University of Colorado
Department of Aerospace Engineering Sciences
ASEN 4028

Project Final Report (PFR)

# Autonomous Rover for Ground-based Optical Surveillance (ARGOS)

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## 2.1 Project Customer and Project Advisor



| Project Customer | | Project Advisor | |
|---|---|---|---|
| Name: | Barbara Streiffert | Name: | Dr. Donna Gerren |
| Email: | barbara.streiffert@jpl.nasa.gov | Email: | Donna.Gerren@colorado.edu |



## 2.2 Team Members



| | |
|---|---|
| Name: Niko de Boucaud<br>Email:Nikolai.deBoucaud@colorado.edu<br>Phone: (858)232-6568 | Name: Margaux McFarland<br>Email: Margaux.Mcfarland@Colorado.edu<br>Phone: (303)803-4406 |
| Name: Henry Felstiner<br>Email: Henry.Felstiner@colorado.edu<br>Phone: (310)310-9139 | Name: N. Thomas Noll<br>Email: neno1328@colorado.edu<br>Phone: (970)443-4127 |
| Name: Harrison Fitch<br>Email: Harrison.Fitch@colorado.edu<br>Phone: (626)664-6751 | Name: Trevor Slack<br>Email: Trevor.Slack@colorado.edu<br>Phone: (415)419-6747 |
| Name: Victoria Gonzales<br>Email: Victoria.Gonzales@colorado.edu<br>Phone: (660)281-7771 | Name: Daniel Stojsavljevic<br>Email: dast7544@colorado.edu<br>Phone: (815)735-0731 |
| Name: Nick Kuljis<br>Email: Nicholas.Kuljis@gmail.com<br>Phone: (949)533-4652 | Name: Jarrod Teige<br>Email: Jarrod.Teige@colorado.edu<br>Phone: (309)357-8619 |
| Name: Luca Kushner<br>Email: Luca.Kushner@Colorado.edu<br>Phone: (415)847-4852 | |

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# Acronyms

**ARGOS** Autonomous Rover for Ground-based Optical Surveillance. 7

**ATLAS** Articulated Transporter for Local Acquisition and Storage. 7

**C&DH** Command and Data Handling. 9

**CHIMERA** Child drone deployment Mechanism and Retrieval Apparatus. 7

**COMM** Communications. 9

**COTS** Commercial Off-The-Shelf. 24

**DRIFT** Drone-Rover Integrated Fire Tracker. 7

**FOS** Factor Of Safety. 12

**FPV** First Person View. 9, 22

**GPS** Global Positioning System. 8

**GS** Ground Station. 7

**HERMES** Hazard Examination and Reconnaissance Messenger for Extended Surveillance. 7

**INFERNO** Integrated Flight Enabled Rover for Natural disaster Observation. 7

**MR** Mother Rover. 7

**URFs** Ultrasonic Range Finders. 22

**V&V** Verification and Validation. 34

# Definitions

**fire line** a trench cleared of any flammable material, dug at the edge of a forest or brush fire to halt the spread. 7

**flame front** the leading edge of the forest fire perimeter. 7

**obstacles** rocks, tree stumps, fallen branches, or other debris found on the forest floor which can have heights up to 7 cm. 9

**terrain** specification of the forest floor which ARGOS must traverse. A full breakdown of various terrains can be found in the appendix. ). 8

**tipping condition** condition when rover tips too far to the side or in the front or back and falls over. 8

**tree density** measure of how many trees will be in an area ( trees/acres ). 8

# Section 1: Project Purpose

Margaux McFarland

Wildfire suppression has become an increasingly pertinent issue in recent years. If the Earth warms 1°C every year, the median amount of area burned by wildfires is predicted to increase by 600 percent [1]. As the area burned by wildfires increases, so does the need for effective fire fighting and wildfire containment, especially in wildfire prone environments. One strategy for wildfire containment is to dig a fire line, a trench cleared of flammable material, along the edge of the fire in order to halt its spread [2]. The purpose of the Autonomous Rover for Ground-based Optical Surveillance (ARGOS) system is to track the spread of wildfires by gathering useful data such as ambient temperature, pictures, and video from a fire line and send said data to a Ground Station (GS) and a Mother Rover (MR). The predicted benefit of ARGOS is a safer alternative for firefighters to visually monitor the spread of the fire at the fire line.

ARGOS is an addition to the existing Fire Tracker System built upon by previous JPL senior projects: INFERNO, CHIMERA, DRIFT, HERMES, and ATLAS. The first of the series INFERNO is a child drone designed to drop sensor packages in a location of interest [3]. CHIMERA is a take-off and landing platform for INFERNO which would later be attached to the mother rover DRIFT [4]. The DRIFT project consisted of integrating CHIMERA to the mother rover in order to extend the range of the child drone through areas affected by forest fires [5]. HERMES is a child scout rover designed to dock and deploy from the mother rover and find a safe path for the mother rover to traverse [6]. ATLAS was a mechanical arm which provided the capabilities to dock and deploy HERMES [7]. This year's contribution to the Fire Tracker System, ARGOS, is another child rover; however, what is novel about this child rover is the ability to take photos and video of the flame front. Another unique feature of ARGOS is its extendable and retractable mast which allows video of the flame front to be taken above the rover's body.

# Section 2: Project Objectives and Functional Requirements

Margaux McFarland

The project can be summarized into four main objectives. The first objective is to navigate to and from a target location near a flame front via commands from the mother rover and the ground station. The second objective is to collect ambient temperature data throughout the duration of the mission. This includes during the navigation phase as well as at the target location. The third objective is to take photos and video of the flame front from a camera sitting on top of an extendable and retractable mast. Lastly, the fourth objective is to transmit the captured photos, video, and temperature data to the ground station and mother rover.

## 2.1 Levels of Success

The first objective and the second objective fall under the Navigation phase, the second and the third objective fall under the Surveillance phase, and the last objective represents the Communications phase. Each of these phases has varying levels of success from one to four as outlined in Table 1. Meeting a level of success implies that all the previous levels were also met.

Table 1: Levels of Success for ARGOS

| | Navigation | Surveillance | Communications |
|---|---|---|---|
| Level 1 | Rover can travel on flat ground for 100 m via manual control. Rover can travel in the forward direction and can turn 360 degrees with a turn radius less than two rover body lengths (2.3 m). | Ambient temperature data is recorded from a temperature sensor with an accuracy of +/- 1°C throughout the mission. Rover records timestamped photos of the flame front via a camera on a mast. | Rover can receive Global Positioning System (GPS) commands from the ground station and the mother rover. Rover can transmit temperature data and video/images to the ground station and mother rover at 1 Hz 0m from ground station in an open area (tree density of 0 trees/acre) or in the same room. |
| Level 2 | Rover can travel on various terrains, including leaves, underbrush, dirt and mud while staying upright. Rover can travel on a 20 degree incline. Rover can turn 360 degrees with a turn radius less than one rover body length (1.15 m). | Rover records timestamped video of the flame front via a camera on a mast. | Rover can communicate with the GS and the MR up to 100 m in an understocked forest (a tree density of 100 trees/acre). |
| Level 3 | Rover can turn 360 degrees on the spot. Rover can follow GPS waypoints and detect large obstacles, such as trees and dense bushes, in its path and avoid hitting them. Rover can detect a tipping condition by measuring its angular motion. | Rover's mast is extendable and retractable. | Rover can communicate with the GS and the MR up to 250 m and in a fully stocked forest (a tree density of 170 trees/acre). |
| Level 4 | Rover can detect small obstacles, such as rocks and small bushes, and navigate a path around them. Rover can navigate to a GPS waypoint within +/-5 m of the coordinates. | N/A | Rover can communicate with the GS and the MR in an overstocked forest (tree density of 200 trees/acre). |

## 2.2 CONOPS

The mission can be illustrated in the CONOPS shown in Figure 1.

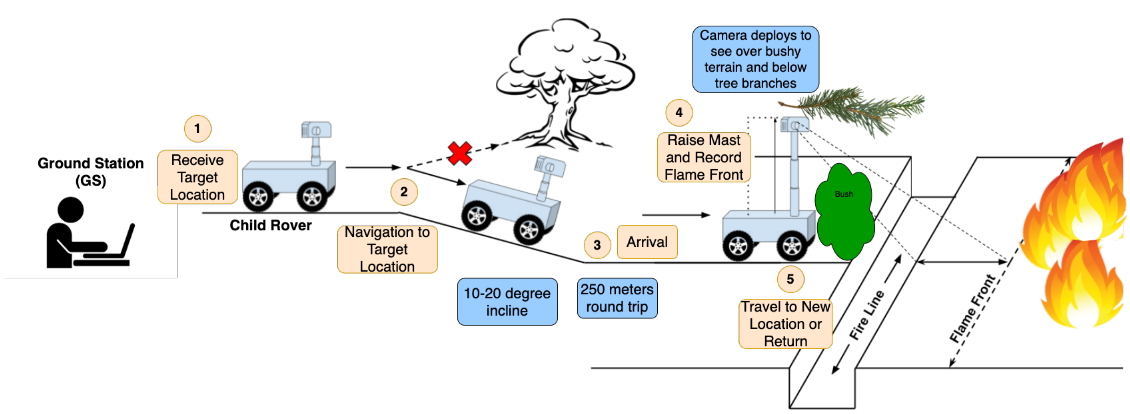
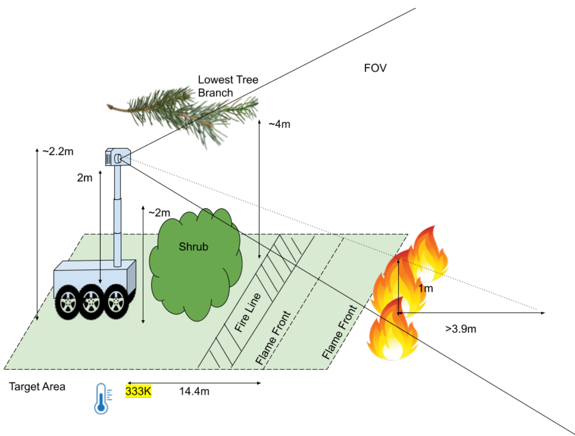


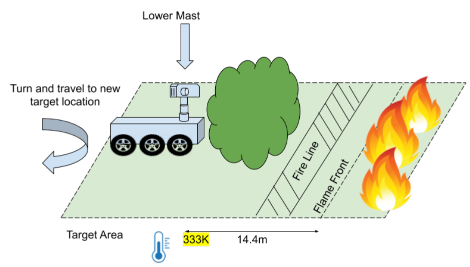

Figure 1: Concept of Operations for ARGOS

In the first stage, the rover is at its starting location and receives a target location from either the ground station or the mother rover. In the second stage, also known as the navigation stage, the child rover is manually controlled by the ground station operator to various waypoints along its path. During the navigation stage, the rover can expect to experience inclines up to 20 degrees and travel over obstacles as tall as 7 cm. These conditions were taken from heritage projects. In the third stage, the child rover arrives at the target location and confirms that its position is within 5 m of the target location. In the fourth stage, or the surveillance stage, the mast is extended to its full height of 2 m, and video data of the flame front is captured and sent to the ground station and mother rover. Finally, in stage 5, the child rover either stays monitoring, receives a new target location, or travels back to the starting location. This entire trip will be at most 250 m in total.

In addition to the overall mission CONOPS, there are zoomed in views of stage 4 and stage 5 or the CONOPS in Figures 2a and 2b.




(a) Stage 4 of CONOPS




(b) Stage 5 of CONOPS

In Stage 4, the child rover is at its target location with its mast extended. The mast height of 2 meters was chosen so that the camera on top of the mast, also called the surveillance camera, can see over shrubs that can reach up to 2 meters as well as not extend into the lowest tree branch, which can be as low as 4 meters [8], [9]. This target location shall be in front of the flame front such that the child rover can record video of the fire; however, the target location must also be far enough away such that all the electronics and the rover itself are safe. A minimum distance to the flame front was set at 14.4 meters which was determined from a thermal analysis. The thermal analysis used heat transfer and thermodynamic principles to calculate the distance at which the temperature of the rover's surface would be 333 K [10]. This temperature limit was chosen because 343 K is the average commercial grade electronics operating temperature limit, and a margin of 10 K was added for safety reasons or in case the fire moves closer as the rover turns and moves away from the fire. It should be noted that this thermal analysis was constructed around the fact that the average brush fire height is 1 meter [11].

In the case that the rover measures a temperature of 333K or more, an alert will be sent to the ground station operator, in which case, the operator can chose a new target location. This action would fall under stage 5 of the CONOPS as illustrated in Figure 2b. The mast would be lowered, and the rover would be manually controlled to the new location away from the fire.

## 2.3 Functional Block Diagram

The following functional block diagram depicts all the major functional components of ARGOS such as Communications (COMM), Command and Data Handling (C&DH), the Rover Mobility which includes the movement sensors and the drivetrain, and Fire Surveillance which includes the mast, surveillance camera, and temperature sensor. It is important to note the use of two different cameras: one is the First Person View (FPV) camera used by the ground station operator for navigation, and the second is the surveillance camera which sits on top of the mast to record video of the flame front. As data and commands are sent into the communications system, specifically the Rocket M2, acknowledgments are also transmitted back to validate that command or the data was received.

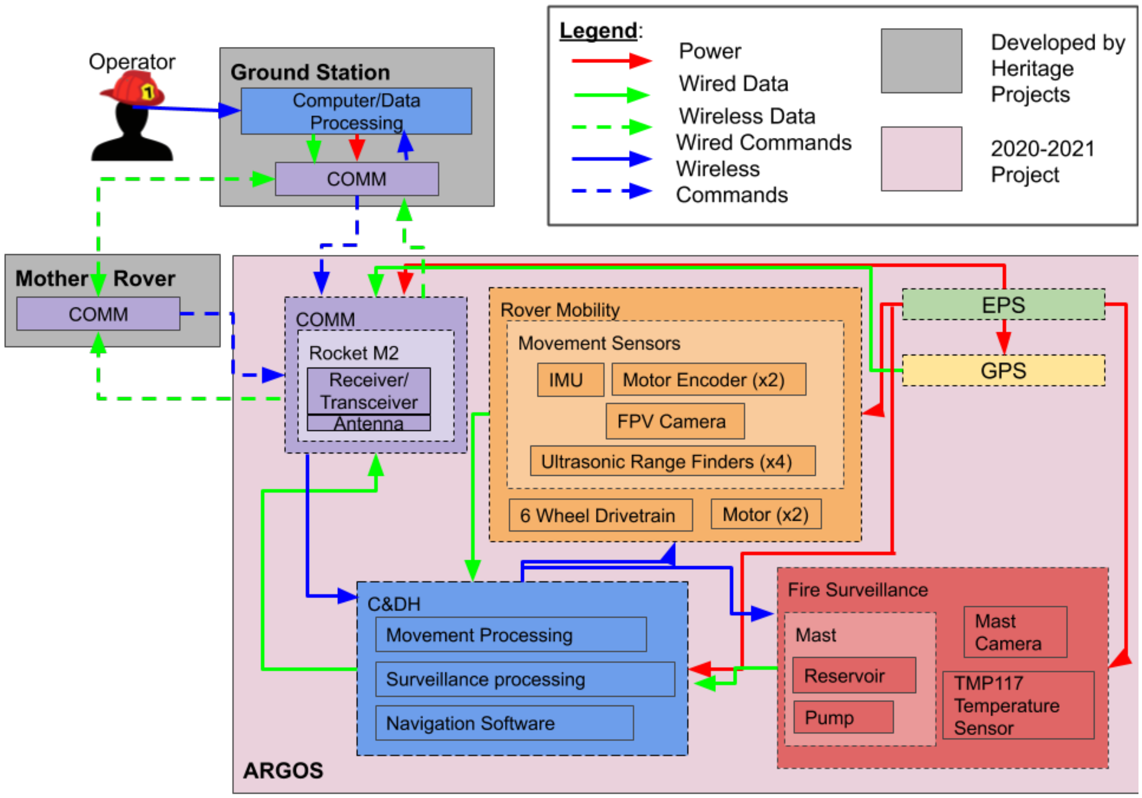



Figure 3: Functional Block Diagram for ARGOS

## 2.4 High Level Functional Requirements

In order to complete this mission, four main functional requirements must be met. These requirements were derived from a list of customer-given requirements and are outlined in Table 2. The first functional requirement deals with the mobility of the rover, the second sets a requirement for the type of data needed to be collected, the third requires the use of an extendable and retractable mast in order to perform the functions of this mission, and the fourth and final requirement requires the child rover to communicate with the ground station and mother rover so that the child rover can be remotely controlled by an operator and also that useful data is transmitted back.

Table 2: The Four Main Functional Requirements for ARGOS

| High Level Functional Requirements | |
|---|---|
| **Requirement ID** | **Description** |
| **FR.1** | The child rover shall move from a starting location to a commanded location of interest and return back to the starting location. |
| **FR.2** | The child rover shall record pictures, video, and ambient temperature data to be sent to the ground station. |
| **FR.3** | The child rover shall use a mast to take photos and video from a vantage point above the rover's body. |
| **FR.4** | The child rover shall be able to receive commands from both the ground station and the mother rover and transmit captured data back to the ground station and mother rover. |

# Section 3: Final Design

Harrison Fitch, Margaux McFarland, Thomas Noll, Niko de Boucaud, Luca Kushner

## 3.1 Functional Requirement 1

| FR.1: The child rover shall move from a starting location to a commanded location of interest and return back to the starting location. | |
|---|---|
| **Design Requirement ID** | **Description** |
| **MOV.1.1** | The child rover shall be able to perform a 360 degree turn. |
| **MOV.1.2** | The child rover shall be able to travel in forward and reverse motion. |
| **MOV.1.3** | The child rover shall be able to travel up and down slopes of 20 degree inclination. |
| **MOV.1.4** | The child rover shall be able to travel over obstacles with heights as tall as 7cm. |
| **MOV.1.5** | The child rover shall be able to travel 250m round trip in any direction from its starting location. |
| **CDH.1.1** | The child rover shall be able to detect when a tipping condition is met (when the rover falls over) and send an alert to the ground station/mother rover. |

### 3.1.1 Rationale

MOV.1.1: In addition to being a customer requirement, performing a 360 degree turn also allows the rover to easily backtrack in the event that communication is lost, making design requirement COM.4.1 more achievable.

MOV.1.2: In addition to being a customer requirement, reverse motion allows the rover to back out of possible hazardous terrain or obstacles blocking navigation without requiring a turn.

MOV.1.3: Based on the heritage rover HERMES, possible inclines during navigation were expected to reach up to 20 degrees.

MOV.1.4: 7 cm tall obstacles were found from the heritage rover HERMES.

MOV.1.5: This distance is a customer requirement. The whole JPL fire tracker rover family has a 250 m range regiment.

CDH.1.1: If the rover has tipped over, a critical failure has occurred and will have to be manually recovered. Alerting the operator when a tipping condition is about to be met will prevent damage that could occur if the operator unknowingly extended the mast at too steep of an incline or continued controlling the rover over too tall of an obstacle.

## 3.2 Functional Requirement 2

| **FR.2: The child rover shall take pictures, videos and ambient temperature data to be sent to the ground station.** | |
|---|---|
| **Design Requirement ID** | **Description** |
| **SURV.2.1** | The camera shall have >100 degrees field of view. |
| **SURV.2.2** | The camera shall provide the operator with pictures and video of fire that occupy at least 20% of the vertical image. |
| **CDH.2.3** | The child rover shall be able to determine the ambient temperature within +/- 1 °K at the location of interest. |

### 3.2.1 Rationale

SURV.2.1: In addition to being a customer requirement, 100 degrees field of view allows for adequate coverage of the environment.

SURV.2.2: To quantify the quality of the image of the fire a 1 meter flame height shall take up 20% of the sensors effective vertical height.

CDH.2.3: In addition to being a customer requirement, measuring temperature withing a 1 °K accuracy will ensure the rover isn't exposed to an environment that damages the rover.

## 3.3 Functional Requirement 3

| **FR.3: The child rover shall use a mast to take photos and video from a vantage point above the rover's body.** | |
|---|---|
| **Design Requirement ID** | **Description** |
| **SURV.3.1** | The child rover shall have a mast capable of extending to a height of 2 m +/- 0.2 m and retracting back down to its original height. |
| **SURV.3.2** | The child rover shall have a mast capable of supporting 5 kg of weight on the top. |

### 3.3.1 Rationale

SURV.3.1: Based on the environment of operations, ARGOS will have to see over possible obstacles such as shrubs while remaining under low tree branches. The team determined that the lower bound of operations is 2 m, based on the max shrub height of 2 m tall, and the upper bound for the max extension is 4 m, based on the lowest tree branch height of 4 m. Therefore, the 2 m mast extension coupled with the chassis height and camera height accounts for a total extension height of 2.2 m.

SURV.3.2: The masts support weight of 5kg was chosen based on the camera's weight of 2.5 kg with a Factor Of Safety (FOS) of 2.

## 3.4 Functional Requirement 4

| **FR.4 The child rover shall receive commands from both the ground station and the mother rover and transmit captured data back to the ground station and the mother rover.** | |
|---|---|
| **Design Requirement ID** | **Description** |
| **COM.4.1** | Upon loss of communication, the child rover shall return to its last known GPS location (storage of waypoints). |
| **COM.4.2** | The child rover shall send time stamped video, image, and temperature data to the ground station and mother rover at a data rate up 25 Mbps. |
| **COM.4.3** | The ground station shall confirm if the child is within +/- 5m of the desired location. |
| **COM.4.4** | The child rover shall send its location every 1.5s to the ground station/mother rover. |
| **COM.4.5** | The mother rover/ground station shall be able to command the child rover to navigate to specified GPS coordinates in real time . |
| **COM.4.6** | The mother rover/ground station shall be able to command video feed on/off. |
| **COM.4.7** | The mother rover shall be able to receive commands from the ground station at a data rate up 25 Mbps. |
| **COM.4.8** | The mother rover shall be able to send temperature data and video to the ground station and vice versa. |

### 3.4.1 Rationale

COM.4.1: Based on the assumption that communications is lost via distance from GS/MR, to rover will have to autonomously relocate to the last known way point to reestablish communications.

COM.4.2: The Data rates required to send just live video feed require multiple Mbps, a communications system at a certain frequency must be chosen to handle these data rates.

COM.4.3: The operator needs an accurate coordinate in case physical retrieval of the rover is required. Accurate coordinates are also vital in providing accurate location data in relation to the flame front.

COM.4.4: Sending locations lets the operator know that there are still communications with ARGOS. The 1.5 second increments are to prevent large deviations in the back-track of the rover if communications are lost.

COM.4.5: Real-time GPS will enable the operator to get a visual of the rover's path and if it is reaching the desired coordinates.

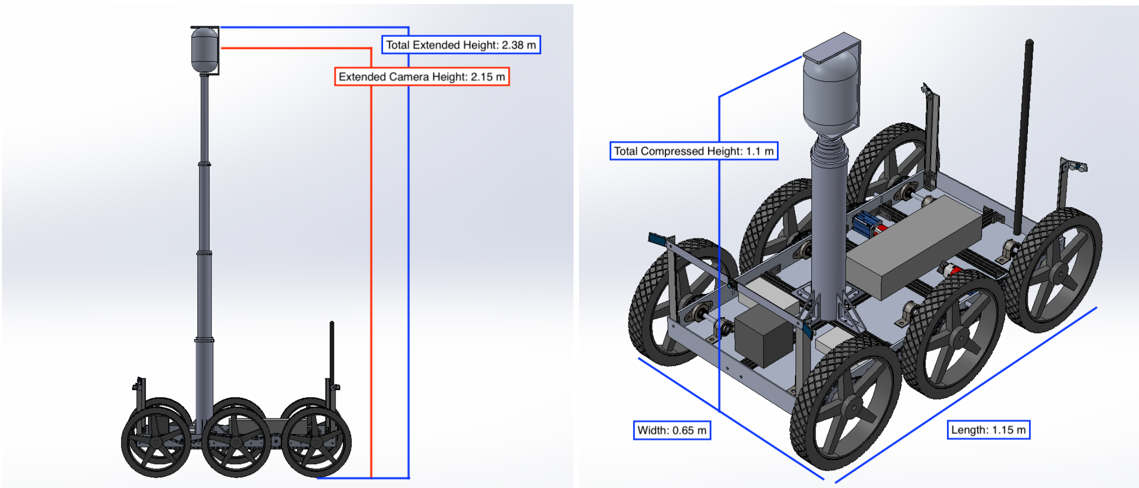
COM.4.6: With one camera operating instead of two, the computational power and latency decrease. This also decreases the amount of bandwidth ARGOS is utilizing.

