control is necessary. Requirement AERO.02 is fully compliant.

AERO.03 states that the DROVER shall maintain stable flight during hover. This requirement simplifies the flight controller inputs for the user. The team wants to provide a product that is easily accessible to inexperienced pilots, so having an inherently stable drone is a requirement. This requirement was tested during flight tests and during the hover test, and it is fully compliant.

Lastly, to satisfy FAA regulations the DROVER cannot exceed a height of 400 feet [18]. Of course, this requirement is non-negotiable; however, the team doesn't see a scenario with the prototype testing in which the DROVER would be required to achieve that height.

As shown in the table above, all Aerodynamic requirements are fully compliant.

Motor Choice (Kyle Kinkade)

Some of the major work the Aerodynamic subsystem has targeted so far is the motor and propeller decisions. Initially, the team identified the T-Motor CINE 66 925 KV motor as an option, primarily because the KV of the motor was around what the team was looking for, and the HSDC had some available for free [34]. Initially, the team was concerned about the 2:1 thrust-to-weight ratio requirement and sought to perform thrust tests using those motors. The team hoped to test a 3-blade, 11-inch diameter propeller and a 5-blade, 10-inch diameter propeller in the Aerospace Experimentation Lab at Florida Tech. Unfortunately, this test failed mainly because the lab instructor prohibited the team from swapping the motor already mounted to the thrust stand.

The failed test resulted in more motor research and the realization that the CINE 66 Motors were not a good option for the DROVER. This is primarily due to the high amp draw at hover. With the estimation of the total system weight to be about 6 kg for the hover test, the CINE 66 Motors have an amp draw of around 65 A at hover [34]. Some basic hand calculations show the issue with achieving SYS.01 (20-minute hover time).

$$Runtime = 20\ minutes$$

$$Amp\ Draw = 65\ A$$

$$Runtime = \frac{\frac{60\ \frac{min}{hr}}{Amp\ Draw}}{Ah\ Required}\ [35]$$

$$Ah\ Required = \frac{Amp\ Draw}{\frac{60\ \frac{min}{hr}}{Runtime}} = \frac{65\ A}{\frac{60\ \frac{min}{hr}}{20\ min}} = 21.66\ Ah => 22000\ mAh\ battery\ needed$$

A 22000 mAh battery was unreasonable for a drone this size, so the team needed to find better motor options to combat this issue.

As stated in the PDR document, the team decided that the T-Motor V3120 as the best option (See Appendix VIII for trade study).

Figure 89: T-Motor V3120 [36]

The main downsides of this motor come with the cost of money and mass. For only four motors, the team spent about $200 and accrued around 600 g of added mass. However, these motors give the team a new maximum system mass (to achieve the 2:1 thrust-to-weight ratio requirement) of more than 7800 g based on Table 14 given by the manufacturer. Furthermore, if the system's total mass is 6000 g, at hover the team expects an amp draw of around 40 A. These two expectations come from T-Motor's specification table with 10.5-inch 3-blade propellers and a 6S battery; however, further testing, which is discussed later in this section, gives accurate numbers for max thrust and amp draw.

Table 9: T-Motor V3120 Specification Table [36]

Propeller	Throttle	Voltage (V)	Current (A)	Power (W)	RPM	Thrust (g)	Torque (N*m)	Efficiency (g/W)
T10.5X5-3	10%	24	0.38	9	1544	25	0.02	2.8
	20%	24	1.35	33	3281	214	0.05	6.6
	30%	24	2.81	67	4538	472	0.09	7.0
	40%	24	4.99	120	5694	786	0.14	6.6
	50%	24	8.73	208	6976	1216	0.21	5.8
	60%	24	13.27	316	8198	1693	0.29	5.4
	70%	24	20.20	479	9327	2204	0.38	4.6
	80%	24	27.88	657	10408	2755	0.47	4.2
	90%	23	37.56	880	11441	3339	0.58	3.8
	100%	23	48.70	1133	12405	3936	0.69	3.5

Using the same equation as before:

$$Ah\ Required = \frac{Amp\ Draw}{\frac{60\ \frac{min}{hr}}{Runtime}} = \frac{40\ A}{\frac{60\ \frac{min}{hr}}{20\ min}} = 13.33\ Ah$$

This means that a 15000 mAh 6S battery should provide the team with over 20 minutes of hover time, fulfilling SYS.01.

Propeller Choice (Francesca Afruni)

Once the motor choice was consolidated, the team focused on finding the best option in terms of propellers. The final decision was between two options. The first option was a three-blade 11-inch in diameter with a 5-inch pitch from Master Airscrew made out of Glass Fiber Composite and weighing 26.1 g (Figure 60). The second option was a three-blade 10.5-inch in diameter with a 5.5-inch pitch from T-Motor made out of Glass Fiber Nylon and weighing 26.5 g (Figure 59). This last option was the one used by the motor manufacturer (T-Motor) to test the thrust of the T-

Motor V3120 700KV, as can be seen in Table 14. The two propellers have similar specifications, similar diameter, pitch, weight, and materials. The final decision was led by the equation for the thrust force of a propeller:

$$Thrust_{prop} = \frac{1}{2}\,\rho A(V_e^2 - V_0^2)\ [39]$$

As can be noted from the equation, the thrust force is directly proportional to the area of the propeller. This means that choosing a propeller with greater area means having greater thrust at lower RPMs, hence greater efficiency overall. In conclusion, the Master Airscrew propeller, with its greater area, lower weight, and slightly higher pitch, was chosen as the propeller for the prototype.

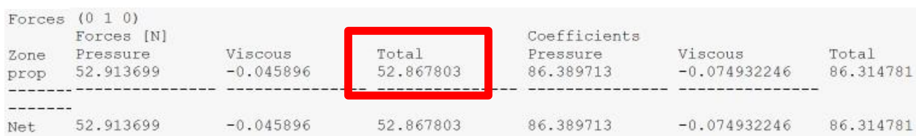
Figure 91: Master Airscrew Propeller [37]

Figure 90: T-Motor Propeller [38]

CFD Analysis (Francesca Afruni)

The team produced a CFD analysis of the propellers using ANSYS Fluent, to support the 2:1 Thrust-To-Weight ratio requirement AERO.01. The team assumed the density of air to be constant (therefore running a pressure-based analysis) while also assuming no compressibility effects affecting the propeller.

Table 10 shows the difference between the thrust value obtained in the simulation (also pictured in Figures 63 and 64) and the one obtained from the actual thrust test (which will be explained further in the testing section 10.1.1.1).



```
Forces  (0 1 0)
        Forces [N]                                   Coefficients
Zone    Pressure       Viscous        Total          Pressure       Viscous          Total
prop    52.913699      -0.045896      52.867803      86.389713      -0.074932246     86.314781
------- -------------- -------------- -------------- -------------- ---------------
-------
Net     52.913699      -0.045896      52.867803      86.389713      -0.074932246     86.314781
```

Figure 92:ANSYS Thrust Result

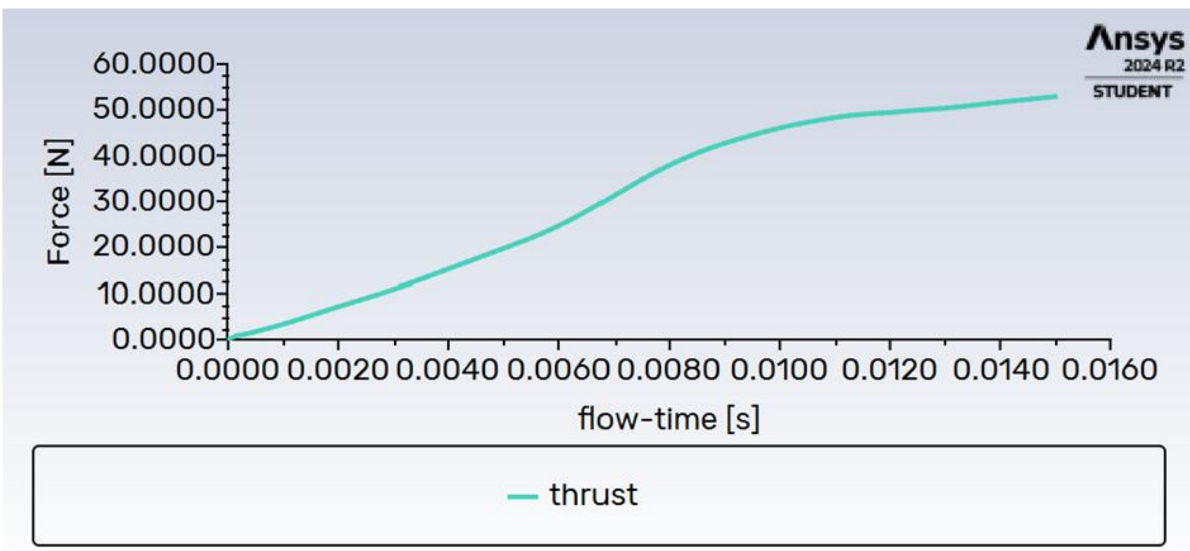


Figure 93: Thrust Force vs Flow Time

There is a difference of approximately 10 N, with an error of about 20%, between the experimental and the simulation values. There are a few reasons that explain this discrepancy. First of all, it is important to note that the propeller used in the simulation is not the same as the one used in the real-life testing. That is because Master Airscrew, the propeller manufacturer, does not provide its customers with the CAD models of their products. Initially, as a way to mitigate this issue, the team tried scanning the Master Airscrew propellers with a 3D scanner, but unfortunately, the high reflectivity of the propeller's material, combined with the poor tolerance of the scanner, did not yield good results.

Therefore, to mitigate this issue, the team downloaded a CAD model of a three-blade propeller available for free to the public. However, this brought up another issue, the propeller found on the internet wasn't the right size as the one planned to be used on the DROVER. Therefore, it needed to be scaled up to 28 cm (11 inches) in the CAD software. The scaling up of the model, which presented a very high pitch already, resulted in an even higher pitch, which can also partially explain the higher thrust number in the simulation.

The simulation was run for 0.015 seconds at 12,000 RPM, which was the maximum RPM given by the motor manufacturer (Table 9). However, this RPM might not have been achieved in the actual real-life testing of the propeller when running the motors "at full throttle", as the team only disposed of a wooden thrust stand with no ability to actually check the RPM of the propellers. This could have also been a potential reason that explains the difference in thrust values.

Table 10: Thrust Comparison

Thrust Test [N]	ANSYS Simulation [N]
44.01	52.87

The following Figures show the pressure, or force (lift), contour plots in the Y direction. Figure 92 shows the front of the propeller, while Figure 93 shows the back of the propeller, which, as expected, presents higher values of pressure. Figure 94 shows the velocity contour plot, and it can be noticed how, as expected, the higher velocity values can be found at the tip of the propeller.

These contour plots are important because even though the values don't perfectly match the experimental ones, they showcase the correct behavior of the flow, confirming the correctness of the analysis.

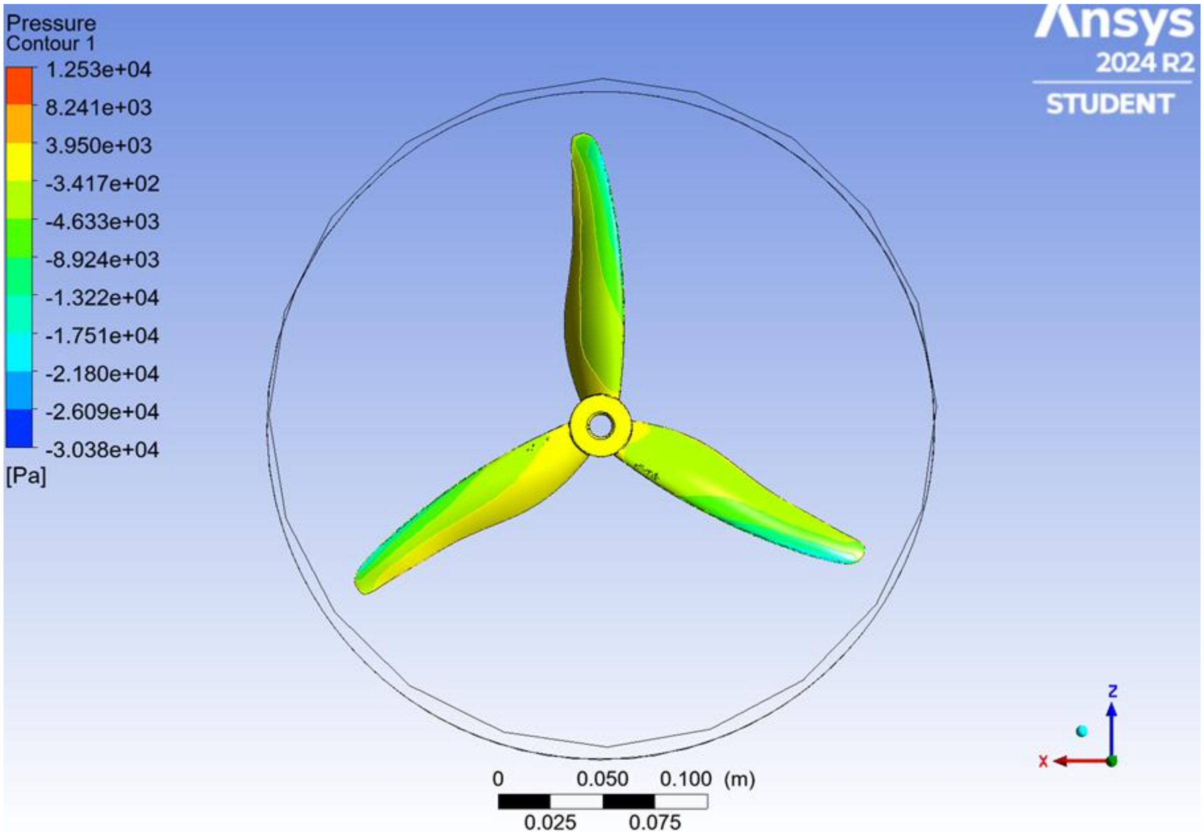


Figure 94: CFD Front of the propeller Pressure (Force – Lift) Contour Plot

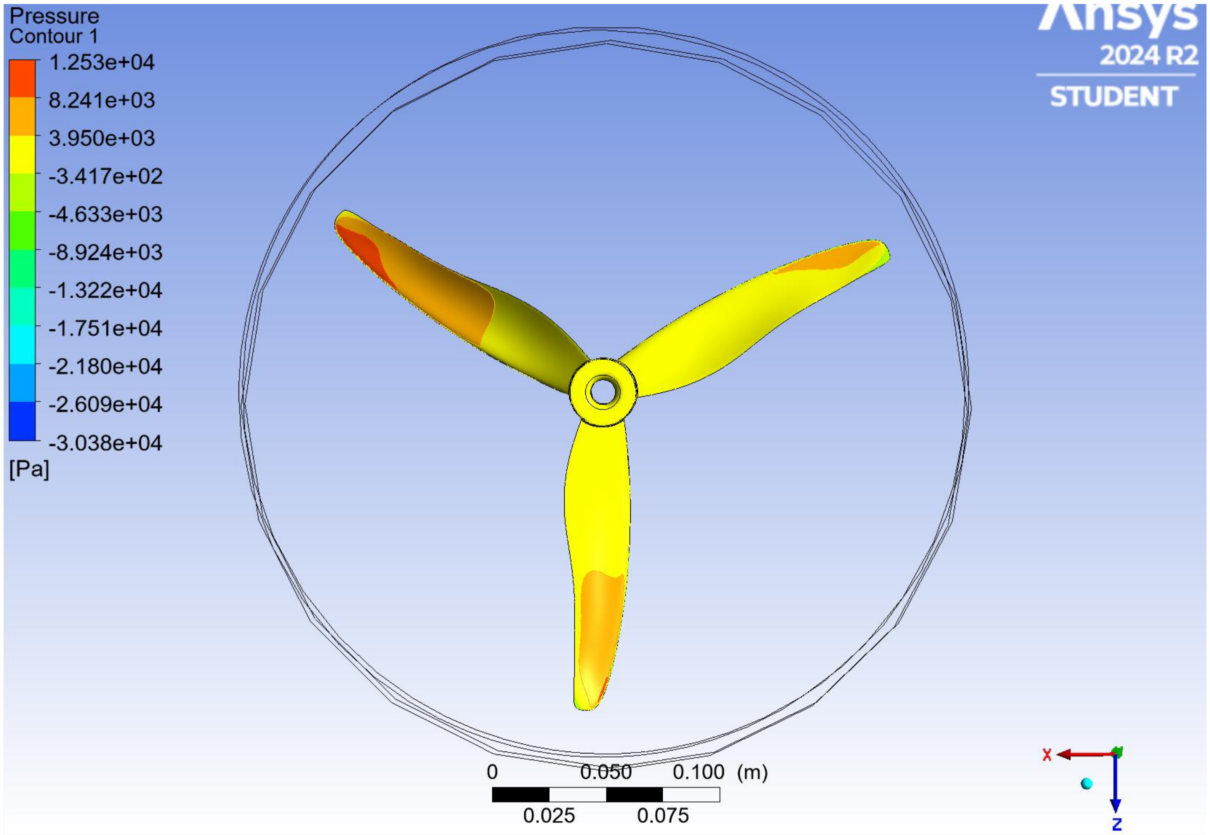


Figure 95: CFD Back of the propeller Pressure (Force – Lift) Contour Plot

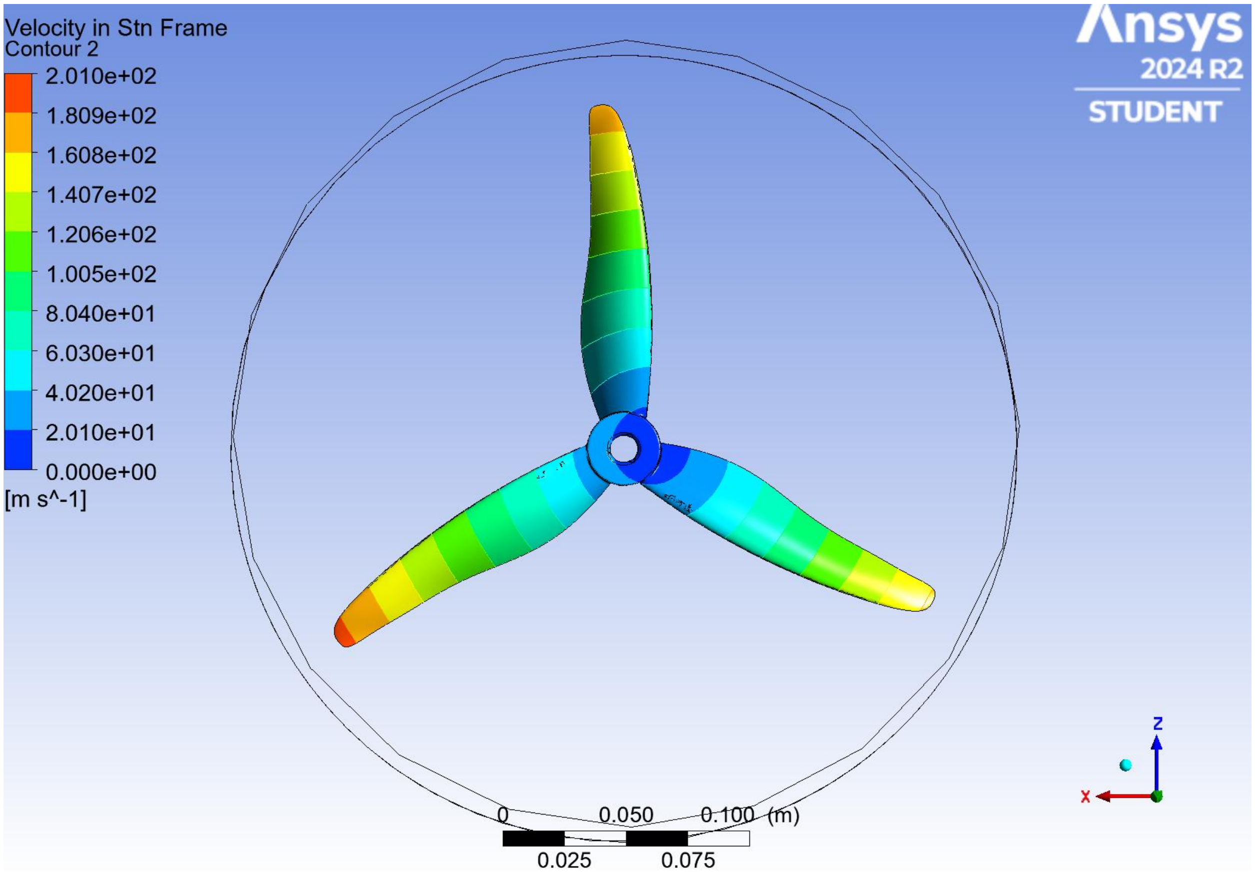


Figure 96: CFD Propeller Velocity Contour Plot

Major Subsystem Test Results Analysis (Kyle Kinkade)

Thrust Test Results:

From the thrust test which was performed with the propeller and motor system described above, a max thrust of 4488 g was found. With this key result it can be calculated that:

$$\text{Max DROVER Weight to achieve 2:1 Thrust} - \text{to} - \text{Weight (AERO.01)}$$

$$= \frac{4488\ g\ * 4\ Propellers}{2} = \mathbf{8976\ g}$$

This total mass is well within the DROVER's current mass budget. The team does not anticipate needing more than 4 kg of thrust per motor to achieve AERO.01.

Amp Test Results:

From the Amp Test, which is described later in this document, it was found that for a 4-motor system at 6000 g of weight it takes 41.92 A to hover. From this result:

$$Required\ Battery\ Capacity\ (Ah) = \frac{Amp\ Draw}{\frac{60\ \frac{sec}{min}}{Runtime}} = \frac{41.92\ A}{\frac{60\ \frac{min}{hr}}{20\ min}} = \mathbf{13.97}\boldsymbol{Ah}$$

Meaning, to achieve SYS.01 (20-minute hover time) the team needs 14000 mAh dedicated for the sole purpose of powering the motors during that duration.

The details of both test results described above can be found in the testing portion of this document.

