University of Colorado
Department of Aerospace Engineering Sciences
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Conceptual Design Document (CDD)

Autonomous Rover for Ground-based Optical Surveillance (ARGOS)

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1 Project Description

1.1 Purpose and Objectives

Wildfire suppression has become an increasingly pertinent issue in recent years. Some models predict a six-hundred percent increase in median burned area per year if the Earth warms an average of one degree Celsius [1]. Therefore, the need for better tools to aid firefighters, especially in wildfire prone environments, is increasing every year. One strategy used to contain wildfires is to create a fire line, a trench cleared of flammable material, on the edge of the fire to halt its spread [2]. The purpose of the Autonomous Rover for Ground-based Optical Surveillance (ARGOS) system is to gather data from a fire line and send said data to a ground station and a mother rover.

ARGOS has three main objectives during its operation: navigation to the fire line, surveillance of the fire line and fire, and communication to the ground station. During navigation, ARGOS will move up to 100 meters away from its point of deployment to the fire line, crossing uneven terrain and inclines of 10 degrees. Once ARGOS has reached the fire line, a mast will extend with a camera to record photos and videos of the flame front. The added height from the mast will allow ARGOS to see past the flame front and foliage. This data can then be used to determine the location of the flame front with respect to the fire line and alert the ground station if the flame front has breached the fire line. Communication will be maintained with the ground station so that ARGOS can relay back timestamped data as well as receive commands. Table 1 contains four levels of success in each category. Meeting a level of success implies that all the previous levels were also met.

Table 1: Levels of Success for ARGOS

	Rover Movements	**Surveillance**	**Communications**
Level 1	Rover can travel on flat ground for 100m. Rover can travel in both forward and reverse and can turn 360 degrees with a turn radius less than two rover body lengths.	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 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 or in the same room via radio remote control.
Level 2	Rover can travel on various terrain, including leaves, scattered 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.	Rover records timestamped video of the flame front via a camera on an extendable and retractable mast.	Rover can communicate with the ground station and the mother rover up to 100m with no obstacles (0 trees/m2).
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 records the distance of the fire line and the flame front over time and calculates the speed of travel of the flame front.	Rover can communicate with the ground station and the mother rover with obstacles (0.25 trees/m^2).
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 +/-5m of the coordinates.	Rover processes a combination of the surveillance data (temperature, video, distance, and/or speed) and determines whether the fire line has been breached.	Rover can communicate with the ground station and the mother rover up to 250m.

1.2 Concept of Operations

The Concept of Operations (CONOPS) visually demonstrates the mission of the child rover. The operation of this rover as seen in figure 1 is divided into 5 stages; Deployment of Rover, Navigation, Arrival at Location of Interest, Deployment of Sensors and Monitoring, and Update/Return signal from the ground station.