COM.4.7: Just like ARGOS, the MR requires the data rates to successfully transfer the data from ARGOS to the GS. This is a customer requirement to ensure that the GS used to communicate with ARGOS can also communicate with the other projects in the Fire Tracker System.

COM.4.8: Live video enables the operator to track the progress of the fire and the temperature data is vital in determining if and when the rover needs to return to the GS after it reaches a determined temperature. This is a customer requirement to ensure that the GS used to communicate with ARGOS can also communicate with the other projects in the Fire Tracker System.

### 3.5 Full System Design

The full system design of the rover can be seen in Figures 4a and 4b, which consists of a six-wheel drivetrain, a surveillance camera on top of a four-stage hydraulic mast, and electronics and sensors resting on the rover's chassis. Each of these major components of the design will be described in the following sections.




(a) Dimensions of Full System with Mast Extended (b) Dimensions of Full System with Mast Compressed

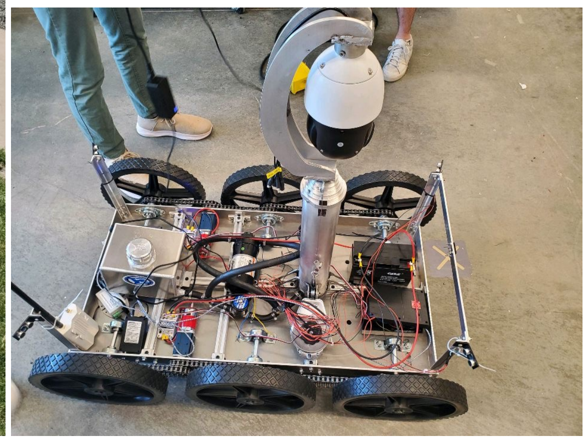
The total extended height of the rover is 2.38 m, and the camera reaches 2.15 m off the ground. When the mast is compressed, the total height of the rover is 1.1 m. All of the dimensions of the rover as well as the total weight are outlined in Table 3.

Table 3: Final System Dimensions and Mass

| | |
|---|---|
| Total Extended Height | 2.38 m |
| Extended Camera Height | 2.15 m |
| Total Compressed Height | 1.1 m |
| Width | 0.65 m |
| Length | 1.15 m |
| Total Mass | 54.25 kg |

Actual images of the fully integrated system are shown in Figures 5a and 5b, one with the painted acrylic housing and one without the acrylic housing, showing the electronics and hydraulic pump system inside. Figure 6 depicts the rover being weighed by the WASP senior project which was built to weight aircraft pods.


(a) Full System with Acrylic Housing

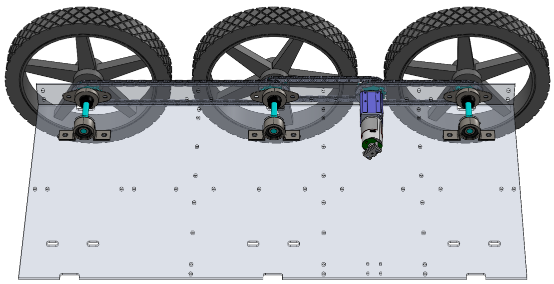


(b) Full System without Acrylic Housing

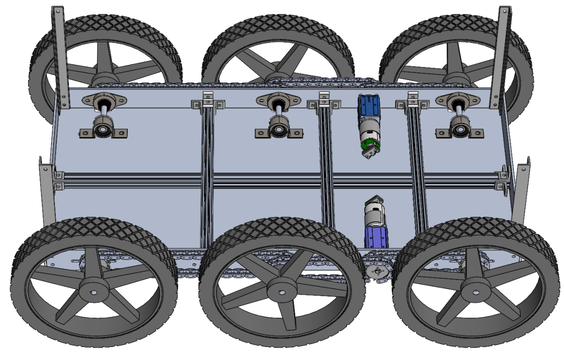
Figure 6: ARGOS being weighed with WASP Project

### 3.6 Drivetrain Design

The drivetrain has many individual components with vital interactions to ensure the rover is capable of translation and rotation even in dense underbrush. Starting at the core of the subsystem, two high-speed DC motors are mated to gearboxes. This reduces the output speed and increases the output torque to the wheels significantly, allowing for obstacle traversal and satisfaction of all movement requirements. Custom 16 tooth sprockets are mated to the output shaft of the gearbox to transmit power to all three wheels on each side. Power is transmitted between sprockets via a standard #40 steel chain. These chains are tensioned by adjusting the distance between each shaft. The shaft bearings are mounted on slots in the chassis, allowing the axles to translate forward and backward; the bearing fittings are then tightened to achieve the desired tension and interaction between the chain and sprockets. The axles are secured to the chassis using pillow block and flange bearings which allow for rotation about the shaft's central axis only. This rotation is finally sent to the wheels to allow for translation and rotation of the rover. The overall subsystem is shown in Figure 7b.



(a) Shaft Mounting And Tensioning



(b) Drivetrain And Chassis Assembly

## 3.7 Mast Design

### 3.7.1 Design Options Considered

First, several designs were considered through a trade study. Criteria for the trade study consisted of cost, support weight/stability, complexity, extendable height/compressible height, power required and speed of retraction/extension. The cost of the design alternatives was based largely on the number of components, including structural and functional components, that the system would require. The support weight and stability encompass the design's ability to remain stable at full extension while holding up a large weight. The complexity refers to the approximate time the design was projected to take to complete, which was estimated based on the number of designed and manufactured components. The extendable height and retractable height refers to the ratio of compacted height to full extension height for each mast type. The power required refers mostly to the mass of the system's functional components and the power required to raise them, but also to the number of motors or pumps the system would need. The speed of retraction/extension refers to the amount of time that the system would take to retract/extend fully (which is related to power required) without damaging the camera or the system itself. The designs considered in the trade study were a hydraulic mast, a scissor lift, a fold-over style mast, a screw lift and a system of pulleys and slides.

The mast design decided on was a telescoping hydraulic cylinder system with four interlinking stages/sections. It was determined to be the most optimal of the design alternatives, bringing great support weight and stability, a larger extendable/retractable height ratio, a low power required, and a reasonable speed of retraction/extension. The cost and the complexity of the hydraulic mast were projected to be high, but seeing as the mast is one of the primary features of ARGOS, these criteria were not weighted as high in the trade study.

### 3.7.2 Final Design and Feasibility Studies

In essence, the system is a single-acting hydraulic cylinder with three moving "pistons", or stages. It consists of a reservoir for hydraulic oil, a hydraulic pump (with an internal check valve), a solenoid valve and, of course, the mast itself. When the ground station operator sends the signal, the pump receives current from the on-board power system and begins pushing oil into the mast at a constant rate until full extension. The pump is then shut off by the ground station operator, and the mast stays extended while data are captured. To lower the mast, the ground station operator opens the solenoid valve for the duration of the mast's descent, and the hydraulic oil flows back into the reservoir. Splits in the hydraulic line allow for the system to use one inlet/outlet to the tank and reservoir each, as can be seen in Figure 8.

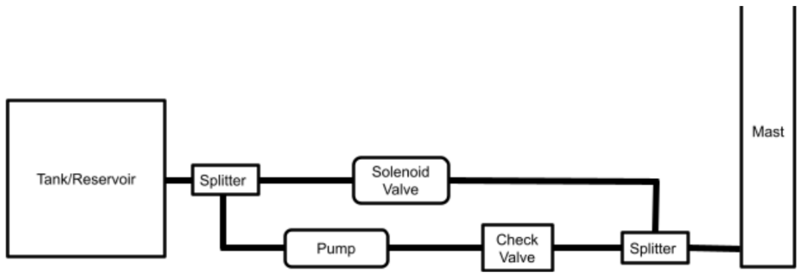



Figure 8: Basic Hydraulic System

To determine the pressure the pump needed to provide, a pressure study was conducted with the following simplifying assumptions:

1. The upward hydraulic pressure force acts only on the top cap of the mast and not on the bottom of each mast stage.
2. The sliding frictional forces on the wear rings are negligible.
3. The outside air is at standard temperature and pressure.
4. The mass of mast hardware is 10 kg.

From these assumptions, a simple force balance between the maximum load (10kg) allowable for the camera, the weight of the mast stages themselves, and the upward pressure force from the hydraulic pump was found. This resulted in the pressure at the pump required being 264,810 Pa (38.4 psi). However, this turned out to be an overestimate of the mass of the system, since the chosen camera was found to have a mass of only 2.6 kg, and the mast hardware was found to have a mass of only 6.05 kg. But, when accounting for the unexpectedly high friction force on the seals/wear rings as well as the spring return system (added after testing, discussed in sections that follow), the overestimated pressure required in the study was likely required to push the real mast sections up.

A simulation was also done using Solidworks to determine the pressure at which the mast would rupture [19]. It was found that the weakest points, the donut connections (described below), would rupture once the pressure reached 400 psi with a factor of safety of 1.5. The pressure in the mast won't ever reach this as the selected pump is only capable of outputting 60 psi [20].

Each section, or "stage", of the mast has the same basic design consisting of two main components: a machined cylindrical tube and a circular piece atop, henceforth known as a "donut." Stage 1 is the bottom tube and does not move up and down with the rest of the stages. Instead, it simply provides a base for the 3 upper stages to slide within and houses a cap on its bottom side, to hold fluid pressure, that doubles as a base mount for the mast, as shown in Figure 9.

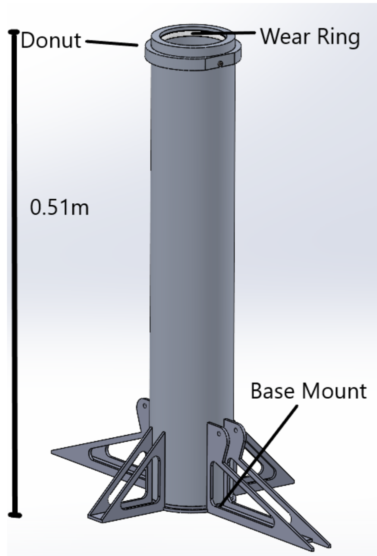



Figure 9: Model View of Stage 1

At the base of each of the top three stages, grooves are cut to hold dynamic seals and wear rings. The purpose of the wear rings is to provide a sliding surface to prevent metal-on-metal sliding, and the purpose of the dynamic seals is to hold pressure and prevent oil from leaking out. Each donut also houses another wear ring providing a secondary surface for the interior section to slide against. The two points of contact mitigate any torque created by an uneven frictional force which would likely result in binding and damage to the mast. In addition, this donut acts as a hard stop to prevent the subsequent interior section from being pushed out of the mast at full extension. For stage four, the donut is replaced with a cap in order to seal off the top of the mast. The cap contains a seal to prevent leakage as well but, since it doesn't have to slide when the mast goes up and down, the seal is a simple O-ring as opposed to a dynamic seal. Figures 10 and 11 show model views of the top three movable stages as well as a section view of two stages sliding within one another, respectively. Figure 12 shows the camera mount design which was welded to the top of stage 4.

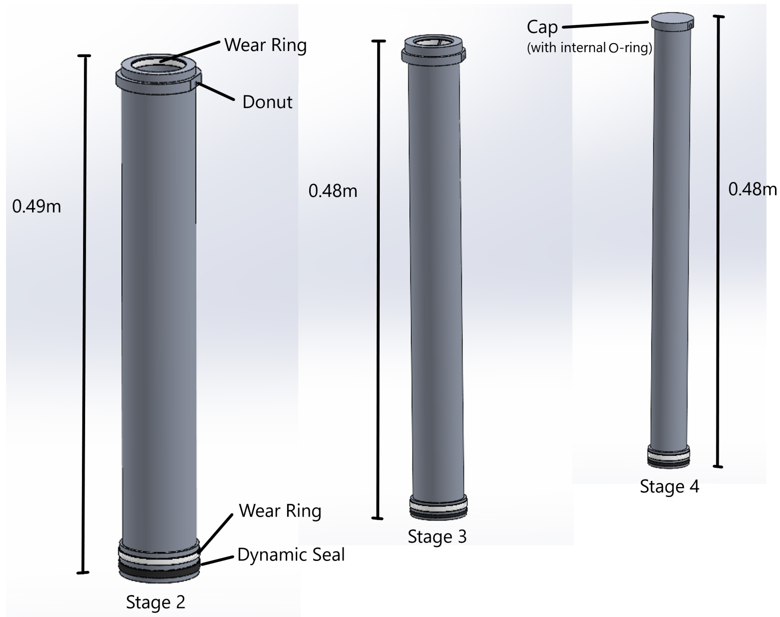



Figure 10: Model View of Top 3 Stages

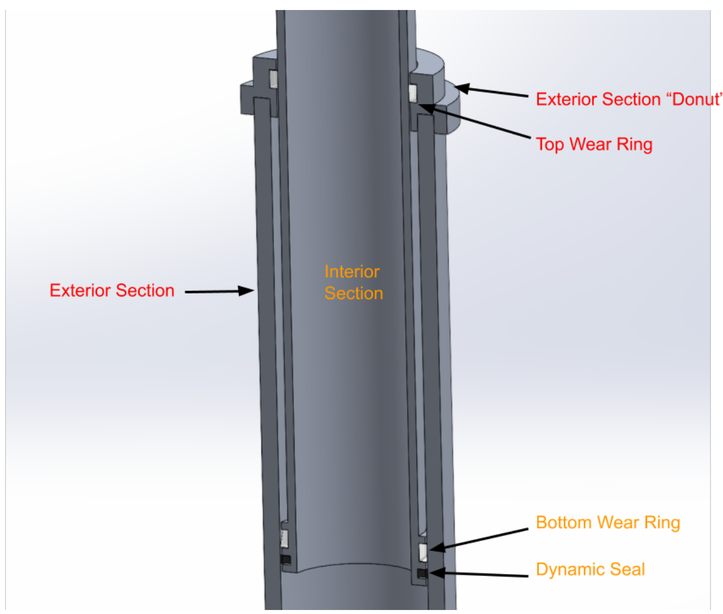
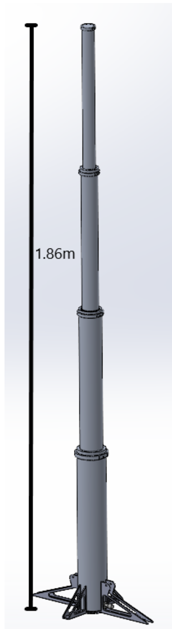


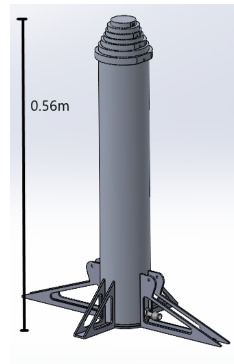

Figure 11: Internals of a Section of the Hydraulic Mast


Figure 12: Camera Mount Model view

Figure 13 shows the full CAD model of the extended and retracted mast. The model includes 4 stages that will extend the mast up to 1.86 meters and, once retracted, the mast will rest at roughly half a meter. The top of the mast will hold the camera mount, which is not pictured in this assembly. Also not pictured is the cable and pulley system designed to pull the stages back to their collapsed state. This cable and pulley system, though not part of the original design, is an addition which was required from the results of testing of the top two stages. The system's design and purpose will be made clear in later sections.




(a) Extended




(b) Retracted

Figure 13: Full CAD Model of Mast (not pictured: camera mount, cable and pulley system)

## 3.8 Electronics and Communication Design

The full electronics and communications design involves five main components: power delivery, computing, sensing, movement, and communication.

### 3.8.1 Power Delivery

The power delivery system is responsible for ensuring that all of the electrical components are supplied with electricity. The power delivery consisted of three batteries. One main 12V lead acid battery powers the motors for movement, the mast pump and solenoid, and the surveillance camera. The second 11.1V lithium battery was used to power a network switch. A third battery was added as needed through a 19V power adapter to power the computing system. The original design used the main 12V battery through the 19V power adapter. This solution worked intermittently but there were frequent shutdowns of the main computer. Switching to an isolated power supply solved this issue. This solution arose during full integration tests as a quicker solutions than trying to root out the main issue behind the shutdowns. Figure 14 is a diagram of the original solution without the third added battery as it was added quickly without an addition to the computer model. The third battery was located on the opposite side of the rover near the main computer which is not shown below.

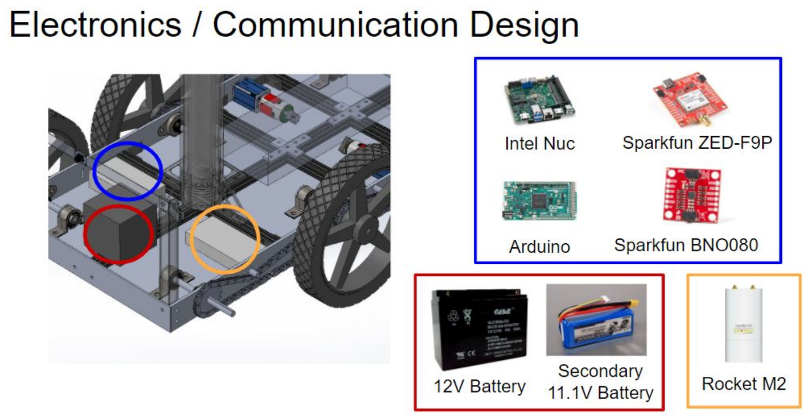



Figure 14: Electronics on Communications View

### 3.8.2 Computing

The computing block on the final design consisted a small Intel NUC computer and and Arduino Due micro controller. The NUC ran the majority of the computing and the Arduino was used to read in sensor data and act as a final bridge to connect commands from the NUC to the motor controllers, described bellow.

### 3.8.3 Sensing

The final design of the sensing system consisted of a GPS unit and an IMU for rover localization, a small First Person View (FPV) camera for operator viewing, a temperature sensor, and the main surveillance camera on the mast. There were also two other groups of sensors that were integrated but not used for the final mission. There were four Ultrasonic Range Finders (URFs) that had been connected and tested originally. However, after shorting the first Arduino micro controller during one of the tests, the ultra sonic range finders were not soldered to the new Arduino. The decision to leave these off of the new Arduino was made to reduce the likely hood of another short and for time considerations. Cutting out these sensors from the final design was deemed acceptable as they are not mission critical, and full mission testing could still be completed without them. Two motor encoders, one for each motor were also implemented but not utilized on the final design. This was due to issues with the data that they produced. The data was sporadic and did not allow the software to properly control the differential drive system. This forced the team to revert to a lower level of control where the operator directly controlled the differential drive, essentially controlling the torque of each motor independently and manually. In the future, adding an encoder chip, like the LS7184, to interface with the motor controllers would possibly help reduce noise.

### 3.8.4 Movement

The electrical design for the movement of the rover consisted of two DC motor and motor controller units. These received commands from the Arduino as described above. This system was largely unchanged between the original and final designs.

### 3.8.5 Communication

The communications design, seen in Figure 15, consisted of the Ubiquity Rocket M2 2.4 GHz radio system. This radio is used as both a transmitter and receiver. This works similarly to a local WiFi network. There was one unit attached to the rover, which used a short omnidirectional antenna, and a second unit used on the ground station connected to a large unidirectional antenna. The ground station was connected to a laptop that displayed the user interface and sent operator commands to the rover. On the rover there was also a small network switch which interconnected the surveillance camera, Intel NUC, and Radio.

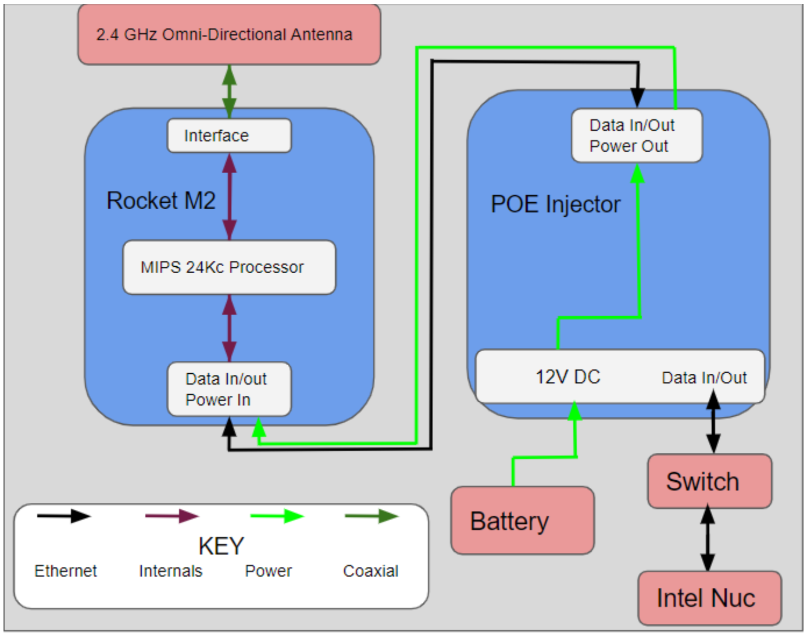



Figure 15: Communications Design

# Section 4: Manufacturing

Daniel Stojsavljevic, Trevor Slack, Luca Kushner, Niko de Boucaud.

## 4.1 Mechanical

### 4.1.1 Chassis and Drivetrain

The chassis and drivetrain system included a vast variety of manufactured parts, but also contained parts that were purchased as well. To begin, the chassis was made from a 0.635 m by 1.143 m aluminum 6061 sheet that was cut to size of the rover. After the sheet was cut, holes where made based off of machine drawings for the locations of where other systems will be mounted on the chassis. Once all the proper holes are cut and drilled on the aluminum pieces, the side panels are then welded on the base plate. Figure 16 represents the full welded chassis with the holes cut and drilled, at this point the chassis is ready for assembly. The chassis was done entirely in the machine shop and the only challenge was the time. There were ordering complications for the aluminum 6061 sheet and a new one had to be ordered from a different supplier. After the new sheet was picked up, it was ready for the machine shop, but the chassis took roughly 2 weeks to be built which was not expected. However, this delay was incorporated in the schedule immediately which did not cause problems for future assembly and testing plans.

Figure 16: Manufactured Chassis

While the chassis was being built, the sprockets, spacers, and shafts for the drivetrain system were also being manufactured as well. The sprockets were Commercial Off-The-Shelf (COTS) parts but needed holes drilled in them, while also needing key slots in them. The holes were needed for the screws that attach the sprocket and the spacers together. The spacers were completely manufactured out of aluminum 6061. They were made in order for the chains (which will be mentioned below) to fit nicely alongside each other. The shafts were also made out of aluminum 6061 and where cut to size while also being keyed. The diameter of the shaft, spacers, and sprockets were all 1.27 cm in order for all of them to fit nicely together. The design was for the sprockets and spacers to fit on the shafts and then using set screws to keep them in place. Figure 17 shows the sprockets and spacers, specifically on the 57 sport gearbox that will be mentioned below. Although, the set screws did not entirely work since when it came to testing the entire drivetrain system. The screws just slipped and the sprockets were loose which caused a problem for movement. The problem was fixed by tightening the set screws and also incorporating a key for the sprockets and spacers for no slipping which successfully worked.

Figure 17: Sprockets and Spacers

The rest of the purchased drivetrain parts include 775 redline motor (X2), 57 sport gearbox (X2), 2-bolt flange bearings (X4), pillow block bearings (X4), and all the mounting screws for the bearings. The chains however were purchased, but needed to be adjusted in order to fit this system. Two 3.048 m roller chains were ordered to connect the sprocket/shaft system on each side of the rover. Each chain needed to be cut into 3 separate ones in order to fit each sprocket spacing.This was difficult to achieve though since the chain splitter in the machine shop did not fit chains that were ordered. To fix this problem, the rivets of the marked link were grinded down using a grinding wheel and then pushed out using a rivet puncher. After the links were taken out, master links were used on each cut chain and attached on to the sprockets. Figure 18 shows the full drivetrain system with the motors, gearboxes, shafts, bearings, and chains all put together and mounted on the chassis.