6.3 Controls Subsystem Requirements (Rhys Wallin, Haylee Fiske, Elizabeth Beraducci)

Table 11: Controls Subsystem Requirements

Parent	Number	Requirement Text	Requirement Rationale	Verification Method	Verification Strategy	Status	Reference Sections
SYS.05	CTRL.01	The DROVER **shall** operate off a single rc radio that controls driving and flying functions	For ease of navigation by the customer, having one controller is necessary	Demonstration	Demonstrate both the flying and driving capabilties from one controller	Fully Compliant	10.1.1.15
SYS.03	CTRL.02	The DROVER **shall** be able to display constant battery voltage to the ground station	Battery voltage must be constantly monitored to ensure the DROVER does not lose power during operation.	Demonstration	Operate the DROVER and monitor the battery voltage from the ground station	Fully Compliant	10.1.1.14
SYS. 03	CTRL. 03	The DROVER **shall** have a live feed standard camera with at least 30 FPS and 480 TVL	A camera is necessary to provide live video for the DROVER to navigate its surroundings	Demonstration	Operate the DROVER and display the live feed of the camera to the ground station	Fully Compliant	10.1.1.14
SYS.03	CTRL.04	The DROVER **shall** have a live feed IR camera	Having an IR camera allows the DROVER to see people that have been trapped under an object	Demonstration	Operate the DROVER and display the live feed of the IR camera on the ground station	Fully Compliant	10.1.1.9
SYS.03	CTRL.05	The DROVER **shall** relay continuous sensor readi ngs to a ground station of at least 2.4 GHz	In order to understand the location of the DROVER, it isimportant to receive constant sensor readings at the ground station	Demonstration	Operate the DROVER and verify the expected location based on the sensor readings	Fully Compliant	6.3
Parent	**Number**	**Requirement Text**	**Requirement Rationale**	**Verification Method**	**Verification Strategy**	**Status**	**Reference Sections**
SYS.02	CTRL.06	The DROVER **shall** be able to execute turns while driving	It's necessary to be able to turn the DROVER in order to complete the mission	Demonstration	Drive the DROVER around in a circle	Fully Compliant	10.1.1.15
SYS. 01 SYS. 02	CTRL.07	The DROVER **shall** have a fail safety mode	To ensure the safe use of the DROVER, a fail safety mode must be issued for both flight and ground transportation	Demonstration	Under a controlled environment, enable the fail safety mode to ensure compliance	Fully Compliant	10.1.1.14
SYS.06	CTRL.08	The DROVER **shall** have a visual observer at all times of flight	14 CFR 107.33	Inspection	Anytime the DROVER is out of sight of the user, direct communication with a visual observer must be maintained	Fully Compliant	3.3
SYS.04	CTRL.09	The DROVER **shall** utilize a microphone and a speaker	The microphone and speaker will provide a method of verbal communication between the operator and the system	Demonstration	Drive the DROVER out of earshot of the user and demonstrate verbal communication	Fully Compliant	10.1.1.5

To control a hybrid vehicle such as the DROVER, it is important that the pilot has a single controller to operate the vehicle, which is why it's the number one control system requirement (CTRL.01). Having one controller and one respective operator will allow for precise and efficient movements of the vehicle. CTRL.01 is fully compliant as the team has demonstrated successful driving and flying capabilities of the DROVER through one RadioMaster TX-16s transmitter.

Each of these test results for the driving and flying capabilities can be seen in test Sections 10.1.1.15 and 10.1.1.18, respectively.

CTRL.02 is in place to ensure there are constant readings of the battery voltage when in use. This is essential to prevent the vehicle from losing power by monitoring the battery life and immediately stopping operation when the battery has hit its limit. Knowing the battery voltage is useful in understanding the efficiency of the driving mechanism in comparison to flight. CTRL.02 is fully compliant as the team has been able to accurately read the battery voltage from the ground station.

CTRL.03 and CTRL.04 are in place for continuous use of the DROVER system outside the operator's field of view. It can be assumed that the vehicle will travel far from the operator, so cameras will be used to display what the drone sees. The camera selected must have at least 30 FPS and 480 TVL to ensure smooth and effective video transmission. 30 FPS ensures smooth transmission with minimal lag to ensure ease of control of the DROVER by the operator, and 480 TVL balances image clarity with efficient streaming. The DROVER has both a regular feed for eyes in the field as well as an IR feed to seek out either people or hot materials quicker, if that is the scenario that the DROVER is in. Both CTRL.03 and CTRL.04 are fully compliant, as both the regular FPV camera and IR camera have been configured separately and off of the DROVER. The test results for the FPV and IR camera can be seen in test sections 10.1.1.4 and 10.1.1.9, respectively.

Much like CTRL.02, requirement CTRL.05 is in place to have more information on the DROVER's position and orientation. This will allow for a greater understanding of the actual environment that the DROVER is in while providing flight data when the DROVER is flying. The sensor readings will be relayed to the ground station at a minimum of 2.4 GHz to ensure there is a good balance between range and bandwidth. In general, the 2.4 GHz band is commonly used in drones due to its good range and penetration capabilities [57]. The team has configured the OSD module to the Pixhawk flight controller to relay the sensor readings to the ground station, making CTRL.05 fully compliant.

To build this kind of system, a differential for the driving wheels isn't an ideal option. Requirement CTRL.06 is in place to specify how the DROVER will maneuver through its environment. The motors used to drive the wheels of the DROVER receive variable amounts of power to turn the DROVER instead of turning the wheels. The team has already verified the turning capabilities on the Demo-DROVER, which verifies CTRL.06 as fully compliant.

An important requirement included for the controls is CTRL.07, as it indicates the safety features required for a manually flown drone. The fail-safe mode must be triggered if the drone encounters a propeller failure during flight or if the operator loses connection to ensure the safety of the users or surrounding personnel. CTRL.07 is fully compliant as both fail-safe mechanisms have been tested and verified which can be seen in 10.1.1.14. CTRL.08 also identifies another safety feature that is required by FAA regulations [18]. The drone must be flown within sight of a visual observer that has direct communication with the user. A visual observer will be used in any tests that require the user to be out of sight of the DROVER (For example, live video/two-way communication demonstrations). In real-world use of the DROVER, a visual observer would not be necessary as the customer would be able to obtain the required licenses to avoid this FAA regulation. CTRL.08 is fully compliant.

CTRL.09 is important to have in place so that consistent communication can be established with anyone found out in the field while the DROVER is in use. CTRL.09 is fully compliant as the team has already configured the microphone and speaker set with the Raspberry Pi. This test result can be seen in the two-way verbal communication test section 10.1.1.5.

Avionics Summary (Rhys Wallin)

This section showcases the main electronics that will directly affect or support the team's requirements stated in the above sections. The first ones to go over are the electronics that control and support the requirements for the drone and driving structure. The first components of these systems are the Radio Master TX16S transmitter and the FRSky R-XSR receiver shown below, which can relay data at least at 2.4 GHz.

Figure 97: Radio Master TX16S [58]

Figure 98: FrSky R-XSR Receiver [59]

The transmitter and receiver shown above are the key components used to manually control the whole system. The joysticks and switches are used on the transmitter to control the drone functions while the knobs at the top of the transmitter are used to control the driving functions. The receiver directly connected to the Pixhawk. The next components for these systems are the Pixhawk 6x, mentioned previously, the Arduino Nano, and the Readytosky M8N GPS all shown below.

Figure 99: Pixhawk 6x [60]

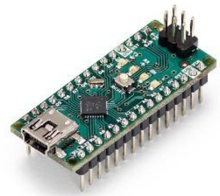


Figure 100: Arduino Nano [61]

Figure 101: ReadyToSky GPS [62]

As mentioned, the Pixhawk directly receives the commands given by the transmitter to control the drone functions. It is also used to pass on the signals from the knobs used for the driving functions. It does this by sending out the values as PWM signals and reading them by the Arduino Nano. The Arduino Nano then takes these values and, with the help of the implemented code, sends data to the motor drivers to control the driving functions. The GPS is used with the drone functions to validate the altitude the system is flying at to ensure the drone is below the FAA regulated altitude.

The next electronics are the ones that support the team's communication-based requirements. This includes the FPV camera, the Reaper Nano VTX, the SoloGood FPV monitor, the MLX90640 IR camera, the Waveshare microphone and speaker system, and the Raspberry Pi 4B all shown below.

Figure 102: FPV Camera [63]

Figure 104: Reaper Nano 25-350MW VTX [64]

Figure 103: FPV Monitor [65]

Figure 107: IR Camera [66]

Figure 106: Microphone & Speaker [67]

Figure 105: Raspberry Pi [68]

The FPV camera is connected to the Reaper Nano VTX card, and the VTX card will be connected to the Pixhawk to relay telemetry data from the drone. The video feed and drone data are then displayed on the FPV monitor. The IR camera and the microphone and speaker system are connected to the Raspberry Pi. The Raspberry Pi then sends the data for the IR camera to a virtual pi software on a computer for video feed. The Raspberry Pi is connected to a hotspot, and a communication software is run so that the team can join the call and communicate with someone in the field. The communication software used in this case was Discord.

The last avionic component to mention is the battery. Previously, the team was going to use two 6s 7500mAh batteries for the 20-minute hover time requirement. This order ended up getting cancelled and the batteries can no longer be ordered. Instead, the team found 6s 8000mAh batteries that were used in its place, and the team does acknowledge the drawbacks of this choice. Although there is a 1000mAh total increase it also comes with a 300g increase to the whole system.

Electrical Schematics (Elizabeth Beraducci)

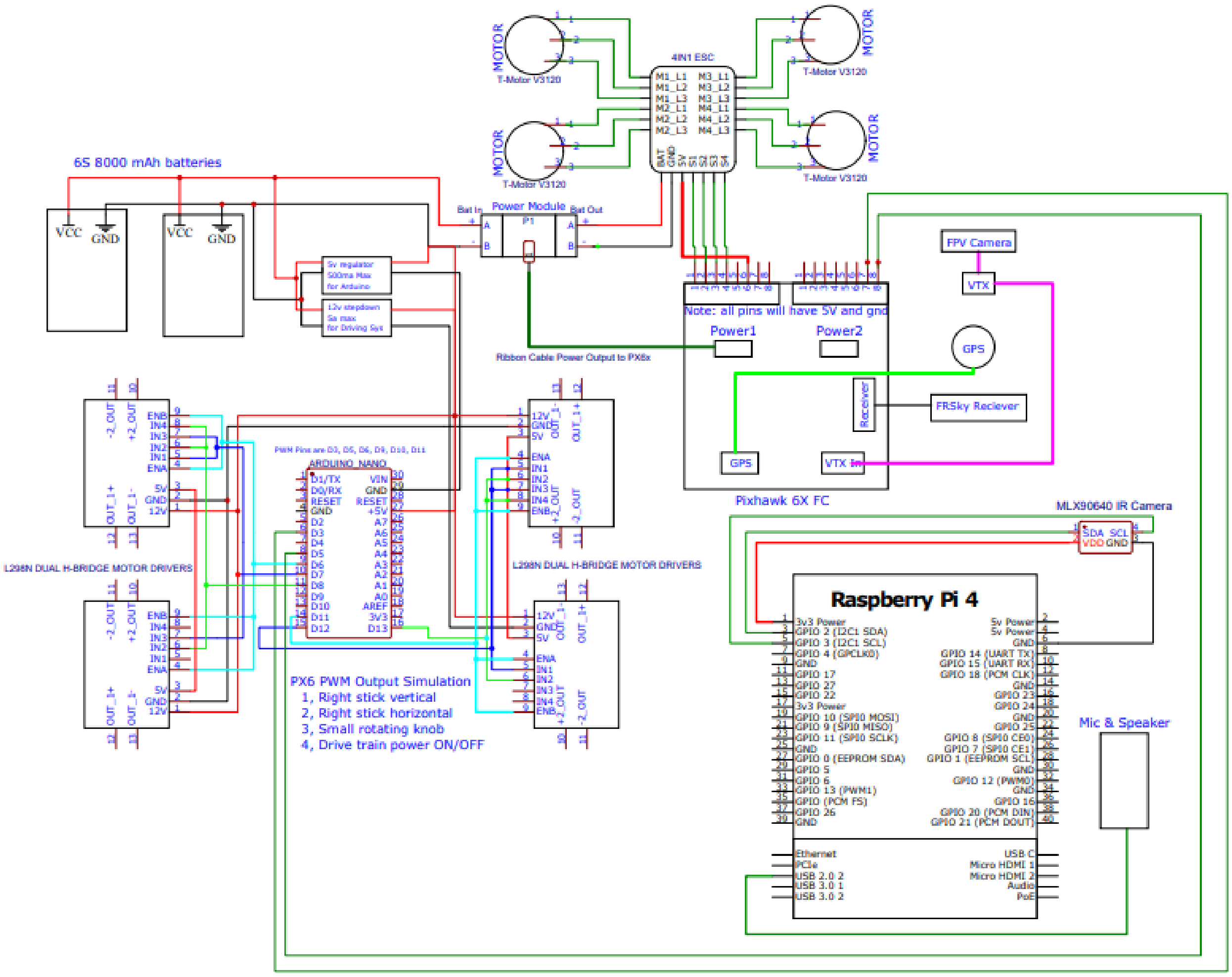


Figure 108: DROVER Wiring Diagram - Full System

The above figure details the connections made between the avionics to control the DROVER. The first keynote in the schematic is that the two 6s LiPo batteries power the entire system. The batteries run in parallel to a direct connection to the power module, which powers the flight system, and the other portion of power is spliced off from the main leads to a 12V step-down converter, which powers the motor drivers. The second keynote is that the schematic supports the driving and flying functions being integrated into a single radio transmitter in support of CTRL.01 requirement. The receiver at the bottom represents the receiver that's used to control both the drone system and the rover system. The SBUS port from the receiver goes to the flight controller, while the PWM output ports set for the two potentiometer nobs located at the top of the RadioMaster are redirected to the Arduino Nano for control over forward and backward movement as well as left and right turning. The Raspberry Pi houses a microphone and speaker along with the IR camera in support of SYS.04 and CTRL. 04, respectively.

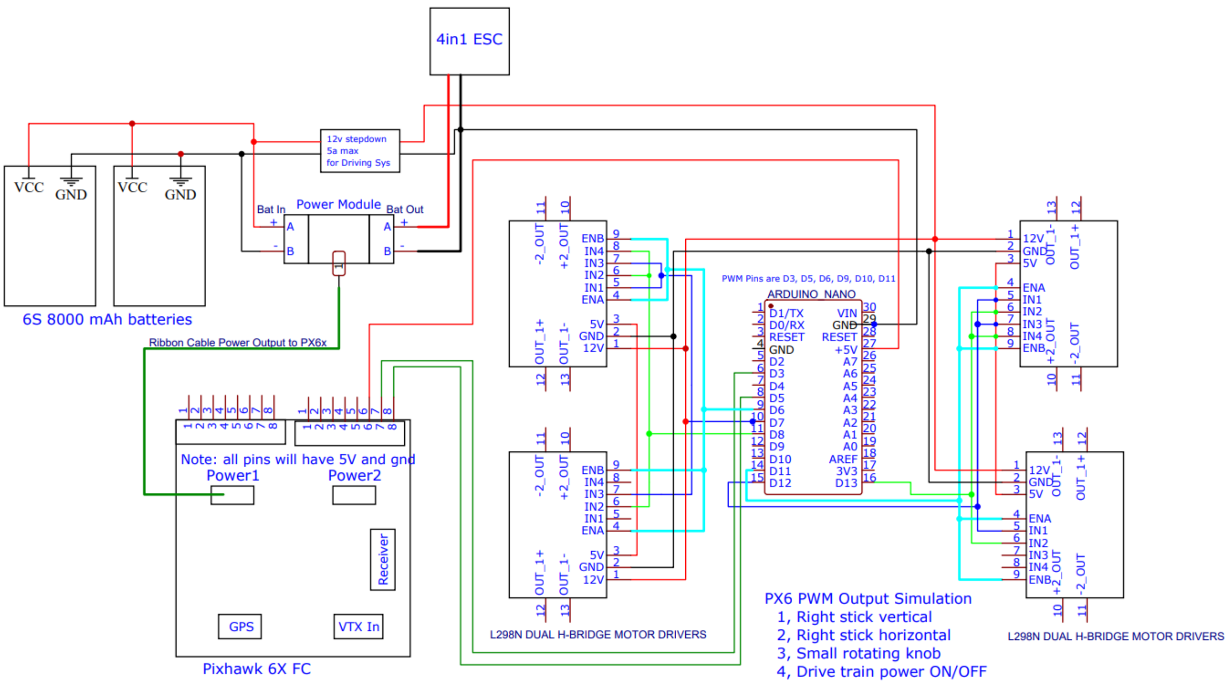


Figure 109: DROVER Wiring Diagram - Driving System

The schematic shown above in Figure 107 highlights the wiring schematic for the driving portion of the DROVER. As previously mentioned, the LiPo batteries go through a 12V step-down converter to power the motor drivers. Alongside this, the Arduino receives 5V from the Pixhawk flight controller. Four motor drivers are connected to the Arduino Nano, and each motor driver can drive two motors. Since only six motors need to be driven, the bottom two drivers only power one motor each. The motor drivers at the top drive the front set of two wheels, and the bottom two motor drivers power the single wheel on each respective side.

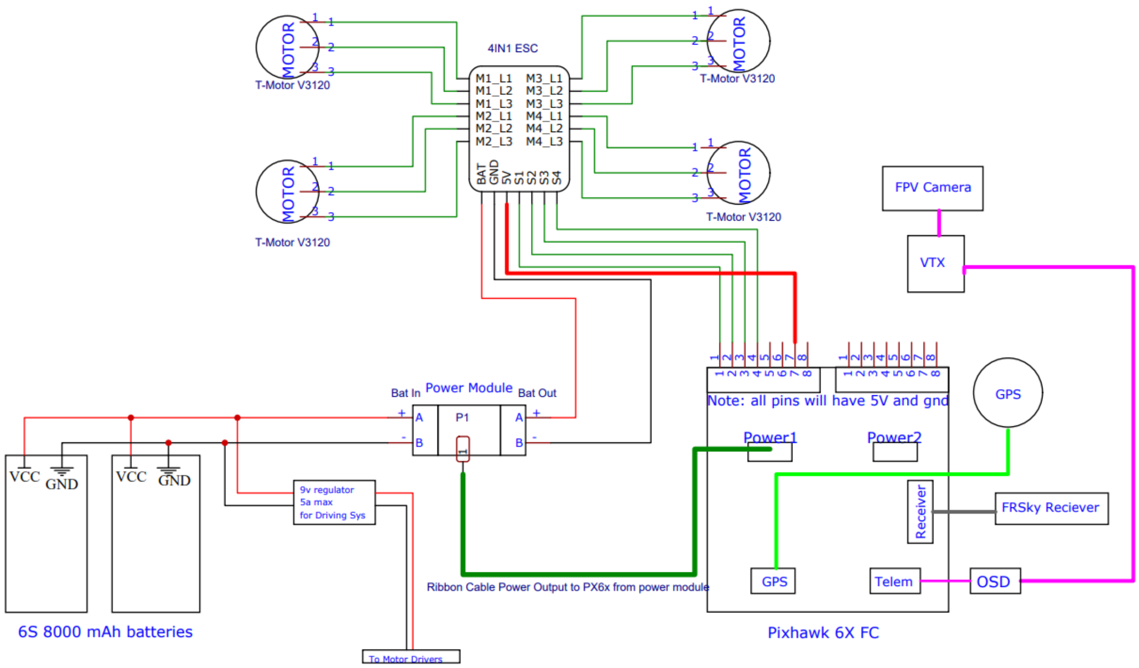


Figure 110: DROVER Wiring Diagram - Flight System

The wiring diagram shown above in Figure 108 outlines the flight system that was integrated into project DROVER. The two LiPo batteries were connected to the power module, which gives power to the 4in1 ESC and the Pixhawk flight controller. Each T-Motor V3120 was soldered to its respective location on the ESC. The GPS was connected to the Pixhawk, which was used to track the location of the DROVER during operation. Alongside the GPS, an OSD module was connected to the Pixhawk, which relayed sensor readings, including the battery voltage, in support of CTRL.05 requirement.

Stability

Rocker-Bogie Center of Gravity and Considerations (Marcelo Samaan, Fabrizio Chigne, Rhys Wallin)

The center of gravity of the assembly is dominated by the position of the approximately 2kg batteries which are in the middle bottom of the drone structure (above the electronics plate). The center of gravity of the CAD model is shown below.

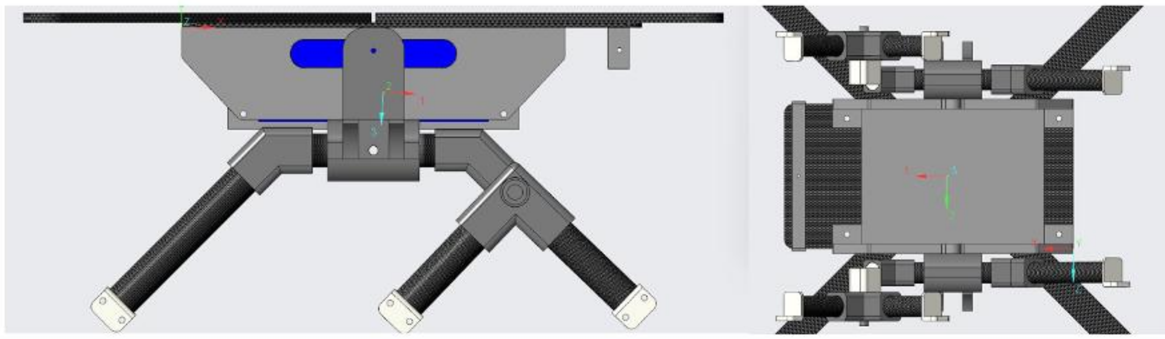


Figure 111: Center of gravity of CAD model

As expected, the center of gravity is aligned with the pin of the differential bar because the assembly is symmetrical in that direction. Nevertheless, it can also be observed that the center of gravity is shifted towards the right of the assembly, and this is due to the fact that DROVER has more weight distribution on that side mainly because of the differential bar, links, and the four back wheels.

Although the center of gravity is slightly shifted to the right, this does not present problems in the wheel's traction. This is because the four back wheels are closer together and thus share uniformly the weight. To confirm that there were no weight distribution problems a short test was performed on the prototype to measure the weight under each wheel, (*Appendix VII*). This test confirmed that there were no major weight distribution problems in the assembly, as the weight under each wheel was mostly even.

For the flight stability the above segments show that the center of gravity is located close to the center of the drone structure where the Pixhawk is located. The ESC and Pixhawk are in the center of the drone structure therefore they do not affect the center of mass greatly. The Drone structure is also a perfect square therefore the motors and propellers are equidistant from the center of gravity, so they do not affect it either. If the center of gravity poses too much of a problem the batteries are able to be adjusted in order to move the CG to a desirable location for the drone without disrupting the mass distribution of the driving structure. Any small discrepancies are handled by the flight controller. The stability of the drone is proven functional by the flight tests in Section 10.1.1.18.