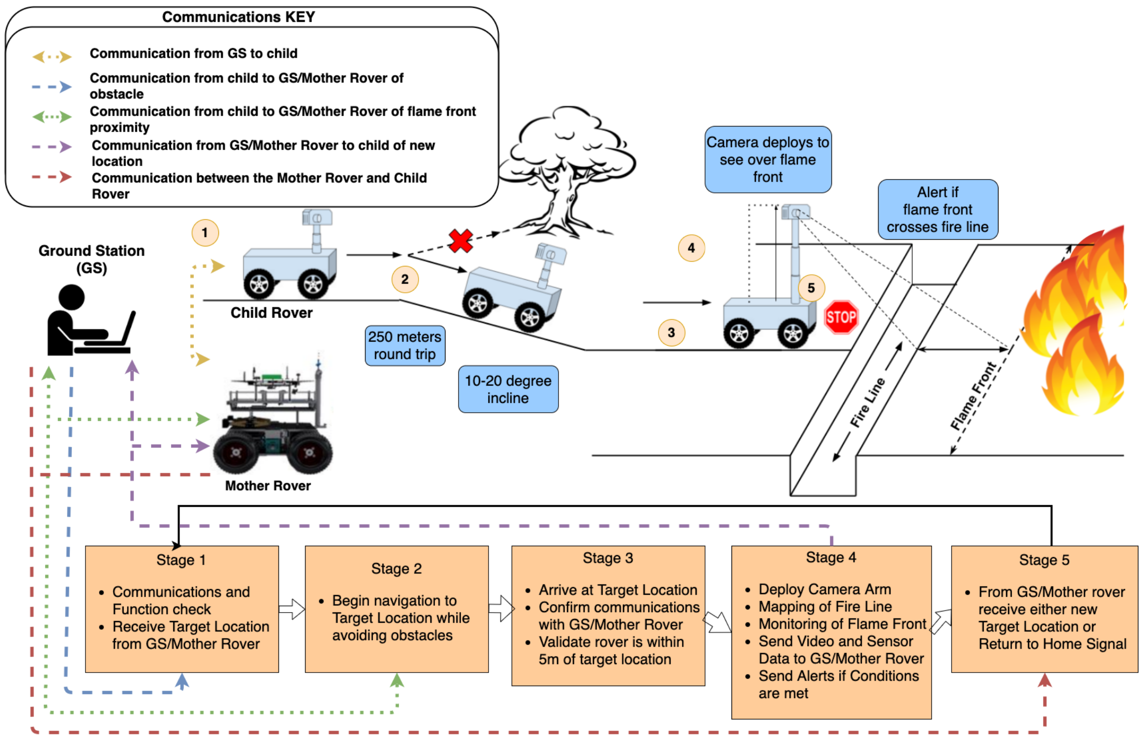


Figure 1: Concept of Operations for ARGOS

1.3 Functional Block Diagram

The following functional block diagram depicts all the major subsystems of ARGOS such as Communications (COMM), Command and Data Handling (C&DH), the Rover Mobility system, and Fire Surveillance which includes the mast and camera.