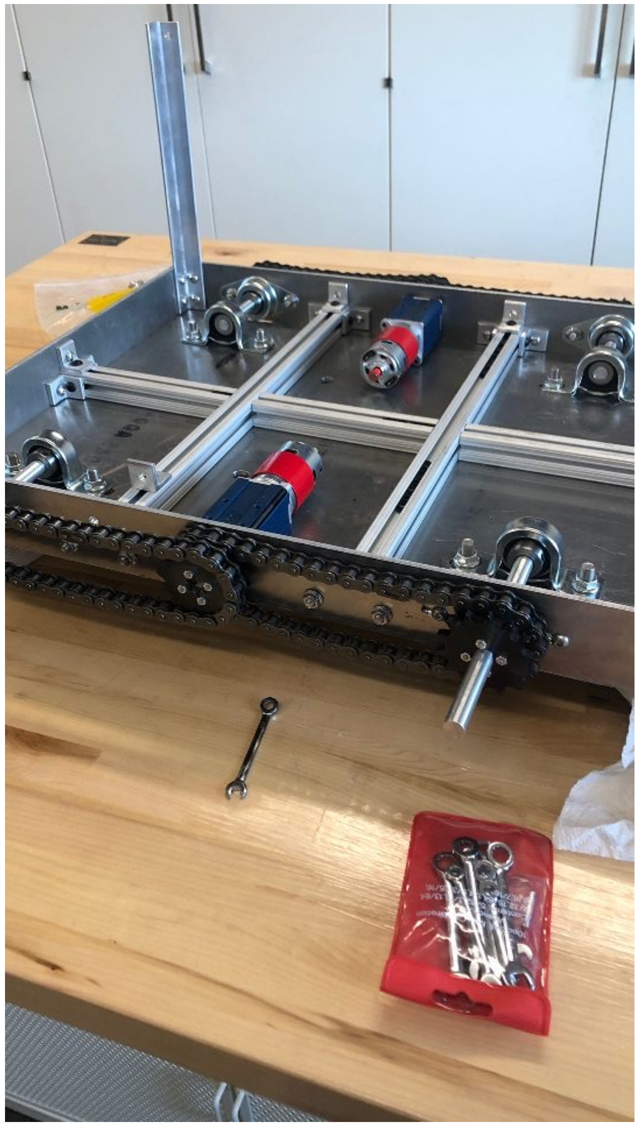


Figure 18: Manufactured Drive Train System with Chains

#### 4.1.2 Mast

The hydraulic nature of the mast requires manufacturing tolerances to be very tight to prevent both binding and leaking. Too tight of a fit and the system would bind up and refuse to move without an extremely high force available to unbind it. Too loose of a fit and the system would leak. For this reason, the manufacturability of the mast needed to be tested to determine if it was feasible or not. The top two stages of the mast, stage 3 and 4, were manufactured and assembled before the other stages in order to test the tolerances and verify the overall design concept of the full mast. By adding a cap to the bottom of stage 3 (stage 4 already included a cap at its top), the system could hold pressure and test extension and retraction at less than or equal to the pressure found in the feasibility study. The mast test rig consisted of those two mast stages, a hydraulic oil reservoir, and an air compressor for pressurization. The air compressor would pressurise the reservoir, which would force hydraulic fluid to extend the mast at the compressor's set pressure. Figure 19 shows the two manufactured assemblies: the PVC testing reservoir and the test rig itself. PVC was chosen as the material for the reservoir for the sole reason that it would be a quick, inexpensive solution.

Since the reservoir would only be used for a single test (with a few trials) it was decided that the risk of explosion due to pneumatic pressure would likely be low. The reservoir was constructed with PVC glue and NPT fittings for sealing. Quick-connect style pneumatic fittings allowed the reservoir to be attached via a hose to the pressurized air and a hose was attached using sealing NPT threads to supply hydraulic oil to the aluminum mast test sections. The top stage of the test rig was turned on a lathe to machine down the outer diameter to the designed shape shown in figure 10 as stage 4.

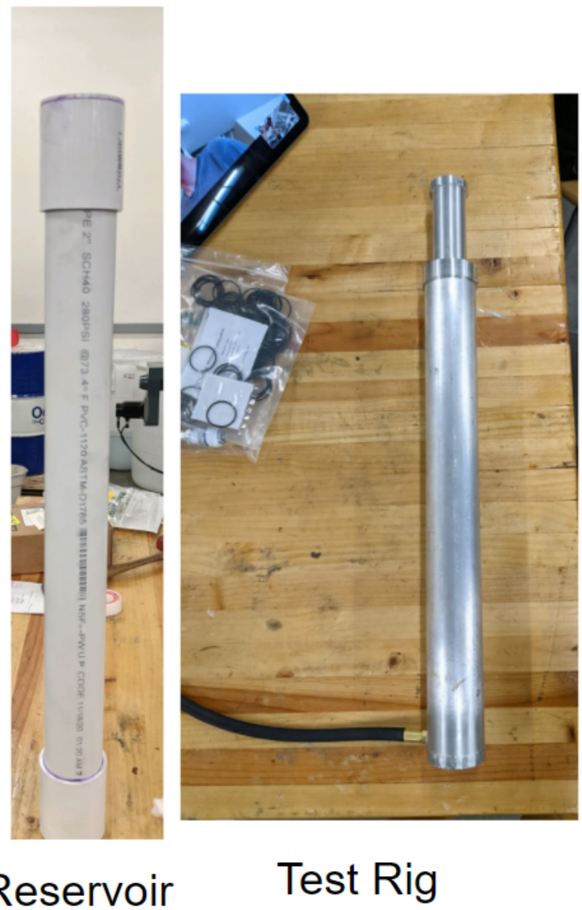


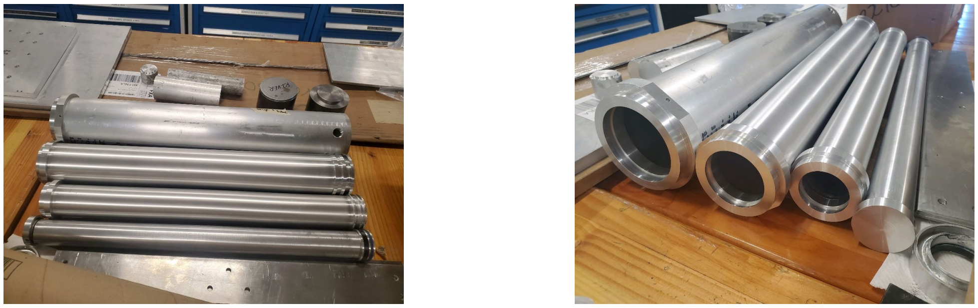

Figure 19: Manufactured Parts for the Mast Test Rig

Due to the difficulty of tooling inside a tube with a small diameter, the interior of each stage would not be machined and would be held to the tolerances that the manufacturer gave to their extruded aluminum tubes ($\pm$ 0.025 inches) which was not as tight as the tolerances that the seals required ($\pm$ 0.002 inches). Therefore, it was expected that the tubes may be too large to seal or that the seals' outer diameter may need to be reduced in order to ensure their fitment within the interior of each stage, depending on which direction the actual inner diameter of the tube went within the given tolerance range. If a tube was too large for the outer diameter of the dynamic seal to contact, either the tube would need to be re-ordered in hopes that the new interior diameter would be on the smaller end of the given tolerance range or the seal would need to be somehow stretched. However, since the dynamic seals were found to plastically deform when they were applied, the seals' tight tolerances turned out to be ruined by the application process and this tolerance mismatch issue did not come into play. It was instead replaced by the problem of every seal being expanded during application and being too large for its required section. Figure 20 shows one of these seals (note that they are two-part seals, an interior rubber part and the exterior PTFE part, these problems are all centered around the exterior PTFE part shown).

Figure 20: The Exterior PTFE Part of a High Speed Dynamic Seal

These seals were selected due to their advertised "high speed" since the lower-than-typical hydraulic pressure inside of the mast wasn't believed to be capable of moving seals designed for low speed and 1000's of psi of hydraulic pressure (much higher friction forces are needed to contain high pressure). This "high speed" was achieved by the seal manufacturer by using a contact surface made of PTFE plastic, which is not an elastic material, as was discovered only after they were applied to the mast test rig section. If the seal manufacturer had kept the PTFE exterior and had attached it to an elastic material (e.g. rubber) then the seals would likely have worked much better. The manufacturer's suggestion was to heat/cool the seals as needed to fit them over their sections and into their grooves which would supposedly prevent plastic deformation. However, this resulted in a complete loss of the tight tolerances given on their website as the seals would not return to their exact original size after being heated or cooled. This heating/cooling method was only used for the seal on stage 2 of the final four-stage mast, though, since machining the seals down enough to fit was found to be a more effective method to achieve sealing as well as low friction. Thus, for the test rig, in order to fit inside of the larger stage, the dynamic seal on the interior stage was machined down by about three thousandths of an inch (7.6e-5 m) on a lathe.

The full mast consists of four stages that were joined in the same manner as the mast test rig. Figure 21 shows the final manufactured stages of the mast. The top of the mast holds a camera mount that was cut on a CNC out of 1/4 inch (0.0064 m) thick aluminum plate, shown in Figure 22 with the camera attached. This was welded together and then welded to the top cap of stage 4. The top three stages needed their diameters to be turned on a lathe to match the designs shown in Figure 10 (stage 4 was already completed thanks to the test rig) and then holes needed to be tapped in them in order to attach the aluminum donuts. The aluminum donuts were also turned on a lathe to fit each mast stage out of aluminum round stock.



(a) (b)

Figure 21: Manufactured Mast Stages

Figure 22: The Camera Mount with Camera Attached

Application of the seals was part of the assembly process of the mast. The seal on stage 4 was not changed since the test rig's success (detailed in Verification and Validation), but stages 3 and 2 still needed seals and wear rings placed on. The wear rings went on without difficulty, but as was discussed earlier in this section, the seals caused a lot of difficulty. After applying the seals for the first time, each stage was fitted within one another and the base mount was welded on, shown in figure 23 with the spring tool balancers attached to it (detailed in following sections). The base mount was poorly designed as was learned during the welding of it to stage 1. Since the mount was made out of 1/8 inch (.0032 m) thick aluminum and stage 1 was much thicker, the two materials heated at different rates, resulting in melting of the mount pieces and poor weld strength. Also, due to a miscommunication, the base mount was welded onto stage 1 with the other stages still inside of it. This resulted in the blowtorch and welding torch heating up stage 1 past the temperature limit of the seals and wear rings. Thankfully, the heat was only able to efficiently transfer to the wear ring and seal at the base of stage 2 and only those two were damaged. After pulling apart stage 2 from stage 1 (this was not an easy task thanks to the melted wear ring), a new wear ring and seal were applied and the seal was machined down again for testing.

Figure 23: The Base of the Mast (mount and spring tool balancers)

Noting that the seal on stage 3 was somewhat deformed due to errors in machining it down on the lathe, testing was conducted anyway to determine the performance of a deformed seal. As expected, in the first test of the four-stage mast system (process detailed in verification and validation) the deformed seal leaked and the mast was taken apart again. After taking it apart, however, the seal on stage 2 was predicted to be too loose to seal as well, so it was decided that stage 2 and 3 seals would be replaced. However, the seal on stage 2 had been machined very carefully to only just fit within stage 1 with some force. It is believed that the welding process affected the shape of stage 1, causing it to be ever-so-slightly oval-shaped and also a different diameter at different places along its length. Since it was also observed that the interior diameter was the smallest at the base of the mast (where the welding occurred), which was not noticed before welding, it isn't likely these changes in diameter and concentricity were present from the manufacturer. Nonetheless, a different method had to be used to apply the seal to stage 2. By putting the stage with a new seal applied into a kitchen freezer, the seal was able to shrink enough to fit into stage 1. However, after testing again, the friction force on this seal was extremely high (since it expanded once it reached room temperature again) and it was unable to compress. With just about one thousandth of an inch (2.5e-5 m) taken off the seal via the lathe, the same freezing process was repeated and every section of the mast sealed and the mast was also able to compress fully, a complete success. Assembly of the hydraulic system attached to it was a relatively trivial process of attaching tubes to each part and ensuring the pump and reservoir had a place to mount to the rover chassis. The full system is shown in Figure 24.

(a)

(b)

Figure 24: Completed Mast System

## 4.2 Electrical

The electrical manufacturing process was completed to integrate a variety of commercial electronics products. To complete this, a wiring harness was created to connect all of the URFs to the Arduino. This wiring harness was soldered to the Arduino and used plastic connectors to attach to the URFs pins. Next, the wires for motor controllers and encoders could be soldered to the Arduino. The IMU and temperature sensors used I2C serial protocols. To connects them, QWIIC connectors were soldered to the Arduino. These connectors carried both power and data. The motors were connected to the encoders using wires with screw terminals for easy connections. Similar screw terminals were added to wires to connect the motor controllers to the main battery. Three power distribution boards were created, while only two were utilized on the final rover. One board was planned to be used to power all of the 5 volt electronics which included the motor controllers, encoders, network switch. This board consisted of three separate 5 volt regulators and corresponding capacitors. Each of these components were hand soldered along with battery connectors that took in a voltage from the secondary 11.1 volt battery. During integration testing, a capacitor on this board was overloaded and burst, catching fire. To avoid this happening again, 5 volt power was switched over to the distribution directly on the Arduino. This may have increased noise from the sensors but was an acceptable concession to avoid another fire. One of the undamaged regulators was used tested and then used as planned to power the network switch. A second power distribution board designed for 3.3 volt was constructed in much the same way as the 5 volt board. This board was tested, but after the fire on the 5 volt board, the 3.3 volt system was also transferred to the Arduino's built in 3.3 volt output. The final distribution board consisted of MOSFETs to switch on and off the mast pump and solenoid. This board was connected to the Arduino for signal and the main 12 volt battery for power. During testing, this board shorted to the Arduino and over volted it. This destroyed the Arduino which was then replaced. The soldering process was repeated for the new Arduino, however, this time the the URFs were not soldered to the Arduino. As for each URF there are four wires to be soldered this was skipped to save time and reduce the chance of a new short. This was allowed as the URFs are not mission critical. Most of the difficulties faced in the manufacturing process arose during testing. A few fixes needed to be completed quickly while some pieces were already mounted on the rover. This caused for some difficulties especially with soldering and managing the cables for tools to be plugged in. After some fixing all of the electrical systems worked successfully.

## 4.3 Software

The manufacturing of the software required the integration of multiple elements from the Robotic Operating System (ROS), Python GUI (PyQT), and Arduino code [18]. Using existing ROS packages and modifying their configuration and parameters the team was able to create a ROS system that handled localization, coordinate transformations, differential drive, and loss of comms. The localization package used was robot_localization [15]. This package handled all the implementation of an Extended Kalman Filter including initialization and selection of process noise. The team was required to format data from the GPS, IMU, and encoders as well as specify the coordinate transformations from those sensor locations to the center of the chassis. For transform specification, the team used the ROS joint_state ecosystem that is included by default with ROS. This package allowed the team to input (x,y,z) sensor locations referenced from the center of the chassis and get back out coordinate transformations. These transformations were then used by the localization package to transform all of the state data to the center point on the chassis. The differential drive package used was ros_control []. This package took in a desired linear speed and angular rate and output a desired motor rate for the left and right motors. The team had to specify the geometry of the rover, specifically the wheelbase dimensions, and give this package speed and angular rate commands. An existing ROS package also handled part of the loss of comms control. Specifically, this package would take in location data from the localization package and compute the necessary linear speed and angular rate commands needed to feed into the differential drive controller in order to command the rover to a desired location. The team had to configure the max speed and angular rate, how closely to follow the previous path, and what to do if the path could not be completed (in this case the rover would stop).

The GUI was created entirely by the team using the PyQT python package. Different displays were created using text boxes and labels to provide the user information on temperature, location, angle, connection, obstacles, and warnings. By listening to the information sent over the communication system the GUI could take data from the ROS ecosystem and output it in an intuitive format for the operator to use. This GUI was running entirely on the ground station computer and thus did not cause bottlenecks in ARGOS's compute time. Figure 25 shows the UI display of the sensor data with an section for warnings.

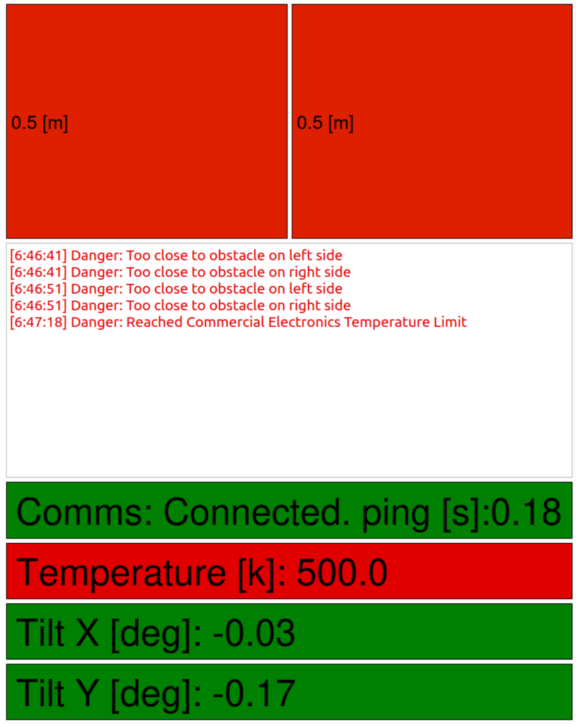



Figure 25: An example output of sensor data from the Ground Station's UI

The Arduino code was run on ARGOS's Arduino Due with the intent of taking in sensor data and controlling the motors and mast. The Arduino connected to the ROS ecosystem using an existing rosserial_python package [18]. The team created all the Arduino code necessary to intake data from the IMU, motor encoders, GPS, and temperature sensor, as well as output commands to the motor controllers, pump, and solenoid valve. The motors were commanded by desired rate and the pump and solenoid valve were controlled by toggling a pin high or low to open and close them.

The surveillance camera was controlled entirely with an existing Sunba package. This software was provided by the manufacturer and the team decided not to create their own version that would integrate with the UI.

Overall the team relied heavily on existing code bases for much of the internal rover control and created new software for the user interface level and the hardware interface level. Figure 26 shows a diagram of the manufactured software indicating parts contributed by the team and those that were pre-made.

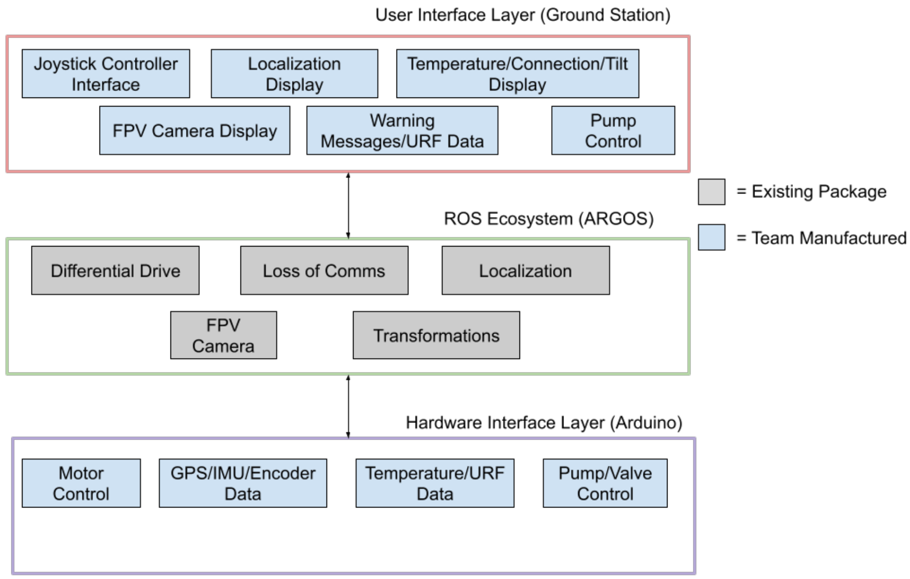



Figure 26: Diagram of Software Manufactured by the team and existing software used.

There were a few major challenges that arose during software manufacturing. Some were solved but one caused the Loss of Comms test to not be completed. The provided Sunba camera control software was only compatible with the Windows operating system, but the team's rover control and UI software required a Linux operating system to run. A few possible solutions were explored for this incompatibility. First, the team tried running the Sunba software on Linux using Wine, a software for Linux that translates Windows commands to Linux [21], but the networking necessary to connect the camera was not handled by the Wine software so this option was discarded. The team also tried getting the ROS software to run on Windows, but multiple of the ROS packages that the team used were not compatible with the ROS Windows version. The ultimate solution that the team used was running a virtual machine (VM) instance of Linux on a Windows computer. The Windows instance would handle the Sunba camera control while the Linux instance would control the UI. This solution worked well as it allowed all software to run on their native operating system.

Another manufacturing issue was getting noisy encoder data into a readable format that could be used with the localization and differential drive software. Without any post-processing of the encoder data, jumps in rate and number of ticks caused the feedback loop in the differential drive control to break down. This software was critical for the Loss of Comms test as the rover would be controlled autonomously and any errors in the encoder data would propagate to errors in commanded position. An operator could correct this error, but the autonomy was not sophisticated enough to do so. Unfortunately, the team ran out of time to solve this issue, but the planned solution was a combination of software and hardware. On the software side, a filter layer between the differential drive and the encoder data could be added to the Arduino code that would remove any significant outlier data points. On the hardware side, an electronic filter chip could be added, specifically the LS 7184 encoder filter chip. The combination of these to physical and software-based filters would likely have made the data smooth enough to be used with the rest of the code.

# Section 5: Verification and Validation (V&V)

Victoria Gonzales, Niko de Boucaud, Jarrod Teige, Nick Kuljis

## 5.1 Mobility Tests

Mobility tests for ARGOS were performed to verify its ability to satisfy the functional requirements involving the rover's movement. These requirements are encompassed by FR.1 which is: the child rover shall move from a starting location to a commanded location of interest and return to the starting location. The design requirements that flow down from this functional requirement that were focused on in testing include MOV.1.1: The child rover shall be able to perform a 360 degree turn, MOV.1.2: The child rover shall be able to travel in forward and reverse motion, MOV.1.3: The child rover shall be able to travel up and down slopes of 20 degree inclination, and MOV.1.4: The child rover shall be able to travel over obstacles with heights as tall as 7 cm. This testing could only be done once many other subsystems were integrated with the drivetrain such as the software for controls, power systems, and communications. This means that testing could potentially show errors in multiple subsystems.

Initial mobility testing was an informal commands to the rover that took place in the projects room. This testing included commanding the rover forwards, backwards, and a 360 degree turn. All of these initial tests went as expected and the rover moved even faster than initially predicted. A temporary 20 degree incline was also made and the rover was able to drive up and hold position on the ramp. This initial testing was considered successful and a more complete and formal test was planned.

This more complete testing was done once the rover was capable of moving without a tether to the ground station. A more stable and complete ramp was constructed for this test which includes an incline section, a flat section, and a decline section, each a little longer than the body of the rover. This testing also took place outside behind the Aerospace Building. This test began with basic movements forwards and backwards, during these movements the rover's controls were very sudden and resulted in an increased amount of jerking motion while driving. This is due to the power applied to the rover in the software was not ramping up which results in very abrupt motion. However the main result that occurred during this testing happened during the incline test. When the rover was commanded to drive up the incline it could again successfully drive up and hold position on the incline; However, when the rover attempted to transition from the incline section to flat section the motors stalled. This led the team to declare the incline test unsuccessful. The pictures below show where the rover could make it to on the ramp successfully before stalling and the rover outside during testing.

Figure 27: Rover on Incline

Figure 28: Rover outside during testing

The team believed that the reason the motors stalled due to becoming over torqued. To resolve this issue, new gearboxes with a higher gear ratio were purchased along with new motors in case the original ones became damaged during testing. Furthermore, it was determined that this was not originally modelled correctly due to a gross underestimate of the mass in the incline model. To really ensure the motors would not be over torqued again, the gear ratio was increased from 64:1 to 100:1. This decision was made because the team did not have the time or money to replace this system again if it failed again, so a higher ratio that will decrease the speed of the rover but greatly increase the torque capacity of the motor was chosen. Once these parts were ordered, arrived, and installed, another incline test was planned.

The second incline test took place in the Aerospace project room. After some setup, the rover successfully made it up the incline and overcame the transition to the flat portion of the ramp with no problems as well as driving down the ramp with ease. It was determined that the high ratio gearboxes fixed the rover's previous problem with the motors becoming over torqued and slope testing was completely successful.

## 5.2 Mast Tests

Both the two stage and full mast test were performed to satisfy functional requirement three: The child rover shall use a mast to take photos and video from a vantage point above the rover's body. This functional requirement was determined successful from testing based on design requirements SURV.3.1: the child rover shall have a mast capable of extending to a height of 2 meters and retracting to original height, and SURV.3.2: the child rover shall have a mast capable of supporting 5 kg of weight on the top. The success of testing was based on these requirements and the method of testing and results are discussed below.