7 TECHNICAL BUDGETS (HAYLEE FISKE)

7.1 Mass Budget

Table 12: Subsystem Allocated Mass

Mass Allocated	
Subsystem	Mass (g)
Structures	2200
Payload	600
Avionics/Electronics	3000
Aerodynamics	200
Total	6000

Table 13: Estimated Total Mass for the System

Mass Budget				
Item(s) Description	Quantity	Individual Mass (g)	Total Mass (g)	Subsystem
Propellers	4	27	108	Aerodynamics
Payload	1	600	600	Payload
Drone Structure	1	997.7	997.7	Structures
Driving Structure	1	709.8	709.8	Structures
Fittings	1	200	200	Structures
Wheels	6	64	384	Structures
Flight Motors	4	150	600	Avionics
Converter	1	22	22	Avionics
4-in1 ESC Drone	1	37	37	Avionics
Flight Battery	2	974	1948	Avionics
Flight Controller	1	74	74	Avionics
Driving Motors	6	55	330	Electronics
Camera	1	11	11	Electronics
Camera Transmitter	1	1	1	Electronics
Mic & Speaker	1	157	157	Electronics
Wires	1	40	40	Electronics
Motor Drivers	4	25	100	Electronics

IR Camera	1	5	5	Electronics
Raspberry Pi	1	50	50	Electronics
Arduino Nano	1	6	6	Electronics
Mirco OSD	1	3	3	Electronics
PCB	1	30	30	Electronics
GPS	1	50	50	Electronics
Total			6463.5	

The total mass of the system shows the mass measurements broken down by components. Individual components, not including the drone and driving structures, were weighed to determine a more accurate assessment of the expected weight of the final design. The (STR.06) requirement for DROVER specifies that the mass is under 55 lbs for FAA compliance, which is about 25 kilograms. Thrust tests on the motors demonstrated that DROVER could weigh up to 8976 grams to achieve the 2:1 thrust-to-weight ratio (AERO.01); however, the team allocated only 6000 grams of mass to help achieve the requirement of 20 minutes of hover flight (SYS.01). The allocated mass was decided upon to maintain the integrity of the electrical system and motors. The motors will be able to draw closer to the rated current with a smaller mass load; therefore, the team aimed to maintain the target weight of 6000 grams for the DROVER system. The final DROVER prototype weighs 6.9 kilograms including the payload, which is over the allocated mass budget and over the estimated mass budget. Mass differences in fittings, wires, adhesives, and 3D printed material could have added to the final weight of the DROVER. The requirement of twenty minutes for hover flight (SYS.01) did not include the payload mass. Not including the payload, the final DROVER system weighs 6.3 kilograms. The payload was only included for the obstacle course completion (SYS.07), which will decrease the mass by 600 grams to stay closer to the allocated mass budget for amp draw during the hover flight (SYS.01). The estimated margin for hover flight was 136.5 grams and is only 2.3% of the mass budget. The final weight of the DROVER was 6.3 kilograms; therefore, the system was over the allocated mass budget by 436.5 grams.

7.2 Electrical Power Budgets

A power budget is crucial to the design of DROVER as it determines the amount of flight time that is achievable in one charge of battery. Through the choice of battery and motors, it was determined that a high battery capacity was needed to achieve the set requirement of twenty minutes of hovering time (SYS.01). The focus within the power budgets was the hover time of the DROVER as it is a set requirement, and driving functions require significantly less power than flying functions. An estimate of the total operating time of the DROVER can be found in *Appendix IX*. The batteries chosen were a set of 6S 8000 mAh Lipo batteries that were connected in parallel to achieve a higher mAh value to run the system for the required hover flight time. Also stated within the electrical power budgets is maximum power. This terminology was included to differentiate the use of the full throttle, which maximized the power used from the system, while hover utilized the lower power. While this max throttle has been noted in the electrical budgets, the team did not utilize max throttle conditions, as the power consumption required was too great for the batteries chosen. The team also noted that the takeoff conditions required slightly more power draw. As it will be explained further in Sections 10.1.1.18 and 12.1, the SYS01 requirement was only partially met and the hover time achieved was of just above 15 minutes.

Table 14: Max Power System Usage

Max Power Budget							
Item(s) Description	Item Category	Battery Capacity (mAh)	Quantity	Current (A)	Voltage (V)	Individual Power (W)	Total Power (W)
Lipo Batteries	Power Source	8000	2	960	22.2	21312	42624
Camera	Instrument		1	0.055	5	0.275	0.275
Camera Transmitter	Instrument		1	0.34	5	1.7	1.7
IR Camera	Instrument		1	0.055	5	0.275	0.275
Microphone & Speaker	Instrument		1	1	5	5	5
Wheels Motors	Drive Mode		6	0.42	12	5.04	30.24
Flight Motors Max	Flight Mode		4	48.7	22.2	1081.14	4324.56
Margin							38261.95

Table 15: Low Power System Usage

Low Power Budget							
Item(s) Description	Item Category	Battery Capacity (mAh)	Quantity	Current (A)	Voltage (V)	Individual Power (W)	Total Power (W)
Lipo Batteries	Power Source	8000	2	960	22.2	21312	42624
Camera	Instrument		1	0.055	5	0.275	0.275
Camera Transmitter	Instrument		1	0.34	5	1.7	1.7
IR Camera	Instrument		1	0.055	5	0.275	0.275
Microphone & Speaker	Instrument		1	1	5	5	5
Wheels Motors	Drive Mode		6	0.42	12	5.04	30.24
Flight Motors Hover	Flight Mode		4	10.48	22.2	232.66	930.62
Margin							41655.89

Table 16: Energy Utilized for Each System Mode

Mode	Load (W)	Duration (min)	Energy Consumed (Wh)
Drive	37.49	20	12.50
Hover	937.87	20	312.62
Max Throttle	4331.81	20	1443.94

Table 17: Battery Capacity Remaining for Each Mode

Battery Capacity (Wh)	355.20
Energy Consumption at Hover (Wh)	312.62
Margin at Hover (Wh)	42.58
Energy Consumption Drive (Wh)	12.50
Margin Drive (Wh)	342.70

The table above demonstrates that the battery capacity will have a positive margin of 42.58 watt-hours after twenty minutes of hover flight. However, this margin was calculated from an amp test conducted, which found that there is 10.48 amps per flight motor drawn at 6000 grams (Section

10.1.1.2), which was 300 grams less than the final mass of the DROVER. As the mass of the system increases, the amp draw also increases. The health of the battery is determined by not fully discharging the cells and maintaining at least 10% capacity [69]. The team expected a weight of 6500 grams to completely drain the batteries, so a margin of 35.5 watt-hours was set to maintain the health of the batteries. However, with the weight increase, the 20-minute hover wasn't achievable, and the fail-safe engaged when the battery voltage got too low. These estimates are also based upon an additional power drawn from instruments, as noted in Table 22, and conditions for stable flight. During the hover test, the DROVER experienced some wind; therefore, this also negatively affected the endurance time. The team expected the amp draw to vary slightly during the flight to maintain hover; however, the estimated margin was not enough with the increased weight of the system and wind effects.

8 FINANCIAL BUDGET / BILL OF MATERIALS / SCHEDULE

8.1 Bill of Materials (Haylee Fiske)

Table 18: Bill of Materials

Bill of Materials						
Item(s) Description	**Vendor**	**# units**	**Price per unit**	**Total Cost**	**Subsystem**	**Order Status**
*** Carbon Fiber Plate 12x12**	HSDC	1	99.76	99.76	Structures	Received
*** Wires**	HSDC	1	5.97	5.97	Electronics	Received
*** Raspberry Pi**	HSDC	1	50.00	50.00	Electronics	Received
*** 3D Print Material**	HSDC	1	190.00	190.00	Structures	Received
*** Laser Cut Wood**	HSDC	2	42.70	85.40	Structures	Received
*** 2x4 Wood**	HSDC	4	3.36	13.44	Structures	Received
*** Pixhawk 6x**	HSDC	1	268.99	268.99	Avionics	Received
*** TX16S Mark II Radio Controller**	HSDC	1	199.99	199.99	Avionics	Received
*** Drive Motors with Gears (8 Pack)**	Amazon	1	9.99	9.99	Electronics	Received
*** PCB**	PCB way	1	30.00	30.00	Electronics	Received

*** Replacement Step Down**	Amazon	1	9.21	9.21	Electronics	Received
11-inch 3-Blades Props Test	Amazon	1	15.99	15.99	Aerodynamics	Received
Controller Li-Ion Battery 2-Pack	Rotor Riot	1	11.99	11.99	Avionics	Received
Battery Tray for Controller	Rotor Riot	1	2.49	2.49	Avionics	Received
Mini Redundancy Receiver for RC Multirotor FPV Racing Drone	Amazon	1	22.79	22.79	Avionics	Received
T-Motor V3120 (Drone)	T Motor	4	48.40	193.60	Aerodynamics	Received
11-inch 3-Blades 5.5 Pitch Propellers	Master Airscrew	4	13.99	55.96	Aerodynamics	Received
LiPo 6S 8000 mAh 2 Pack	Amazon	1	152.99	152.99	Electronics	Received
Arduino Nano	Amazon	1	19.90	19.90	Electronics	Received
Carbon Fiber Plate 12x6	McMaster	1	61.79	61.79	Structures	Received
Carbon Fiber Cylinders	McMaster	4	34.65	138.60	Structures	Received
Wheels 4 Pack	Amazon	2	16.99	33.98	Structures	Received
Drive Motors 8 Pack	Amazon	1	17.99	17.99	Electronics	Received
Camera	Amazon	1	16.99	16.99	Electronics	Received
Camera Transmitter	Rotor Riot	1	24.90	24.90	Electronics	Received
4x1 ESC (Drone)	Get FPV	1	89.99	89.99	Avionics	Received
Motor Drivers	Amazon	1	9.99	9.99	Electronics	Received
Step Down Converter	Amazon	1	9.21	9.21	Electronics	Received
Microphone & Speaker	Amazon	1	16.99	16.99	Electronics	Received
IR Camera	Amazon	1	81.99	81.99	Electronics	Received
GPS Module	Amazon	1	32.99	32.99	Avionics	Received
FPV Camera Monitor	Amazon	1	60.00	60.00	Electronics	Received
Parallel Battery Connector	Amazon	1	8.99	8.99	Electronics	Received
Micro OSD	HolyBro	1	19.99	19.99	Avionics	Received

VTX Antenna	Amazon	1	24.99	24.99	Electronics	Received
Replacement Motor	T Motor	1	56.90	56.90	Aerodynamics	Received
Replacement Propeller	Master Airscrew	1	13.99	13.99	Aerodynamics	Received
Final Drive Motors	NFPShop	6	15.00	90.00	Electronics	Received
TOTAL (including items purchased by HSDC and Personal *)				**2248.73**		
TOTAL actually detracted from budget				**1285.98**		

Table 19: Financial Budget

Total Budget	Item Total	Estimated Shipping (10% total)	Total Spent	Remaining
$ 1,750.00	$ 1,295.19	$ 128.60	$ 1414.58	$ 335.42

The bill of materials contains all the materials that were utilized in the fabrication process of project DROVER. Final ordering was completed and approved by the customer. Items specified by an asterisk were either personal expenses or given to the team for free by the HSDC; however, a cost assumption was attached to these items to show the true cost of building from scratch. The team also utilized a variety of fasteners; however, these were also obtained from the HSDC. Fabrication of DROVER has been fully completed. The team's reserved contingency budget was utilized for a flight motor and propeller in case of failure to ensure completion of testing requirements. Overall, the team was under budget by $335.42 including the estimated cost of shipping.

8.2 Schedule (Elizabeth Beraducci)

The overall project schedule was created using Gantt Project, highlighting key actions, dependencies, and milestones. The schedule is split into three primary phases: phase one included all design planning, phase two focused on design analysis and the PDR, and phase three encompassed CDR, assembly, and testing prior to the final report and showcase at the end of the Spring semester.

A red vertical line on the Gantt chart indicates the current date, which helped the team track their progress on key actions. The team stayed up to date on all actions with minor setbacks throughout the project. In phases one and two, the greatest schedule risk in this project was a potential delay in the CAD model because this would have delayed both FEA and CFD analyses. However, this risk was successfully mitigated by completing the full CAD model by the scheduled deadline. In phase three, the greatest schedule risk was a failed test where the structure breaks or an electronic component fried as this would cause the team to have to rebuild the DROVER. Although the team encountered damage to the structure and electronics during testing, the team quickly recovered to stay on schedule by preparing additional material ahead of time. Extra components were 3D printed ahead of time, and key electronic components including the ESC and batteries were ordered to mitigate large schedule delays. Aside from this, delays in shipments remained a concern throughout the project as this delayed test plans when all necessary components had not arrived yet.

Each team member remained aware of their responsibilities through an internal document regularly updated by all members, ensuring accountability for individual tasks. To guarantee that the project was completed and ready for the showcase, the team followed a critical path, which began in phase one. First, all detailed trade studies were completed before submitting the EDS report so that the initial design and CAD model could be completed. After this, any necessary modifications to the CAD model were made until it was finalized and ready for an FEA analysis. Based on the results of the FEA analysis, the team then refined the CAD if needed. All necessary components were purchased, and the team began 3D printing all connection pieces in PLA so that the demo-DROVER prototype was able to be completed in the beginning of the Spring semester. After the prototype was assembled, various driving tests were completed to ensure the system functions as expected. Finally, the team moved forward with 3D printing necessary connection pieces in Onyx to result in a full, final DROVER assembly. After assembly was completed, the team began testing to verify the functionality of the DROVER system. Regarding the main tests of this project, the driving test was completed first, then a flight test, followed by an obstacle course test, and finally, the hover test. The hover test was completed last since this has the greatest risks associated with possible damage to the structure if an unsuccessful flight or hard landing occurred.

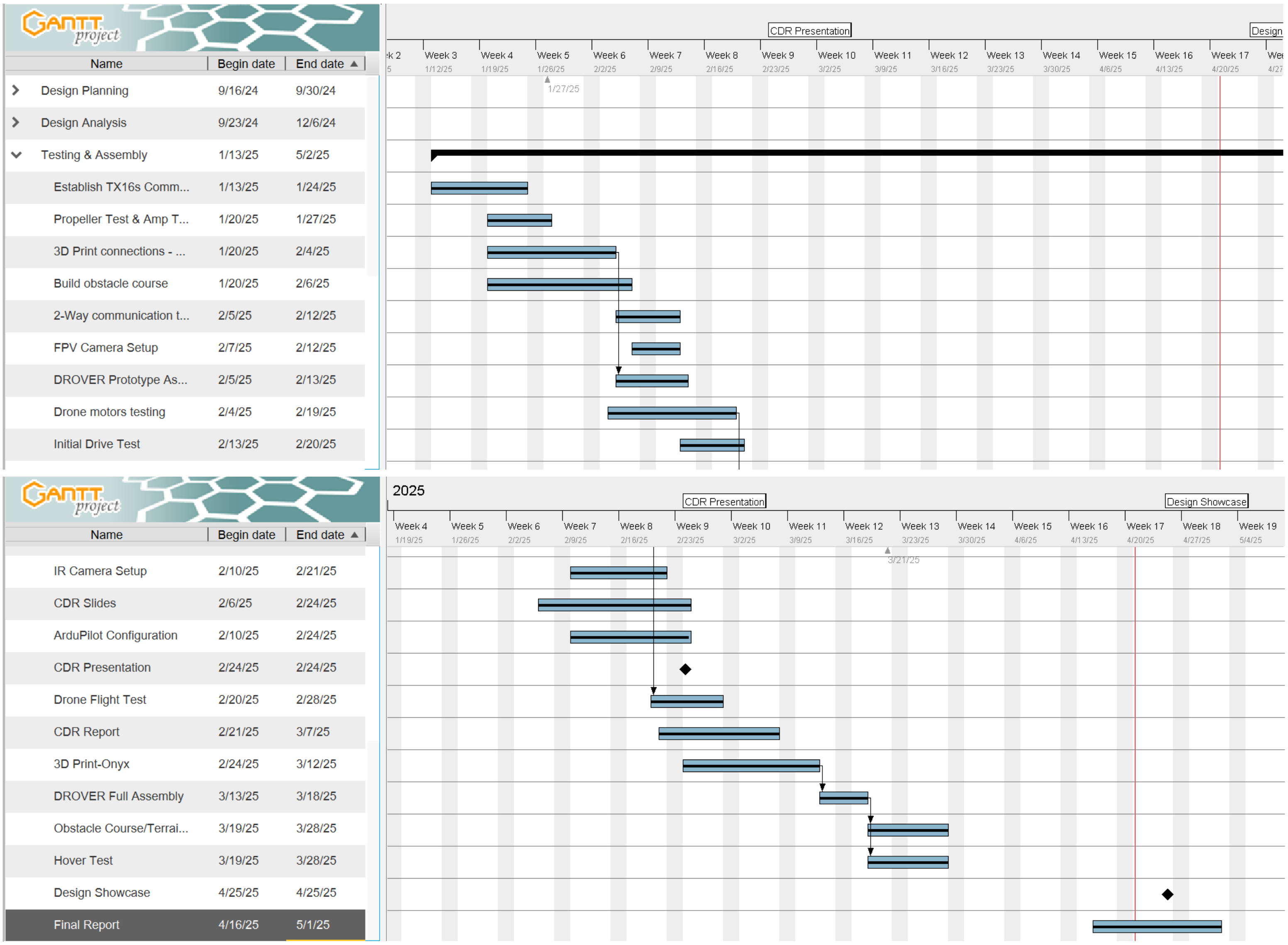


Figure 112: Gantt Chart

9 FABRICATION PLAN (RHYS WALLIN, HAYLEE FISKE, ELIZABETH

BERADUCCI)

Subsystem	Description	Manufacturing Method & Process	Status
Structures (Rover)	Legs of the rover for the DROVER's rocker-bogie suspension system	Cut the carbon fiber tubes with the Kobalt Wet Tile saw at the desired length	Manufactured
Structures (Rover)	Connections for the DROVER's rocker-bogie suspension system (including motor mounts, motors' shafts, etc)	3D-print all the attachments and connections in Onyx	Manufactured
Structures (Rover)	Rocker-bogie assembly	All Onyx 3D-printed attachments epoxied to the carbon fiber tubes, and the wheels	Manufactured
Electronics (Rover)	Wheels and motors assembly	The motors are fastened to the motor mounts and wired appropriately	Manufactured
Structures (Drone)	Drone Plate	Cut the carbon fiber plate with the Water Jet in the fiber direction	Manufactured
Structures (Drone)	Drone Arms	Cut the carbon fiber plate with the Water Jet in the fiber direction and epoxy them together to achieve greater thickness	Manufactured
Structures (Drone)	Drone structure assembly	The arms and the other attachments are fastened to the carbon fiber plate with M6 and M3 screws accordingly	Manufactured
Electronics (Drone)	Motors assembly	The four drone motors are soldered and connected to the ESC and then fastened to the arms	Manufactured
Subsystem	Description	Manufacturing Method & Process	Status
Electronics (Drone)	Configure TX16s to control both driving and flying functions	Integrate Pixhawk and Arduino to RadioMaster transmitter	Manufactured
Electronics (Drone)	Establish communication between transmitter and receiver	Bind receiver to transmitter	Manufactured
Electronics (Drone)	Establish a working failsafe	Use drone testing and coding through Ardupilot	Manufactured
Electronics (DROVER)	Drone and Rover integration	Use code to be able to swap back and forth between or use in tandem	Manufactured
Electronics (DROVER)	Setup FPV camera	Solder VTX to FPV camera and view through ground station monitor	Manufactured
Electronics (DROVER)	Configure IR Camera	Connect IR camera to Pi and configure Pi to read in thermal values	Manufactured
Electronics (DROVER)	Microphone and speaker	Connect microphone and speaker module to USB port on Pi	Manufactured
Structures (DROVER)	Final DROVER assembly	The drone structure and the rover structure are secured together using fasteners	Manufactured

The above figure shows the fabrication plan for the entire project. Starting at the top, there is the Rocker-bogie components which include the legs, the attachments, the assembly of these parts, as well as the wheels and motors. The legs are made out of carbon fiber tubes that were cut using a Kobalt Wet Tile Saw to the desired length.

Figure 113: Kobalt Wet Tile Saw

The attachments were printed using the 3D printers located in the HSDC and were printed using an onyx filament. Once these components were manufactured and verified, they were then assembled and were ready to be attached to the rest of the structure. The motors have specially designed mounts that were made from onyx and are attached to the inside of the legs. In addition, there is an adapter made from polycarbonate for the wheels to fit on the shaft of the motors. The attachments and the motor mounts were attached to the carbon fiber tubes using an epoxy found in the HSDC.

The next portion of the fabrication plan is the drone structure. This includes the drone plate, the drone arms, the assembly of these with the whole structure, as well as the mounting of the drone motors. They were manufactured from the same carbon fiber sheet using the PROTOMAX water jet located in the HSDC.

Figure 114: ProtoMAX Water Jet [41]

The team only cut out one plate while there were eight arms cut out, so there was enough to double stack the four arms for deflection resistance. These arms were attached together using the same epoxy used to attach the rocker-bogie components. The last thing the team did in this category was mount the drone motor onto the arms to ensure a good fit. All attachments were mounted using bolts. The arms were attached to the plate using M6 bolts, and the motors were attached to the arms using M3 screws. The full drone structure was assembled and mounted onto the final rocker-bogie assembly.

Moving on, the chart shows the more technical fabrications. At the top of that list is the configuring of the Radio Master Controller. This is complete due to having reconfigured all of the channels and it has been tested to be able to control both the driving and flying functions. This does support the latter plan for drone and rover integration. Next, the chart shows where the receiver was bound to the controller and set up with the Pixhawk for valid communication. The chart then shows the fabrication of all systems related to the communication-based requirements. This includes the FPV camera, the IR camera, and the microphone and speaker system. As shown these fabrications have all been completed and the systems have been mounted on the final assembly. The last thing on the chart is the final assembly, which has been completed before showcase.

10 Test Planning (Elizabeth Beraducci, Francesca Afruni, Francesco De Luca, Haylee Fiske)

10.1 Test Series Summary

Table 20: Test Planning

Test Type	Description	Requirement(s) Verified	Test Locations / Comments	Expected Completion Date	Status
Thrust Test	Measure thrust produced by propellers to verify manufacturer thrust values	SYS.01, AERO.01	HSDC	January 27th, 2025	Fully Compliant
Amp Test (Thrust Test)	Check the current draw to actively predict the hover time of the DROVER	SYS.01	HSDC	January 27th, 2025	Fully Compliant
Rover Motors Test	Ensure full functionality of the rover motors	SYS.02	HSDC	February 7th, 2025	Fully Compliant
Camera Test	Install and check functionality of the normal camera	SYS.03, CTRL.03	HSDC	February 12th, 2025	Fully Compliant
Two-Way Communication Test	Install and check functionality of the microphone and speaker	SYS.04, SYS.06	HSDC	February 12th, 2025	Fully Compliant
Drone Motors Test	Ensure full functionality of the drone motors	SYS.01	HSDC	February 19th, 2025	Fully Compliant
Driving Test (Demo-DROVER)	Test the structural design capacity, weight distribution, and the driving code before implementation of expensive materials	SYS.02, SYS.05, STR.04	HSDC	February 20th, 2025	Fully Compliant
Obstacle Course Test (Demo-DROVER)	Test the ability of the rocker-bogie system	SYS.02, STR.02, STR.03	Compound or other suitable location	February 20th, 2025	Fully Compliant
IR Camera Test	Install and check functionality of the IR camera	SYS.03, CTRL.04	HSDC	February 21st, 2025	Fully Compliant
Drone Test	Initial test to check the flight control systems before implementing the rover to minimize risks	SYS.01, SYS.05, AERO.02, AERO.03, CTRL.02	Compound or other suitable location	February 28th, 2025	Fully Compliant
Drop Test (Demo-DROVER)	Check, in case of accidental loss of power during flight, that the structure will survive the fall	This test does not verify any specific requirements but allows for risk mitigation purposes	HSDC or other suitable location	March 21st, 2025	Fully Compliant
Hover Test (DROVER)	Test the capability of the DROVER to fly for at least 20 minutes	SYS.01, SYS.03, SYS.04, SYS.05, SYS.06, SYS.07, AERO.01, AERO.02, AERO.03, AERO.04	Compound or other suitable location	April 17th, 2025	Fully Compliant
Obstacle Course Test (DROVER)	Test the final design of the structure to withstand rough terrain and obstacles	SYS.02, SYS.08, STR.02, STR.03	HSDC or other suitable location	April 10th, 2025	Fully Compliant
Terrain Test (DROVER)	Test the ability of the rover motors and wheels to drive over different types of terrain	SYS.02, STR.04, STR.03	Compound or other suitable location	April 10th, 2025	Fully Compliant

10.1.1.1 Thrust Test

Test Description/ Test Objectives. *This test aimed to verify expected thrust values produced by a Master Airscrew 11x5.5x3 inches propeller while using a T-Motor V3210 700KV motor. Measured thrust values were compared to the motor data sheet and Ansys CFD results.*

Test Article/ Test setup: *The team used the wooden thrust stand provided by the HSDC. The motor was mounted to the thrust stand, and the propeller was attached to the motor shaft. The motor mount was changed to a higher mount; therefore, the thrust values had to be corrected for that additional height away from the pivot point shown below. A 6S LiPo battery was connected to an 80A ESC to power the motor*

Figure 115: Thrust Test Setup

Test Methodology and Safety Measures.