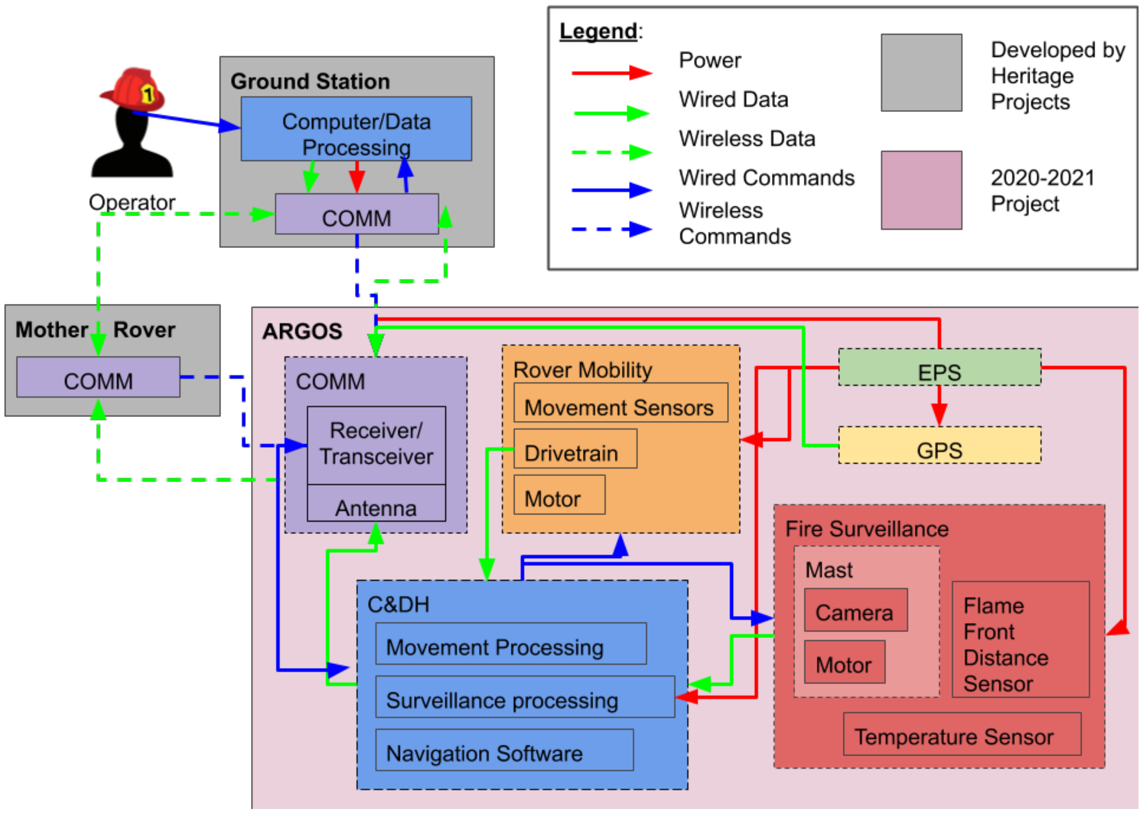


Figure 2: Functional Block Diagram for ARGOS

1.4 High Level Functional Requirements

High Level Functional Requirements	
Requirement ID	**Description**
FR.1	The child rover shall be able to move from a starting point to a location of interest and return.
FR.2	The child rover shall be able to survey a fire line while taking ambient temperature data that can be used for analysis.
FR.3	The child rover shall have an extendable and retractable mast to take photos and video of the flame front from multiple positions.
FR.4	The child rover shall be able to receive commands from a ground station and mother rover and communicate back photos, video, and temperature data.

2 Design Requirements

2.1 Verification and Validation

Each of the requirements stated above aren't meaningful without a reasonable way to test and prove the functionality when applied to the rover. The verification methods for each requirement will be done in one of three ways, investigation, demonstration, or a test. Those are defined more

thoroughly below.
Inspection: This verification method consists of looking for certain specifications or manufacturer-given descriptions of a part that satisfy the requirement. This would be used mainly for validating measurements made by a part, such as by sensors or cameras.
Demonstration: This method of validation will be satisfied if a certain part can show ability to complete a small activity, an example of this would be the rover turning 360 degrees.
Test: With this method of verification/validation the requirement will be satisfied by performing a specified test procedure depending on the system being used. These procedures will be specified further in the table below.

Testing Procedures	
Test	**Test Description**
Communication	The child rover will be placed a various distances (0-250m) from the ground station and mother rover to test the transfer of temperature and video/image data. Large obstacles will be placed at these varied distances to test for any attenuation of the signal.
Disconnected Navigation Recovery	The child rover will be placed at a specified starting point and will be commanded to move to a certain points of interest (0-250 m) away from the specified starting point . Once the child rover has successfully moved (or is moving to) the point of interest, it will be purposefully disconnected from the ground station or mother rover and evaluated on its ability to return to its starting location.
Obstacle Maneuverability	The child rover will be placed in a terrain with numerous obstacles and will be tested by commanding the child rover to navigate to a location past the obstacles such that the rover must detect and avoid the objects in its path.
Camera Operation	The child rover's equipped camera will be commanded to rotate anywhere from 0 to 100 degrees in order to test its field of view.
Rangefinder Accuracy	The child rover will be placed at different distances from a fire and will test the rangefinder's accuracy based off of a known distance to the fire.
Inclination	The child rover will be placed in various inclined terrains (0-20 degrees) on which it will be commanded to travel. The test will be determined to be a success if the child rover can traverse the various degrees of incline.

2.2 Requirements Flowdown

FR.1: The child rover shall be able to move from a starting point to a location of interest and return.		
Design Requirement ID	**Description**	**Validation & Verification**
MOV.1.1	The child rover shall be able to perform a 360 degree turn.	Demonstration
MOV.1.2	The child rover shall be able to travel in forward and reverse motion.	Demonstration
MOV.1.3	The child rover shall be able to travel up and down slopes of 20 degree inclination.	Test - Inclination
MOV.1.4	The child rover shall be able to traverse forest floors (underbrush).	Test - Obstacle Maneuvering
MOV.1.5	The child rover shall be able to travel 250m round trip in any direction from its starting location.	Demonstration
CDH.1.1	Upon loss of communication, the child rover shall return to its last known GPS location (storage of waypoints).	Demonstration
CDH.1.2	The child rover shall be able to determine how high the mast can extend without creating a tipping condition.	Demonstration