### 5.2.1 Two Stage Mast Test

The initial test of the mast was performed with the goal of determining if the team would move forward with the a fully manufactured hydraulic mast or to change course and purchase a commercial off-the-shelf (COTS) pneumatic mast instead. The COTS mast has a number of downsides compared to the hydraulic mast including cost, complexity of the pneumatic system, programming complexity and power consumption. However, if the hydraulic mast was deemed too difficult to manufacture to be feasible, the alternative was required. This initial test with only the top two stages of the mast will indicate whether or not the design is feasible to manufacture.

This test was performed in the aerospace building in one of the testing rooms near the machine shop. First, the reservoir and mast were filled separately with hydraulic oil using a funnel, then sealed and connected. Then, the mast and reservoir were both clamped to a test stand. A large barrier for the team's safety was used in case a catastrophic failure. The airline was connected to the reservoir and once the team was safely behind the barrier, the system was pressurized. The pressure was increased until the second stage started to raise. This pressure was recorded and then the system was depressurized. The mast did not compress on its own, so the weight required to fully compress the mast was also recorded. This test was repeated twelve times and the testing setup is shown in Figure 29

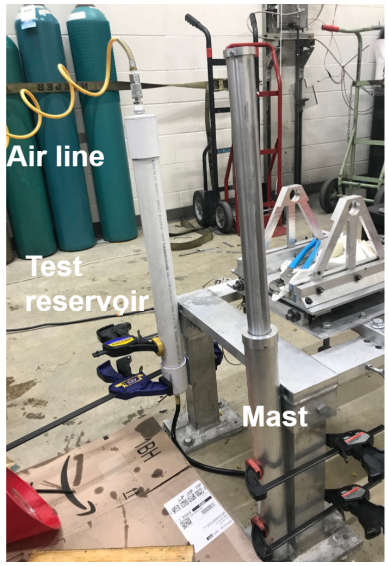



Figure 29: Two-Stage Mast Test Rig Set Up

After testing was completed, the team came to several conclusions based on the results. First, the test was completely successful as the mast could extend to full height and compress, with the addition of weight, fully with no leakage or damage. What was unexpected was the amount of additional weight needed to compress the mast, which was around 30 lbs (13.6kg) of mass. This cannot be achieved by just the weight of the camera so an additional system needed to be added to achieve compression before deciding to move forward with this mast concept. The solution the team came up with was a constant force spring mechanism than could apply enough force pull the sections down during compression. The constant-force springs chosen for this application were in the form of two tools known as spring tool balancers, used for holding heavy tools so that the tool can be let go of and hung safely nearby. The spring tool balancers are mounted to the base mount of the mast, which only required minor modifications to the design for implementation, where their cables are redirected upward by pulleys to attach at the top of stage 4. With each spring capable of applying between 7 and 15 lbs (3.1 - 6.8 kg) to the top of the mast (maximum force is adjustable via a dial on the constant-force springs), the downward force on the top of the mast can reach the 30 pounds of force required to compress it fully. With this solution in mind, the fully manufactured mast design was deemed feasible and the team chose to move forward with it.

#### 5.2.2 Full Mast Test

From the results of the test rig, the hydraulic mast was selected over the COTS pneumatic mast system. The next phase of testing consisted of the four-stage mast test. As discussed in the manufacturing section, multiple tests were conducted on the system, with manufacturing stages in between until it successfully completed the tests. In order to test the final mast design, a similar test to the two stage mast was conducted. The only difference in the test procedure is that instead of using a hydraulic fluid reservoir and an air compressor this test used the hydraulic fluid reservoir and the hydraulic pump that will move the hydraulic fluid from the reservoir into the mast.

The test started with filling the reservoir and mast with hydraulic fluid using a funnel. Once this was completed, the reservoir, pump, and mast were connected as shown in Figure 8 and were fastened to a wooden board for testing. The wooden board was clamped to some stools to keep the system off the ground. The system was then bled in order to remove any air still left inside the tubes or mast itself. Then the pump was turned on and the mast was observed extension, looking for any binding of the stages. Once fully extended, the pump was turned off and the solenoid valve was opened in order to allow fluid to flow back into the reservoir. While the mast compresses, it will also be observed to confirm that no binding of the stages occurs. This test was completed multiple times, both without the cable retraction system attached and then with it, in order to to test the durability of the system. As described previously, after one test failed due to a leaking seal and one test failed due to binding during retraction, the mast passed the final testing set without leaks and with full retraction thanks to the spring tool balancers. It was able to extend to its full height of 2.85 meters and retract back down to its compressed height of 0.56 meters. Multiple weeks later, during the full system test, the mast successfully extended to its maximum height, but then compressed all but about 2 inches (0.05 m) of the way down. It isn't clear what caused this slight difference in results as the full system test was conducted at the same temperature as the others and no additional weight was added to the mast. It seems that the seals may be breaking themselves into the interior sections of the mast and possibly sealing better, but also increasing friction. Shown in Figures 30 and 31 is an image from the full system test wherein the mast was raised and data was captured.


Figure 30: Full System Test Extended


Figure 31: Full System Test Compressed

### 5.3 COMM Tests

To verify functional requirements one and four, the rover must have the ability to transmit live video, photos, all sensor data, and receive commands at a range up to 250 meters away. To ensure that this is feasible, three tests were conducted. An open field test to verify our free space path loss model, An attenuation test that was conducted in a similar environment ARGOS will be operating in, and a full data throughput test to verify that the communications system has the bandwidth capable of handling all the data from the sensors running concurrently.

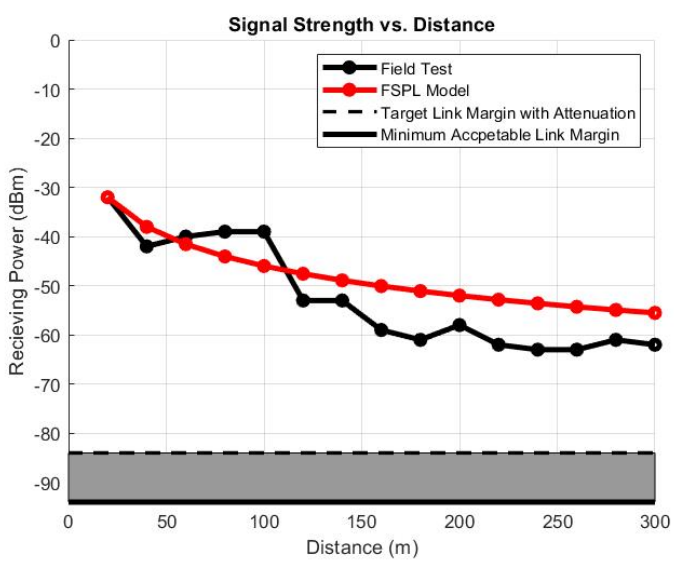



Figure 32: Open Field Communications Test

The open field test consisted of walking one of the two Rocket M2 radios out to 300 meters at

20 meter increments. The bandwidth and receiving power was recorded at each increment.

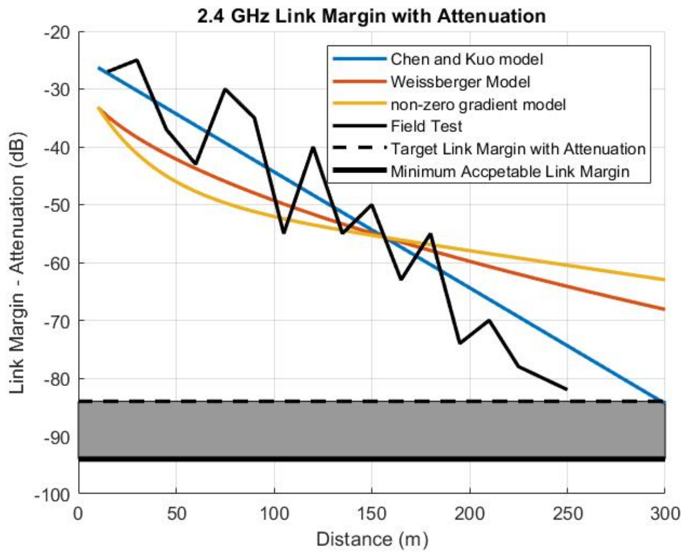



Figure 33: Communications Attenuation Test

The attenuation test consisted of walking one of the two Rocket M2 radios out to 250 meters at 20 meter increments in a forest environment similar to what ARGOS will be operating in. The bandwidth and and receiving power was recorded at each increment.


Figure 34: Total Data Throughput Test

By running all the sensors on the rover concurrently, our team was able to obtain the maximum data rates the communications system will be handling.

Table 4: Communications Testing Results

| Test | Result | Implication | Comparison to Model |
|---|---|---|---|
| Open Field | 23 dBm left of 57 dBm link budget @ 300m. Bandwidth of 41MBps @ 300m | Design meets FR1 at Level of Success 1 | Predicted 28 dBm left of 57 dBm link budget @ 300m. |
| Attenuation | 2 dBm left of 57 dBm link budget @ 250m. Bandwidth of 27Mbps @ 250m. | Design meets FR1 at Level of Success 4 | Predicted 10 dBm left of 57 dBm link budget @ 250m |
| Full Throughput | Maximum data rate of 4 Mbps Margin of 23Mbps | Design meets FR1 at Level of Success 4 | Predicted maximum 5.7Mbps |

From the open field testing, there was 23 decibal-milliwat (dBm) of the 57 dBm link budget with a bandwidth of 41 megabits per second (Mbps) at a range of 300 meters. This satisfies FR1. at a level of success one. The model's predicted link budget was 28 dBm out of the 57 dBm. This 5 dBm discrepancy is likely due to the radio's receiver sensitivity and alignment of the directional antenna to the second radio. For the attenuation test, there was 2 dBm left of the 57 dBm with a bandwidth of 27 Mbps. This satisfies FR1. at a level of success four. The model's predicted link budget was 10 dBm left outof the 57 dBm. This increase in the rate at which the signal is attenuating is likely due to the loss in the line of sight of the second radio, because of the elevated terrain between both radios. Ideally, conducting more tests would likely decrease the discrepancy between the physical data and model's predicted data. The final test conducted was the total throughput test. The maximum data rate achieved was 4 Mbps out of the 5.7 Mbps predicted data rate with all the sensors running at once. This meets FR1 at a level of success four.

## 5.4 Loss of COMM Test

To satisfy design requirement COM.4.1: Upon loss of communication, the child rover shall return to its last known GPS location. A loss of communications test needed to be conducted to ensure that rover has the ability to backtrack its previous movement and return to the last recorded GPS location within the predicted maximum deviation of .51 meters at a factor of safety (FOS) of 1.5. The test would consist of manually cutting off communications to ARGOS, after not receiving a confirmation ping from ground station after 5 seconds, The rover will retrieve the stored movement data after one minute, invert the path, and back-track to the last recorded GPS coordinates, which is being recorded at a frequency of 10 Hz. This will go on loop until communications has been successfully reestablished. Due to large delays in shipments and noise in the encoder data, the loss of communications testing could not be accomplished given the time constraints.

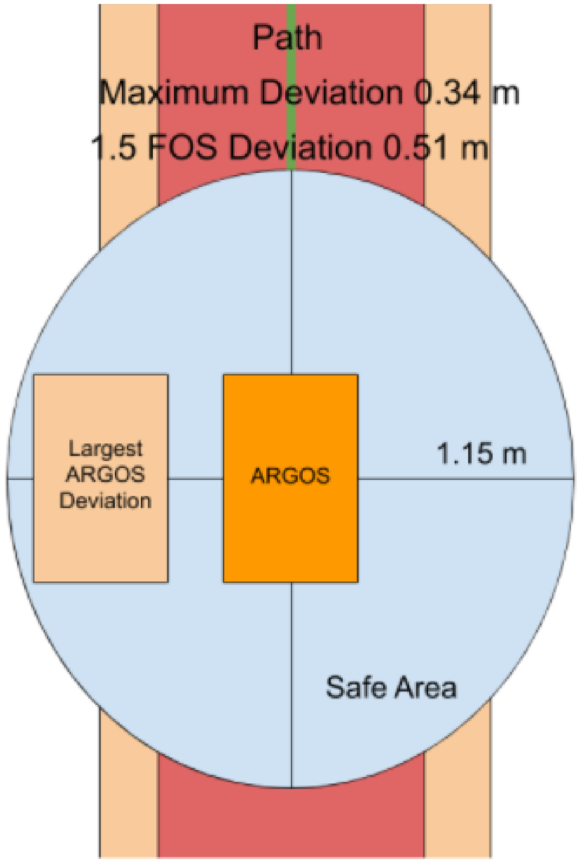



Figure 35: Loss of Communications Flow Chart

### 5.5 Full Mission Simulation

The full mission simulation for ARGOS aims to test the full operational ability of the rover. The simulation will combine aspects of tests covered above including mobility test, mast test, and COMMs test. It will further prove our levels of success as well as show successful subsystem integration and operation. The mission overview is displayed below.

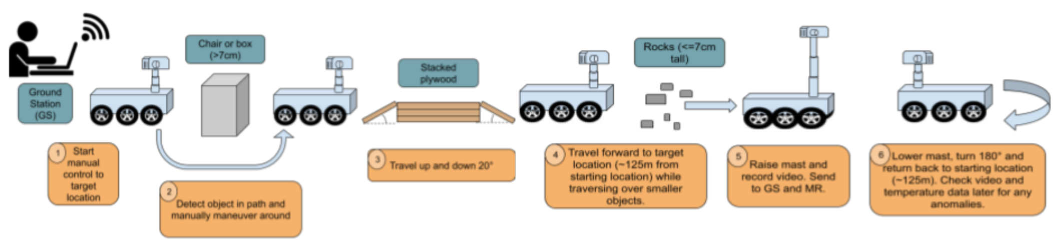



Figure 36: Full Mission Simulation Diagram

The rover was brought to an open grass field south of the Aerospace building at CU Boulder. As the diagram shows, the first step is to identify and avoid object. Then the rover is to ascend the plywood ramp similar to mobility testing. After this the rover is to extend the mast, take temperature readings, and use the camera to observe location before retracting mast and returning home.

During the test, the rover was able to successfully connect to ground station and be manually controlled using a Xbox controller at 125m. The user was also able to see the GPS location, temperature data, and video output on the user interface. The mast was able to extend and retract successfully. And the surveillance camera was powered on. The user had pan, tilt, and zoom control from the ground station. However, there were some issues with the drive train. The wheels began to shake while given high speed and turning commands. This was most likely due to the new higher ratio gear boxes. Going from 64:1 to 100:1 may have changed the movement dynamics since the first mobility tests. It also could have come from the axles and chains not being fastened tightly.

Overall the mission simulation demonstrated all subsystems of the rover integrated and performing together. If there was more time in the testing window, the rover mobility issues would have been able to be addressed.

# Section 6: Risk Assessment and Mitigation

Henry Felstiner

The following section discusses the major risks that the team predicted would affect the project in the fall. These risks were monitored during the testing phase of the project. This section also discusses the steps that were taken to mitigate these risks. The four major risks centered around software development, design of hydraulic mast, attenuation of communication signal, and overheating of the motors. Finally, this section discusses the issues that did occur during testing, such as the hydraulic mast leak and also failure of the motors during testing.

## 6.1 Quantifying Risk

The quantification of risk for this project is broken down into two types of risk: technical and scheduling risk. The technical aspect of risk will look at the subsystems that require a complex design and manufacturing limitations. The scheduling risks will take into consideration subsystems that are not as technically complex, but are expected to be time consuming. The risks will then be placed into numerical categories based on their severity and likelihood. Figure 37 shows a detailed breakdown for the definitions of each level of severity in technical and scheduling.

| Levels | Technical | Schedule |
|---|---|---|
| 1 | Minimal or no impact | Minimal or no impact |
| 2 | Slightly below expectations but still in operational requirements | More time required to complete task but still able to be completed by time deadline |
| 3 | Slightly below operational requirements, needs minimal modification to design | Minimal schedule slip and completion deadline needs to be moved back |
| 4 | Performance is at an unacceptable level, off ramp design or redesign of subsystem is necessary | Schedule is pushed back to an extent that the critical path of the project is delayed |
| 5 | Unacceptable performance that does not have a solution | Key milestones in the project are unachievable |

Figure 37: Definitions of Severity Levels

The likelihood of occurrence for each risk is also broken down into five levels which include improbable, remote, occasional, probable, frequent. These levels of likelihood are listed in order of increasing likelihood.

## 6.2 Risks: Before Mitigation

The first risk that was monitored during the semester was software development. This risk is a scheduling risk due to the volume of ROS packages that had to be modified and connected in order for ARGOS to complete its mission objectives. Therefore, based of the severity and likelihood definitions in Figure 37 this risk was a level five severity and a level five likelihood risk.

The second risk that was monitored was the hydraulic mast design. This risk was a technical risk due to the design complexity and also the connection between each nested stage. Also the complexity of manufacturing contributes to the severity of the risk since the tolerances have to be exact in order to eliminate the possibility of fluid leaking from the mast. Therefore, this risk based on the definitions above falls under a severity of four and a likelihood of four.

The third risk monitored was the attenuation of the communication signal from the ground station to ARGOS. This risk was a technical risk since the rover has to have a large enough link budget in order to avoid loss of communication which would lead to the possible loss of the rover during its mission. This would cause the rover to not meet its functional requirement of sending live photos and videos back to the ground station operator. Therefore, this risk was considered to be a severity level four and likelihood level three.

The fourth and final major risk that was monitored this semester was failure of the drive terrain due to the motors overheating. The cause of the overheating is due to the motors stalling in rough terrain. If the motors fail during the mission the rover would be unable to complete its functional requirement of traveling 250m round trip. Therefore, this risk was ranked as a severity level four and likelihood level three.

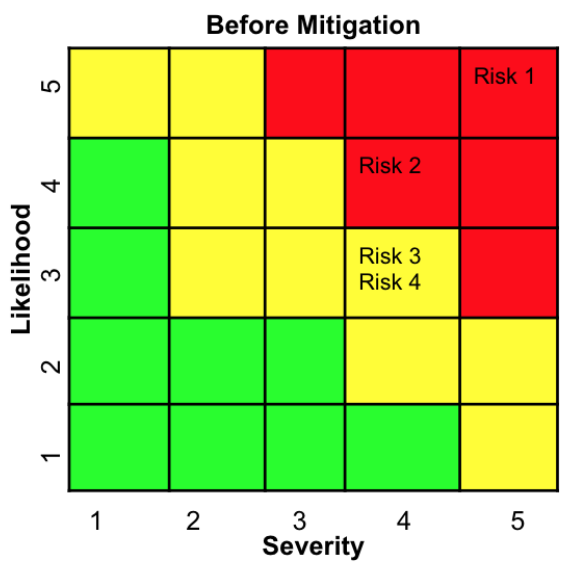



Figure 38: Risk Matrix Before Mitigation

The figure above displays a 5x5 matrix and the four major risks that were monitored before mitigation.

## 6.3 Risks: After Mitigation

In order to reduce the severity and likelihood for the four major risks, steps to mitigate the risks were taken for the rover development this semester.

For the first risk which is the software development of the rover most of the ROS packages used in processing data in the Intel Nuc have already been completed or started. In addition four team members have been assigned to this subsection and shall be conducting frequent code reviews. The final mitigating step for this risk is that ROS packages are being used in which the team members have experience using in other projects. Therefore, based off of these mitigation strategies the severity level for this risk decreases to a three and also the likelihood decreases to a three.

For the second risk which is the hydraulic mast a test mast with two stages has already been developed and send to the machine shop for manufacturing. The mast will be tested next semester and if the mast doesn't satisfy testing requirements by January 22ND of next year, then the COTS mast will be chosen and deployed on the ARGOS rover. From these mitigation strategies the severity level is reduced to a two and the likelihood is reduced to a three for risk two.

The mitigating steps taken for the third risk, which is the attenuation of the communication signal, include an early test of the communication system in the phase one testing schedule. The communication system will also use high gain antennas which provide a factor of safety of 1.5 to the link budget, ensuring that likelihood of loss of communications is minimized. Finally, using a ROS package to design for a loss of communication scenario in which the rover will return to the last known GPS coordinate where communication was occurring. This will reduce the severity level of this risk down to level two and will also decrease the likelihood to a level one.

For the final risk the mitigating steps taken to reduce the likelihood and severity of the motors overheating for stalling include adding vent plate spacers and heat sinks to the motor. Both of these components will ensure that sufficient airflow reaches the motor inside the chassis during operating conditions of the rover. This will reduce the severity level down to a two and the likelihood down to a level two.

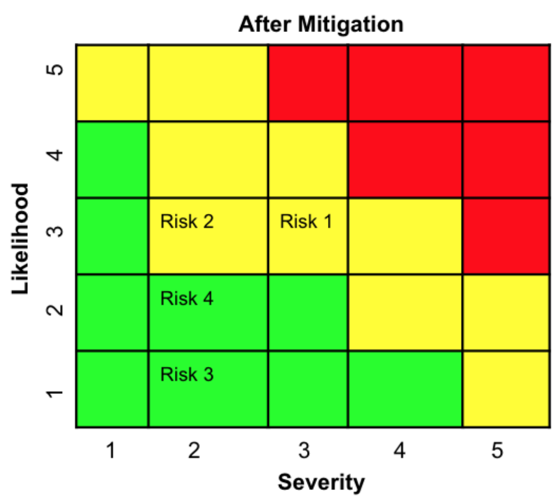



Figure 39: Risk Matrix After Mitigation

In Figure 39 the 5x5 risk matrix after mitigation is shown with each of the four major risks identified.

## 6.4 Risk Assessment Results After Project Completion

This section will discuss the results of the mitigating steps taken during this semester and the unforeseen issues that arouse during the semester.

For Risk 1 the complexity of the code in scheduling was well accounted for and the time margin allowed for code development allowed for timely completion of code development. The weekly code review sessions allowed for plans for debugging the code and the steps that needed to be taken to complete task on time. The only issue that faced code development was the delayed delivery of parts which let to the cutting of the autonomous loss of communications protocol from the rover. Therefore, overall the risk assessment and mitigating step taken for risk 1 can be considered a success in this project.

For Risk 2 the technical complexity of the mast and the tight manufacturing tolerances a few issues arouse during the semester. The first issue occur ed during the the two stage mast test in which the mast was unable to return to its compressed height. This was caused by the tight manufacturing tolerances that were needed to seal the mast causing more frictional forces than predicted. To fix this a spring system was added to the mast to pull the mast back to its compressed height. The next issue that occurred was a leak of the full mast during integration testing which was also caused by the seals, this time the seal in the first stage failed during extension causing hydraulic fluid to leak out of the mast. To fix this a new seal had to be put in the stage which fixed the issue. Overall the prediction that risk two would be a likely occurrence was accurate and the team was prepared to to deal with the issues that arouse do to planning and time allotted for mast development.

For Risk 3 no major issues arouse during testing of the communication system and when integrated with the rover the communication system functioned as expected. Therefore, the mitigating steps taken result in the communication functioning as expected.

For Risk 4 a major failure occurred during the testing of the motors on the rover. This was caused by a 20kg weight growth in the rover which wasn't properly monitored during development. Therefore during testing of the rover the team was unaware of the large load being placed on the 64:1 gear ration motors. This caused the motors to completely fail and be unusable. The team order new motors with a high ratio of 100:1 to account for the weight growth of the rover. Once tested again the new motors functioned as expected. Therefore, the severity of risk placed on risk 4 was underestimated due to the fact that the weight growth of the rover wasn't properly accounted for.

# Section 7: Project Planning

Margaux McFarland

The following section details the project planning for the past year. This includes an Organizational Chart of the team's structure and responsibilities, the Work Breakdown Structure of what tasks have been completed and what did not get completed, the Work Plan or schedule to complete the tasks for the Work Breakdown Structure, the expected Cost Plan compared with the actual budget, and, finally, the Test Plan for each phase of testing that was completed.

## 7.1 Organizational Chart

In Figure 40, the Organizational Chart depicts the flow down of responsibility from top to bottom and each team member's role and responsibilities. At the top is the project's customer and advisor which flow advise and instruct the project manager who organizes and delegates all tasks and helps manage the following four general leads. The Safety and Test Lead is tasked with creating tests plans and managing any safety concerns as well as mitigating any high risks for the project. The Chief Financial Officer helps manage the overall project budget and places any orders for part or materials. The Manufacturing Lead reviews all design's manufacturability and ensures that all components are manufactured within appropriate time and budget constraints. The Systems Engineer oversees all the high level technical aspects of the project and from the Systems Engineer stems the technical leads for each subsystem of ARGOS: Structures, which consists of the drivetrain and chassis, Mast/Camera, Sensors, Electronics, Software, and Communications. The technical leads helped carry out and assign smaller tasks to other contributors for that subsystem.