The thrust test was completed in the HSDC using the wooden HERMES thrust stand. The test operator made sure to securely attach the motor and propeller onto the mount to prevent either piece from falling off. When the test began, the operator slowly increased the speed of the propeller. All present members wore safety glasses and stood to the side of the test stand.

Test Location/ Related Logistics and Approvals.

Location Name: HSDC: 150 W. University Blvd.

The test was completed during regular HSDC hours.

Test Measurements and Data Collection: *The thrust produced by the propeller was measured by a scale positioned under the thrust stand. The test was recorded to ensure accurate thrust values were measured. The results of this test showed that the propellers and motors produced a max individual thrust of 4488 g for each motor to support the 2:1 thrust requirement (AERO.01). This test also verified that the thrust numbers lined up with the manufacturer's datasheet.*

Schedule: Anticipated to start on 1/20/2025 and was completed by 1/27/2025.

Test Personnel. Primary POC: Francesca Afruni. Other participants: Elizabeth Beraducci, Kyle Kinkade, Rhys Wallin, Haylee Fiske, Fabrizio Chigne, Marcelo Samaan, Francesco De Luca.

10.1.1.2 Amp Test

Test Description/ Test Objectives. *This test aimed to verify the expected amperage input for thrust numbers while using a T-Motor V3210 700KV motor. The measured amp draw was compared to the motor data sheet and will be used for hover time estimation.*

Test Article/ Test setup: *The team used the HERMES wooden thrust stand provided by the HSDC, paired with an additional Racer Star RPM and Power Meter. The motor was mounted to the HERMES thrust stand, and the propeller was attached to the motor shaft. A fully charged 6S LiPo battery was connected to an 80A ESC to power the motor.*

Figure 116: Amp Test Setup

Test Methodology and Safety Measures.

The amp test was completed in the HSDC using the wooden HERMES thrust stand. The test operator made sure to securely attach the motor and propeller onto the mount to prevent either piece from falling off. When the test began, the operator slowly increased the speed of the propeller. All present members wore safety glasses and stood to the side of the test stand.

Test Location/ Related Logistics and Approvals.

Location Name: HSDC: 150 W. University Blvd.

The test was completed during regular HSDC hours.

Test Measurements and Data Collection: *The amp draw was measured by the Power Star device located in the HSDC. The test was recorded to ensure accurate amp draw values were measured. The test results showed that the amp draw was consistent with the manufacturer's number for amp draw based on thrust values. For a calculated predicted hover thrust, the amp draw of all four* *motors was 41.92A; the max amp draw to be able to hover for 20 minutes for the prototype weight is 47.6A; therefore, this test supports the 20-minute hover flight time requirement (SYS 01).*

Table 21: Amp Test Results

AMP Test		
Thrust (g)	Corrected Thrust (g) *	Current (A)
1540	1506.5	10.48
1600	1565.2	11.39
1720	1682.6	12.3
1840	1800.0	13.66
1915	1873.4	14.11
2000	1956.5	15.02

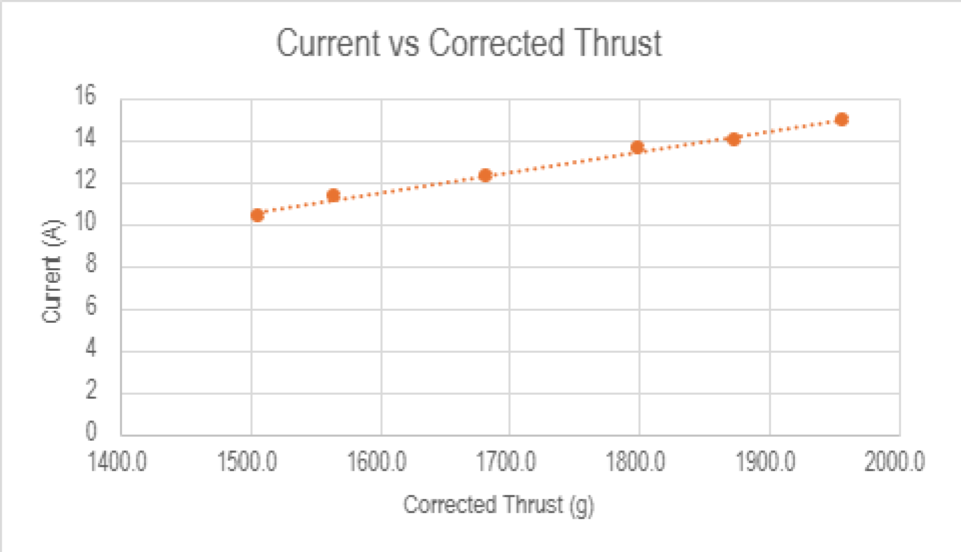


Figure 117: Amp Test Results

Schedule: Anticipated to start on 1/20/2025 and was completed by 1/27/2025.

Test Personnel. Primary POC: Francesca Afruni. Other participants: Elizabeth Beraducci, Kyle Kinkade, Rhys Wallin, Haylee Fiske, Fabrizio Chigne, Marcelo Samaan, Francesco De Luca.

10.1.1.3 Rover Motors Test

Test Description/ Test Objectives. *This test aimed to verify the full functionality of all rover motors purchased by the team.*

Test Article/ Test setup: *The team used an Arduino Uno, a breadboard, L298N motor driver, rover motors, and a 12V power supply. The motor driver pins were wired to the breadboard, which was connected to the Arduino Uno. The breadboard then received 12V, which powered the motor drivers. The outputs of the motor drivers can be connected to two separate motors at a time. Once the motors were connected and receiving power, the motors began to rotate.*

Test Methodology and Safety Measures.

The Rover Motors test was completed in the HSDC. The team used a multimeter to verify expected voltage to ensure no electronics were fried. When the motors received power, the rotation was observed and verified by other present team members. The team kept a safe distance from the spinning motors.

Test Location/ Related Logistics and Approvals.

Location Name: HSDC: 150 W. University Blvd.

The rover motors test was completed in the HSDC using electronic components purchased by the team. The rover motors received power from the motor drivers, and the team verified the functionality of the motors. The test was completed during regular HSDC hours.

Test Measurements and Data Collection: *The rover motor function was verified by completing this test.*

Schedule: Anticipated to start on 1/27/2025 and was completed by 2/7/2025. This time frame gave the team enough time to troubleshoot any possible issues with electronic components.

Test Personnel. Primary POC: Francesca Afruni. Other participants: Elizabeth Beraducci, Kyle Kinkade, Rhys Wallin, Haylee Fiske, Fabrizio Chigne, Marcelo Samaan, Francesco De Luca.

10.1.1.4 FPV Camera Test

Test Description/ Test Objectives. *This test aimed to verify the functionality of the purchased FPV camera in support of CTRL. 03 requirement. Once the camera received power from the VTX, the ground station found the signal and relayed the from the camera.*

Test Article/ Test setup: *The team used the purchased FPV camera, VTX, and ground station monitor. The FPV camera was soldered to the VTX according to the wiring diagram provided by the manufacturer. After this, the ground station monitor was turned on, and found the signal outputted from the VTX. Once the signal had been picked up, the monitor relayed the live video feed from the FPV camera.*

Test Methodology and Safety Measures.

The FPV camera test was completed inside the HSDC using electronic components purchased by the team. Proper care was taken when soldering the VTX to the FPV camera, and all necessary PPE was worn.

Test Location/ Related Logistics and Approvals.

Location Name: HSDC: 150 W. University Blvd.

The FPV camera test was completed in the HSDC using the electronic components purchased by the team. The test was completed during normal HSDC hours.

Test Measurements and Data Collection: *The proper functionality of the FPV camera, VTX, and ground station monitor were all verified through this test.*

Schedule: Anticipated to start on 2/7/2025 and was completed by 2/12/2025.

Test Personnel. Primary POC: Francesca Afruni. Other participants: Elizabeth Beraducci, Kyle Kinkade, Rhys Wallin, Haylee Fiske, Fabrizio Chigne, Marcelo Samaan, Francesco De Luca.

Figure 118: FPV Camera Test

10.1.1.5 Two Way Verbal Communication Test

Test Description/ Test Objectives. *This test aimed to configure the microphone and speaker set with the Raspberry Pi to verify the expected functionality of the microphone and speaker in support of SYS. 04 requirement.*

Test Article/ Test setup: *The team used the purchased Raspberry Pi 4b along with the microphone and speaker set. The microphone and speaker were plugged into the USB port on the Raspberry Pi. The team then accessed the Pi through VNC, which is a virtual desktop. Through VNC, the team initiated a Discord call to the DROVER to verify that the microphone and speaker worked as expected.*

Test Methodology and Safety Measures.

The two-way verbal communication test was completed inside the HSDC. The team has taken proper care of the Raspberry Pi to ensure no damage occurred.

Test Location/ Related Logistics and Approvals.

Location Name: HSDC: 150 W. University Blvd.

The two-way verbal communication test was completed inside the HSDC. The test was completed during regular HSDC hours.

Test Measurements and Data Collection: *This test verified the functionality of the microphone and speaker module in support of SYS.04 requirement.*

Schedule: Anticipated to start on 2/5/2025 and was completed by 2/12/2025. This timeframe gave the team enough time to troubleshoot any possible electronic issues.

Test Personnel. Primary POC: Francesca Afruni. Other participants: Elizabeth Beraducci, Kyle Kinkade, Rhys Wallin, Haylee Fiske, Fabrizio Chigne, Marcelo Samaan, Francesco De Luca.

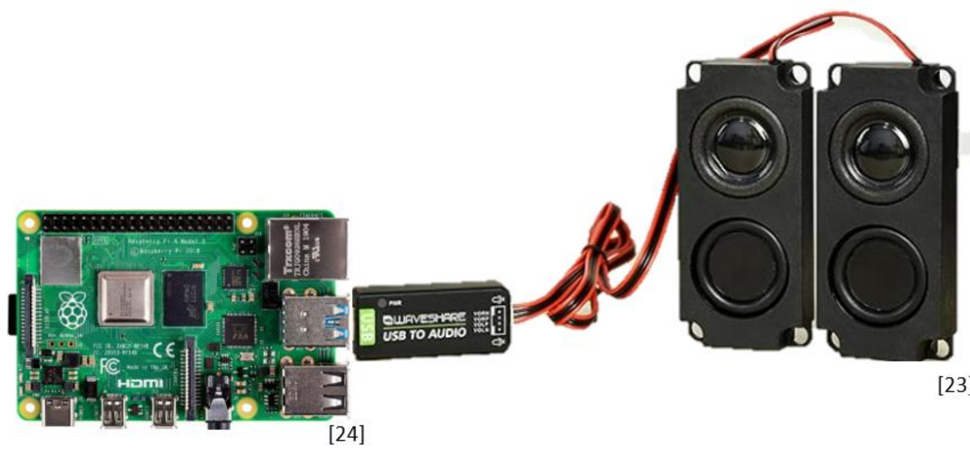


Figure 119: Two-Way Communication Test [67][68]

10.1.1.6 Drone Motors Test

Test Description/ Test Objectives. *This test aimed to verify full functionality of all purchased T-Motor V3120 drone motors.*

Test Article/ Test setup: *The team soldered each wire from the drone motor to its respective location on the 4in1 ESC. Next, each of the signal wires from the motors were connected to its respective pin location on the Pixhawk flight controller. The 6s 8000 mAh LiPo battery was* *connected to the power module, which was connected to the 4in1 ESC. The Pixhawk was connected to a laptop using a USB cable, and the team then commanded a motor test through ArduPilot to verify that each motor demonstrated full functionality and rotated in the correct direction for the quadcopter configuration.*

Test Methodology and Safety Measures

The drone motor test was completed in the HSDC using the drone motors, 4in1 ESC, Pixhawk flight controller, and LiPo batteries purchased by the team. The team ensured no propellers were attached to the motors to ensure the safety of all members. Additionally, the motors were only given 5% throttle during the test.

Test Location/ Related Logistics and Approvals.

Location Name: HSDC: 150 W. University Blvd.

The test was completed during regular HSDC hours.

Test Measurements and Data Collection: *The functionality of the drone motors was verified when the motors began to rotate. The direction of the rotation was observed and recorded by present team members by attaching a small piece of tape to the top of the motor and watching the direction. If any motor was spinning in the incorrect direction, the motor was desoldered from the ESC, and any two of the wires would swap locations. The test was completed again until all motors rotated in the expected direction based on ArduPilot documentation.*

Schedule: Test was completed by 2/19/2024.

Test Personnel. Primary POC: Francesca Afruni. Other participants: Elizabeth Beraducci, Kyle Kinkade, Rhys Wallin, Haylee Fiske, Fabrizio Chigne, Marcelo Samaan, Francesco De Luca.

10.1.1.7 Driving Test (Demo-DROVER)

Test Description/ Test Objectives. *This test aimed to verify the expected functionality of the rocker-bogie suspension system in the Demo-DROVER prototype.*

Test Article/ Test setup: *The team used the purchased electronic components along with 3D printed connections to assemble the Demo-DROVER. Once the prototype was assembled, all motors were given power, and an Arduino code was run to control the Demo-DROVER using the TX-16s transmitter. Once all connections had been established, the Demo-DROVER was commanded to drive in a straight line and turn.*

Test Methodology and Safety Measures.

The driving test for the Demo-DROVER was completed outside of the HSDC. The team used a multimeter to ensure all electronic components were receiving proper battery voltage. All present team members stood out of the way of the Demo-DROVER

Test Location/ Related Logistics and Approvals.

Location Name: HSDC: 150 W. University Blvd.

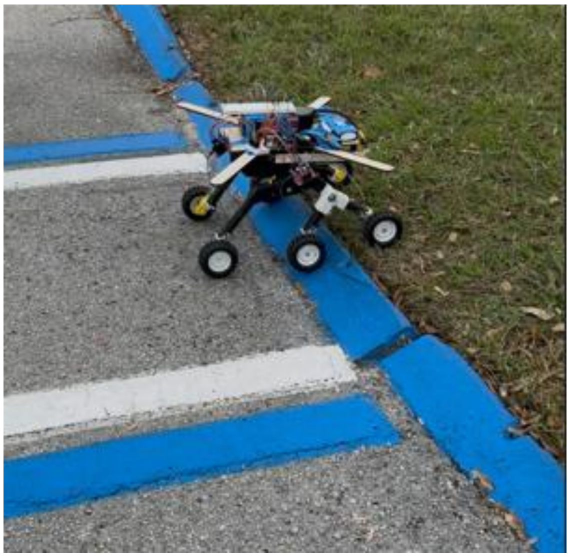
The driving test for the Demo-DROVER was completed outside the HSDC in a large open area. Once all motors had been given a proper connection, the Demo-DROVER was commanded to drive in a straight line and turn. The test was completed during regular HSDC hours.

Test Measurements and Data Collection:

The driving test of the Demo-DROVER was overall considered a success, as it was mainly used to check the driving code as well as the functionality of the rocker-bogie suspension system. However, the first round of testing ended with the disassembly of the bogie set of legs (Figure 118), that is because the rocker-bogie suspension system was held together with hot glue. The reason behind this was that the team didn't want to commit immediately to the use of epoxy in case of a major failure. Overall, as stated previously, in the end, all driving tests were considered a success, and they were fundamental to improving the structure in preparation for the manufacturing of the final design. The test results are used to support the driving on a straight line (SYS.02) and the all-wheel drive (STR.03) requirements

Schedule: Anticipated to start on 2/13/2025 and was completed by 2/20/2025.

Test Personnel. Primary POC: Francesca Afruni. Other participants: Elizabeth Beraducci, Kyle Kinkade, Rhys Wallin, Haylee Fiske, Fabrizio Chigne, Marcelo Samaan, Francesco De Luca.



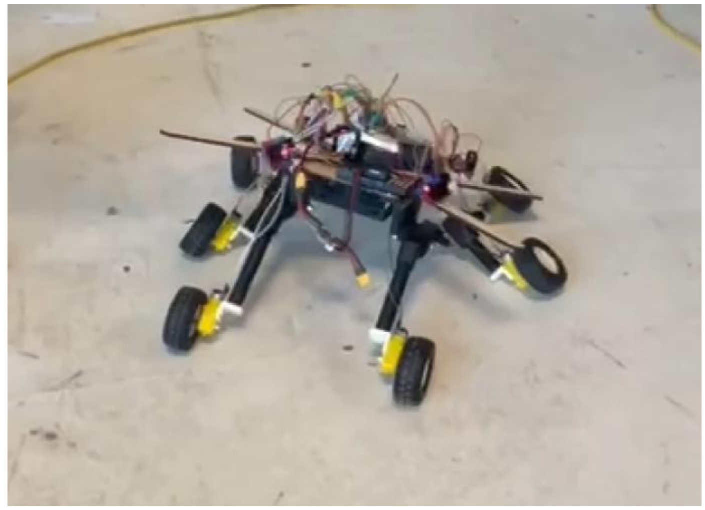


Figure 120: Demo-DROVER first driving test

Figure 121: Demo-DROVER in driving test

10.1.1.8 Obstacle Course Driving Test (Demo-DROVER)

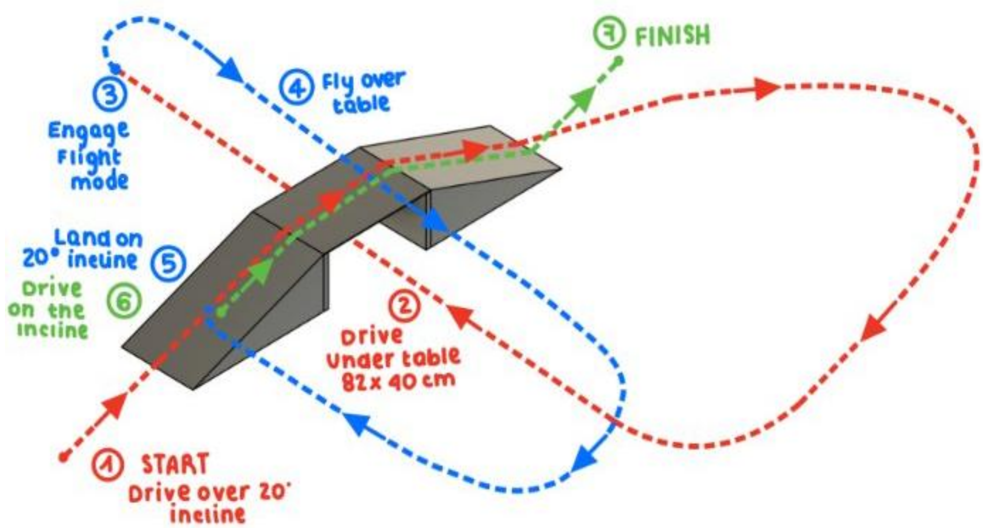


Figure 122: Obstacle Course Path

Test Description/ Test Objectives. *This test aimed to verify the full functionality of the driving capabilities of the Demo-DROVER by completing the driving portion of the obstacle course, which can be seen above in Figure 120.*

Test Article/ Test setup: *The team used the Demo-DROVER prototype along with the obstacle course. The pilot manually controlled the Demo-DROVER to start driving up the 20° incline, then drive down the 20° incline before executing a turn and driving under the 82x40 cm table.*

Test Methodology and Safety Measures.

The Demo-DROVER obstacle course test was completed outside the HSDC in a large open and flat space. All electronic components were checked with a multimeter before providing the battery power. Once given power, all members stood out of the way of the Demo-DROVER.

Test Location/ Related Logistics and Approvals.

Location Name: HSDC: 150 W. University Blvd.

The test was completed during regular HSDC hours.

Test Measurements and Data Collection: *The obstacle course test with the Demo-DROVER supported that the driving system worked as expected to climb up and down the 20° incline for the STR.02 requirement. However, this test helped the team realize that the DROVER was going to need stronger rover motors, once heavier, to smoothly clear the 20° incline. The new motors were identified and later tested on the new DROVER structure.*

Schedule: Anticipated to start on 2/13/2025 and was completed by 2/20/2025.

Test Personnel. Primary POC: Francesca Afruni. Other participants: Elizabeth Beraducci, Kyle Kinkade, Rhys Wallin, Haylee Fiske, Fabrizio Chigne, Marcelo Samaan, Francesco De Luca.

10.1.1.9 IR Camera Test

Test Description/ Test Objectives. *This test aimed to configure the IR camera with the Raspberry Pi 4b to verify the expected functionality of the IR camera in support of CTRL. 04 requirement.*

Test Article/ Test setup: *The team used the IR camera and the Raspberry Pi 4b. The IR camera was connected to the Raspberry Pi based on the provided wiring diagram from the manufacturer (Figure 120). Once the IR camera was set up, it was configured on the Pi through a set of commands in the terminal. Finally, a Python code was run on the Pi, which pulled up a live video feed from the IR camera.*

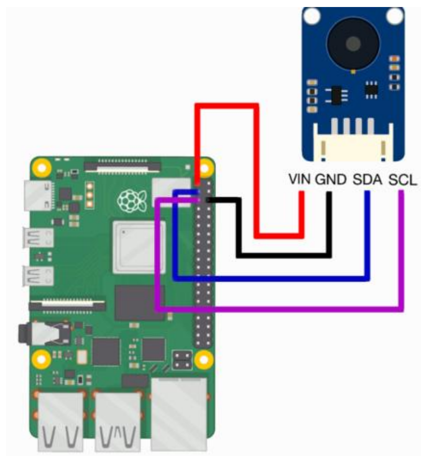


Figure 123: IR Camera Wiring Diagram to Pi [70]

Test Methodology and Safety Measures.

The IR camera test was completed inside the HSDC. Proper care was taken of all electronic components by using a multimeter to check the power supply and using an anti-static mat to place components on.

Test Location/ Related Logistics and Approvals.

Location Name: HSDC: 150 W. University Blvd.