FR.2: The child rover shall be able to survey the fire line while taking ambient temperature data that can be used for analysis.		
Design Requirement ID	**Description**	**Verification& Validation**
SURV.2.1	The child rover shall be able to determine its distance to a flame front and/or fire line using a range finder.	Test - Range
CDH.2.2	The child rover shall be able to determine if the flame front crosses the fire line.	Demonstration
CDH.2.3	The child rover shall be able to determine the ambient temperature within +/- 5 degrees C at the location of interest.	Demonstration

FR.3: The child rover shall have an extendable and retractable mast to take photos and video of the flame front from multiple positions.		
Design Requirement ID	**Description**	**Verification& Validation**
SURV.3.1	The child rover shall have image and video capability with >100 degrees field of view.	Test - Camera Operation
SURV.3.1.1	The video camera shall have >100 degrees field of view.	Inspection
SURV.3.1.2	The video camera shall provide the operator with video and images of sufficient quality to support mission operations.	Inspection

FR.4: The child rover shall be able to receive commands from a ground station and mother rover and communicate back photo, video, and temperature data.		
Design Requirement ID	**Description**	**Verification& Validation**
COM.4.1	The child rover shall be able to receive commands from the mother rover.	Test - Communication
COM.4.1.1	Upon loss of communication with the mother rover, the child rover shall return to the last known GPS coordinates.	Test - Disconnected Navigational Recovery
COM.4.2	The child rover shall be able to receive commands from the ground station.	Test - Communication
COM.4.3	The child rover shall send time stamped video, image, and temperature data to the ground station and mother rover.	Test - Communication
COM.4.4	The ground station shall confirm if the child is within +/- 5 m of the desired location.	Test - Communication
COM.4.5	The mother rover shall be able to command the child rover to navigate to specified GPS coordinates in real time.	Test - Communication
COM.4.6	The mother rover shall be able to command video feed on/off.	Demonstration
COM.4.7	The mother rover shall be able to receive commands from the ground station.	Test - Communication
COM.4.8	The mother rover shall be able to send data to the ground station.	Test - Communication

3 Key Design Options Considered

In order to meet the design requirements, key design options were considered in various categories that are considered critical for this mission such as the rover's drivetrain, the rover's mast, the movement sensors, the mast sensors, communications, and software.

3.1 Rover Drive Train

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.

Design Option 1: Tank Treads

The first option that was considered for the drive train was tank treads. This was examined mainly because of the tank tread's adequate ability to drive over rough terrain. Figure 3 shows how it would be implemented and table 3 below shows the pros/cons.

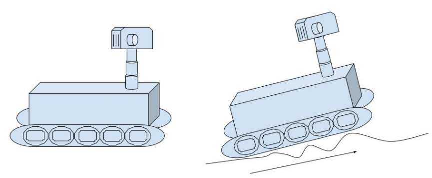


Figure 3: Tank Treads on Child Rover

Table 2: Pros and Cons Table for Tank Treads

Condition	Pro	Con
Can maneuver over obstacles	X	
Very stable	X	
Requires less power	X	
Mechanically complex		X
Results in slower speeds		X
Does not provide any redundancy		X

Design Option 2: 4 Wheels

The second design option considered was a drive train consisting of four wheels fixed directly to the body each supplied with power. This configuration was taken into consideration for its simplicity in design with sufficient capability to satisfy the requirements. Figure 4 shows how the four wheels will be implemented and table 3 below refers to its pros/cons.

(a) 6 Wheel with powered middle wheel

(b) 6 Wheel without powered middle wheel

Figure 5: Both 6 Wheel Configurations

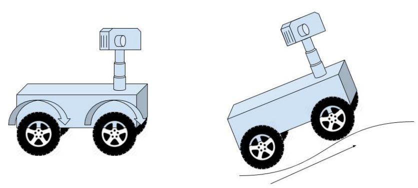


Figure 4: 4 Wheel Child Rover

Table 3: Pros and Cons Table for 4 Wheels

Condition	**Pro**	**Con**
Mechanically simple	X	
Easy to manufacture	X	
Does not provide any redundancy		X
Obstacle maneuvering		X

Design Option 3: 6 Wheels

The third design option that was taken into consideration for the drive train was 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. A detailed image below (figure 5) shows how the 6 wheels would be implemented in both cases as well as tables 4 and 5 show their pros and cons.