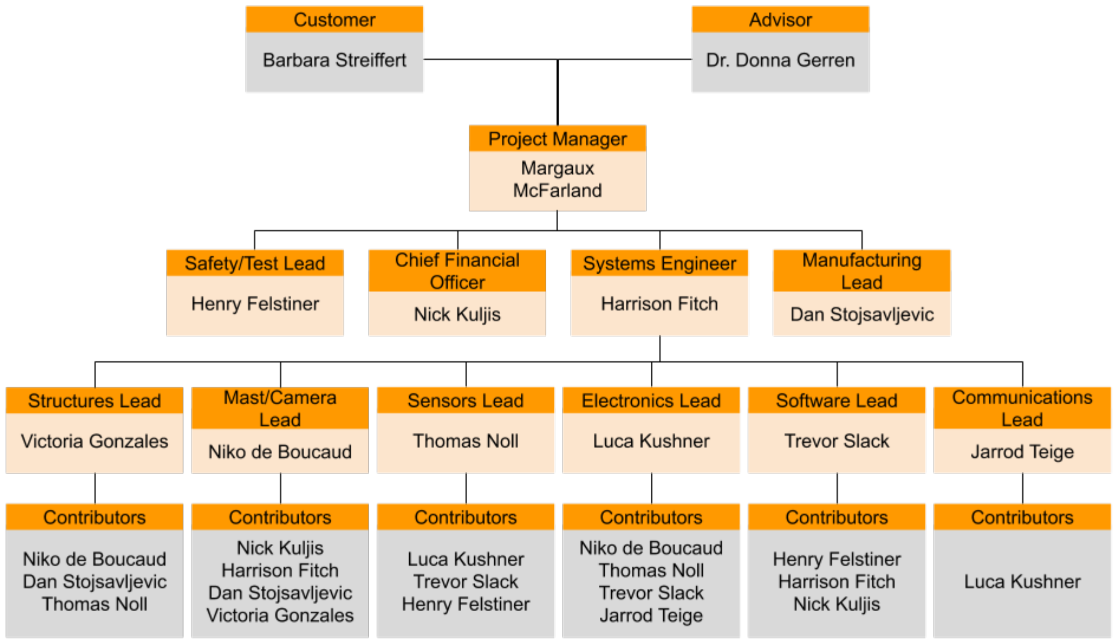



Figure 40: Organizational Chart for ARGOS

## 7.2 Work Breakdown Structure

The Work Breakdown Structure in Figure 41 details the work that has been completed in blue and was not completed this year in grey. The tasks are broken down into deliverables such as reviews and reports, tasks for certain subsystems, and integrated tasks. All subsystems completed the preliminary models, parts and individual component selection, and final design determination first semester during the planned process. During the second semester, the subsystems completed their their manufacturing and initial component and subsystem tests. The full system was entirely integrated and then a full mission simulation was competed; however, the loss of comm test was not able to be tested on the completed system due to time constraints.

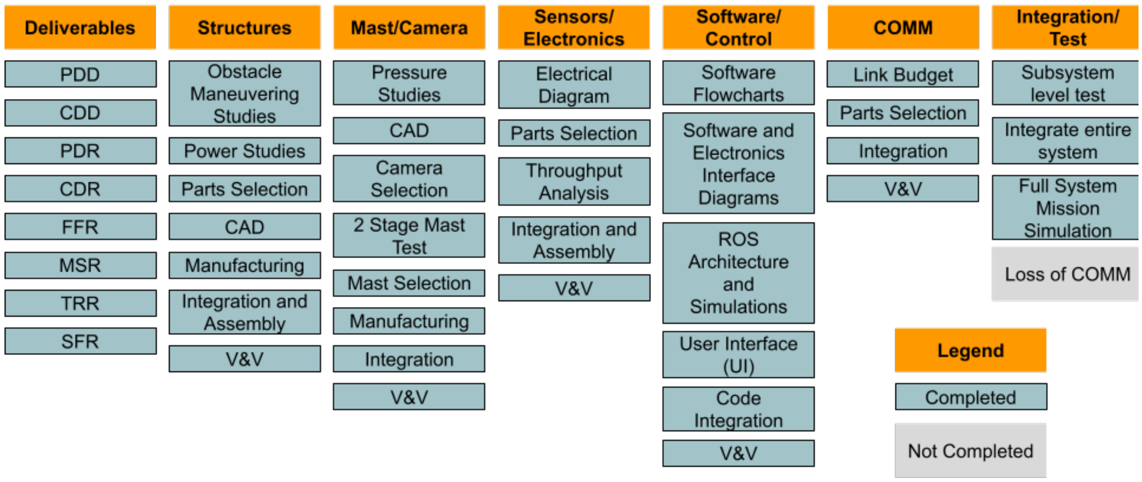



Figure 41: Work Breakdown Structure for ARGOS

## 7.3 Work Plan

The necessary tasks and milestones for manufacturing, testing, and integration of the project were organized in a Gantt Chart. The full Gantt Chart for all of the spring semester is illustrated in Figure 42 in order to see all the dependencies for the tasks and the relative order. Zoomed in views for each task group, which were split up according to subsystem, are outlined below. The critical path for each task group, as seen in green, follows the order: manufacturing, phase 1 testing, assembly and integration, phase 2 testing, final integration, then phase 3 testing.

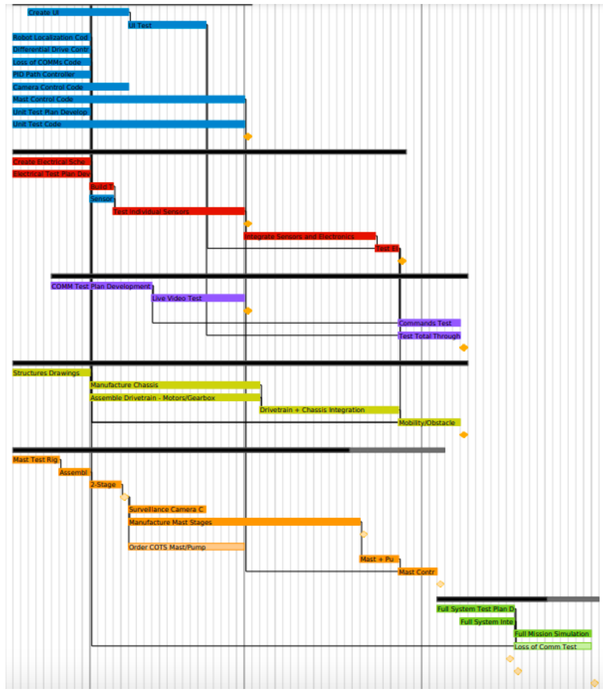


Figure 42: Full Gantt Chart

The software tasks and electronics/sensors tasks, shown in Figure 43, consists of manufacturing and code development, test plan development and testing. The software subsystem only had a phase 1 test, or unit tests, for sections of the code. The rest of the code was tested with other subsystem tests. This was completed March 1 along with the electronics and sensors phase 1 tests. Testing each sensor took longer than originally planned for because components took longer to arrive, and there were issues with the encoder testing code. Later, it was determined that a cable was never delivered that was necessary to test the encoders.

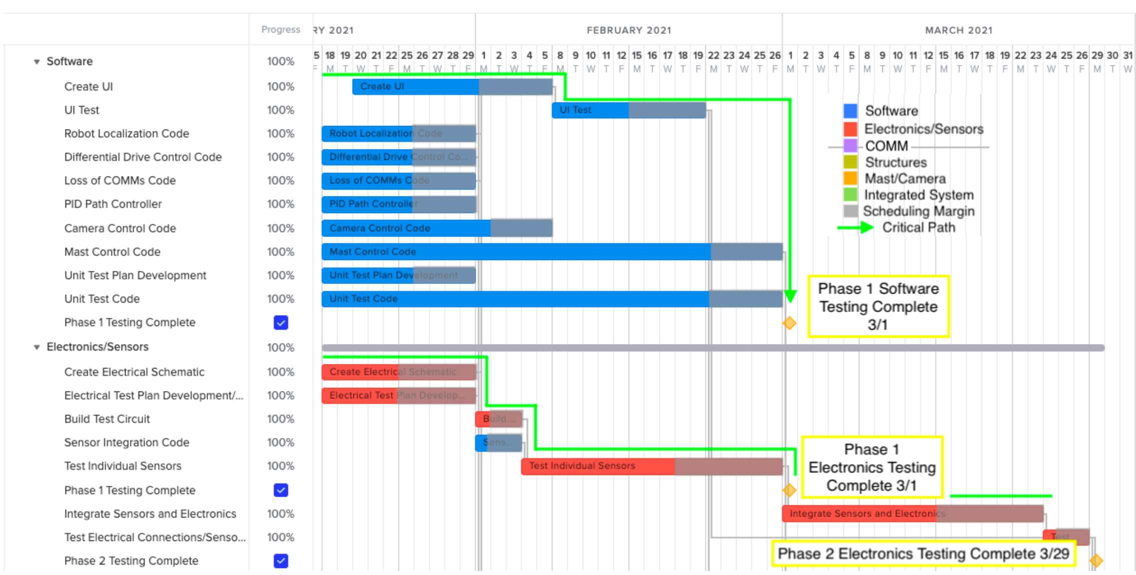



Figure 43: Gantt Chart: Software and Electronics/Sensors Tasks

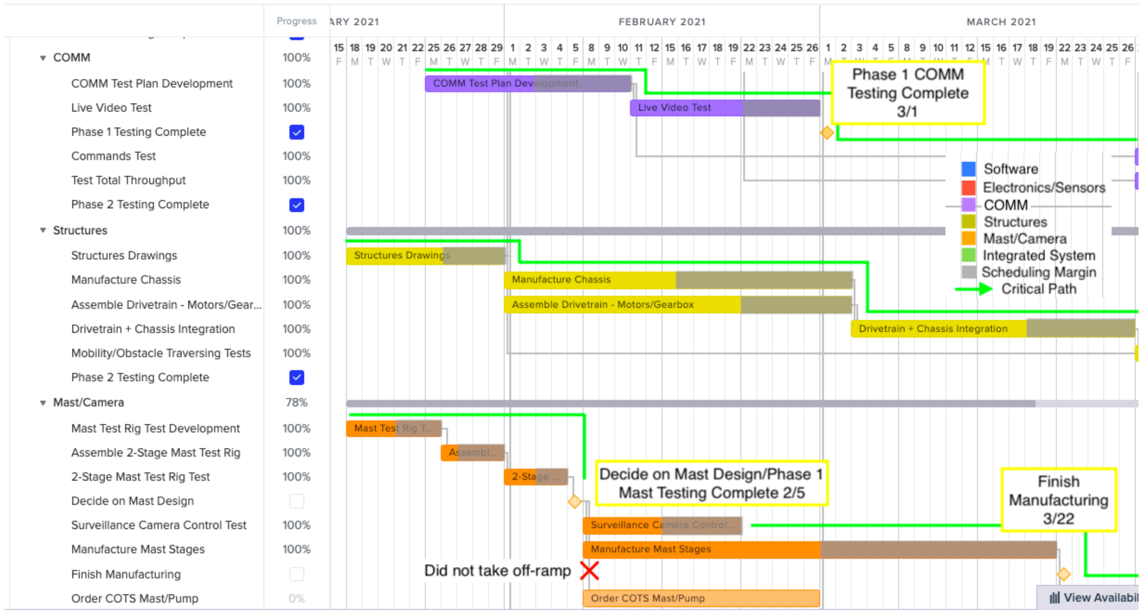



Figure 44: Gantt Chart: COMM/Structures/Mast Tasks

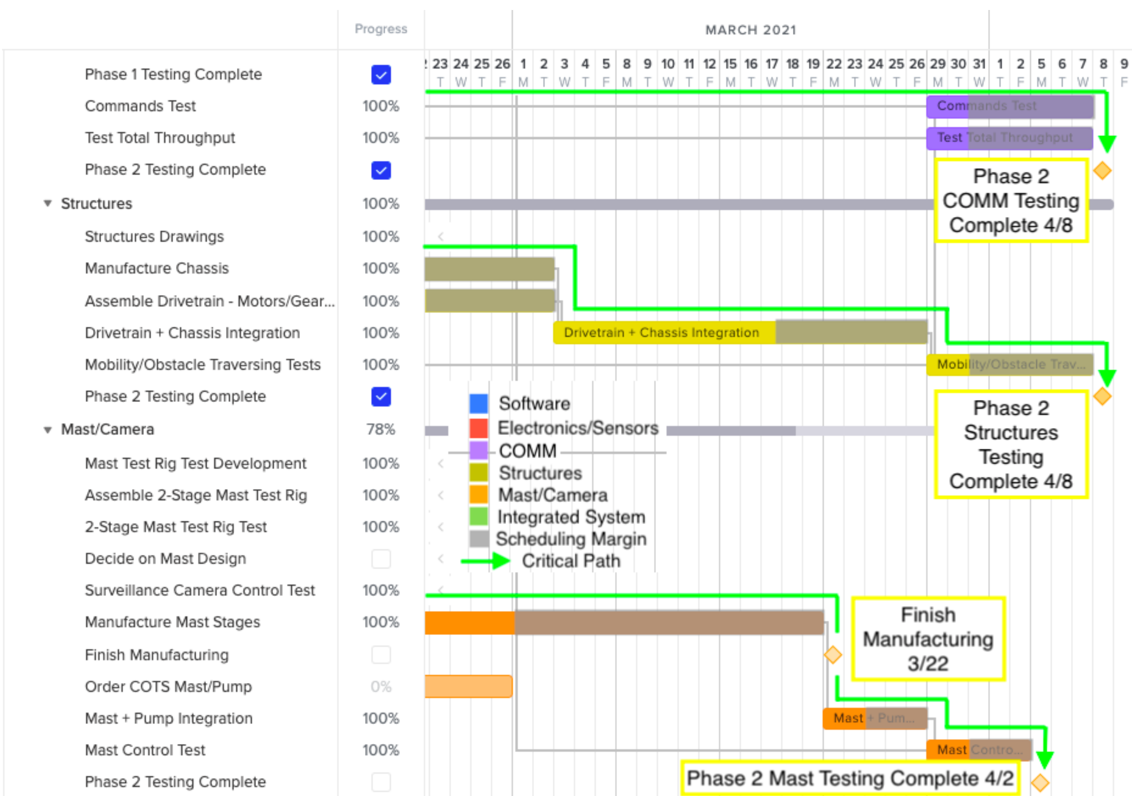



Figure 45: Gantt Chart: COMM/Structures/Mast Tasks continued

Figures 44 and 45 illustrate the tasks for the COMM, structures, and mast subsystems. Figure ?? has the manufacturing and phase 1 testing tasks for each subsystem, while Figure 45 has mostly integration and phase 2 testing tasks. More scheduling margin, which can be seen in grey on the figures, was added to manufacturing tasks because there was more uncertainty on how long those tasks would take and when the machine shop would get started on the tasks. In addition to the machine shop having a lot of other projects they had to manufacture and machine for at the same time as this project, the mast was a complex component to manufacture. Therefore, the mast manufacturing task had about three weeks scheduling margin built in. This allowed for enough time to manufacture everything on time, and even start mast integration before scheduled.

Lastly, the full system tasks were to be completed after phase 2 testing was completed. These tasks are shown in Figure 46. Similar to the subsystem task groups, the critical path for this task group flows from test plan development and integration to testing. The full mission simulation and the loss of COMM tests were to be completed April 30. The full mission simulation was completed ahead of schedule on April 26, but the loss of COMM test was not able to be completed as stated in the Work Breakdown Structure.

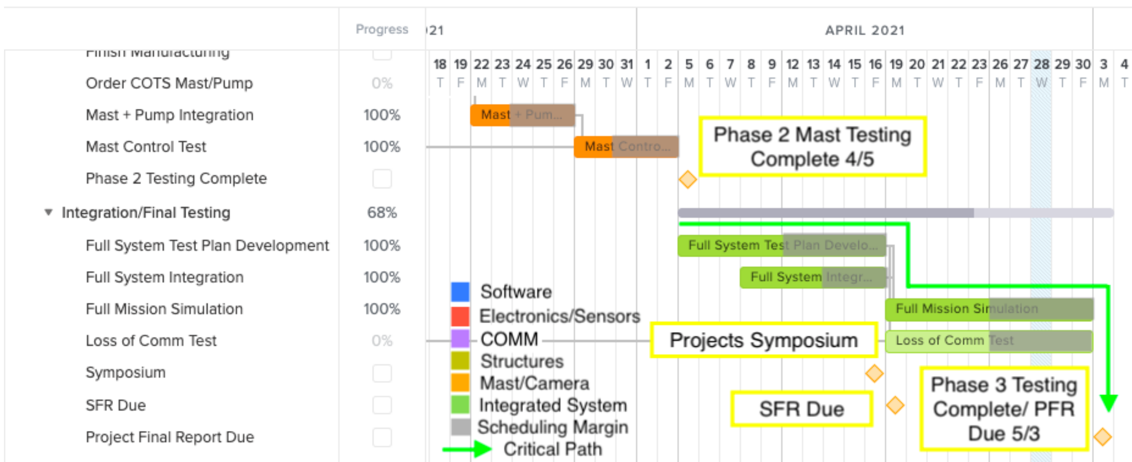
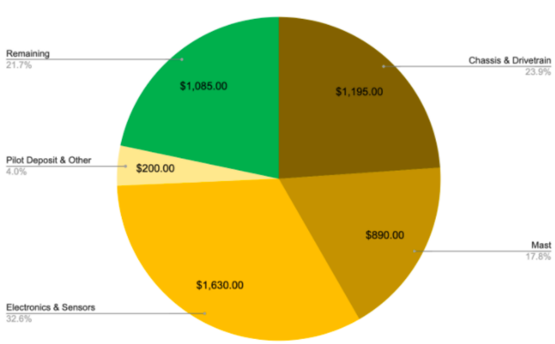


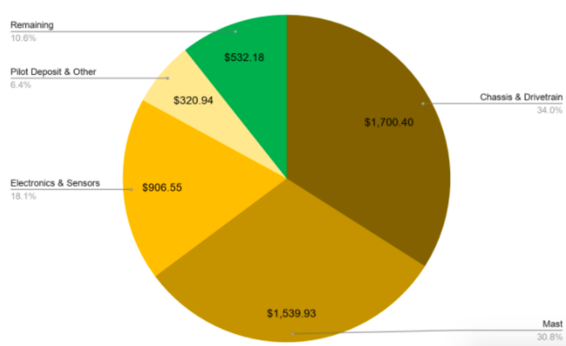

Figure 46: Gantt Chart: Fully Integrated System Tasks

## 7.4 Cost Plan

The planned budget for this project as well as the actual budget can be seen in Figures 47a and 47b, respectively. The breakdown of cost for each major subsystem and category can also be seen in Table 5. This illustrates how more was spent on the drivetrain, chassis, and mast than originally planned, but less was spent on electronics and sensors. This was in part due to rented equipment from the electronics shop, like the Intel NUC. Overall, there was a $752.82 difference from the planned budget or about a 15 percent increase of the total $5,000 budget.




(a) Planned Budget




(b) Actual Budget

Table 5: Breakdown of Estimated and Actual Costs

| Category | Estimated Cost ($) | Actual Cost ($) |
|---|---|---|
| Chassis/Drivetrain | 1,195 | 1,700.40 |
| Mast | 890 | 1,539.93 |
| Electronics/Sensors/COMM | 1,630 | 906.55 |
| Pilot Deposit and Other | 200 | 320.94 |
| Total Cost | 3,715 | 4,467.82 |
| Margin | 1,285 | 532.18 |

## 7.5 Test Plan

All the tests conducted in the spring semester are broken down into three phases. The first phase consists of individual component testing, the second phase involves more integrated subsystem testing, and the third and final stage consists of tests that involve a fully integrated system. Each test in the three phases are outlined below.

### Phase 1 Testing

Table 6 shows all the major component tests, their completion date, testing facility, and special equipment. All these tests were successful, meaning each part's functionality was validated and more integrated tests could be complete. Phase 1 testing was completed by March 1, 2021.

Table 6: Phase 1 Tests

| Phase 1 | | | | |
|---|---|---|---|---|
| **Subsystem(s)** | **Test** | **Date** | **Testing Facility** | **Equipment** |
| Mast/Camera | • Mast test rig - fit of tubes, leaks | 2/4/21 | Aero Machine Shop | Compressed air supply |
| Sensors | • Individual sensor accuracy and throughput | 3/1/21 | Aero Building/at Home | Test circuit/controller |
| Software | • UI of ground station with sample data<br>• Unit Tests | 3/1/21 | At Home | none |
| COMM | • Live video | 3/1/21 | Outside | Ground station |

### Phase 2 Testing

Table 7 shows all the major subsystem tests. These tests required more integrated and assembled subsystems and also used completed software and electronics that were tested in Phase 1. Phase 2 testing was completed by April 8, 2021. This was in time to present the results at the Projects Symposium on April 16.

Table 7: Phase 2 Tests

| Phase 2 | | | | |
|---|---|---|---|---|
| **Subsystem(s)** | **Test** | **Date** | **Testing Facility** | **Equipment** |
| Structures | • Mobility Tests | 4/8/21 | Outside/Aero Building | Ramp/Obstacles |
| Mast/Camera | • Full Mast Test | 4/1/21 | Machine Shop | Assembled Pump System |
| COMM | • Total Throughput Test | 4/8/21 | Outside | Ground Station/Integrated Electronics |

**Phase 3 Testing**

Finally, Table 6 shows the full system tests. The full mission simulation was completed April 26, 2021. Fortunately, the weather was nice that day, but had it been raining or snowing, the test would have been delayed. The Loss of COMM test, however, was not completed by the expected completion date of April 30, 2021. If there was more time to work through problems with the movement sensors required for autonomous control, specifically the motor controllers, this test could have been completed.

Table 8: Phase 3 Tests

| Phase 3 | | | | |
|---|---|---|---|---|
| **Subsystem(s)** | **Test** | **Date** | **Testing Facility** | **Equipment** |
| all | • Full Mission Simulation | 4/26/21 | Outside | Ramp/Obstacles |
| all | • Loss of COMM Test | 4/30/21 | Outside | none |

# Section 8: Lessons Learned

Harrison Fitch

Key lessons learned in the development of this project were driven by the challenges the team faced. Early on in the being of the fall semester the team faced serious challenges with the project's definition and scope. Trying to balance the customers requirements, teams ambition, and what was realistically achievable was a challenge. Exploiting both the PAB's knowledge and instate in what was achievable along with the help of the JPL staff reviews helped the team redefine an achievable project. Early feedback before deliverables were due helped resolve these issues. Weekly emails to our JPL customer Barbara Streiffert, setting up reviews with the TA's, and scheduling one on one meeting with PAB members helped the team better realize the specifics of the project. Meeting times for group task assignments also proved to be a challenge. Utilizing the website https://www.when2meet.com/ the teams availability could be quickly realized. We highly recommend the use of this website due to the speed and ease of use for quickly finding working times during teammates busy class and work schedule. In the Spring semester this website proved invaluable for team member Harrison Fitch since the normal Lab meeting time conflicted with a necessary class to graduate.

During the spring semester the team experienced both logistical and physical challenges. Logistical challenges dealing with shipping packages not arriving with all components, unreliably manufactures not notifying the team, and verification of manufacture specs upon arrival. The team was both missing components, the mother encoder cables and the aluminum chassis plate, and had a significant mass growth from 30kg to 54.25kg. Validating order forms and full package contents upon arrival along with manufacture spec sheets would have helped the team greatly. The physical challenges consisted of the manufacturing of the hydraulic mast. The team started early with a test rig early before the spring semester however the complexity of the full mast proved challenging. The mast seals malfunction multiple times throughout the manufacturing and preliminary testing requiring replacements. The mast seals not being extremely expensive but enough to not warrant an excessive amount, led the team to ordering only one set of backups. The team learned that on a high risk component, such as the mast, backups should be ordered beforehand, especially with an high budget margin. Had the team ordered additional the team's mast development time would have significantly increased. That being said, the majority of the project was still able to be completed on time.