The IR camera test was completed in the HSDC using the electronic components purchased by the team.

Test Measurements and Data Collection: *The IR camera test verified that the camera works as expected when integrated with the Raspberry Pi. The test results are seen below.*

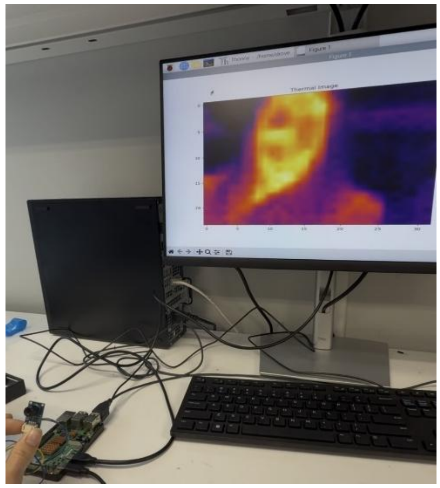


Figure 124: IR Camera Test Results

Schedule: Anticipated to start on 2/10/2025 and was completed by 2/21/2025. This timeframe ensured the team had enough time to configure the IR camera with the Raspberry Pi.

Test Personnel. Primary POC: Francesca Afruni. Other participants: Elizabeth Beraducci, Kyle Kinkade, Rhys Wallin, Haylee Fiske, Fabrizio Chigne, Marcelo Samaan, Francesco De Luca.

10.1.1.10 Drone Test

Test Description/ Test Objectives. *This test aimed to verify that the final drone structure was stable, including proper functionality of all drone motors working together, and that the power budgeting was correct.*

Test Article/ Test setup: *The team used the final drone structure with a modified platform base to have a flat surface to land on. The battery, ESC, and Pixhawk were attached to the structure using zip ties and Velcro to ensure they were held securely in place.*

Test Methodology and Safety Measures:

The drone test was completed outside in an open field, and the present team members walked 15 yards away and were stationed behind a soccer goal. The flight test was conducted close to the ground so that an emergency shutdown would result in minimal damage to the drone.

Test Location/ Related Logistics and Approvals.

The flight test was conducted at the Brevard Soccer fields in Melbourne while no other pedestrians were present, and the wind was calm.

Test Measurements and Data Collection:

The results of the test showed that all motors were functioning properly and the calculations for amp draw and trust required were accurate. The drone was not as stable as the team would have preferred, but after taking the drone structure back, the team realized that the Pixhawk was sitting at an angle, which was the main culprit of the drift. All other drifts were minor, and the team agreed that they were due to wind. This test was in support of the flying, hovering (SYS.01), maneuvering (AERO.02), and stable flight (AERO.03) requirements.

Schedule:

The test was completed on February 28, 2025

Test Personnel. Primary POC: Rhys Wallin, Elizabeth Beraducci. Other participants: Francesca Afruni, Kyle Kinkade, Haylee Fiske, Francesco De Luca.

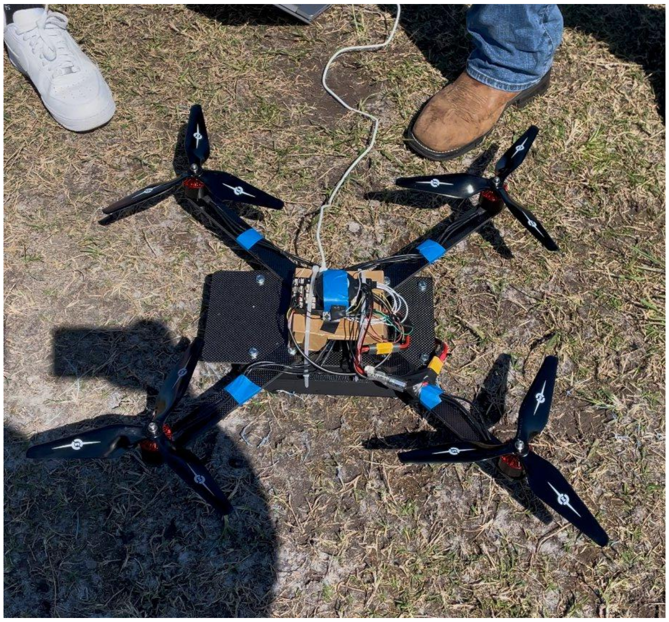


Figure 125: Drone before flying test

Figure 126: Drone mid-flight

10.1.1.11 Drop Test (Demo-DROVER)

Test Description/ Test Objectives:

This test aimed to determine the structural integrity of the Demo-DROVER.

Test Article/ Test setup:

The team used the Demo-DROVER prototype, and the test consisted of a drop that will take place 0.46m off the ground to simulate an emergency fall. This test verified the impact analysis, which indicated that the structure would survive an impact at 3 m/s.

Test Methodology and Safety Measures:

The test was done in the HSDC and only the team member dropping the system was close to the test. All other team members were stationed behind the bench.

Test Location/ Related Logistics and Approvals:

The drone test was completed inside the HSDC in an open area.

Test Measurements and Data Collection:

The results of this test showed that the structure of the Demo-DROVER behaved as expected, with primary damage to the PLA components. This test verified the accuracy of the FEA impact analysis.

Schedule

The Drop test was performed on March 31, 2025.

Test Personnel. Primary POC: Francesca Afruni. Other participants: Elizabeth Beraducci, Kyle Kinkade, Rhys Wallin, Haylee Fiske, Fabrizio Chigne, Marcelo Samaan, Francesco De Luca.

10.1.1.12 Flight Test with Leg Structure

Test Description/ Test Objectives:

This test aims to verify that the full system can fly without the driving portion of the project interfering with the flight

Test Article/ Test setup:.

The team used the final drone and driving structure without the electronics, the batteries were attached to the plate using Velcro.

Test Methodology and Safety Measures:

The drone test was completed outside in an open field, and the team members present walked 15 yards away and were stationed behind a soccer goal. Also, the flight test happened close to the ground, so an emergency shutdown was an option for minimal damage to the drone.

Test Location/ Related Logistics and Approvals:

The flight test was conducted at the Brevard Soccer fields in Melbourne while no other pedestrians were present, and the wind was calm.

Test Measurements and Data Collection:

The results of the test showed that the driving structure had no effect on the flying system. The drone was not as stable as the team would have preferred, but the drone was in altitude hold mode so the drone was able to be pushed by the wind. This test was in support of the flying, hovering (SYS.01), maneuvering (AERO.02), and stable flight (AERO.03) requirements.

Schedule:

The test was completed on March 8th, 2025

Test Personnel: Primary POC: Rhys Wallin, Elizabeth Beraducci. Other participants: Francesca Afruni, Kyle Kinkade, Haylee Fiske.

Figure 127: Flight Test With Leg Structure

10.1.1.13 Flight Test with Loiter

Test Description/ Test Objectives:

This test aims to verify that the GPS works with the flight controller and that the loiter flight mode will hold the drone in place based off of position data gathered from the GPS.

Test Article/ Test setup:.

This test was done with the full DROVER prototype and everything was secured with Velcro, zip ties, or electrical tape.

Test Methodology and Safety Measures:

The drone test was completed outside in an open field, and the team members present walked 15 yards away and were stationed behind a soccer goal. Also, the flight test happened close to the ground, so an emergency shutdown was an option for minimal damage to the drone.

Test Location/ Related Logistics and Approvals:

The flight test was conducted at the Brevard Soccer fields in Melbourne while no other pedestrians were present, and the wind was moderate to verify loiter.

Test Measurements and Data Collection:

The results of the test showed that the Pixhawk was able to use the GPS, and that the loiter function worked. There was fluctuation in the altitude but that is to be expected because the flight controller wasn't tunned perfectly. This test was in support of the flying, hovering (SYS.01), maneuvering (AERO.02), and stable flight (AERO.03) requirements.

Schedule:

The test was completed on April 8th, 2025

Test Personnel. Primary POC: Rhys Wallin, Elizabeth Beraducci. Other participants: Francesca Afruni, Kyle Kinkade.

Figure 128: Loiter Flight

10.1.1.14 Fail Safety Test

Test Description/ Test Objectives:

This test was to verify that the fail safes worked. One fail safe was for when the battery reached a certain voltage, and the other was made for if the drone lost connection to the radio controller at any point during flight.

Test Article/ Test setup:.

This test was done with the full DROVER prototype and everything was secured with Velcro, zip ties, or electrical tape.

Test Methodology and Safety Measures:

The drone test was completed outside in an open field, and the team members present walked 15 yards away and were stationed behind a soccer goal. Also, the flight test happened close to the ground, so an emergency shutdown was an option for minimal damage to the drone.

Test Location/ Related Logistics and Approvals:

The flight test was conducted at the Brevard Soccer fields in Melbourne while no other pedestrians were present, and the wind was moderate.

Test Measurements and Data Collection:

The results of this test showed that both the battery, and connection fail safes worked and that at these points the drone will safely land wherever it is. This test also confirmed that the OSD module is working as intended, which supplies the operator with a range of knowledge including voltage and altitude (CTRL.02 and AERO.04).

Schedule:

The test was completed on April 10th, 2025

Test Personnel. Primary POC: Rhys Wallin, Elizabeth Beraducci. Other participants: Francesca Afruni, Kyle Kinkade, Haylee Fiske, Marcelo Samaan.

Figure 129: Failsafe Auto Land Enabled (From FPV Camera)

10.1.1.15 Obstacle Course Test (DROVER)

Test Description/ Test Objectives. *This test aimed to verify the full functionality of the driving capabilities of the DROVER by completing the driving portion of the obstacle course, which can be seen above in the figure.*

Test Article/ Test setup: *The team used the DROVER prototype along with the obstacle course built by the team. The pilot manually controlled the DROVER to start driving up the 20° incline, then drive down the 20° incline before executing a turn and driving under the 82x40 cm table.*

Test Methodology and Safety Measures.

The DROVER obstacle course test was completed outside in a large open and flat space. All electronic components were checked with a multimeter before connecting the battery power. Once given power, all members stood out of the way of the DROVER for safety.

Test Location/ Related Logistics and Approvals.

The obstacle course test was conducted at the Brevard Soccer fields in Melbourne while no other pedestrians were present, and the wind was calm.

Test Measurements and Data Collection: *The results of this test showed all systems were able to be used in tandem. The obstacle course test with the DROVER verified that the driving system works as expected to climb up and down the 20° incline for the STR.02 requirement.*

Schedule: *The obstacle course test was completed on April 10th, 2025.*

Test Personnel. Primary POC: Francesca Afruni. Other participants: Elizabeth Beraducci, Kyle Kinkade, Rhys Wallin, Haylee Fiske, Marcelo Samaan

Figure 130: Obstacle Course Test (Right before landing on 20-degree incline)

10.1.1.16 Terrain Test (DROVER)

Test Description/ Test Objectives. *This test aimed to verify that the final rocker-bogie structure is robust, the motors are all functioning properly, and to confirm that the team's power budgeting is correct.*

Test Article/ Test setup:

The team used the final prototype with the final driving structure and new motors. Weights and blocks of woods were used as "obstacles" for the test

Test Methodology and Safety Measures.

The terrain test was completed outside on uneven terrain to verify that the rocker-bogie suspension system worked as intended and that the protype was able to traverse uneven terrain.

Test Location/ Related Logistics and Approvals.

The flight test was conducted at the Brevard Soccer fields in Melbourne while no other pedestrians were present, and the wind was calm.

Test Measurements and Data Collection:

This test supported STR.03, and STR.04 with a demonstration of the suspension system and all-wheel drive capabilities of the final DROVER. This test also supports the SYS.02 requirement by demonstrating straight driving and turns. The DROVER easily completed the rugged terrain test, which would not have been possible without the rocker-bogie system.

Schedule: *The terrain test was completed on April 10th, 2025.*

Test Personnel. Primary POC: Francesca Afruni. Other participants: Elizabeth Beraducci, Kyle Kinkade, Rhys Wallin, Haylee Fiske, Marcelo Samaan.

Figure 131: Terrain Test Showcasing Rocker-Bogie

10.1.1.17 First Hover Test

Test Description/ Test Objectives:

This test was to verify the teams system 1 requirement of having a 20-minute hover time with the full working prototype.

Test Article/ Test setup:.

This test was done with the full DROVER prototype and everything was secured with Velcro, zip ties, or electrical tape.

Test Methodology and Safety Measures:

The drone test was completed outside in an open field, and the team members present walked 15 yards away and were stationed behind a soccer goal. Also, the flight test happened close to the ground, so an emergency shutdown was an option for minimal damage to the drone.

Test Location/ Related Logistics and Approvals:

The flight test was conducted at the Brevard Soccer fields in Melbourne while no other pedestrians were present, and the wind was moderate.

Test Measurements and Data Collection:

This test ended in a crash resulting from a blown capacitor on the esc. The only things that broke were the platform bases, and the motor shafts which were easily remade using the 3D printers at the HSDC. One battery was also scraped and no longer usable, so another battery was ordered. All other major components were not damaged from the crash.

Schedule:

The test was completed on April 11th, 2025

Test Personnel: Primary POC: Rhys Wallin. Other participants: Elizabeth Beraducci, Kyle Kinkade, Francesca Afruni, Haylee Fiske, Fabrizio Chigne, Marcelo Samaan, Francesco De Luca.

Figure 132: First Hover Test at Impact

10.1.1.18 Final Hover Test

Test Description/ Test Objectives:

This test was to verify the teams system 1 requirement of having a 20-minute hover time with the full working prototype.

Test Article/ Test setup:.

This test was done with the full DROVER prototype and everything was secured with Velcro, zip ties, or electrical tape.

Test Methodology and Safety Measures:

The drone test was completed outside in an open field, and the team members present walked 15 yards away and were stationed behind a soccer goal. Also, the flight test happened close to the ground, so an emergency shutdown was an option for minimal damage to the drone.

Test Location/ Related Logistics and Approvals:

The flight test was conducted at the Brevard Soccer fields in Melbourne while no other pedestrians were present, and the wind was moderate.

Test Measurements and Data Collection:

The results of this test were unideal but proved that the protype could hover for roughly 15 minutes at a time. The team thinks that this number could increase a few minutes based on a few assumptions. Due to minor complications the batteries were not fully charged, as well as they were not drained as much as they could have been. The voltage plot shown below shows the max voltage of only 25.0 V, which means the test lost a valuable 0.2 V before hover even started. Furthermore, after the test, the voltage was measured to be 19.2 V, which means there was 1.2 V still available to be discharged safely. There were numerous other things that could have improved this hover time but the team is confident that with the current prototype 20 minutes may be unobtainable based on the plots shown below. From the test, there was an average current draw of 62 A, which is significantly higher than the expected amp draw (45-50 A). The reason for this is discussed in the open issues portion of this report.

This test also supports the stable hover requirement (AERO.03) and roll-pitch-yaw requirement (AERO.02). From the flight logs, which are shown below, there are plots for both rotational velocities of the DROVER, alongside GPS latitude and longitude locations. From the rotational velocities plot, there is evidently minor corrections done by the flight controller to maintain hover stability. These minor corrections are done in all three axes, which graphically supports the roll-pitch-yaw capabilities of the DROVER. It also shows that these were all minor corrections with a mean of zero; this coupled with the video of the flight satisfies AERO.02. Additionally, the latitude and longitude graphs show the location of the DROVER during the test. These plots have an incrementation of 0.000001 Degrees, which is roughly 0.11 m. Meaning that for the 15 minute flight the DROVER did not leave a circular diameter of more than 1 m, staying almost exactly in the same position consistently. From the hover video, the rotational velocity graph, and latitude/longitude graphs, it can be concluded that AERO.03 is satisfied.

Schedule:

The test was completed on April 17th, 2025

Test Personnel: Primary POC: Rhys Wallin. Other participants: Elizabeth Beraducci, Kyle Kinkade, Francesca Afruni, Haylee Fiske.

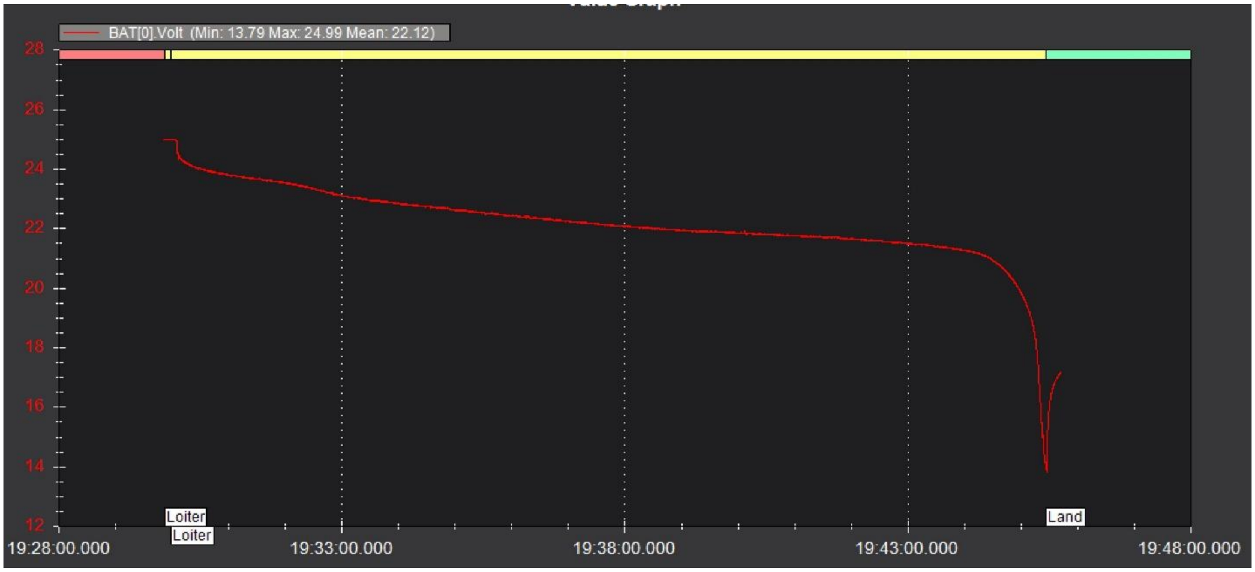


Figure 133: Hover Test Voltage (Voltage vs Time)

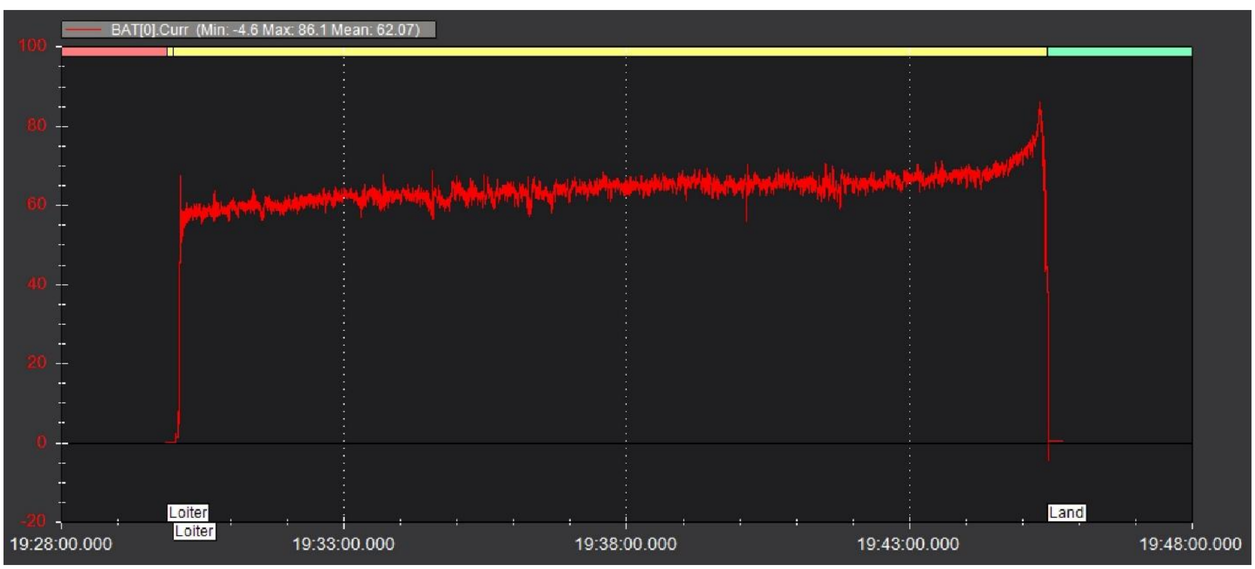


Figure 134: Hover Test Amp Draw (Amps vs Time)

Figure 135: Hover Test Rotational Velocities (Roll-Pitch-Yaw) (Radians/sec vs Time)

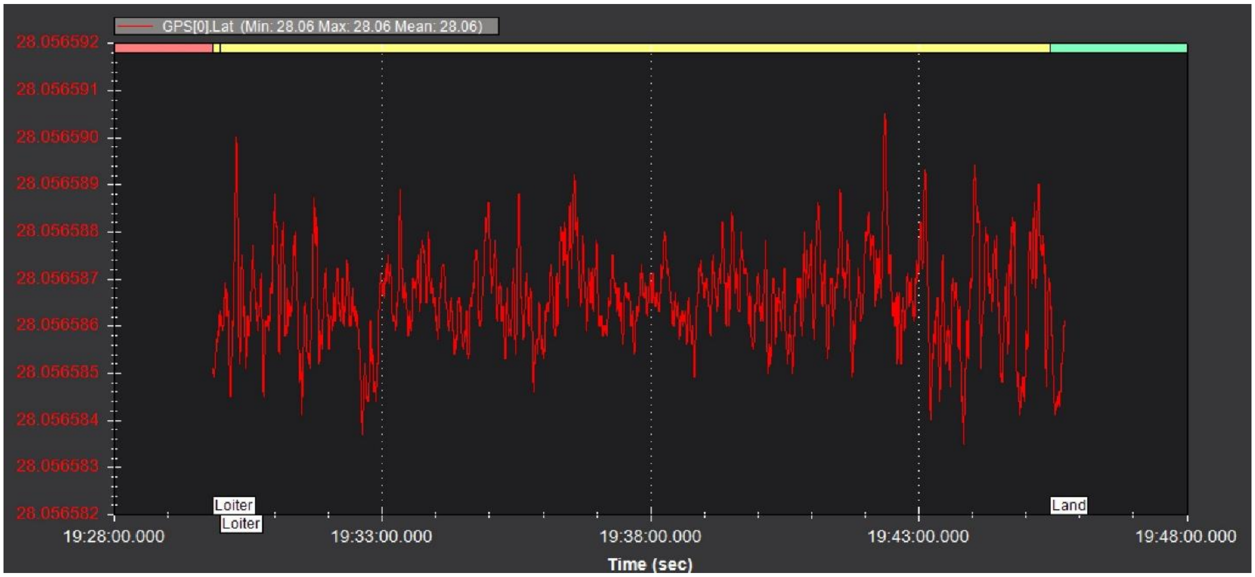


Figure 136: Hover Test Latitude Location (Degrees vs Time)