Table 4: Pros and Cons Table for 6 Wheels: Powered Middle Wheels

Condition	Pro	Con
Obstacle maneuvering	X	
Simple to manufacture	X	
Each wheel is powered	X	
Mechanically complex (Controls)		X
Excessive power usage		X
Expensive		X

Table 5: Pros and Cons Table for 6 Wheels: Unpowered Middle Wheels

Condition	Pro	Con
Good obstacle maneuvering, including ground discontinuities	X	
Simple to manufacture	X	
Mechanically simple	X	
Inexpensive	X	
Less power required	X	
Could get stuck on unpowered wheels		X
Unpowered wheels slow vehicle down		X

Design Option 4: Rocker Bogie

The fourth and final option is a rocker bogie suspension arrangement. This configuration consists of six wheels but instead of the wheels being fixed to the body they are connected through linkages. The larger linkage is fixed to the body and called the rocker which hold on one side a wheel and the other side is connected to second, smaller linkage called the bogie that holds in place two wheels. This description is visualized in figure 6 below. The main advantage of this set up is its ability to keep the body of the rover stable while in motion. This capability will allow the rover to extend the mast with less disturbances and take steady video data even while in motion. This configuration is also very good at going over obstacles. For instance, the rocker bogie suspension can traverse an obstacle twice the size of its wheel. A list of pros and cons for this system can be seen in table 6 below.

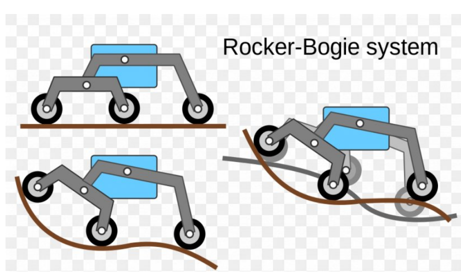


Figure 6: Rocker Bogie

Table 6: Pros and Cons Table for Rocker Bogie

Condition	Pro	Con
Keeps rover body stable	X	
Obstacle maneuvering	X	
Mechanically complex		X
Unstable at high speeds		X
Unreliable parts		X

3.2 Rover Mast

The rover's mast is a critical project element to the design of the fire surveillance and the core objective of this project. To survey the fire, the camera system must extend to gain an elevated vantage point once the rover comes near the fire line in order to see the flame front and proximity to the fire line. 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.

Design Option 1: 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.

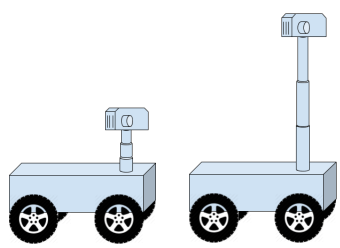


Figure 7: Extension of camera by telescoping mast

Table 7: 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 (load dependent)		X
Relatively high cost		X

Design Option 2: Fold-Over (Dual Joint)

The dual-joint fold-over mast consists of two members with two hinges, one connecting the two members and one connecting the bottom member to the rover. It will articulate up and down via two separate motors, located at each hinge, turning the members until they are straight. This has high complexity, due mostly to the motor at the middle hinge, as well as support weight dependent on the power and torque of the motors. It excels at compressing to a low profile.

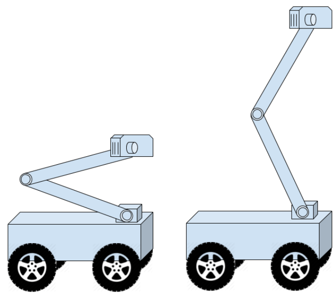


Figure 8: Extension of camera by Fold Over mast

Table 8: Pros and Cons Table for Fold-Over

Condition	**Pro**	**Con**
Good extension/retraction speed	X	
Good ratio of maximum height to compacted height	X	
Low stability and support weight (motor in middle joint)		X
Mechanically complex		X
Relatively high cost		X

Design Option 3: 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.