## Section 9: Individual Report Contributions

Table 9: Table of Team Members' Contributions

| Name | Contributions |
|---|---|
| Niko de Boucaud | Mast Design, Mast Manufacturing, Mast Testing |
| Henry Felstiner | Risk Assessment and Mitigation |
| Harrison Fitch | Final Design, Lessons Learned |
| Victoria Gonzales | Mobility Testing and Mast Testing |
| Nick Kuljis | Full Mission Simulation |
| Luca Kushner | Final Design, Manufacturing |
| Margaux McFarland | Project Purpose, Project Objectives and Functional Requirements, Full System Design, and Project Planning |
| N. Thomas Noll | Final Design |
| Trevor Slack | Software Manufacturing |
| Daniel Stojsavljevic | Drivetrain Manufacturing and Testing |
| Jarrod Teige | Electronics/COMM Final Design, COMM Testing, and Loss of COMM |

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# Appendix

## Terrain Definition

Table 10: Terrain Definitions and Classifications

| Terrian | Forest | Ground | Underbrush | Max Incline |
|---|---|---|---|---|
| **Type A** | Open:<br>0 trees per acre | Mud Grain Size:<br>0.00006 - 0.0039 mm | Dirt with no vegetation:<br>- Refer only to ground classification<br>- Scattered leaves | 0 degrees,<br>level ground |
| **Type B** | Understocked:<br>~100 trees per acre | Silt Grain Size:<br>0.0039 - 0.0625 mm | Grass, Fallen Leaves, and No shrubbery:<br>- Full ground coverage by leaves<br>- Grass between 2cm - 10cm height<br>- Small roots 1-2 cm in diameter | 10 degrees |
| **Type C** | Fully Stocked:<br>~170 trees per acre | Sand Grain Size:<br>0.0625 - 2.00 mm | Grass, Fallen Leaves, and Scattered Shrubbery<br>- Shrubbery spaced by at least 1 meter<br>- Includes type A and B underbrush<br>- Medium roots: 3-4 cm in diameter | 20 degrees |
| **Type D** | Overstocked:<br>~200 trees per acre | Gravel Grain Size:<br>2.00 - 4.096 mm | Grass, Fallen Leaves, and Dense Shrubbery<br>- No spacing between shrubbery<br>- Includes type A, B, and C underbrush<br>- Large Roots: 5-7 cm in diameter | 20 degrees |

## Design Options Considered

In order to meet the functional requirements listed above, various designs were considered for different major functional components of the project. Designs for the drivetrain, mast, surveillance camera, sensors, and communications will be discussed in that order. For the purpose of brevity, only some designs will be considered per section which are written in bold.

### Drivetrain

The ARGOS drive train is critical to the success of the entire project so selecting the most appropriate option was considered thoroughly and thoughtfully. The design options considered for the drive train include tank treads, four wheels, six wheels, and a rocker bogie system. The six wheeled configuration was broken up into two options: powered middle wheels and unpowered middle wheels. Each design option was researched and the pros and cons were summarized in a table for each. **Here, the two different six wheeled configurations will be highlighted because of their similarities in the drive train trade study.**

**6 wheel:** This design option includes a system with six wheels fixed to the rover's body. Two versions of this configuration were taken into consideration, one with the two middle wheels powered and one with the two middle wheels unpowered. The version with all six wheels powered was considered based on the maneuvering around obstacles and and ground discontinuities effectively but has significant drawbacks with power consumption. Although, the version with the two middle wheels unpowered would have a similar effect of maneuvering but much less power consumption, yet it has a significant drawback for ground discontinuities. Both Designs, however are costly due to prices of DC motors and gear boxes and would be similar for both cases. A detailed image below (Figure 4) shows how the 6 wheels would be implemented in both cases as well as tables 3 and 4 show their pros and cons.


(a) 6 Wheel with powered middle wheel

(b) 6 Wheel without powered middle wheel

Figure 48: Both 6 Wheel Configurations

Table 11: Pros and Cons Table for 6 Wheels: Powered Middle Wheels

| Condition | Pro | Con |
|---|---|---|
| Obstacle maneuvering | X | |
| Ground Discontinuities | X | |
| Torque | X | |
| Power Usage | | X |
| Cost | | X |

Table 12: Pros and Cons Table for 6 Wheels: Unpowered Middle Wheels

| Condition | Pro | Con |
|---|---|---|
| Obstacle maneuvering | X | |
| Ground Discontinuities | | X |
| Torque | | X |
| Power Usage | X | |
| Cost | | X |

**Mast**

The rover's mast is a critical project element necessary to meet the third functional requirement. The mast must extend a camera above brushes and shrubs immediately in front of the rover in order to get a clear and unobstructed view above the rover's body. Design options considered for the mast include a telescoping, fold-over, scissor lift, screw lift, rigging pulley, zipper mast, and a fold-over/telescoping hybrid. Appropriate scores and rationale are shown in the Trade Study

Process and Results section. **Here, The telescoping design and scissor lift design will be focused on based on their similarities in the mast trade study**

**Telescoping:** A telescoping mast consists of a set of mast pieces with varying diameters placed inside one another such that the largest, lowest piece extends the subsequent smaller pieces above it. This allows it to achieve an extended height that is much more than its compressed height. This comes with the caveat of high complexity in order to achieve the extension of multiple nested pieces. A diagram of this configuration is shown below in figure 49 and its respected pros and cons chart is shown in table 5.

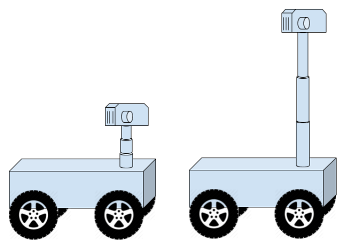


Figure 49: Extension of camera by telescoping mast

Table 13: Pros and Cons Table for Telescoping

| Condition | Pro | Con |
|---|---|---|
| High stability and support weight | X | |
| High ratio of maximum height to compacted height | X | |
| Good extension/retraction speed | X | |
| Mechanically complex | | X |
| Relatively high cost | | X |

**Scissor Lift:** A Scissor lift consists of criss-crossing metal supports that elongate as the mast platform is raised, usually electronically or hydraulically powered. This mast allows for a large support weight and stability at the cost of increased failure points and a larger base. A diagram of this configuration is shown below in figure 50 and its respected pros and cons chart is shown in table 6.

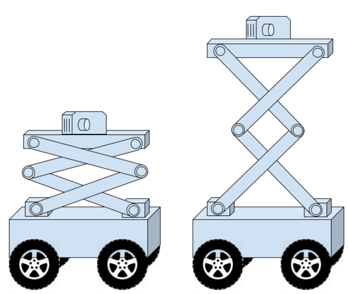


Figure 50: Extension of camera by Scissor Lift mast

Table 14: Pros and Cons Table for Scissor Lift

| Condition | Pro | Con |
|---|---|---|
| High stability and support weight | X | |
| High ratio of maximum height to compacted height | X | |
| Good extension/retraction speed | X | |
| Mechanically complex | | X |
| Relatively high cost | | X |

**Surveillance Camera**

The surveillance camera on ARGOS is critical to the success of the mission's surveillance objective, to monitor a flame front by taking photos and videos from behind the fire line. The surveillance camera will also help meet the second functional requirement. The designs options considered were a PTZ security camera, 360° Camera, Thermal Camera, and an Action camera. Appropriate scores and rationale are shown in the Trade Study Process and Results section.

**PTZ Security Camera:** PTZ stands for Pan Tilt Zoom and is the typical consumer-grade type of camera used by business and residential security systems. With the integrated pan and tilt capabilities on the camera mount, this type of camera can survey the fire line in higher definition than most other camera types.

PTZ Security Camera

Table 15: Pros and Cons Table for PTZ Security Camera

| Condition | Pro | Con |
|---|---|---|
| Image Quality | X | |
| Optical Zoom Capability | X | |
| Field of View | X | |
| Mass | | X |
| Cost | | X |

**360 Degree Camera:** 360 degree cameras typically consist of two 180 degree lenses and sensors on either side of the camera, which, when the images are stitched together, provide a full, spherical view in 360 degrees around around the camera. Video in this mode has large distortions in order for the whole image to appear on a screen.

Figure 51: 360 Degree Camera

Table 16: Pros and Cons Table for 360 Degree Camera

| Condition | Pro | Con |
|---|---|---|
| Image Quality | | X |
| Optical Zoom Ability | | X |
| Field of View | X | |
| Mass | X | |
| Cost | | X |

**Thermal Camera:** Thermal cameras use an infrared sensor to pick up heat radiation such that they can highlight objects that are at higher temperature than the surroundings. With a thermal camera, the flame front would pop out in images and video but other parts of the environment (including the fire line) would blend together and be much more difficult to recognize.

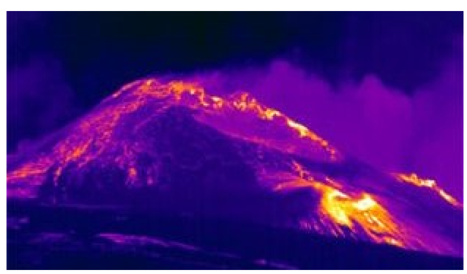


Figure 52: Thermal Camera

Table 17: Pros and Cons Table for Thermal Camera

| Condition | Pro | Con |
|---|---|---|
| Image Quality | | X |
| Optical zoom Capability | X | |
| Field of View | X | |
| Mass | X | |
| Cost | | X |

**Action Camera:** Action cameras are a class of small, consumer-grade cameras that can be mounted to objects and are often used for sports filming, like a GoPro. With an action camera on the rover mast, video and image quality are somewhat sacrificed for a more rugged, lightweight design.


Figure 53: Action Camera

Table 18: Pros and Cons Table for Action Camera

| Condition | Pro | Con |
|---|---|---|
| Image Quality | | X |
| Optical Zoom Capability | | X |
| Field of View | X | |
| Mass | X | |
| Cost | X | |

**Sensors**

**Translational Movement Sensors**

In order to validate that the requirement of a 250m round-trip was met —-, distance traveled measurements must be taken throughout the mission. Therefore, certain translational movement sensors that either measure distance traveled or measure other quantities that can be used to calculate distance traveled are considered for this design.

**GPS:** The first translational movement sensor design option considered is using GPS signal and coordinates to track the location of the rover over time.

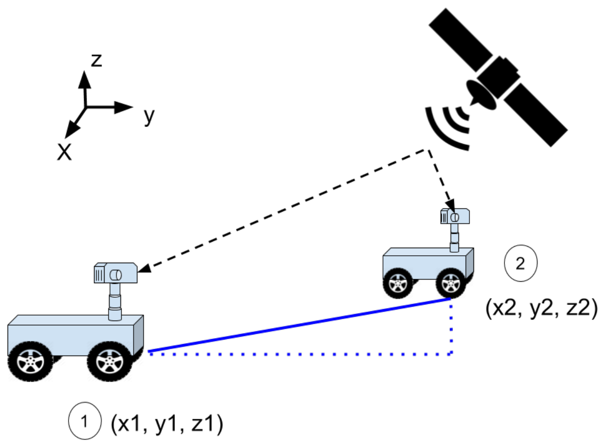



Figure 54: Diagram of Distance Traveled as Measured by GPS

As shown in Figure 54, basic trigonometry and the distance formula can be implemented to back out the distance traveled from GPS coordinates. Some of the pros and cons to this approach are outlined in Table 19.

Table 19: Pros and Cons Table for GPS

| Condition | Pro | Con |
|---|---|---|
| Signal Processing | X | |
| Ability to Transmit Position | X | |
| Position accuracy | | X |

**Wheel Odometer:** The second design option for translational movement sensors is a computerized wheel odometer such as the devices made for bicycles.

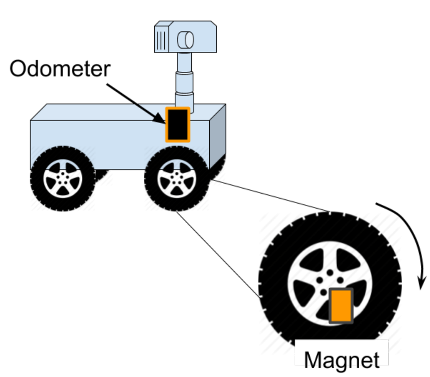



Figure 55: Diagram of Distance Traveled as Measured by a Wheel Odemeter

As shown in Figure 55, these devices consist of a magnet attached to outer edge of the wheel spokes and an odometer at some point above the wheel so that it counts each time the magnet passes that point. With some user input about the wheel's dimension, the distance traveled is calculated and directly output on the odometer display. Some of pros and cons to this approach are outlined in Table 20.

Table 20: Pros and Cons Table for Wheel Odometers

| Condition | Pro | Con |
|---|---|---|
| Signal Processing | X | |
| Ability to Transmit Position | | X |
| Position Accuracy | | X |

**Motor Encoder:** The last design option considered for translational movement sensors is the motor encoder. This design involves utilizing the existing functionality of a motor encoder to calculate distance traveled.

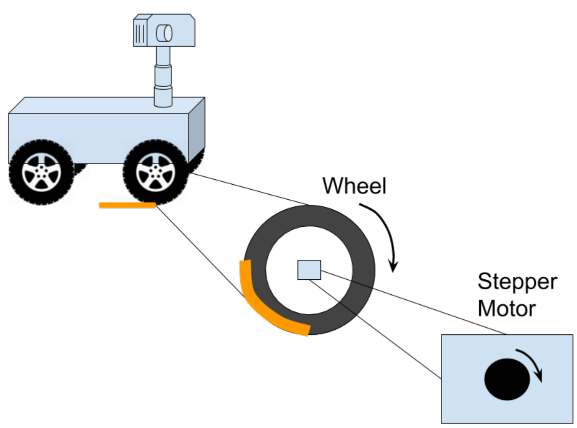



Figure 56: Diagram of Distance Traveled as Measured by a Motor Encoder

The motor encoder counts the number of steps it takes to make one revolution which translates to a certain angular displacement of the wheel. Then, knowing the circumference of the wheel, the arc length, or in other words the distance traveled, can be calculated as illustrated in Figure 56. Some of the pros and cons to this approach are outlined in Table 21.

Table 21: Pros and Cons Table for Motor Encoder

| Condition | Pro | Con |
|---|---|---|
| Signal Processing | X | |
| Ability to Transmit Position | X | |
| Position Accuracy | | X |

**Rotational Movement Sensors**

In order to prevent the rover from going past the tipping condition from the mast extension, the angular position of the rover must be measured during the mission. Thus, rotational movement sensors that either directly measure the inclination of the rover or measure other quantities that can be used to calculate angle of inclination are considered for this design.

**Micro-Electromechacnical Systems(MEMS) Gyroscope:** The first rotational movement sensor design option that was considered is a MEMS gyroscope that uses the coriolis force to calculate angular rate for the rover.

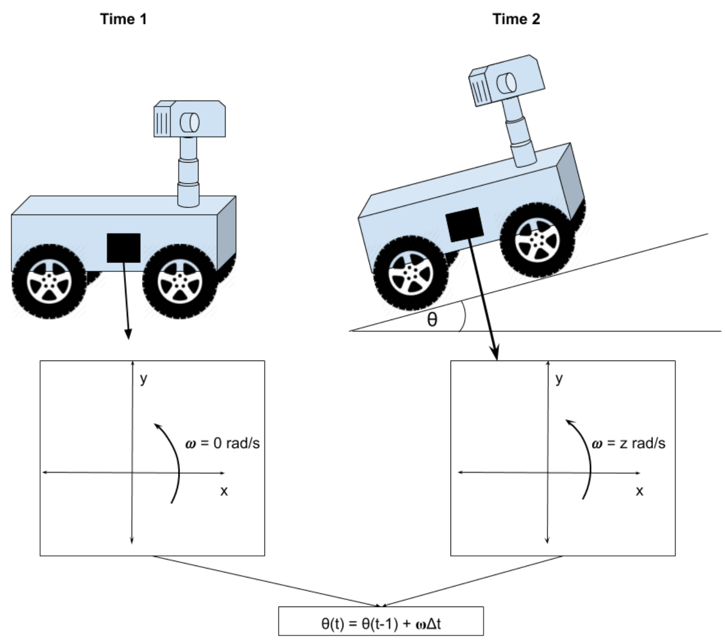



Figure 57: Diagram of Inclination as Measured by MEMS Gyroscope

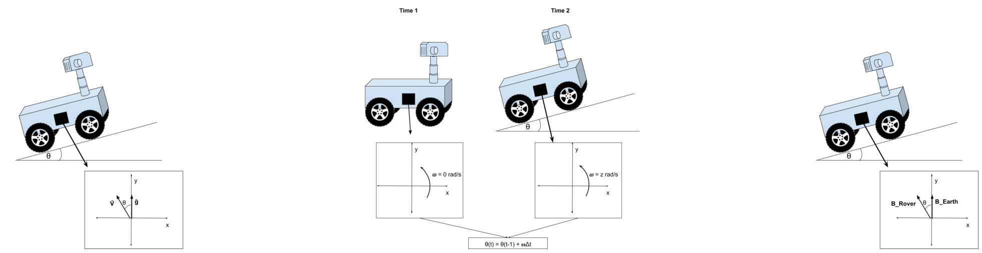
As shown in figure 57, the angular rate from the gyroscope is integrated to get angular position of the rover.

The pros and cons for this approach are listed below in Table 22.

Table 22: Pros and Cons Table for MEMS Gyroscope

| Condition | Pro | Con |
|---|---|---|
| Amount of Measurements | X | |
| Signal Accuracy/Amount of Noise | X | |
| Signal Processing | | X |

**Inertial Measurement Unit (IMU):** The second design option for rotational movement sensors is a nine degree of freedom IMU.




(a) Accelerometer (b) MEMS Gyroscope (c) Magnetometer

Figure 58: Sensors Used in Determining Rover Inclination with IMU

As shown in figure 58, this device consists of a 3-axis accelerometer, 3-axis gyroscope, and a 3-axis magnetometer. The 3-axis accelerometer uses gravity to output a voltage that is measured with a relative angle to the earth's gravity. This angle can be used to find the inclination of the rover. As stated above the gyroscope uses the Coriolis force to calculate angular velocity. This can then be integrated to find angular position of the rover. The 3-axis magnetometer uses earth's magnetic field to calculate the inclination of the rover in relation to the magnetic field. The pros and cons of this approach are listed in Table 23.

Table 23: Pros and Cons Table for IMU

| **Condition** | **Pro** | **Con** |
|---|---|---|
| Amount of Measurements | X | |
| Signal Accuracy/Amount of Noise | X | |
| Signal Processing | | X |

**Accelerometer:** The final design option considered for rotational movement sensors is an accelerometer, which uses the gravity of earth to output a voltage that is related to the inclination of the rover.

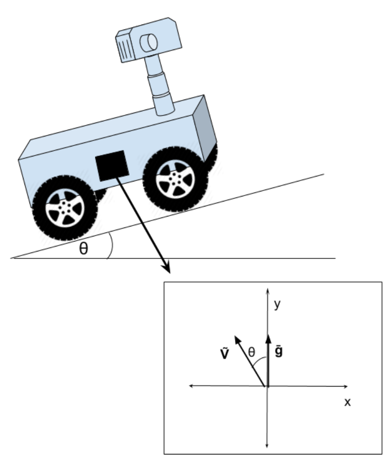



Figure 59: Diagram of Inclination as Measured by Accelerometer

As shown in the figure 59, the output voltage from the accelerometer is used to calculated the angle of inclination of the rover. The pros and cons for this approach are listed below in Table 24.

Table 24: Pros and Cons Table for Accelerometer

| Condition | Pro | Con |
|---|---|---|
| Amount of Measurements | X | |
| Signal Accuracy/Amount of Noise | | X |
| Signal Processing | X | |

**Object Detection Sensors**

Object detection sensors are needed for the rover to safely navigate to the fire line. A variety of object detection sensors exist and were narrowed down to six different sensors to be considered with the intent of picking multiple as the final sensor types used for obstacle avoidance.

**RADAR:** Radio detection and ranging (RADAR) is a form of distance measurement that uses a radio wave emitting device and a receiver that measures the reflected radio waves. RADARs come in a wide variety of types, ranges, and field of views. They are often used in robotics to detect obstacles. Figure 60 shows an example diagram of the how a radar transmits and receives a radio signal. Table 25 shows a list of pros and cons for RADAR.

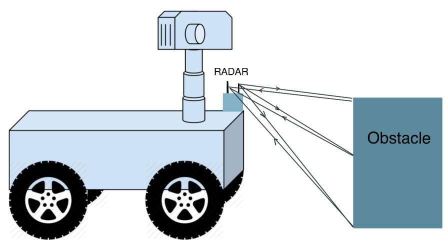



Figure 60: Diagram of RADAR functionality.

Table 25: Pros and Cons Table for RADAR

| Condition | Pro | Con |
|---|---|---|
| Ability to Measure Obstacles and Distance | X | |
| Field of View | X | |
| Accuracy Based on Shape Discontinuities | | X |

**Ultrasonic Range Finder:** Ultrasonic range finders use a speaker and receiver to transmit sound waves and receive their reflection. They can measure distance to an object but are limited in their range. Ultrasonic range finders are very inexpensive and are often used in robotics to detect obstacles at a short range. Figure 61 shows a diagram of how an ultrasonic range finder is used to detect an object. Table 26 is a list of pros and cons for ultrasonic range finders.

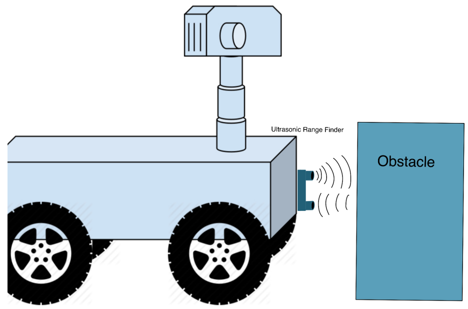



Figure 61: Diagram of ultrasonic range finder functionality.

Table 26: Pros and Cons Table for Ultrasonic range finder

| Condition | Pro | Con |
|---|---|---|
| Ability to Measure Obstacles and Distance | X | |
| Field of View | | X |
| Accuracy Based on Shape Discontinuities | | X |

**FPV Camera:** First-person-view (FPV) cameras are video cameras used to control a system. An FPV camera on the rover would allow a human controlling the rover to have visual feedback when driving. The camera does not have direct obstacle detection but, if needed, image processing can be employed to extract some information about obstacle location and distance. Figure 62 shows a diagram of the view that an FPV camera would provide. Table 27 is a list of pros and cons for the FPV camera.

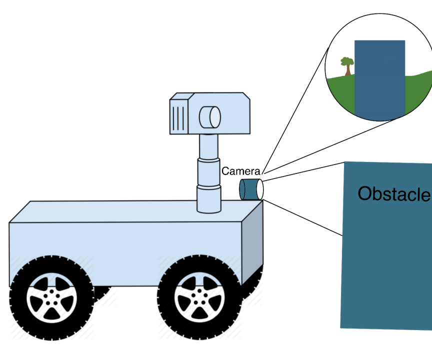



Figure 62: Diagram of FPV camera functionality.

Table 27: Pros and Cons Table for FPV Camera

| Condition | Pro | Con |
|---|---|---|
| Ability to Measure Obstacles and Distance | | X |
| Field of View | X | |
| Accuracy Based on Shape Discontinuities | X | |

**Bumper Sensor:** Bumper sensors are a form of direct obstacle detection. If the obstacle collides with the sensor it will produce a signal. This form of sensor has no range as it requires a collision. Figure 63 shows a diagram of how the bumper sensor functions.

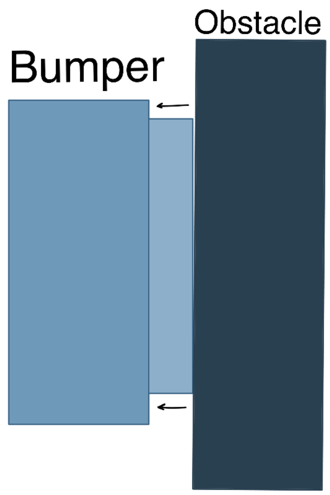



Figure 63: Diagram of bumper sensor functionality.

Table 28: Pros and Cons Table for Bumper Sensor

| Condition | Pro | Con |
|---|---|---|
| Ability to Measure Obstacles and Distance | X | |
| Field of View | | X |
| Accuracy Based on Shape Discontinuities | | X |

**IR Transceiver:** Infrared (IR) transceiver send infrared light and measure its reflection off an obstacle with a receiver. These systems can detect obstacle distance and a relatively inexpensive. However, their range is limited. Figure 64 is a diagram of how IR transceivers detect an obstacle. Table 29 is a list of pros and cons for IR transceivers.