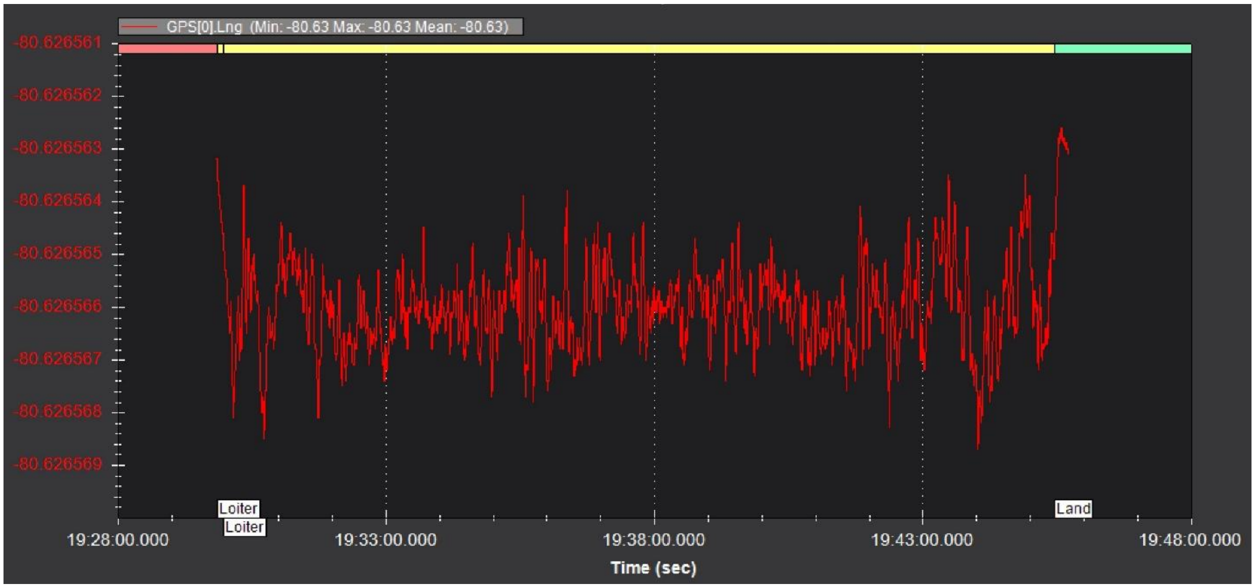


Figure 137: Hover Test Longitude Location (Degrees vs Time)

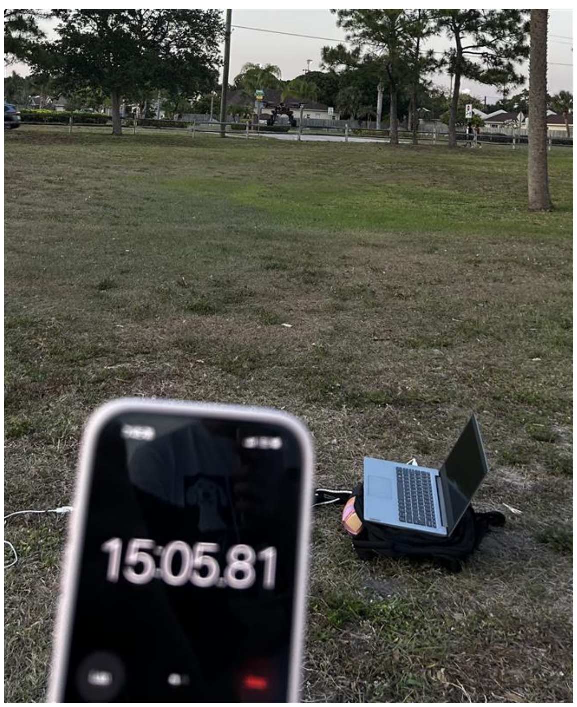


Figure 138: Final Time of Hover Flight

11 Risk Management (Haylee Fiske)

The team has submitted a risk assessment to the HSDC, and the table below includes the associated risks and measures to be taken to minimize them. Further details have also been included to demonstrate the team's ability to maintain safety and ensure that the project will succeed.

Table 22: Risk Management

Risk Type	If...	Then...	Likelihood	Risk Level	Control Measures	New Risk Level
Technical	Propeller Disconnects	Harm the Test Team	Very Low	Med	Wear Correct PPE	Very Low
	Propeller Breaks	Loss of Aerodynamics	Low	Med	Propeller Inspection	Low
	Control is Lost	Harm the Test Team and DROVER	Low	Med	Kill Switch/Fail Safety System	Low
	Battery Fails	DROVER Loses Power	Low	Med	Live Battery Feedback	Low
	Motor Fails	Loss of Propulsion	Low	Med	Inspect Motors Before Flight	Low
	Fabrication without PPE	Harm Fabricator	Low	High	Wear PPE and Complete Safety Classes	Low
	DROVER Lose Control	Crash into Test Team	Very Low	Low	Keep Distance from DROVER	Very Low
Schedule	Late HSDC Ordering	Loss of Fabrication Time	Med	Med	Order Very Early	Low
	Late 3D Printing	Loss of Fabrication Time	Med	Med	Start 3D Printing Early	Low
	Long DROVER Build	Long Fabrication Time	Med	Med	Follow Fabrication Plan and Gantt Chart	Low
Budget	Carbon Fiber Cutting	Failure to Cut Along Fiber Direction	Low	Low	Double Check Fiber Direction Before Cuts	Low
	Carbon Fiber Cutting	Failure to Plan Enough Material for Cuts	Low	Med	Double Check Cutting Area	Med
	Motor Fails	Need Replacement Motors	Low	Med	Motor Inspection	Low

11.1 Team Technical Risks

Propeller Disconnection: This is a hazard that could occur if the propellers are not placed properly. If a propeller disconnects, then it could harm the test team. This risk has a very low likelihood but would be medium in risk as it could harm the test team. To correct this risk, the team will wear PPE, including safety glasses, to have a very low risk.

Propeller Breaks: Alongside disconnection, the propellers are at risk of breaking if not placed right and hit another object. If a propeller breaks, then there is a risk of loss of aerodynamics. The team determined that this risk is of low likelihood due to the outside testing environment will prevent collisions to the propellers. The team also determined that there is a medium risk to the final project to satisfy the needs for aerodynamics. The mitigation plan for this risk is to visually inspect the propellers before flight and keep two extra propellers on hand to maintain a low risk.

Control Loss: This hazard could occur if a connection is lost between the radio controller and the DROVER. If control is lost, then it could harm the test team and DROVER. This risk has a low likelihood but medium risk as it could harm individuals and damage the project. To manage this risk to be low, the team will include a failure safety system within the controls of the DROVER.

Battery Failure: The batteries could fail from using too much power, leading to DROVER powering off. If the batteries fail, then the DROVER will lose power. The likelihood of the batteries failing is low; however, the risk was determined to be medium as the batteries would need to be assessed and possibly recharged to run the system. To mitigate the risk, the ground station will receive live feedback on the level of power that is remaining in the batteries to ensure that the system can run.

Motor Failure: Due to the nature of the project and the high RPM needed to sustain lift, motor failure can occur if there is too much loading on the motors. If the motors fail, then the DROVER will have loss of propulsion. The team determined that this is a low likelihood risk as the motors chosen were rated for the RPM and power that the team is planning on utilizing. There is a medium risk to the project to meet the needs for propulsion. The team is mitigating the risk by inspecting the motors before flight to maintain a low risk.

Failure to Wear PPE: The project contains multiple rotating propellers as well as different saw types during fabrication; therefore, proper PPE is essential for maintaining safety. If team members do not wear PPE, then they may sustain injuries. This risk is low likelihood because there is access to PPE; however, the risk is high as the project must be safe for individuals to use and fabricate. The team has completed proper training courses to have a low risk of injury.

DROVER Lose Control: DROVER is controlled manually by a radio controller, which could lead to improper use or loss of control while flying. If there is a loss of control of DROVER, then DROVER may crash into the test team. This was determined to be a very low likelihood risk and low risk outcome due to the low speeds the team will test at. The team also will maintain a distance from the DROVER while being operated to have a very low risk of crash and injury to the team.

11.2 Team Program Risks: Schedule and Budget

Late HSDC Ordering: The project contains many components that are necessary to achieve the requirements set. If the team does not order parts early enough, then there will be a loss of fabrication time for the project. Both the likelihood and risk were determined to be medium due to the nature of the fabrication process. This will be mitigated to low risk as project components have been ordered early, as noted in the project schedule.

Late 3D Printing: The DROVER fabrication plan contains some components that will be 3D printed to maintain structure and weight. If the team does not 3D print early enough, then the fabrication process will be longer. The team determined this to have a medium likelihood and risk as these components are necessary to the project. The team has submitted the parts for 3D printing early, as mentioned in the project schedule, to have a low risk of lengthened fabrication time.

Long DROVER Fabrication: All the components of DROVER must be put together with specific tools. If the team takes a long time to build the DROVER, then the DROVER may not meet the time frame for designated completion. This risk is medium likelihood and risk due to the number of parts required for the system. However, the team has structured a fabrication plan and schedule to lower this risk.

Carbon Fiber Cutting: The fabrication of the DROVER requires components to be cut from carbon fiber pieces which are a large portion of the project budget. The carbon fiber must also be cut in the fiber direction to maintain the best material properties needed for structural integrity. The team has associated two risks with carbon fiber cutting. If the fabricator fails to cut along the fiber direction, then the component must be cut out again. This was determined to be a low likelihood and risk; however, the fabrication team will be double-checking the fiber directions before making any cuts. If the team failed to plan enough material area for cutting, then more carbon fiber must be ordered. Due to the schedule and budget concerns, the team determined the cutting area to be low likelihood with a medium risk. Therefore, prior to ordering, the area required was calculated, and extra carbon fiber plates were acquired to lower the risk.

Motor Failure: As stated earlier, there is a risk associated with the failure of motors at the RPM and lift the team is wanting to achieve within the project. If motors fail, then there will be a loss of time and budget to get replacement motors. Failure of the motors was determined to have a low likelihood with medium risk to the project. The mitigation measures to lower the risk have already been instilled by including an additional flight motor to the bill of materials to negate the time taken for shipping early in the process.

12 Open Issues / Future Work

12.1 Open Issues (Kyle Kinkade)

The only requirement that is not considered fully compliant with the DROVER is SYS.01 requirement. As mentioned in section 4 of this report, this requirement was not met because the team’s test flight yielded a hover time of just over 15 minutes. This test result is 5 minutes short of the 20-minute hover time goal. The reason for this reduced time is higher amp draw than anticipated during hover operations. The calculations used to support the 20-minute hover are from the amp test, which occurred in ideal conditions and assumed no additional amp draw necessary for stable flight corrections. The team does believe that under better conditions, such as, no wind and improved PID tuning, the hover time would approach closer to 20 minutes but still may not reach it.

However, there are other ways to mitigate this issue in future iterations of the DROVER. The primary ways of mitigation are mass reduction and volume optimization. The best way to reduce the amp draw is to lower the system's total weight. Some weight reductions can occur in the geometry of the DROVER. The team can reduce the system's total weight with more time and a larger focus on utilizing topology optimization from ANSYS. More particularly, some major components that could be reduced include the top carbon fiber plate, the drone arms, the platform bases, and all the onyx rocker-bogie attachments. Figure 117 from the Amp draw test in section 10.1.1.2 shows that reducing the weight of the total system only 400 grams can provide up to a net loss of 8 amps during hover, which is more than 10% of the total hover amp draw (Average of 62 A). More time on structural optimization should yield hundreds of grams. There is also additional hardware optimization, such as utilizing nylon fasteners for lower stress joints. The team believes that at least eight M6 steel fasteners could be swapped with nylon counterparts, further reducing the weight of the system.

Furthermore, a consolidation of all major electronic components (Pixhawk, Arduino, Raspberry PI, motor drivers) would yield more weight reduction. This combination of electronics would likely take a dedicated team, more time, and a larger budget.

Another option to increase the hover time closer to 20-minutes is a different Aerodynamics subsystem design. The aerodynamic subsystem was designed primarily based on three major factors: area (SYS. 08), the motor's amp draw, and the weight of the subsystem. The subsystem design was optimized, completed, and purchased prior to a final geometry change to the drone arms orientation. The updated arm geometry yielded additional available area. This area provides an opportunity for slightly larger propellers. With larger propellers, bigger, but much more efficient motors could also be introduced to the design. Overall, a larger area utilized by the aerodynamic subsystem design would provide a more efficient flight.

One final optimization that would help satisfy the 20-minute hover time is improved battery technology. The batteries chosen by the team are 1/3 of the total DROVER's assembly mass. If the mass of the batteries could be reduced by utilizing higher energy density Li-Ions, the amp draw at hover would drop drastically.

Overall, in a future iteration of the DROVER, there are a number of ways to improve flight efficiency and increase the hover time. With the current design only a few minutes short of the desired 20 minutes, a combination of these options would provide the efficiency necessary and potentially even more.

12.2 Future Work (Francesca Afruni, Marcelo Samaan, Francesco De Luca, Fabrizio Chigne, Haylee Fiske)

- Two-Way Communication

The current state of the two-way communication system can be improved by introducing a cellular hat for the Raspberry Pi to improve communication and replace the current hotspot. Another improvement could be introducing a higher-quality speaker and microphone.

- Retractable/Foldable Flight System

Future development would focus on conceptualizing and prototyping a retractable/foldable flight system for DROVER to enhance its versatility and mobility in missions. Initial efforts would include feasibility studies, materials selection, and mechanical design simulations to ensure reliable deployment and structural integrity.

- Motor Shafts Material

The decision to change the onyx motor shafts was made due to their inability to hold properly the heat brass inserts, as seen in the following figure.

Figure 139: Onyx shaft with brass heat insert

Consequently, polycarbonate shafts were used instead, as they were able to hold the heat brass inserts consistently, and their reliability was proven after multiple driving tests. Nevertheless, the polycarbonate shafts cracked easily, and multiple broke during a harsh landing (Figure 140).

Figure 140:Broken Polycarbonate Shafts

Therefore, for future iterations of this project, aluminum or steel shafts should be used, without the need for brass heat inserts. The bolts can be attached by directly adding threading into the metal. These shafts, although heavier, should ensure that shafts stay in place even during crashes or hard landings.

This improvement mainly supports and improves the verification of SYS 02 (The DROVER shall be capable to drive in a straight line and turn), which parents STR.03 (DROVER shall have a suspension system)

- Wheels Friction, Turning, and Alignment

To verify CTRL 06 and achieve turning capabilities, DROVER uses the friction of the wheels to generate torques about its center of gravity. Therefore, to turn right, the left side wheels of the DROVER will drive while the right side remains unmoved. These coupled torques proved effective in achieving turning. Nevertheless, the unmoved wheels experience excessive friction, which not only wears down the wheel but also detaches the tire from the rim, as seen in the following picture.

Figure 141: Wheels after zero-point turning

Therefore, adding steering capabilities would completely mitigate this issue. Steering could be achieved by adding servo motors and an extra pin connection at the motor mounts before the driving motors.

Nevertheless, steering capabilities would not be as effective due to the fact that the back wheels are not aligned with the front wheels, meaning there would be different turning radiuses. Consequently, alignment between all wheels shall be required which can be done by modifying and extending the main rocker-bogie attachment in the following way with the necessary geometry.

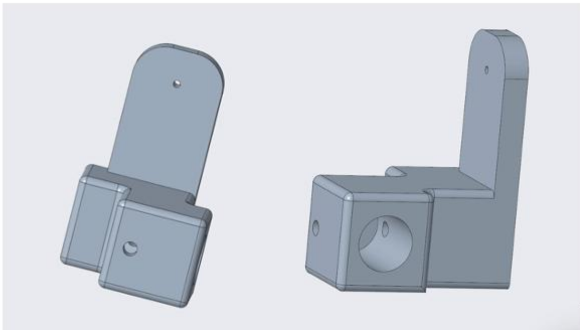
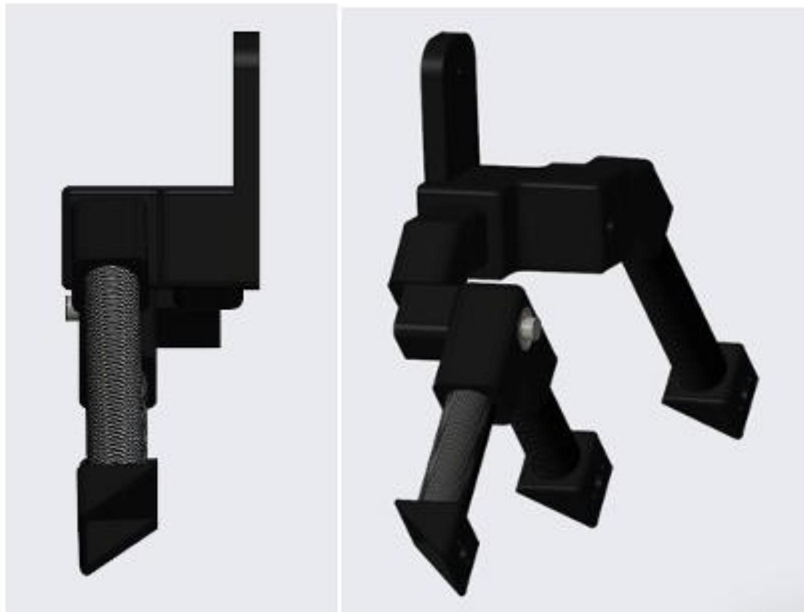


Figure 142: Main attachment modification for complete alignment

Therefore, with this attachment all rocker-bogie wheels are perfectly aligned with each other, as seen in the following figure.



Furthermore, this alignment should slightly improve the weight distribution as now there is more symmetry in the DROVER.

- Climbing angle improvements

The rocker-bogie design has a 45-degree angle between the carbon fiber rod and the normal contact force on the ground.

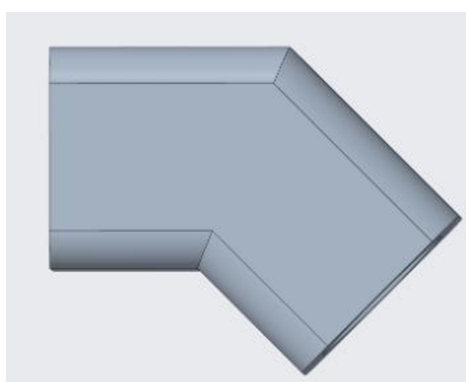


Figure 143: 45-degree rocker attachment

Nevertheless, an increase in this angle could improve the climbing capabilities of the DROVER. An increase of the angle from 45 degrees to 55 degrees looks at the rocker onyx attachment in the following way.

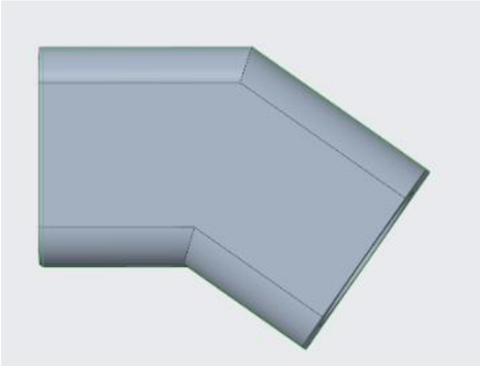


Figure 144: 55-degree angle attachment

The reason is that by maintaining the same DROVER height and increasing these attachment angles, thus requiring longer carbon fiber rods, the torques generated about the pivot points increase, making it easier to lift the wheels for both rockers and bogies. This reasoning can be observed in the following figure.

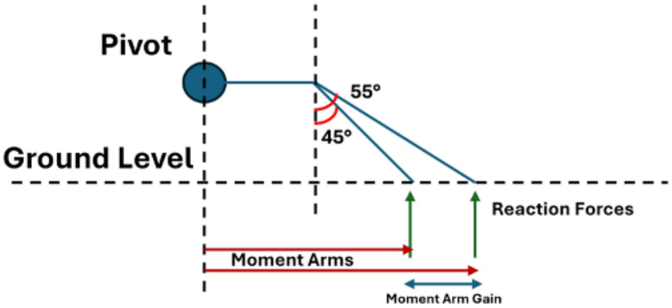


Figure 145: Moment arm gain by increasing angle

The same reasoning is applicable to the bogies, and it can be done by modifying the bogie attachment.

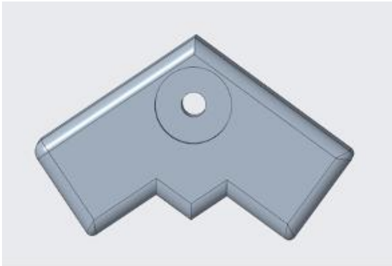


Figure 146: Bogie Attachment with 55-degree angle

Therefore, the new rocker-bogie leg structure would look as follows.

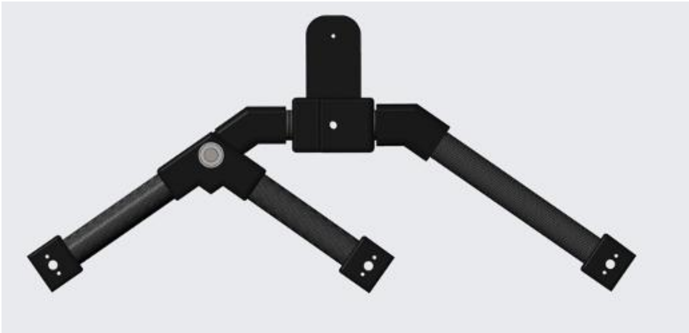


Figure 147: Rocker-Bogie Leg design with increased attachment angles

The trade-off with this climbing improvement is manageable, as the drone capabilities should still be able to perform effectively even with slightly longer and heavier legs. This improvement supports STR 03 as the suspension system's ability to climb obstacles properly should be enhanced.

- Structural Improvements

After the DROVER crash after one of the hover tests, multiple PLA parts of the main body broke. These were the plate supports and the electronics plates.

Figure 148: Broken Plate Support

As seen in the picture above the plate supports broke at the bolt's connection. To counteract the possibility of breaking again, the following structural addition should be implemented.

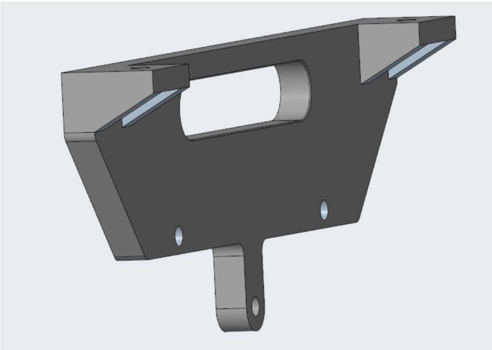


Figure 149: Triangular Structures at Plate Supports

This triangular structure helps during bending and should provide increased stiffness, thus impeding the plate support of breaking easily during harsh landings.

On the other hand, the PLA electronics plate bent easily due to its relatively low thickness which proved enough to hold the two batteries but broke during the abrupt landing. The solution to this problem is to replace it with a carbon fiber plate.