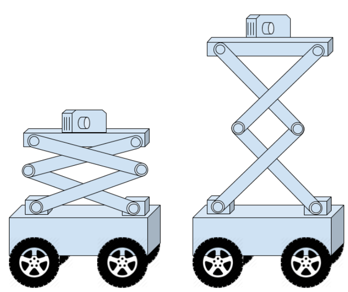


Figure 9: Extension of camera by Scissor Lift mast

Table 9: 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	
Many potential failure points		X
Relatively high cost		X

Design Option 4: Screw Lift

A screw lift mast uses two screws at 90° angles to one another with interlacing teeth in order to convert rotational motion to transnational. The advantages of this mast are a stable and high support weight with low cost and relatively simple mechanical complexity. This comes at the cost of a low maximum extendable height and slow extension/retraction speed.

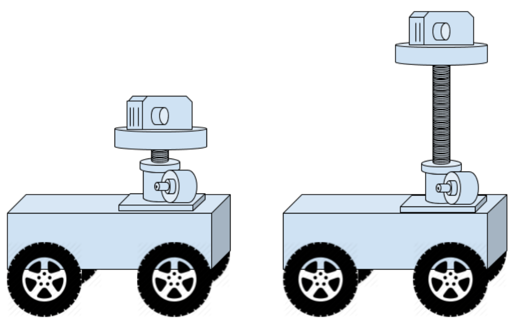


Figure 10: Extension of camera by Screw Lift mast

Table 10: Pros and Cons Table for Screw Lift

Condition	Pro	Con
High stability and support weight	X	
Low mechanical complexity	X	
Low cost	X	
Low extension/retraction speed		X
Low ratio of maximum height to compacted height		X

Design Option 5: Rigging Pulley

A rigging pulley has multiple vertical members placed side-by-side and extends via a motor providing tension to pull each member up. It has a relatively simple design and a good maximum height, but cannot compress very low and isn't as rigid as others when fully extended.

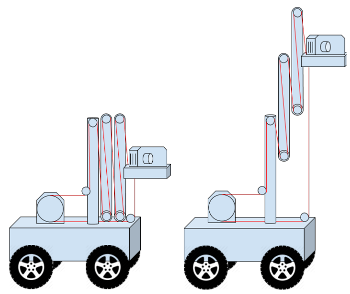


Figure 11: Extension of camera by Rigging Pulley mast

Table 11: Pros and Cons Table for Rigging Pulley

Condition	Pro	Con
Moderate stability and support weight	X	
Moderate mechanical complexity	X	
Low cost	X	
Low extension/retraction speed		X
Moderate ratio of maximum height to compacted height		X

Design Option 6: Zippermast

A zippermast consists of three sets of interlinking "zippers" which are chains of flat members with slits that that lock up when pushed parallel to one another, driven by a screw in the center, but can also be rolled together to retract. The three sets of zippers interlink together and form a triangular prism for increased strength over just one or two zippers. This results in a high ratio of extendable height to compacted height because of the ability to roll the zippers together, but has high complexity and just moderate support weight.

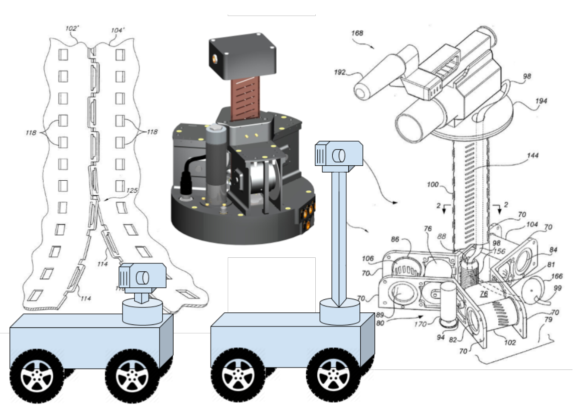


Figure 12: Extension of camera by zippermast

Table 12: Pros and Cons Table for Zippermast

Condition	Pro	Con
Moderate stability and support weight	X	
High ratio of maximum height to compacted height	X	
High extension/retraction speed	X	
High cost		X
High mechanical complexity		X

Design Option 7: Fold-Over Telescoping Hybrid

The fold-over telescoping hybrid is a combination of the fold-over concept (with only a single joint) and the telescoping mast. This means it has a very high ratio of extendable height to compressible height but is more complex than the telescoping mast alone since it also has to pivot at its base to fold over.