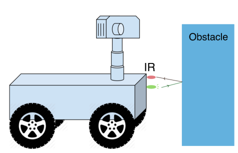



Figure 64: Diagram of IR transceiver functionality.

Table 29: Pros and Cons Table for IR Transceiver

| Condition | Pro | Con |
|---|---|---|
| Ability to Measure Obstacles and Distance | | X |
| Field of View | X | |
| Accuracy Based on Shape Discontinuities | | X |

### Communications

Communications is vital component of many design requirements for the ARGOS mission. ARGOS must communicate with the mother rover and ground station at a maximum distance of 250m. Data such as video, pictures, temperature, location, and control commands need to be transmitted and received at fast enough rates and at a low latency to prevent data loss and keep integrity. The data being transmitted and received must also overcome the attenuation due to various obstacles, range, and outside noises. High-band radio is a form of communication that allows high data transfer rates at frequency ranges comparable to Wi-Fi. Low-band radio has slower data rate transfer but operates at longer ranges and has been utilized by previous senior projects. Both Low-band and high-band will also have the option of using omnidirectional antenna or a point-to-point network connection, which will need to be further studied. Cellular connection and Laser are the last options considered for this project.

**High-Band Radio:** High-band radio in this context is considered at frequencies from 2.5-5GHz. The Mother Rover, Ground Station, and ARGOS Rover all communicate according to the diagram below.

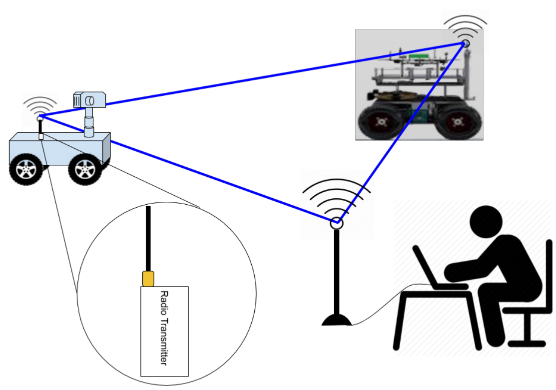



Figure 65: Radio Systems

Table 30: Pros and Cons Table for High-Band Radio

| Condition | Pro | Con |
|---|---|---|
| Data Transfer Rate | X | |
| Attenuation Due to Obstacles | | X |
| Costs Due to Range | | X |

**Low-Band Radio:** Low-band radio operates at smaller frequencies such as 900Mhz. The diagram for the highband radio communication will also apply for this option, with only a change to the frequency of the transmitters.

Table 31: Pros and Cons Table for Low-Band Radio

| Condition | Pro | Con |
|---|---|---|
| Data Transfer Rate | | X |
| Attenuation Due to Obstacles | X | |
| Costs Due to Range | X | |

**Cellular Networking:** Cellular connection or Long-Term Evolution (LTE) is an option that uses a cellular network for communications. A cellular tower will become the access point for the MR, GS, and ARGOS for transmitting/receiving data.

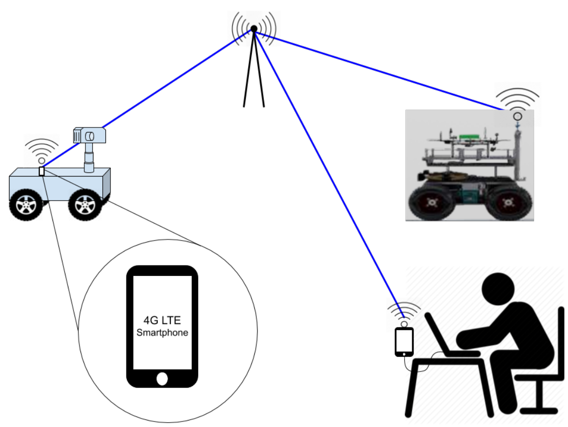



Figure 66: Cellular Data

Table 32: Pros and Cons Table for Cellular

| Condition | Pro | Con |
|---|---|---|
| Data Transfer Rate | X | |
| Attenuation Due to Obstacles | | X |
| Costs Due to Range | X | |

**LASER Optical Communications:** A laser communications system comprises of a set of laser emitters and receivers. The receivers can either be some form of a photo-detector or ambient light sensor that can measure the change is light based on whether the laser is on or off.

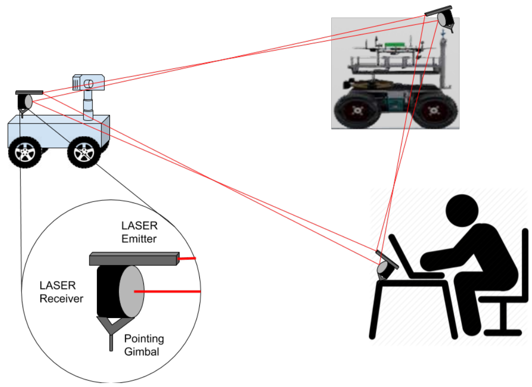



Figure 67: LASER

Table 33: Pros and Cons Table for LASER

| Condition | Pro | Con |
|---|---|---|
| Data Transfer Rate | X | |
| Attenuation Due to Obstacles | | X |
| Costs Due to Range | | X |

## Trade Studies

### Drivetrain

**Trade Criteria Selection:** Seven criteria were used in comparing the different designs for drivetrain: Stability, Manufacturability / Mechanical Complexity, Obstacle Maneuverability, Reliability, Speed, and Cost.

Stability defines the ability for the rover to remain upright and level enough for the sensors to collect usable data while stationary and in motion. A higher score indicates a more stable option.

Manufacturability / Mechanical Complexity defines the feasibility of manufacturing an option based on its complexity and material requirements. The design must be feasible to design and manufacture within the allotted timeframe. A higher score indicates a less complex solution

Obstacle Maneuverability defines the rover's ability to traverse obstacles it may encounter during the mission; such as rocks, branches, ditches, etc. A higher score indicates a more maneuverable option.

Reliability defines the durability and redundancy of parts and systems in the drivetrain. A higher score indicates the design is more reliable based on innate redundancy and durability.

Speed qualitatively defines the speed at which the rover can move in a straight line over nominal terrain. A higher score indicates a higher possible straight-line speed.

Cost defines the overall monetary cost of the drivetrain system based on material, manufacturing, and prebuilt costs. It is an important criteria for budgeting and scoping. It is important that the drivetrain stays in budget and does not cut into the budget of other subsystems. This also assists with budget allocation. A higher score indicates a less expensive option.

**Weighting Assignments and Rationale:** The following table assigns the weights and rationale for each trade criteria.

| Criteria | Weight | Reasoning |
|---|---|---|
| **Stability** | 0.25 | Instability could result in the rover becoming inoperative |
| **Manufacturability/ Mechanical Complexity** | 0.25 | If the system is too complex to build then it is unrealistic to complete in the scope of this project. Complexity also adds to cost and could detract from reliability |
| **Obstacle Manueverablity** | 0.175 | The terrain the rover will be implemented on includes many small obstacles and slopes that will be necessary to navigate to reach the target location |
| **Reliability** | 0.1 | It is important to have redundancy in the system to mitigate risk of failure |
| **Speed** | 0.05 | Given the distance the rover must travel, getting there quickly is not a main priority |
| **Power Required** | 0.125 | With more power required comes with more space needed on the rover and more complexity but this is taken into to account in the Mechanical Complexity section |
| **Cost** | 0.05 | This project has budget but other aspects of this system are more important to the success of the rover |

**Score Assignment:** Below are the score assignments for each trade criteria.

| Criteria | 1 | 2 | 3 | 4 | 5 |
|---|---|---|---|---|---|
| **Stability** | Can easily be flipped over with little effort and body may not stay level during motion or while turning | Can be flipped over with some effort and body may not stay level during motion | Could be flipped over but with a significant amount of effort and difficulty, could still not keep the body of the vehicle steady during motion | Very unlikely to tip or flip over but the body may still move significantly while in motion | Extremely unlikely to tip or flip over and the body is steady while vehicle is in motion |
| **Manufacturability /Mechanical Complexity** | This configuration is extremely difficult to manufacture and implement in design and likely not doable in the scope of this project | This configuration is very difficult to manufacture and implement but is possible in the scope of this project | This configuration can be implemented but with some difficulties and complicated processes, but is doable in the scope of this project | This configuration can be implemented with little difficulty but may contain some complications in the process. Very doable in the scope of this project | This configuration is easy to build and implement with very little difficulty. This configuration is extremely doable in the scope of this project |
| **Obstacle Maneuverability** | This configuration will make it very difficult for the vehicle to maneuver even small obstacles and may have a hard time turning | This configuration can traverse over flat ground, small obstacles and over 5 degree inclines, it also has moderate turning ability | This configuration can traverse easily over flat terrain, small obstacles, and a 10 degree incline and can make a 360 degree turn | This configuration can traverse easily over flat terrain, medium obstacles, and a 20 degree incline, as well as make a 360 turn | This configuration will make it very easy for the vehicle to maneuver or drive over even larger obstacles and can navigate slopes well as make a 360 degree turn |

| | | | | | |
|---|---|---|---|---|---|
| **Reliability** | Mission-critical elements can break under normal operation and leave the rover inoperable | Mission-critical elements can break under extensive operation and leave the rover inoperable | Mission-critical elements can break under extensive operation, but the rover is still operable | Mission-critical elements must be serviced or replaced after missions | Mission-critical elements last multiple missions and do not need to be serviced often |
| **Speed** | Speed is insufficient to get to the fireline in a reasonable amount of time and cannot outrun the flame front (∼3 m/s) | Speed is such that the rover can reach the fireline but not patrol effectively and cannot outrun the flame front (∼3 m/s) | Speed is such that the rover can reach and slowly patrol the fireline. Cannot outrun the flame front (∼3 m/s) | Speed is sufficient to reach, patrol, and return from the fireline in a reasonable amount of time. Cannot outrun the flame front (∼3 m/s) | Speed is sufficient to reach, patrol, and return from the fireline in a reasonable amount of time. Can outrun the flame front (∼3 m/s) |
| **Power Required** | Power required requires large batteries which put the rover overweight | Excessive power required limits power usage by other subsystems | Power required meets expectations but does not leave room for unexpected power use | Drivetrain uses less power than allotted, allowing for more use by other subsystems | Drivetrain uses far less power than allotted, saving on battery weight |
| **Cost** | Drivetrain is severely over budget and would cut into other subsystem budgets | Drivetrain is over budget but does not cut into other subsystems | Drivetrain is in budget but still overpriced | Drivetrain is reasonably priced and under budget | Drivetrain is economical and well under budget |

**Trade Matrix:** The following table assigns the scores for each design alternative.

| Criteria | Weight | Tank Treads | 4 Wheels | 6 Wheels 4WD | 6 Wheels 6WD | Rocker Bogie |
|---|---|---|---|---|---|---|
| **Stability** | 0.25 | 4 | 3 | 4 | 4 | 5 |
| **Manufacturability / Mechanical Complexity** | 0.25 | 2 | 5 | 4 | 3 | 2 |
| **Obstacle Manueverablity** | 0.175 | 4 | 2 | 2 | 4 | 5 |
| **Reliability/Redundancy** | 0.1 | 2 | 2 | 4 | 5 | 3 |
| **Speed** | 0.05 | 3 | 4 | 3 | 4 | 2 |
| **Power Required** | 0.125 | 5 | 4 | 4 | 3 | 2 |
| **Cost** | 0.05 | 3 | 5 | 3 | 3 | 3 |
| **Total Weighted Score:** | **1** | 3.325 | 3.5 | 3.55 | **3.675** | 3.425 |

### Mast

**Trade Criteria Selection:** The rover's mast is the functional component which holds the camera that takes images of the fire line and flame front. An extendable and retractable mast allows the camera to gain an elevated vantage point, but also brings the camera closer to the rover body during travel. Therefore, the following trade study for an extendable and retractable mast was conducted. The trade study criteria are cost, support weight/stability, complexity, extendable height/compactable height, power required and speed of retraction. First of all the cost of the design alternatives was based largely on the number of components, including structural and functional, that the system would require. The support weight and stability encompasses the mast type's ability to remain stable at full extension while holding up a large weight, while balancing the size and weight of the structural components required to achieve that level of stability. The complexity takes into account the minimum number of functional components that the system can have in order to function and balances that with the minimum amount of programming required. The extendable height and retractable height refers to the ratio of compacted height to full extension height for each mast type. The power required refers mostly to the mass of the system's functional components and the power required to raise them, but also to the number of motors/hydraulic pumps the system needs. The speed of retraction refers to the amount of time that the system would take to bring the camera back down without damaging the camera or the system itself.

**Weighting Assignments and Rationale:** The following table assigns the weights and rationale for each trade criteria.

Table 35: Trade Criteria Weights and Rational for Rover Mast

| Criteria | Weight | Rationale |
|---|---|---|
| Cost | 0.05 | To limit expenditures and remain within the budget of the project |
| Support Weight/ Stability | 0.3 | To allow the camera and other sensors mounted at the top of the mast to be of sufficient quality, the mast needs to support the weight of those components and should be relatively stationary when shooting. The quality of images should not be heavily limited by the mast's inability to maintain a steady shot. It also needs to be considered whether or not the mast holds up a pan and tilt mechanism that mounts to the camera/sensors at the top. |
| Complexity | 0.25 | To allow the team to properly design and manufacture the technology for raising the camera, its design complexity can't be outside the scope of the teams skills. |
| Extendable Height/ Compactable Height | 0.3 | The mast must be able to retract to a size that doesn't inhibit the rover's motion by catching on obstacle in the rover's path. It also must be able to extend to its maximum height given the space available on/inside the rover body, which the design choice will have influence over |
| Power Required | 0.05 | The mast's extension based on design should be within a reasonable required power for the motors. |
| Speed of Retraction | 0.05 | The speed of retraction would only be important if the rover is in immediate danger. Overall, the speed of each mast type will be relatively similar and minor differences won't greatly affect its ability to survey the fire line and gather data. |

**Score Assignment:** Below are the score assignments for each trade criteria.

Table 36: Score Assignments and Rational for Rover Mast

| Criteria | 1 | 2 | 3 | 4 | 5 |
|---|---|---|---|---|---|
| Cost | The system is estimated to take more than 10% of the project budget. | The system is estimated to take between 5% and 10% of the budget. | The system is estimated to take between 2.5% and 5% of the budget. | The system is estimated to take between 1% and 2.5% of the budget. | The system is estimated to take less than 1% of the budget. |
| Support Weight/ Stability | Supports less than 20% of the mast weight. | Supports between 20% and 30% of the mast weight. | Supports between 30% and 40% of the mast weight. | Supports between 40% and 50% of the mast weight. | Supports more than 50% of the mast weight. |
| Complexity | More than 200 hours to design and manufacture | Between 150 and 200 hours to design and manufacture. | Between 100 and 150 hours to design and manufacture. | Between 50 and 100 hours to design and manufacture. | Less than 50 hours to design and manufacture. |
| Extendable Height/ Compactable Height | Ratio of maximum height to compacted height is less than 2 | Ratio of maximum height to compacted height is between 2 and 3 | Ratio of maximum height to compacted height is between 3 and 4 | Ratio of maximum height to compacted height is between 4 and 5 | Ratio of maximum height to compacted height is greater than 5 |
| Power Required | Raise and lower takes more than 4% of the total system power. | Raise and lower takes between 3% and 4% of the total system power. | Raise and lower takes between 2% and 3% of the total system power. | Raise and lower takes between 1% and 2% of the total system power. | Raise and lower takes less than 1% of the total system power. |
| Speed of Retraction | Greater than 1 minute retraction time. | Between 30 seconds and 1 minute retraction time. | Between 15 and 30 seconds retraction time. | Between 5 and 15 seconds retraction time. | Less than 5 seconds retraction time. |

**Trade Matrix:** The following table assigns the scores for each design alternative.

| Criteria | Weight | Telescoping | Fold-Over (dual joint) | Scissor Lift | Screw Lift | Rigging Pulley | Zippermast | Fold-Over Telescoping |
|---|---|---|---|---|---|---|---|---|
| **Cost** | 0.05 | 3 | 2 | 3 | 5 | 4 | 2 | 2 |
| **Support Weight/ Stability** | 0.3 | 4 | 3 | 4 | 4 | 4 | 3 | 3 |
| **Complexity** | 0.25 | 3 | 2 | 3 | 5 | 4 | 2 | 2 |
| **Extendable Height/ Compactable Height** | 0.3 | 4 | 3 | 4 | 1 | 2 | 5 | 5 |
| **Power Required** | 0.05 | 4 | 2 | 2 | 4 | 5 | 4 | 3 |
| **Speed of Retraction** | 0.05 | 4 | 4 | 4 | 2 | 2 | 5 | 3 |
| **Total** | 1 | 3.7 | 2.7 | 3.6 | 3.3 | 3.35 | 3.45 | 3.3 |

### Surveillance Camera

**Trade Criteria Selection:** The mission that the rover is designed to carry out is centered around the mast camera taking photos of the fire line and flame front. In order to effectively take these photos and be able to send them to the ground station there are a few considerations to take into account. These trade study criteria are: image quality, field of view, video transfer time, durability, mass, flame visibility, cost and optical zoom capability. The most critical of these to the proper functioning of the camera is the camera's image quality. The image quality refers to the resolution of the camera and its dynamic range, but also its distortion of shapes and colors. For example, a thermal camera will distort colors when viewing a thermal image since it is representing an infrared image rather than a visible light image. Field of view refers to the angular range that the camera can sense in front of it and results in more distortion the larger it becomes. Video transfer time refers to the size of the files that the camera creates when it takes photo or video, as the larger the file is the more data needs to be transferred. Durability is the camera's resilience to blunt force, such as that which would result in the camera hitting a tree branch or the rover tipping over and hitting the camera on the ground. Mass is self-explanatory and is determined from average mass estimates of the camera type in question. The flame visibility is the camera's ability to highlight flames in photo or video, such as having thermal capability. Cost is also based on average estimates from the camera type in question and also takes into account integration costs. Lastly, optical zoom capability refers to the camera's ability to use a lens to zoom, since simple digital zoom results in a loss in quality of the image.

**Weighting Assignments and Rationale:** The following table assigns the weights and rationale for each trade criteria.

Table 37: Trade Criteria Weights and Rational for Mast Camera

| Criteria | Weight | Reasoning |
|---|---|---|
| **Image Quality** | 0.2 | To provide the ground station with the best data possible to analyze the fire line, the camera should be of reasonably high quality and lack distortion such that this task is as easy as possible |
| **Field of View** | 0.15 | To provide the ground station with the best data possible to analyze the fire line, the camera should be able to take in as much of the environment as possible and limit necessary camera movement |
| **Video Transfer Time** | 0.15 | To provide the ground station with information about the fire line as quickly as possible, the video/images taken by the rover need to have as low of a transfer time as possible |
| **Durability** | 0.1 | If the camera were to break or be damaged on impact with an obstacle, the mission would likely need to be aborted |
| **Mass** | 0.1 | To limit the potential tipping conditions when the mast is fully extended, the camera shouldn't be too heavy |
| **Flame Visibility** | 0.1 | In order to more easily identify the flame front, the ground station should receive images in which the flame front is as clearly visible as possible |
| **Cost** | 0.1 | To limit expendatures and remain within the budget of the project |
| **Optical Zoom Capability** | 0.1 | Since the rover may often need to post up far from the fire line to avoid becoming trapped by the fire, it is desirable to have optical zoom capabilities in the camera lens so that the fire line can be effectively seen from afar |

**Score Assignment:** Below are the score assignments for each trade criteria.

| Criteria | 1 | 2 | 3 | 4 | 5 |
|---|---|---|---|---|---|
| **Image Quality** | The image quality is low, 480p or less or objects are distorted or difficult to make out | The image quality is less than full HD (1080p) or objects are somewhat distorted but still visible | The image quality is full HD (1080p) and objects lack most distortion resulting in a relatively clear picture | The image quality is between 4K and 1080p and there is almost no distortion with clear picture | The image quality is 4K or above and the picture lacks any distortion with very sharp, clear picture |
| **Field of View** | The field of view with this mast imaging system is very narrow and will likely not provide useful data for the purposes of this project | The field of view for this mast imaging system is slightly too narrow to provide the quality of data necessary to satisfy the purposes of this project | The field of view for this mast imaging system is sufficient for proper data collection but does not provide extra width that could improve the usefulness of this system | The field of view for this mast imaging system is sufficient for data collection and adds some extra width to the images that improve the quality of data being collected | The field of view for this mast imaging system is beyond sufficient for data collection purposes and the extra wide field of view could offer significant quality bonuses to the images collected |

| | | | | | |
|---|---|---|---|---|---|
| **Video Transfer Time** | The video being transferred from the child to the mother rover and/or ground station is lagging significantly and not close to a livestream | The video feed transfer is somewhat lagging but is closer to a livestream | The video feed is able to be livestreamed to the mother rover and/or ground station but there is a significant decrease in video quality | | The video feed is able to be livestreamed to the mother rover and/or ground station with no significant decrease in quality |
| **Durability** | The mast imaging system is very easily broken and will likely not be able to sustain a mission in the conditions relevant to this project | | The mast imaging system is somewhat easily broken but will likely last at least a few missions in the conditions relevant to this project | | The mast imaging system is not easily broken and will be able to withstand many missions in the conditions relevant to this project |
| **Mass** | The mast imaging system is very heavy and will likely not be able to be supported by the mast system and slow down the rover | The mast imaging system is heavier than ideal and could potentially cause mechanical failures in the mast system and effect the speed of the rover | The mast imaging system is not heavy enough to cause mechanical failures but may slow down the extension of the mast and speed of the rover | The mast imaging system is a weight that will not cause mechanical failures and will likely not cause the rover to move slower but may still effect the mast extension slightly | The mast imaging system is lightweight and will not cause any difficulties with mast extension or rover speed |
| **Flame Visibility** | Using this mast imaging system the flame front is not easily identifiable | | Using this mast imaging system the flame front is somewhat easy to identify | | Using this mast imaging system the flame front is very easy to identify |
| **Cost** | (>$700) | (500−700) | (300−500) | (100−300) | ($100<) |
| Optical Zoom Capability | The optical zoom capabilities of this system are severely lacking or nonexistent, | | The optical zoom capabilities of this system are somewhat lacking, it can zoom some amount but not enough to provide useful data | | The optical zoom capabilities of this system are very useful, it can zoom a significant amount |

**Trade matrix:** The following table assigns the scores for each design alternative.

Table 39: Trade Matrix for Mast Camera

| Criteria | Weight | 360 Camera | PTZ Security Camera | Thermal Camera | Action Camera |
|---|---|---|---|---|---|
| **Image Quality** | 0.2 | 3 | 5 | 1 | 4 |
| **Field of View** | 0.15 | 5 | 5 | 3 | 4 |
| **Video Transfer Time** | 0.15 | 3 | 4 | 3 | 4 |
| **Durability** | 0.1 | 3 | 4 | 3 | 5 |
| **Mass** | 0.1 | 3 | 2 | 3 | 5 |
| **Flame Visibility** | 0.1 | 4 | 4 | 5 | 3 |
| **Cost** | 0.1 | 3 | 2 | 2 | 3 |
| **Optical Zoom Capability** | 0.1 | 3 | 5 | 4 | 2 |
| **Weighted Total** | 1 | 2.4 | **4.1** | 1.6 | 3.8 |

**Sensors**

**Translational Movement Sensors**

**Trade Criteria Selection:** In order to thoroughly compare the different translational movement sensors and how they would best meet the mission objectives, certain criteria were chosen. The first criteria, accuracy, is a measure of how accurate the distance traveled measurement or calculation will be. Because different sensors have inconsistent accuracy claims, accuracy will be measured based on the sources of error in a sensor and the assumptions made in order to calculate the distance traveled. The data processing complexity involves all the necessary programming, analysis, and/or signal processing necessary. Hardware integration involves all the mechanical pieces and electrical connections necessary to keep the sensor attached as well as to transmit data. Environmental reliability of a translational movement sensor is a measure of how the environment, including the location, terrain, and surroundings, affects the sensor's performance. Cost was chosen to compare how well the sensors would maintain the mission's budget.

**Weighting Assignments and Rationale:** The following table outlines the weight assigned to each criteria and why that weight was chosen based on the requirements and levels of success.