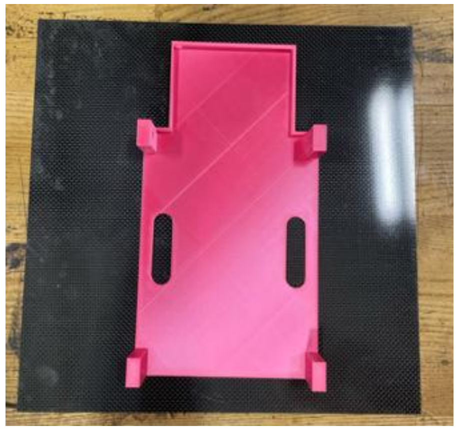


Figure 150: Area comparison of Electronics Plate and acquired Carbon Fiber plate

To connect the carbon fiber plate to the DROVER, the following modification can be done to the plate supports design.

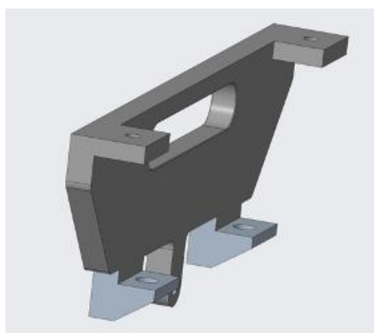


Figure 151: New plate support for new electronics plate

The carbon fiber plate would be attached in the following way to the plate supports with the use bolts and by using the waterjet to cut holes into the carbon fiber plate.

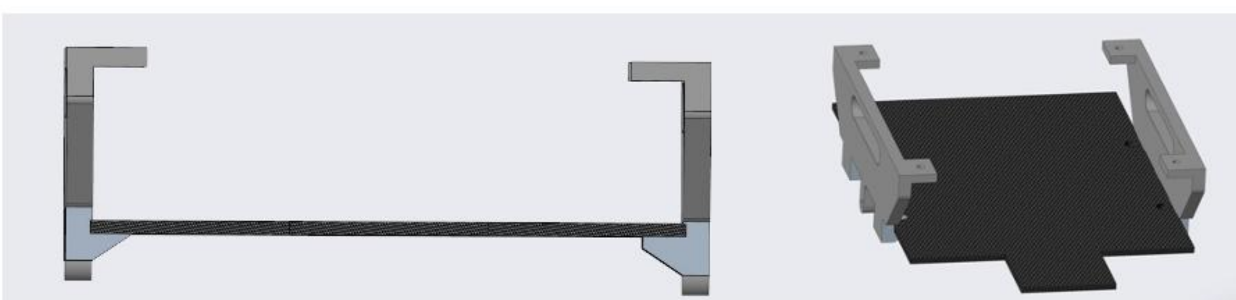


Figure 152: Carbon Fiber Plate and supports

- Protective electronic casing: Canopy design

During the initial driving and flying tests that were performed, the team observed firsthand how unprotected electronics such as the PCB, ESC and wires could be compromised by the environment in which the hybrid operates. While running the first flight test on a grassy terrain, the airflow generated by the four propellers lifted dust, small rocks, and leaves that started to build up on components and endangered the completion of the test.

For the DROVER to be ready for production, the hybrid cannot present unprotected electronics, therefore, the team has designed a CAD model which serves as a preliminary protective case against flying debris.

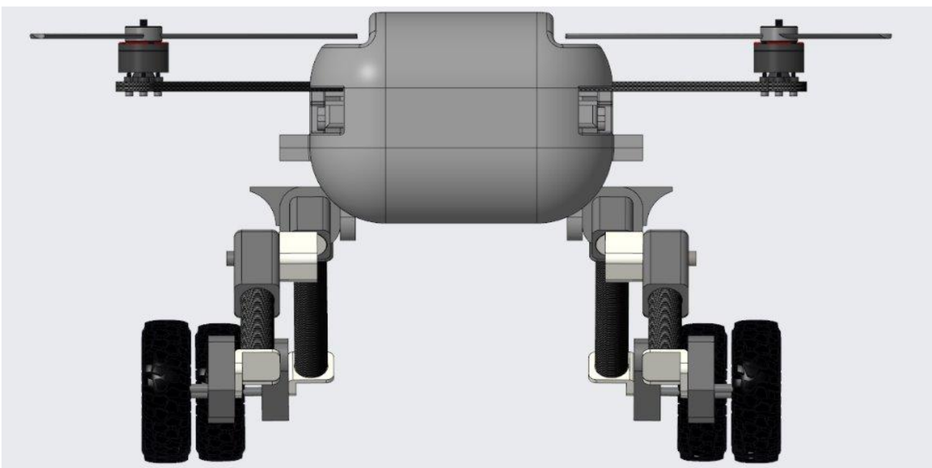


Figure 153: First iteration of the Canopy

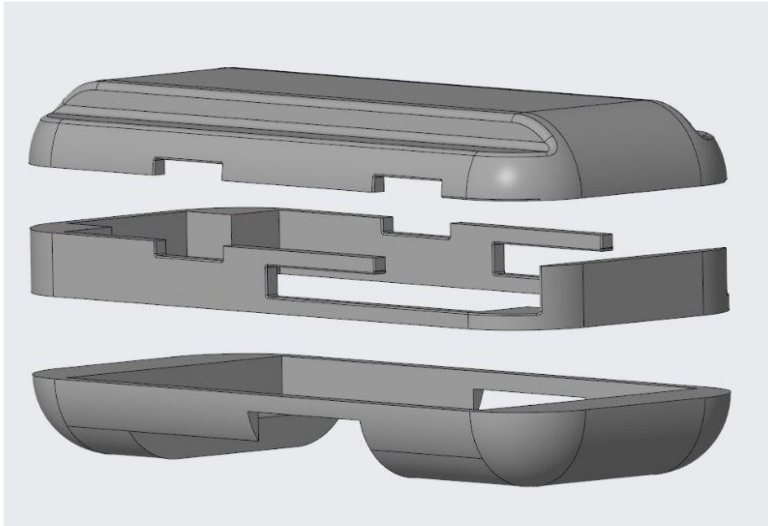


Figure 154: Canopy's CAD model

The first CAD iteration of the canopy focused on creating a lightweight, modular shell. This shell was molded using a Thermal Vacuum Former around the 3-D printed CAD design using two sheets of Thermoplastic Polyurethane (TPU). The team suggests that the refinement of the canopy is future work as the team was not able to test this protection in real flying/driving situations and as the shape of the canopy's geometry can be later improved for better aerodynamic properties.

- Protective Electronic Casing: Driving Motor Caps and Wiring

Another aspect of protecting electronics is the driving motors. These had exposed wires that could potentially be pulled off, touch another metal object, or come into contact with a person. To protect both the electrical system and a person interacting with DROVER, these motor caps would provide a guard around the exposed wire. Alongside this issue is the wiring of the driving system with the wires traveling along the outside of the legs. The team ultimately decided to tape down the wires to prevent detaching and tangles within the system; however, a future design iteration could include ports at the end of the legs to encase the wires inside the current tube design.

- Propeller Guards

One important area for future development is the integration of propeller guards into the DROVER system. These components play a critical role in ensuring operational safety, particularly in close-proximity environments, such as urban search and rescue scenarios where the vehicle may encounter debris, narrow passages, or human presence.

Early in the design phase, a set of propeller guards were designed in CAD (See Figure 155 and Figure 156), tailored to the specific geometry and size constraints. However, due to strict mass limitations and the need to prioritize more critical subsystems such as the driving system and electronics, propeller guards were excluded from the final prototype.

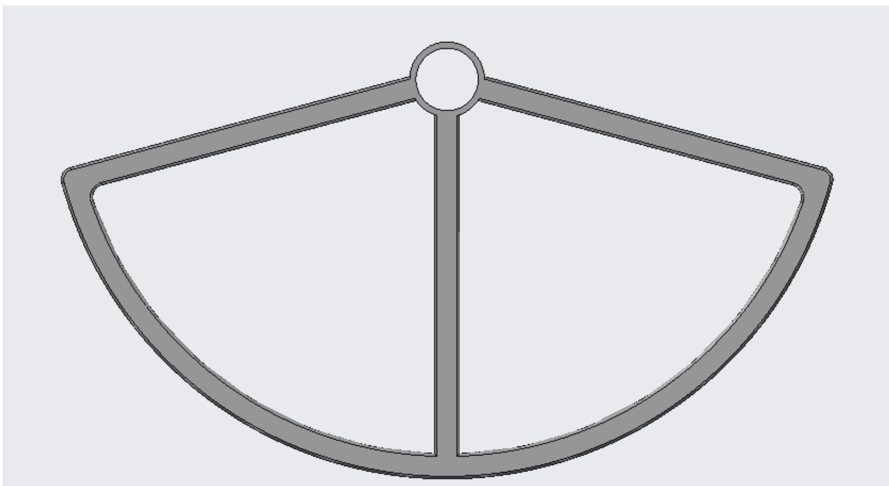


Figure 155: Propeller Guard's CAD model

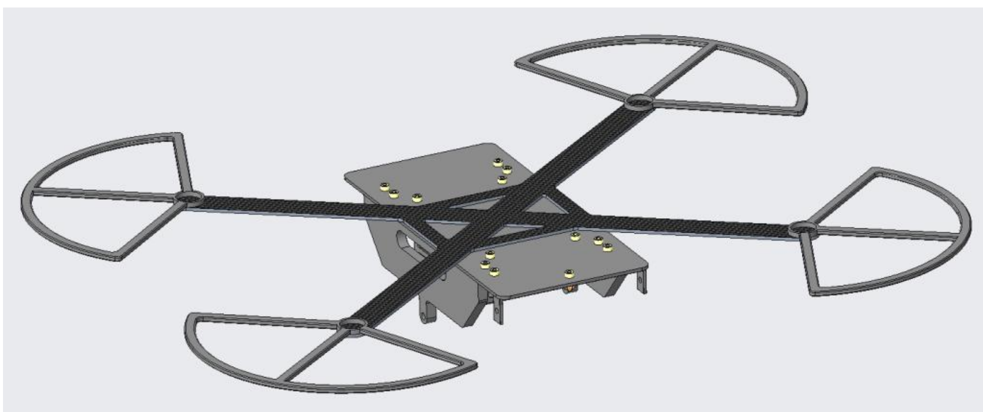


Figure 156: First Drone Structure CAD model

Figure 157: Add-on Drone Cage [71]

Figure 158: Initial CAD Draft for "drone cage" concept

Despite their omission in the current build, the inclusion of propeller guards remains essential for making DROVER industry ready. Therefore, the team researched some concepts, and a first CAD model was designed. Nevertheless, the materials, geometry, and other parameters have not been determined (See Figure 157 and Figure 158).

Propeller guards would significantly enhance user safety, equipment durability, and mission reliability, especially during takeoff and landing in unstructured environments. Future iterations of DROVER should revisit lightweight materials and optimized geometries to reintegrate propeller guards without compromising the vehicle's flight performance.

13 Conclusions and Plans for Forward Work (Francesca Afruni)

In conclusion, Project DROVER was completed successfully, marking an important step forward in developing hybrid drone-rover technologies, especially for search and rescue operations.

By integrating aerial and terrestrial mobility, the team has achieved a dual-mode vehicle that is capable of adapting to various terrains and scenarios. DROVER was designed, fabricated, and tested in accordance with engineering standards, and most system requirements were fully met, with only minor shortfalls, such as in hover time, addressed through documentation and analysis.

Ultimately, Project DROVER sets a foundation for versatile unmanned vehicles that can aid in humanitarian missions, environmental monitoring, military reconnaissance, and more. The team's work meets the goals of the 2024-2025 Senior Design Capstone at Florida Tech while also contributing to the growing field of hybrid systems.

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15 APPENDIX TRADE STUDIES AND ALTERNATIVES CONSIDERED AT CDR

Appendix I: Material Trade Studies (Fabrizio Chigne)

Table 23: Drone Plate Material Trade Study

Drone Plate		Concept Alternatives					
		Aluminum 6061		Carbon Fiber		Onyx	
Criteria	Importance Weight %	Rating	Weighted Rating	Rating	Weighted Rating	Rating	Weighted Rating
Cost	20%	3	0.6	1	0.2	4	0.8
Weight	25%	1	0.25	3	0.75	4	1
Strength	35%	3	1.05	4	1.4	0	0
Manufacturability	15%	3	0.45	2	0.3	4	0.6
Repairability	5%	3	0.15	2	0.1	4	0.2
Totals	100%		**2.5**		**2.75**		**2.6**

The table above shows the trade study performed to determine the material for the drone quadcopter plate. The options were aluminum 6061, carbon fiber, and onyx. Carbon fiber was selected due to its strength, and since it is where the loads are going to be applied it was the better choice for this component.

For the rest of the parts of the drone structure, another trade study was conducted. In this case, onyx won the trade study since it is a durable and lightweight material.

Table 24: Attachment Parts Material Trade Study

Propeller Guards & Attachment Parts		Concept Alternatives					
		Aluminum 6061		Carbon Fiber		Onyx	
Criteria	Importance Weight %	Rating	Weighted Rating	Rating	Weighted Rating	Rating	Weighted Rating
Cost	25%	3	0.75	2	0.5	4	1
Weight	30%	1	0.3	3	0.9	4	1.2
Strength	20%	3	0.6	4	0.8	1	0.2
Manufacturability	20%	3	0.6	3	0.6	4	0.8
Repairibility	5%	3	0.15	2	0.1	4	0.2
Totals	100%		**2.4**		**2.9**		**3.4**

Appendix II: Suspension System Complete Trade Study (Marcelo Samaan)

The alternatives considered were the following:

- **Rocker-Bogie Suspension**
- **Tracked Vehicle Suspension**
- **Torsion Bar Suspension**
- **Independent (Spring) Suspension**

These alternatives were compared using a Pugh Matrix considering the following factors:

- **Weight:** Crucial for the DROVER as it directly affects the lift required. More weight also affects energy efficiency as more power will be required to operate the suspension system.
- **Speed:** Higher speeds will be beneficial for search and rescue operations.
- **Climbing Capability:** How well the suspension system can climb over obstacles.
- **Terrain Adaptability**: How well the suspension system performs on various challenging terrains, such as slopes, mud, rocky surfaces, and other rough conditions.
- **Complexity:** How complex the suspension system will be in terms of manufacturing and design.
- **Cost:** Cost of parts and manufacturing.

1. Rocker-Bogie Suspension

Mechanism that enables a six-wheeled vehicle to keep all six wheels in contact with uneven terrain, providing superior stability and obstacle-climbing capability [43] and maintains a substantially constant weight, and therefore traction, on all wheels. This is possible due to a differential bar that connects the movements of both main legs of a rover, and thus the force experienced by one front wheel is transferred to the opposite front leg. The mechanism consists of six wheels, rockers (front bigger legs), bogies (smaller legs with two wheels), and a differential bar. Historically used at slow speeds to minimize dynamic shocks and fatigue [44].

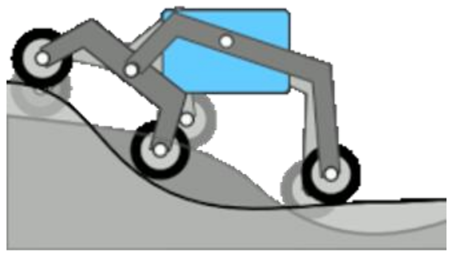

Figure 159: Rocker-Bogie Suspension [42]

Table 28: Rocker-Boogie Suspension Pros and Cons

Advantages	Disadvantages
Grants extremely high stability	Low speeds
Capable of climbing over tall obstacles	Heavier design
Possible to manufacture with campus resources	Requires 6 wheels and 6 motors
Not expensive to build	Requires precise geometry
Can be fabricated in the machine shop	Design complexity is high
Favored by NASA	Center of gravity and pivot points considerations
Precise balance with correct pivot points	

2. Tracked Vehicle Suspension

Tracked vehicles offer a versatile platform that is required to operate over diverse terrains, including extremely difficult ground. Moving a tracked vehicle takes more force due to their larger size [45]. Tracks have an increased surface area, providing better traction on soft or hard terrains, where wheels could potentially get bogged down [45].

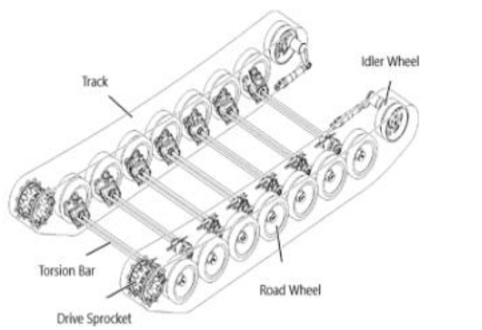

Figure 160: Tracked Suspension [45]

Table 29: Tracked Suspension Pros and Cons

Advantages	Disadvantages
High traction due to increased surface	Very high weight due to tracks
Can navigate effectively through different terrains	Complex Design
Stable and can go over small obstacles	Potentially expensive due to components that the team must buy. (Material for large track, and shock absorbers)

3. Torsion Bar Suspension

Suspension that uses a torsion bar as its main weight-bearing spring. Suspension consists of a long metal bar with one end attached firmly to the vehicle chassis and the opposite end terminating in a lever connected to the wheel [46]. Therefore, when the wheel moves up or down it causes the bar to twist around its axis which is resisted by the bar's torsional resistance producing elastic deformation [46].

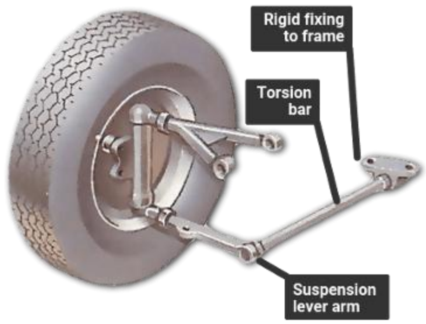

Figure 161: Torsion Bar Suspension [52]

Table 30: Torsional Bar Suspension Pros and Cons

Advantages	Disadvantages
Can navigate effectively through rough terrains. (Independent Suspension makes wheels move up or down independently)	Cannot climb over tall obstacles
Moderately easy to design and perform analytical calculations (Beam twist angle calculations under torsional load)	High Volume (Torsional bars might be long and difficult to place properly within a design)

4. Independent (Spring) Suspension

Coiled suspension system. Many design alternatives are used in RC cars and vehicles like Double Wishbone MacPherson Strut. Design can be simplified to our needs. As it is independent, each wheel would move up or down independently.

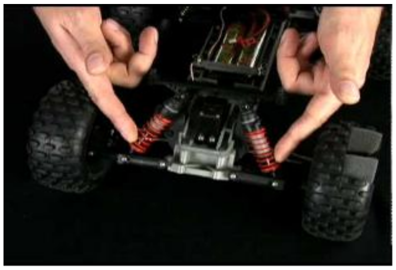

Figure 162: Independent Spring Suspension [52]

Table 31: Independent Suspension Pros and Cons

Advantages	Disadvantages
No high complexity in design. (Simple RC car designs can be followed).	Independent suspension cannot climb over tall obstacles effectively
Low Cost	Springs might struggle in rough terrains
Low Weight (Only four wheels, springs are lightweight)	

The Pugh matrix evaluating the four alternatives is the following.

Pugh Matrix

Concept Selection Legend

Better	+
Same	S
Worse	-

Key Criteria	*Importance Rating*	Rocker-Bogie	Tracked Suspension	Torsion Bar	Independent Suspension	No Suspension
Weight	8		-	S	+	+
Speed	4		S	+	+	-
Obstacle Climbing Capabilities	10		-	-	-	-
Terrain Adaptability	7		+	-	-	-
Complexity	5		S	+	+	+
Cost	6		-	-	S	+
Sum of Positives			1	2	3	3
Sum of Negatives			3	3	2	3
Sum of Sames			2	1	1	0
Weighted Sum of Positives			7	9	17	19
Weighted Sum of Negatives			24	23	17	21
TOTALS			**-17**	**-14**	**0**	**-2**

Figure 163: Suspension Pugh Matrix

As observed, both the rocker-bogie suspension and independent suspension were good alternatives for the DROVER design. Nevertheless, the **rocker-bogie suspension was chosen** as the design of the suspension system due to its overall better climbing capabilities, and as its complexity should be, although higher, manageable.

Appendix III: Leg Shape Trade Study (Marcelo Samaan)

As the decision to use carbon fiber had already been made, the only important design decision left was that of the shape of the legs: either cylindrical tubes or rectangular beams. The rockers and bogies (the leg's main components) will handle two different types of loads.

- Bending Loads: Normal reaction from the weight of the rover (distributed among the 6 wheels). This load will increase while the rover climbs obstacles and tilts or due to landing impact loads.
- Torsional Loads: Coming from the wheel and leg attachment, as there is a distance generating a moment arm between the point of contact of the wheel and the position of the leg. These might increase when landing loads are taken into consideration.

Trade Study Criteria:

- Shape properties: bending loads, torsional loads, fatigue, and stress concentrations.
- Weight
- Cost
- Complexity of design

Tensile Strength: Both options have equal maximum strength.

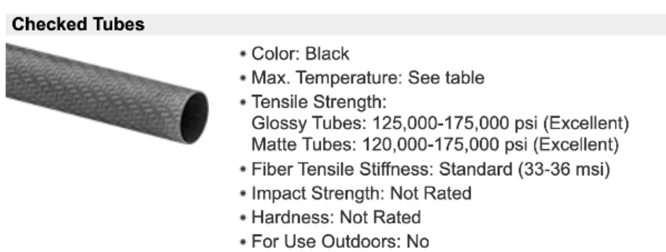

Figure 164: Cylindrical Tube Tensile Strength [24]

Figure 165: Rectangular Beam Tensile Strength [24]

Moment and Force Determination:

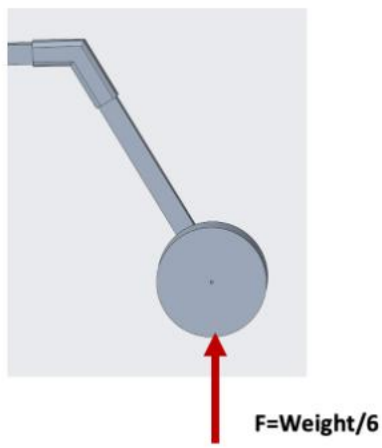

Figure 166: Force applied at wheels due to weight

Each wheel will transmit to the rocker a force equal to the total weight of the rover divided by the six wheels. For the purposes of this analysis and to represent higher loads in the calculations, the assumption that the full force creates bending has been applied, and thus ignoring the parallel component of the force as it does not create bending.

$$Moment = \frac{Weight}{6} * L$$

Where L represents the moment arm, and thus the total length of the leg.