Table 40: Trade Criteria Weights and Rational for Translational Movement Sensors

| Criteria | Weight | Rationale |
|---|---|---|
| Accuracy | 0.25 | An accurate sensor will ensure that the requirement MOV.1.5 is met. Because having a certain distance traveled is a customer-provided requirement, the accuracy criteria is weighted as one of the highest. |
| Data Processing Complexity | 0.25 | The sensors must interface with the chosen software or some degree of signal processing. If processing the data becomes too complex, the data from the sensors could lose its significance making the Rover Movement level of success unknown. Processing the translational movement data will also prove whether or not requirement MOV.1.5 is met; therefore, it it set at one of the highest weights. |
| Hardware Integration Complexity | 0.20 | It is necessary that the sensors ride on the body of the rover in order to measure the distance traveled, but it is not anticipated to be the most challenging aspect of these designs, so it is weighted as lower than accuracy and data processing complexity. |
| Environmental Reliability | 0.15 | ARGOS will be traveling in forested areas, so it is important that the sensors still function correctly in this environment. There are only a few environmental impacts that may affect these sensors, such as the actual location of the rover and tree density, so it is not weighted as heavily as the other criteria. |
| Cost | 0.15 | The cost of the chosen design alternatives are relatively low, so the cost does not make a significant impact for any alternative. |

**Score Assignment:** The following table outlines what each score means for each trade criteria.

Table 41: Score Assignments and Rational for Translational Movement Sensors

| Criteria | 1 | 2 | 3 | 4 | 5 |
|---|---|---|---|---|---|
| Accuracy | Sensor does not measure or cannot convert to distance traveled. | Many sources of error are very likely to occur. Incorrect assumptions were made when computing distance traveled. | A few sources of error are somewhat likely to occur. Some assumptions are made that hold true under most circumstances. | Only one or two sources of error may occur during the mission. Assumptions are made that are valid. | No likely sources of error will contribute to inaccurate readings. Little to no assumptions are made when computing distance traveled. |
| Data Processing Complexity | Sensor is not compatible with the available software and data processing. On-board computations are too challenging to complete in the given time frame. | Distance traveled is not easily computed from the sensor data. Requires separate software. | Involves multiple step data processing to extract distance traveled that is somewhat time-consuming/ challenging, but feasible. | Distance traveled is easily computed from the sensors and can integrate with the chosen software system. | Distance traveled measurement is directly outputted by the sensor. No on-board computations or data-processing needed. |
| Hardware Integration Complexity | Involves too many components that cannot be manufactured/too expensive. Integration is too difficult/ time-consuming. | Involves extensive integration with multiple components that are not easily attainable. | Involves extensive integration with multiple components, but is still feasible to complete in the given time frame. | Integration takes an average amount of time with only one to two extra components to connect the sensor. | Integration takes very little time and involves little to no extra components to integrate. |
| Environmental Reliability | No measurements can be made in any forested areas, only open space. Sensors can only operate on level ground. | Sensors can measure the distance traveled with uneven/loose terrain or in a covered area (0.25 trees/m2). Only one of these conditions is met, not both. | | Sensors can measure the distance traveled with uneven/loose terrain, but not in a covered area (0.25 trees/m2). | Sensors can measure distance traveled whether it be in open or forested areas (0.25 trees/m2) or on level ground or at a 20 degree incline with 7cm tall obstacles. |
| Cost | Greater than or equal to $1000 | $100 to $999.99 | $10 to $99.99 | $1 to $9.99 | Less than $1 |

**Trade matrix:** The following table outlines the scores each criteria received for each design alternative.

Table 42: Trade Matrix for Translational Movement Sensors

| Criteria | Weight | GPS | Wheel Odometer | Motor Encoder |
|---|---|---|---|---|
| Accuracy | 0.25 | 4 | 3 | 2 |
| Data Processing Complexity | 0.25 | 4 | 5 | 4 |
| Hardware Integration Complexity | 0.2 | 5 | 1 | 5 |
| Environmental Reliability | 0.15 | 2 | 4 | 4 |
| Cost | 0.15 | 5 | 3 | 5 |
| Total | 1 | 4.05 | 3.25 | 3.85 |

**Rotational Movement Sensors**

**Trade Criteria Selection:** The angle of inclination determination is critical for protecting the rover from reaching its tipping condition. If the rover is unable to determine the angle of inclination, the rover would tip and cause damage or the inability to be retrieved. To prevent this three sensors were studied using five trade criteria to find the best suited sensor to fulfill design requirement COM.1.1 and MOV.1.3. Accuracy of the sensor takes into account the noise in the data from terrain and the systematic error associate with the data. The data processing of the sensor takes into account the complexity of steps the measured value from the sensor will have to go through in order to produce the angle of inclination. The hardware integration complexity takes into account the size of the sensor and the number of components necessary to attach the sensor to the rover. The environmental reliability take into account the the vibrations produced by the terrain the rover travels across and the effects the vibrations have on the sensors. Finally, the cost of the sensors accounts for the overall money spent in integrating the sensors with the rover.

**Weighting Assignments and Rationale:** The following table lists the weighted values assigned for each trade criteria and the reasoning for each value.

Table 43: Trade Criteria Weights and Rational for Rotational Movement Sensors

| **Criteria** | **Weight** | **Rationale** |
|---|---|---|
| Accuracy | 0.30 | Tipping could prevent the rover from traveling any further which would not satisfy requirement MOV.1.5. Therefore, the accuracy of the sensors is weighted the highest |
| Data Processing | 0.25 | These design alternative will require varying levels of data processing to obtain useful information about the angular position of the rover. If data is complex and unable to be interpreted the rover could pass its tipping condition and cause damage or the inability to recover the rover. Since this aspect of the rotational sensors is integral to completing the mission, it has a large weight. |
| Hardware Integration Complexity | 0.20 | The complexity of the hardware integration is determined by the number of sensors needed to obtain the tilt of ARGOS and also the required location on the rover. This aspect of is not anticipated to be that challenging therefore it has a lower weight than data processing and accuracy. |
| Environmental Reliability | 0.15 | ARGOS will be traveling through forested areas which will cause vibration issues for the sensors. However, this issue can be easily accounted for within the software causing environmental reliability to be weighted as one of the lowest criteria. |
| Cost | 0.10 | The cost of the chosen design alternatives are relatively low and similar, so the cost does not make a significant impact for design choice |

**Score Assignment:** The following table lists the score and reasoning for each trade criteria.

Table 44: Score Assignments and Rational for Rotational Movement Sensors

| Criteria | 1 | 2 | 3 | 4 | 5 |
|---|---|---|---|---|---|
| Accuracy | Sensor does not measure tilt or any rotational value that can be used to calculate tilt | Sensor produces data with many sources of error. The assumptions made to calculate tilt are incorrect | Sensor has a few sources of error associated with it. Assumptions used in tilt calculation are true the majority of the time but do not account for all variables | Sensor provides data with minimal sources of error and assumptions made for the tilt calculation are valid | There is no likely source of error in sensor data. The sensor provides redundant data to check accuracy of sensor measurements |
| Data Processing Complexity | Sensor is not compatible with the software on board the rover. Calculation of the tilt is to challenging to complete before rover reaches tipping condition | Sensor data is challenging to compute. A different software platform is required to calculate the data | | Sensor data requires a multi-step approach to calculating the tilt of the rover. The chosen software platform is compatible with data calculation | Tilt is easily computed from the given data and is easily integrated with the chosen software platform |
| Hardware Integration Complexity | Requires too many components that are not easily manufactured or obtainable. Integration is too time consuming to complete. | | Requires multiple components that are easily manufactured or attainable. Integration time is feasible but still time consuming | Requires one or two extra components for integration. The time required to integrate is reasonable. | Requires no additional components for integration and takes little to no time to install on ARGOS |
| Environmental Reliability | Measurements can not be made while the rover is moving. Only able to calculate tilt while stationary. | Sensor can take measurements while moving through even terrain with a slope but vibrations cause the data to be hard to read and calculate the tilt while on uneven terrain | Sensor can take measurements while on uneven terrain but vibrations still cause tilt calculations to be highly inaccurate | | Sensor can measure tilt on most uneven terrains. Vibration noise in the signal can be easily accounted for and removed from the data |
| Cost | Greater than or equal to $500 | $100 to $499.99 | $50 to $99.99 | $10 to $49.99 | Less than $10 |

**Trade matrix:** The following table assigns the scores for each sensor and is used to determine final sensor used in the baseline design.

Table 45: Trade Matrix for Rotational Movement Sensors

| Criteria | Weight | MEMS Gyroscope | IMU | Accelerometer |
|---|---|---|---|---|
| Accuracy | 0.30 | 4 | 5 | 3 |
| Data Processing Complexity | 0.25 | 4 | 4 | 5 |
| Hardware Integration Complexity | 0.20 | 4 | 3 | 4 |
| Environmental Reliability | 0.15 | 3 | 5 | 3 |
| Cost | 0.10 | 4 | 3 | 5 |
| Total | 1 | 3.85 | 4.15 | 3.9 |

**Object Detection Sensors**

**Trade Criteria Selection:** Object detection and localization is critical to ensuring the safety and reliability of the rover. Without proper obstacle avoidance many of the mission objectives may be put in jeopardy. To ensure the best suited sensor types are chosen six trade criteria were selected. Accuracy encompasses the certainty of the sensor data, possible erroneous data, and the effect of the objects material and shape. Data processing complexity represents the computational load that each sensor will put on the processor. Sensor data will have to be computed quickly and efficiently in order to have adequate time to avoid obstacles. Hardware integration complexity represents the ease of integration with the rover physically. The sensors have to operate in hazy or smoky conditions as the rover will be close to active fires, so environmental reliability is also important. The sensor range is taken into account to better highlight sensors that cover a diversity of distances. Finally, the cost must also be accounted for, as extremely expensive sensors may not be within the budget.

**Weighting Assignments and Rationale:** The following table outlines the weight assigned to each criteria and why that weight was chosen based on the requirements and levels of success.

Table 46: Trade Criteria Weights and Rational for Object Detection Sensors

| Criteria | Weight | Rationale |
|---|---|---|
| Accuracy | 0.25 | An accurate object detector will ensure ARGOS does not get stuck or damaged on an obstacle. If either of those cases occurred due to an inaccurate object detector, requirement MOV.1.5 would not be satisfied and the entire rover or other components could be damaged beyond use. Therefore, the accuracy criteria is weighted as one of the highest. |
| Data Processing Complexity | 0.25 | The sensors must integrate with software in order to convert the outputted data into meaningful information and recognize that an obstacle in its path. If processing the data becomes too complex to implement effectively, the rover could become stuck by detecting obstacles that are not actually there or crash into other objects. Because this could result in a failure to meet MOV.1.5 or loss of the system, this criteria is weighted as one of the highest. |
| Hardware Integration Complexity | 0.20 | It is necessary that the sensors ride on the body of the rover to detect objects that in front of the rover, but it is not anticipated to be the most challenging aspect of these designs, so it is weighted as lower than accuracy and data processing complexity. |
| Environmental Reliability | 0.15 | While ARGOS has the possibility of operating in high temperatures and smokey conditions, it is not listed in the requirements; therefore, it is not weighted as heavily as the other criteria. |
| Cost | 0.10 | The cost of the chosen design alternatives are relatively low, so the cost does not make a significant impact for any alternative. |
| Range | 0.05 | There is no need to detect objects from very far distances, but rather it is only necessary to detect object with enough space to turn and avoid the object. The range criteria is weighted the least because the sensors will not have to reach relatively far distances. |

**Score Assignment:** The following table lists the score and reasoning for each trade criteria.

Table 47: Score Assignments and Rational for Object Detection Sensors

| **Criteria** | **1** | **2** | **3** | **4** | **5** |
|---|---|---|---|---|---|
| Accuracy | Sensor cannot detect objects | Sensor can detect objects but is prone to many sources of error. Object shape and material have a large effect on the accuracy. | There are a few sources of error that are somewhat likely to occur. Some objects shape and material effect the accuracy. | There is only one or two sources of error that may occur during the mission. Object shape and material rarely effects accuracy. | There are no likely sources of error that will contribute to inaccurate readings. Little to no effects from object material and shape. |
| Data Processing Complexity | Sensor is not compatible with the available software and data processing/on-board computations are too challenging to complete in the given time frame. | Object location is not easily computed from the sensor data. Requires a different software platform from the system. | Involves multiple step data processing to extract distance traveled that is somewhat time-consuming and challening, but feasible. The chosen software platform is appropriate for computing the location of the object. | Object location is easily computed from the sensors and can integrate with the chosen software system. | Object location is directly outputted by the sensor. Does not need any on-board computations or data-processing. |
| Hardware Integration Complexity | Involves too many components that are not able to be manufactured or are too expensive. Integration is too difficult and/or time-consuming to complete. | Involves extensive integration with multiple components that are not easily attainable. | Involves extensive integration with multiple components, but is still feasible to complete in the given time frame. | Integration takes an average amount of time with only one to two extra components to connect the sensor. | Involves little to no extra components to integrate the sensor to the system. Integration takes very little time. |
| Environmental Reliability | No measurements can be made in any forested areas , only open space. Heavily effected by smoke and other particulates. Sensors can only operate on level ground. | | Sensors can still take meaningful data even with uneven terrain or in a covered area with a tree density of 0.25 trees/m2. Only one of these conditions are met, not both. Some accuracy is effected by smoke and particulates. | | Sensors can still measure object location whether it be in open areas or forested areas with a tree density of 0.25 trees/m2 or level ground or at a 20 degree incline with 7cm tall obstacles. Little to no effect from smoke and particulates. |
| Range | Sensor range is very limited to either only close (<1 m), medium (1-5m), or far distances (>5m). | | Sensor range covers at least two distance categories. | | Sensor covers all distance categories. |
| Cost | greater than or equal to $100 | $75 – $99.99 | $50 – $74.99 | $25 – $49.99 | less than $25 |

**Trade matrix:** The following table assigns the scores for each design alternative.

Table 48: Trade Matrix for Object Detection Sensors

| Criteria | Weight | RADAR | Ultrasonic | FPV Camera | IR Transceiver | Bumper Sensor |
|---|---|---|---|---|---|---|
| Accuracy | 0.25 | 3 | 3 | 3 | 1 | 2 |
| Data Processing Complexity | 0.25 | 3 | 4 | 2 | 4 | 5 |
| Hardware Integration Complexity | 0.2 | 3 | 4 | 5 | 4 | 3 |
| Environmental Reliability | 0.15 | 3 | 3 | 3 | 3 | 1 |
| Range | 0.05 | 3 | 1 | 3 | 4 | 5 |
| Cost | 0.1 | 2 | 4 | 5 | 3 | 1 |
| Weighted Total | 1 | 2.9 | 3.43 | 3.35 | 3.15 | 2.95 |

### Communications

**Trade Criteria Selection:** The criteria that have been chosen for the communications system are cost, power, data rates, attenuation, integration complexity and range. Over the course of the mission it is prudent that communications are maintained between ARGOS, the mother rover, and the ground station in order for data transfer to happen. These criteria were chosen to ensure we meet the range, budget, required data transfer rates, and the ease of integration between the MR and GS. Our Rationale for choosing each trade criteria is outlined in table below.

**Weighting Assignments and Rationale:** The following table outlines the weight assigned to each criteria and why that weight was chosen based on the requirements and levels of success.

Table 49: Trade Criteria Weights and Rational for Communications

| Criteria | Weight | Rationale |
|---|---|---|
| Range | 0.25 | The range for communication needs to meet the 250 meter requirement. This requirement not being met would defeat the purpose of it's main objective. |
| Cost | 0.15 | Our project will have a budget in place. This Trade criteria is important to ensure our communications system is within budget. |
| Integration Complexity | 0.2 | Integration of the system so that it can meet the requirement of communication with the ground station and mother rover. Ease of integration will reduce hours spent on integration. |
| Power | 0.1 | Coincides with the output of the signal strength. Power needs to be considered for in power budget. |
| Data Transfer Rate | 0.2 | Mission requires data transfer from various sensors and camera on rover. A sufficient speed needs to be implemented to handle the data transfer. |
| Attenuation | 0.1 | The signal will pass through obstacles such as, trees, rocks and foliage during the mission, which will reduce the signal strength. Maintaining a connection is vital to mission success. |

**Score Assignment:** The following table outlines what each score means for each trade criteria.

Table 50: Trade Criteria Weights and Rational for Communications

| **Criteria** | **1** | **2** | **3** | **4** | **5** |
|---|---|---|---|---|---|
| Range | >250m | 250m-300m | 300-350m | 350m-400m | >400m |
| Cost | > $500 | $200-$500 | $50-$200 | <$50 | Free |
| Integration Complexity | Completely new system on the mother rover and/or ground station | | Some new components on the mother rover and/or ground station | | Nothing added |
| Power Consumption | >6W | 3W-6W | 1W-3W | 79mW-1W | <79mW |
| Data Transfer Rate | <250Kbps | 250Kbps-1Mbps | 1Mbps-10Mbps | 10Mbps-100Mbps | >100Mbps |
| Attenuation | Complete loss due to obstacles | | Some loss due to obstacles | | No loss due to obstacles |

**Trade matrix:** The following table outlines the scores each criteria received for each design alternative.

Table 51: Trade Matrix for Communications

| **Criteria** | **Weight** | **High Band** | **Low Band** | **Cellular** | **Laser** |
|---|---|---|---|---|---|
| Range | 0.25 | 4 | 5 | 2 | 5 |
| Cost | 0.15 | 3 | 3 | 4 | 2 |
| Integration Complexity | 0.2 | 4 | 5 | 4 | 1 |
| Power consumption | 0.1 | 2 | 2 | 3 | 3 |
| Data Rate Transfer | 0.2 | 5 | 5 | 3 | 5 |
| Attenuation | 0.1 | 1 | 3 | 3 | 1 |
| Weighted Total | 1 | 3.55 | 4.2 | 3.1 | 3.15 |

## Bill of Materials

| Component | Distributer | Quantity | Unit Price | Shipping | Total Price | Subsystem |
|---|---|---|---|---|---|---|
| GPS-RTK-SMA Breakout - ZED-F9P | Sparkfun | 1 | 219.95 | 0 | 219.95 | Sensors |
| RedLine Encoder Kit | AndyMark | 2 | 47 | 0 | 94 | Sensors |
| Zio Ultrasonic Distance Sensor - HC-SR04 (Qwiic) | Sparkfun | 4 | 13.95 | 0 | 55.8 | Sensors |
| SLAMTEC A2M8 | SAMTEC | 1 | 319 | | 319 | Sensors |
| Runcam Nano 2 FPV Camera | Flight Test | 1 | 19.99 | | 19.99 | Sensors |
| Infrared Thermometer - MLX90614 | Sparkfun | 1 | 29.95 | 0 | 29.95 | Sensors |
| SparkFun VR IMU Breakout - BNO080 (Qwiic) | Sparkfun | 1 | 34.95 | 0 | 34.95 | Sensors |
| Arduino Due | amazon | 1 | 39.9 | 0 | 39.9 | electronics |
| Intel NUc | Intel | 1 | 247 | 10 | 257 | electronics |
| Kingston A400 120G Internal SSD M.2 | amazon | 1 | 19.99 | 0 | 19.99 | electronics |
| GPS/GNSS Magnetic Mount Antenna | Sparkfun | 1 | 12.95 | 0 | 12.95 | electronics |
| SPARK Brushed DC Motor Controller | AndyMark | 2 | 50 | 10 | 110 | electronics |
| NETGEAR 5-Port Gigabit Ethernet Unmanaged Switch (GS305) | amazon | 1 | 15 | 0 | 15 | electronics |
| REDGO Video Audio VHS VCR USB Video Capture Card to DVD Converter Capture Card Adapter | amazon | 1 | 10.99 | 0 | 10.99 | electronics |
| SMAKN Waterproof DC/DC Converter 12V (10-30V) Step UP to 48V/4A 192W Power Supply Module | Amazon | 1 | 29.99 | | 29.99 | electronics |
| 12V 16Ah Deep Cycle LiFePO4 Battery | Amazon | 1 | 49.99 | | 49.99 | electronics |

Figure 68: Screenshot of Bill of Materials (1 of 4)

| | | | | | | |
|---|---|---|---|---|---|---|
| Qwiic JST Connector - SMD 4-pin (Horizontal) | spark fun | 4 | 0.5 | 0 | 2 | electronics |
| 2-Bolt Flange Bearing | Grainger | 6 | 19.35 | 12.83 | 128.93 | Drivetrain |
| Metal Gear | McMaster | 0 | 60.4 | | 0 | Drivetrain |
| Standard Sprocket | Misuni | 10 | 8.19 | 13.4 | 95.3 | Drivetrain |
| Radial Ball Bearing | Grainger | 12 | 3.91 | 0 | 46.92 | |
| Pillow Block Bearing | Grainger | 6 | 21 | 0 | 126 | Drivetrain |
| Talon SRX Speed Controller | AndyMark | 2 | 99 | 0 | 198 | Drivetrain |
| Ventilation Spacer | AndyMark | 2 | 5 | 0 | 10 | Drivetrain |
| 1/2" Shaft | McMaster | 6 | 8.71 | | 52.26 | Drivetrain |
| Chain | McMaster | 10 | 5.49 | | 54.9 | Drivetrain |
| 775 Redline Motor | AndyMark | 2 | 19 | 8.5 | 46.5 | Drivetrain |
| Swisher 13.75 in Rear Wheel | Lowe's | 6 | 24.1 | 0 | 144.6 | Drivetrain |
| 57 Sport Gearbox | AndyMark | 2 | 96 | 0 | 192 | Drivetrain |
| 6061 Aluminum Sheet 20x36.5 | MidWest Steel & Aluminum | 1 | 52.33 | 10.48 | 62.81 | Drivetrain - Chassis |
| Plexiglass Black Acrylic Plate 24inx36inx1/8in | Home Depot | 2 | 39.99 | 0 | 79.98 | Drivetrain - Chassis |

Figure 69: Screenshot of Bill of Materials (2 of 4)

| | | | | | | |
|---|---|---|---|---|---|---|
| Plexiglass Black Acrylic Plate 24inx36inx1/8in | Home Depot | 2 | 39.99 | 0 | 79.98 | Drivetrain - Chassis |
| 1-3/4" Bore Wear Ring | McMaster | 2 | 4.73 | | 9.46 | Mast |
| 1/4 Machine Screws | McMaster | 2 | 2.83 | | 5.66 | Mast |
| 3/8 Machine Screws | McMaster | 2 | 2.74 | | 5.48 | Mast |
| 2" OD 1.25" ID Aluminum Tube | McMaster | 1 | 95.58 | | 95.58 | Mast |
| 2.25" OD 1.75" ID Aluminum Tube | McMaster | 1 | 78.26 | | 78.26 | Mast |
| 1-3/4" Bore Dynamic Seal | McMaster | 1 | 5.93 | | 5.93 | Mast |
| O-ring 1.25" bore x100 for whatever reason | McMaster | 1 | 6.95 | | 6.95 | Mast |
| Quick Disconnect Fitting | McMaster | 1 | 11.3 | | 11.3 | Mast |
| SUNBA 601-D25X | Amazon | 1 | 269.99 | | 269.99 | Camera |
| Rocket M2 | Amazon | 2 | 80 | | 160 | Communication |

Figure 70: Screenshot of Bill of Materials (3 of 4)

| | | | | | | |
|---|---|---|---|---|---|---|
| POE TP-DCDC-1224 Adapter | PoETexas | 2 | 5.49 | | 10.98 | Communication |
| TRENDnet Reverse SMA Female to N-Type Male Weatherproof Connector Cable (6.5ft, 2M), TEW-L202 | Trendnet | 1 | 19 | | 19 | Communication |
| Antenna 2.4GHz 12dBi Omni-Directional WiFi w/ RP-TNC | Data Alliance | 1 | 8.99 | | 8.99 | Communication |
| 1ft Cat6 550 MHz UTP Snagless Ethernet Network Patch Cable, Blue | Cable Leader | 2 | 0.77 | | 1.54 | Communication |
| 1 Foot Male to Male 2.1mm x 5.5mm Plug DC Power Adapter Cable 18GA | Valley Enterprises | 1 | 3.99 | | 3.99 | Communication |
| Tupavco tp511 Panel Antenna 2.4 GHz 20 dBi directional antenna | Tupavco | 1 | 54.98 | | 54.98 | Communication |
| TP-Link 5 Port Fast Ethernet 10/100Mbps PoE Switch | Amazon | 1 | 34.99 | | 34.99 | Communication |
| USB 2.0 Audio/Video Converter | Amazon | 1 | 11.99 | | 11.99 | Communication |
| Total | | | | | 3354.72 | |

Figure 71: Screenshot of Bill of Materials (4 of 4)