Moment of Inertia Calculations

- Rectangular beam:

Outside				Inside		12" Lg.		32" Lg.	
Wd.	Wd. Tolerance	Ht.	Ht. Tolerance	Wd.	Ht.		Each		Each
0.04" Wall Thick. (-0.02" to 0.02")									
0.83"	-0.02" to 0.02"	0.83"	-0.02" to 0.02"	3/4"	3/4"	2040N11	$55.20	2040N12	$139.99

Figure 167: Rectangular Beam Dimensions [24]

Outside Width = 0.83" = 0.021082 m
Outside Height = 0.83" = 0.021082 m
Inside Width = Inside Height = ¾" = 0.01905 m

The following formula calculates the area moment of inertia of the rectangular beam **[25]**

$$I_x = \frac{1}{12} * (B_O Ho^3 - B_I H_I^3)$$

$$I_x = \frac{1}{12} * (0.021082^4 - 0.01905^4)$$

$$\boldsymbol{I_x = 5.4865 * 10^{-9} m^4}$$

- Hollow tube:

0.064" Wall Thickness (-0.005" to 0.005")									
0.378"	-0.008" to 0.008"	1/4"	-0.003" to 0.003"	180°	0°/90°	5287T79	18.23	47.76	86.83
0.503"	-0.008" to 0.008"	3/8"	-0.003" to 0.003"	180°	0°/90°	5287T81	20.97	54.92	99.86
0.628"	-0.008" to 0.008"	1/2"	-0.003" to 0.003"	180°	0°/90°	5287T82	23.70	62.08	112.88
0.878"	-0.008" to 0.008"	3/4"	-0.003" to 0.003"	180°	0°/90°	5287T83	34.65	90.74	164.98
1.128"	-0.008" to 0.008"	1"	-0.003" to 0.003"	180°	0°/90°	5287T84	50.15	131.33	238.79
1.378"	-0.008" to 0.008"	1 1/4"	-0.003" to 0.003"	180°	0°/90°	5287T85	55.61	145.66	264.83
1.628"	-0.01" to 0.01"	1 1/2"	-0.005" to 0.005"	180°	0°/90°	5287T86	67.47	176.71	321.29
1.878"	-0.01" to 0.01"	1 3/4"	-0.005" to 0.005"	180°	0°/90°	5287T87	75.55	197.86	359.74
2.128"	-0.01" to 0.01"	2"	-0.005" to 0.005"	180°	0°/90°	5287T88	81.81	214.26	389.57
2.628"	-0.012" to 0.012"	2 1/2"	-0.005" to 0.005"	180°	0°/90°	5287T89	103.82	271.91	494.38

Figure 168: Hollow tube Dimensions (Highlighted) [24]

Outer Diameter = 0.878" = 0.0223012 m
Inner Diameter = ¾" = 0.01905 m
Wall thickness = 0.064"

The following formula calculates the area moment of inertia of the hollow cylinder [26]

$$I_z = \frac{\pi}{4} * (R_{outer}^4 - R_{inner}^4)$$

$$I_z = \frac{\pi}{4} * ((0.0223012/2)^4 \ - (0.01905/2)^4)$$

$$\boldsymbol{I_z = \ 5.677 * 10^{-9}\ m^4}$$

Bending Stress Calculation

The following formula calculates bending stresses **[25]**

$$\sigma_{max} = \frac{Mc}{I}$$

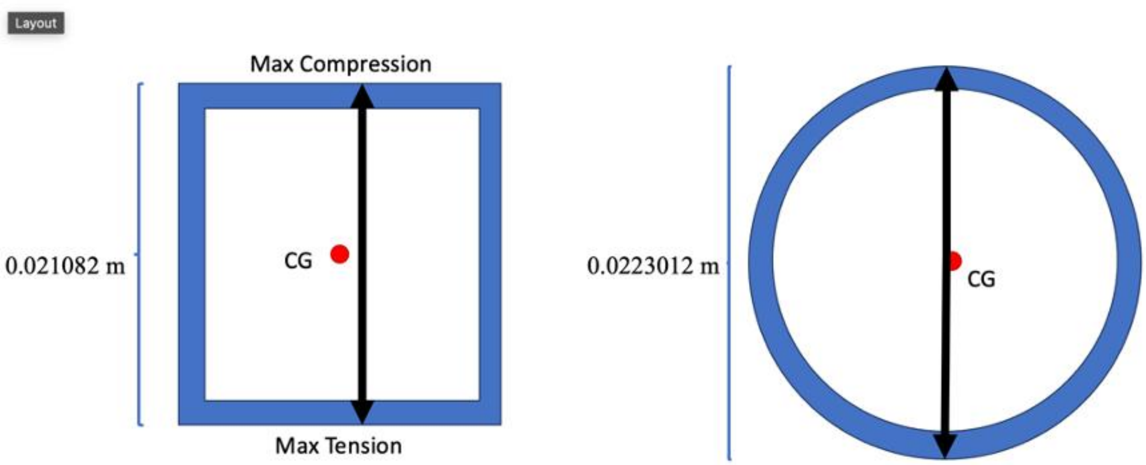

Figure 169: Dimensions and center of gravity of each component

- Rectangular beam:

$$\sigma_{max} = \frac{Weight}{6} * L * \frac{0.010541}{5.4865 * 10^{-9}}$$

$$\boldsymbol{\sigma_{max} = 320210\ W * L}$$

- Hollow Tube:

$$\sigma_{max} = \frac{Weight}{6} * L * \frac{0.0111506}{5.677 * 10^{-9}}$$

$$\boldsymbol{\sigma_{max} = 327361\ W * L}$$

As observed from these results and despite the higher moment of inertia of the hollow tube, the rectangular beam will have lower maximum stresses mainly because of its lower distance from its center of gravity to its maximum tension case.

Yield Strength

The tensile strength for both shapes ranges from 125,000 psi to 175,000 psi [24]. For the purpose of this analysis, the lower value will be considered. 125000 psi = 861844662 Pa
Assuming a total weight of 6 kg (58.86 N).

$$\sigma_{max\,rect.} = 18847561 * L$$
$$\sigma_{max\,tube} = 19268468 * L$$

And considering that L will range from 0.2 to 1 meter as a maximum value. The yield strength value will be one order of magnitude greater than the maximum tensile stresses for both cases.

Fatigue and Stress Concentrations

- Sharper corners in the hollow rectangular beam contribute to high stress concentration factors [27] from where cracks can initiate and propagate. This is a clear disadvantage in the hollow rectangular beam when compared to the hollow tube.
- For the applications of the rover and the constant cycling stresses that it will experience, it is thus crucial to minimize stress concentrations to prolong its useful life.
- It is possible that because of these advantages, NASA's rovers, like Perseverance, use hollow titanium tubing for the legs of the rover [28] and not rectangular beams.

Torsional loads

Torsional loads come from the moment arm created by the distance from the point of contact of the wheel and the leg. This force creates a torque transmitted through the leg and wheel attachment. Although the moment arm is short in length, this torque can create shear stresses.

- Rectangular beam formula [53]:

$$\tau_{avg} = \frac{T}{2t(a-t)^2}$$

Where t is the thickness and a is the outer length of the square.

$$\tau_{avg} = \frac{F * l}{2t(a-t)^2}$$

Torque is generated from the same reaction force from the ground and l is the moment arm.

$$\tau_{avg} = \frac{W/6 * l}{2 * 0.001016 * (0.021082 - 0.001016)^2}$$

$$\tau_{avg} = 203706 * W * l$$

- Hollow tube formula **[29]**:

$$\tau_{max} = \frac{Tc}{J}$$

$$J = \frac{\pi}{4}(D_o^4 - D_i^4)$$

$$J = \frac{\pi}{32}(0.0223012^4 - 0.01905^4)$$

$$J = 1.135 * 10^{-8}$$

$$\tau_{max} = \frac{\frac{W}{6} * l * 0.010541}{1.135 * 10^{-8}}$$

$$\tau_{max} = 154787\, W * l$$

It can be observed that the maximum shear stress for a hollow tube is lower than the average shear stress of a rectangular hollow beam, demonstrating the superior properties of hollow tubing with torsional loads.

Weight

- Rectangular Beam (20 cm long): 25.6 grams
- Hollow Tube (20 cm long): 33.2 grams

Cost

- Rectangular beam: 12” $55.20

- Hollow Tube: 12” $34.65

Complexity of Design

- Rectangular beams, with their flat sides, are easier to use for attachments. Screws and bolts can be easily placed to secure the beam to components such as motors and wheels.
- On the other hand, hollow tubes increase the complexity of the design since screws and bolts are less effective due to reduced contact area. Additionally, attaching motors and wheels becomes more challenging, and might require the use of epoxy to secure components to the beam and multiple attachments.

Pugh Matrix

Figure 170: Carbon Fiber Hollow Tube [24]

Figure 171: Carbon Fiber Rectangular Beam [24]

Pugh Matrix			
		Solution Alternatives	
Concept Selection Legend Better + Same S Worse - Key Criteria	*Importance Rating*	Hollow Tube	Rectangular Beam
Strength Properties	9		-
Weight	5		+
Cost	5		-
Design Complexity	5		+
Sum of Positives			2
Sum of Negatives			2
Sum of Sames			0
Weighted Sum of Positives			10
Weighted Sum of Negatives			14
TOTALS			-4

Figure 172: Legs' shape Pugh Matrix

Consequently, the decision to design the rocker-bogie with hollow cylindrical tubes was made.

<u>Appendix IV: Slope Angle and Friction Calculations (Haylee Fiske)</u>

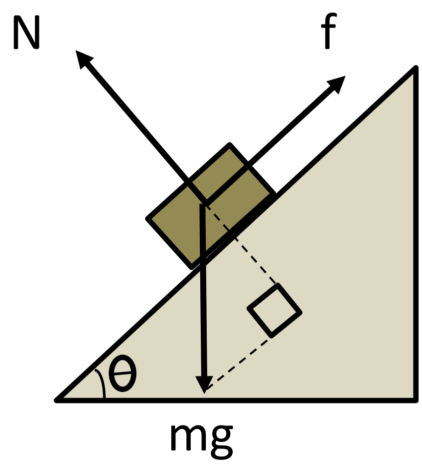

Figure 173: Inclined Slope

Assume static vehicle upon landing

$$f_s = mgsin\theta$$

$$f_s = \mu_s N = \mu_s mgcos\theta$$

$$mgsin\theta = \mu_s mgcos\theta$$

$$\mu_s = tan\theta$$

$$\theta = \tan^{-1}(\mu_s)$$

$\mu_s = 0.54$ for Oak on Oak [48]

$$\theta = \tan^{-1}(0.5) = 28.37°$$

$\mu_s = 0.5$ for Rubber on Cardboard [49]

$$\theta = \tan^{-1}(0.5) = 26.6°$$

$\mu_s = 1$ for Tire on a Dry Road [49]

$$\theta = \tan^{-1}(1) = 45°$$

Appendix V: Control System Trade Studies (Rhys Wallin, Haylee Fiske, Elizabeth Beraducci)

Table 24: Flight Controller Choice and Trade Study

Flight Controler		Concept Alternatives							
		CAUV V5 Nano		Pixhawk 6C Mini		Pixhawk 4		CUAV Nora	
Criteria	Importance Weight %	Rating	Weighted Rating	Rating	Weighted Rating	Rating	Weighted Rating	Rating	Weighted Rating
Number of PWM I/O	30%	4	1.2	1	0.3	1	0.3	4	1.2
Weight	20%	3	0.6	3	0.6	4	0.8	2	0.4
Cost	35%	3	1.05	3	1.05	4	1.4	1	0.35
Dimensions	10%	4	0.4	3	0.3	2	0.2	2	0.2
Built in Sensors	5%	4	0.2	3	0.15	3	0.15	4	0.2
Totals	100%		3.45		2.4		2.85		2.35

Shown above is the trade study done for the flight controller that was going to be used for the project to control the drone systems. The categories that the team was focused on were the number of PWM ports, weight, and cost. The team was aiming to have over 10 PWM ports in order to control the rover portion of the project with the flight controller as well. As shown above, the CAUV V5 nano and the CUAV Nora had the same rating as far as that was concerned, so price was the deciding factor.

Although this flight controller would have worked for the project it was nearly $200. Instead of making this choice, the team decided to go with a Pixhawk 6x that was provided to the team by the HSDC. This meant that the team had a more reliable and powerful flight controller to do the job the team needed done, and it saved the team money. This flight controller does only have 8 PWM ports so the DROVER will use a separate microcontroller that accepts some of the outputs from the radio controller to control the rover portion of the vehicle.

Figure 174: Pixhawk 6x Flight Controller [40]

Battery Choice & Trade Study.

To fulfill SYS.01 requirement, the team estimated that a 6S 15000 mAh should provide enough power for the DROVER to achieve 20 minutes of hover time, assuming the mass stays about 6 kg.

Table 25: Battery Choice and Trade Study

Batteries		Batteries							
		6S 13000 mAh		6S 7500 mAh (x2 Set)		6S 16000 mAh		6S 7200 mAh (x2 Set)	
Criteria	Importance Weight %	Rating	Weighted Rating	Rating	Weighted Rating	Rating	Weighted Rating	Rating	Weighted Rating
mAh	40%	1	0.4	3	1.2	4	1.6	2	0.8
Cost	15%	3	0.45	2	0.3	3	0.45	4	0.6
Weight	30%	4	1.2	4	1.2	2	0.6	4	1.2
C-Rating	5%	2	0.1	4	0.2	2	0.1	3	0.15
Volts	10%	3	0.3	4	0.4	3	0.3	3	0.3
Totals	100%		2.45		3.3		3.05		3.05

The trade study prioritized mAh rating since this is the key criteria to allow the DROVER to achieve 20 minutes of flight time. Below this, weight had the second greatest weighting to ensure the total weight of the DROVER stays about 6 kg. The cost had the third greatest weighting to ensure the team stayed within the allocated budget. By completing this weighted matrix, the team decided to choose a set of two 6S 7500 mAh batteries, which will be connected in parallel as this choice has a high mAh rating while also maintaining a good balance between cost and weight.

Figure 175: Zeee 6S 7500 mAh Battery [19]

The team will purchase two of these batteries, which will cost a total of $231.18 while adding 1608g total mass. These batteries will be connected in parallel so that the total mAh rating equals 15000, which should allow the DROVER to achieve 20 minutes of hover to verify the SYS.01 requirement.

Appendix VI: Rocker-Bogie Materials (Kyle Kinkade, Fabrizio Chigne, Marcelo Samaan Samaan)

Table 26: Materials Trade Study for Rocker-Bogie Suspension

Rocker Bogie		Concept Alternatives					
		Aluminum 6061		Carbon Fiber		Onyx	
Criteria	Importance Weight %	Rating	Weighted Rating	Rating	Weighted Rating	Rating	Weighted Rating
Cost	25%	3	0.75	2	0.5	4	1
Weight	30%	1	0.3	3	0.9	4	1.2
Strength	20%	3	0.6	4	0.8	1	0.2
Maneufacturability	20%	3	0.6	3	0.6	4	0.8
Repairibility	5%	3	0.15	2	0.1	4	0.2
Totals	100%		**2.4**		**2.9**		**3.4**

From this trade study, the decision to use carbon fiber and onyx was made. Although onyx won the overall trade study, both materials will be used for different parts of the rocker-bogie to take advantage of their different properties. The manufacturability of 3D printing onyx makes it ideal for designing components with complex shapes like assembly attachments. On the other hand, the strength of carbon fiber is ideal for the rockers and bogies, which will handle most of the operating loads.

Appendix VII: Weight Distribution Test (Marcelo Samaan)

The weight distribution test consisted of placing a scale underneath each wheel when all six wheels are on the same level. This test did not have the purpose of knowing exactly what the weight under each wheel was going to be, as the prototype did not have all the components and thus the real weight of the DROVER. Therefore, this test was conducted to grasp the weight distribution of the assembly with the two batteries in place in order to detect if there were relevant anomalies in the weight distribution.

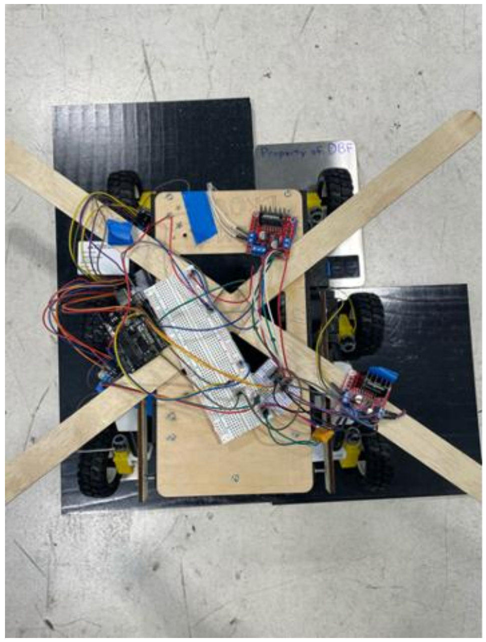

Figure 176: Test Setup (Prototype tested contained the carbon fiber drone structure, not the prototype in this figure)

Because of inaccuracies in the scale, the weight under each wheel was measured several times, and an average was taken. The test results are shown below.

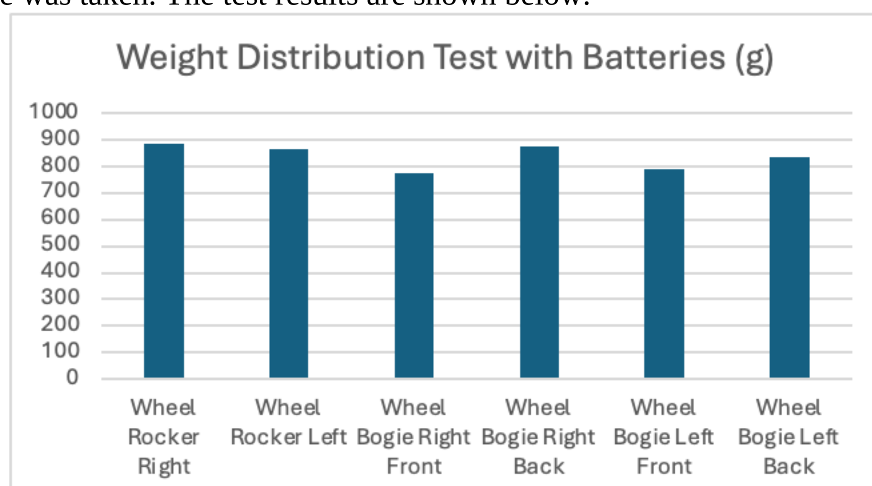

Figure 177: Weight Distribution Test Results

The total weight of the DROVER assembly was of 4900 grams, whereas the total calculated from this graph was of 5005 grams, and thus an error of 105 grams, a percent error of less than 3%. Consequently, it is possible to affirm that there are no major weight distribution concerns in this design. Nevertheless, due to the difficulty in operating the scale in this test to get measurements, driving tests will also be performed to ensure that proper traction in each wheel is accomplished.

Appendix VIII: Aerodynamics Trade Studies (Francesca Afruni, Kyle Kinkade)

Table 27: Motor Trade Study

Motors		Concept Alternatives					
		GEPRC SPEEDX2		T-Motor V3115		T-Motor V3120	
Criteria	Importance Weight %	Rating	Weighted Rating	Rating	Weighted Rating	Rating	Weighted Rating
Weight	10%	2	0.2	3	0.3	2	0.2
Cost	20%	2	0.4	2	0.4	2	0.4
Max Thrust	40%	4	1.6	2	0.8	3	1.2
Amp Output	30%	1	0.3	3	0.9	4	1.2
Totals	100%		**2.5**		**2.4**		**3**

Rotorcraft Type - Pugh Matrix

Concept Selection Legend	
Better	+
Same	S
Worse	-

		Solution Alternatives	
Key Criteria	***Importance Rating***	Quadcopter	Hexacopter
Weight	**5**		-
Thrust	**4**		+
Cost	**3**		-
Complexity of Design	**1**		-
Size	**3**		-
Sum of Positives			1
Sum of Negatives			4
Sum of Sames			0
Weighted Sum of Positives			4
Weighted Sum of Negatives			12
TOTALS			-8

Appendix IX: DROVER Estimated Total Operating Time (Marcelo Samaan)

It is possible to approximate the total life of the DROVER with some mathematical calculations. However, these calculations have to take into account that DROVER is a hybrid and as such it consumes different amount of powers depending if it's in rover or drone mode.

Table 28: Power Consumption of Different Modes

Mode	Load (W)
Drive	18.05
Hover	937.87

The total battery capacity is of 355.2 Wh. The following formulas help estimate the total operating time of the DROVER, where t is the variable for time, E for energy in Wh, and P for power in W.

$$t_{total} = t_{drone} + t_{rover}$$

$$E_{Battery} = P_{drone} * t_{drone} + P_{rover} * t_{rover}$$

$$t_{total} = \frac{E_{Battery}}{P_{drone} * \frac{t_{drone}}{t_{total}} + P_{rover} * \frac{t_{rover}}{t_{total}}}$$

By having ratios of time in rover and time in drone modes with respect to the total time, it's possible to assign percentages to these values and proceed with the calculations. The following table contains the estimated total operating life of the DROVER when different percentages at each mode are considered.

Table 29: Total Operating Time of DROVER

Drone Time %	Rover Time %	Drone Operating Time (h)	Rover Operating Time (h)	Total Operating Time (h)
0%	100%	0.00	19.68	**19.68**

5%	95%	0.28	5.27	5.55
7%	93%	0.30	4.01	4.31
10%	90%	0.32	2.91	3.23
20%	80%	0.35	1.41	1.76
30%	70%	0.36	0.85	1.21
40%	60%	0.37	0.55	0.92
50%	50%	0.37	0.37	0.74
60%	40%	0.37	0.25	0.62
70%	30%	0.38	0.16	0.54
80%	20%	0.38	0.09	0.47
90%	10%	0.38	0.04	0.42
100%	0%	**0.38**	0.00	0.38

The following graph plots the total operating time vs the time percentage spent in drone mode

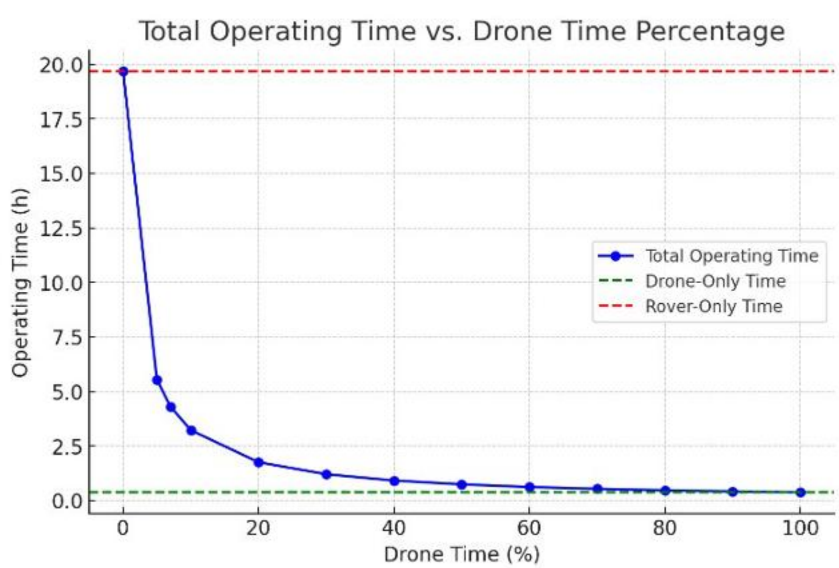

Figure 178: Plot of Operating Time vs. Drone Time Percentage

Consequently, it is possible to observe how the operating life is dominated by the drone mode which consumes much more power than the driving mode. However, it is possible to observe that the benefits of the driving mode, and thus the hybrid, start gaining relevance when the driving mode is used for 50% or more of the total operating time.