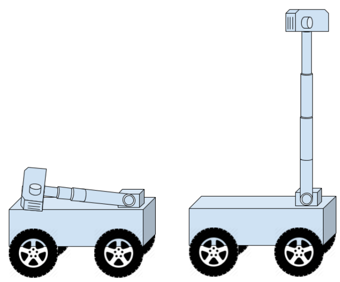


Figure 13: Extension of camera by Scissor Lift mast

Table 13: Pros and Cons Table for Fold-Over Telescoping Hybrid

Condition	Pro	Con
Moderate stability and support weight	X	
High ratio of maximum height to compacted height	X	
Low extension/retraction speed		X
Mechanically complex		X
High cost		X

3.3 Movement Sensors

The rover's movements were determined to be a critical portion of the design as indicated by the levels of success in Figure 1 as well as one of the major subsystems as illustrated in the functional block diagram in Figure 2. Multiple design requirements also entail how the rover moves, so, to satisfy these requirements, different design options were considered. Because there are different motions that ARGOS will experience such as forward/reverse movement, tipping about different axes, and turning, the movement sensors were split into the following three sections: translational movement sensors, rotational movement sensors, and object detection to measure the respective motions.

3.3.1 Translational Movement Sensors

In order to validate that the requirement of a 250m round-trip was met (MOV.1.5), 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.

Design Option 1: GPS

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

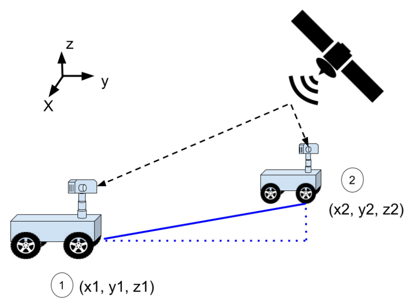


Figure 14: Diagram of Distance Traveled as Measured by GPS

As shown in Figure 14, 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 14.

Table 14: Pros and Cons Table for GPS [3]

Condition	Pro	Con
5m accuracy in optimal environment and accurate timing	X	
Already using GPS to transmit coordinates	X	
Position accuracy issues when in a canyon or forest		X

Design Option 2: Wheel Odometer

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

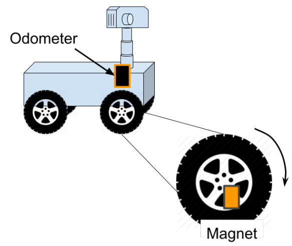


Figure 15: Diagram of Distance Traveled as Measured by a Wheel Odemeter

As shown in Figure 15, 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 15.

Table 15: Pros and Cons Table for Wheel Odometers [4]

Condition	Pro	Con
Distance traveled is clearly displayed	X	
No signal processing or additional computations required	X	
Cannot communicate data back to GS or MR		X
Less accurate in loose terrain such as underbrush		X

Design Option 3: Stepper Motor

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

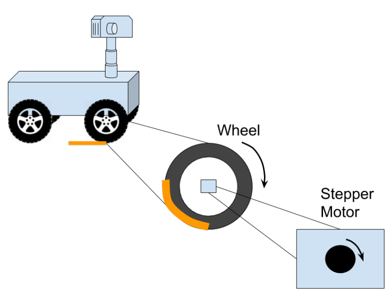


Figure 16: Diagram of Distance Traveled as Measured by a Stepper Motor

The stepper motor 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 33.

Some of the pros and cons to this approach are outlined in Table 16.

Table 16: Pros and Cons Table for Stepper Motors [5]

Condition	Pro	Con
Already using a stepper motor to power drivetrain	X	
No signal processing required	X	
Less accurate in loose terrain such as underbrush		X

3.3.2 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.

Design Option 1: 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.

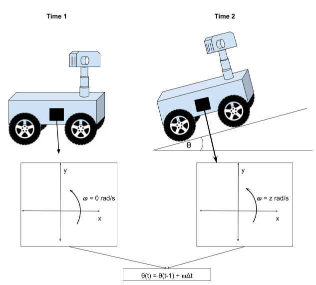


Figure 17: Diagram of Inclination as Measured by MEMS Gyroscope

As shown in figure 17, the angular rate from the gyroscope is integrated to get angular position of the rover.

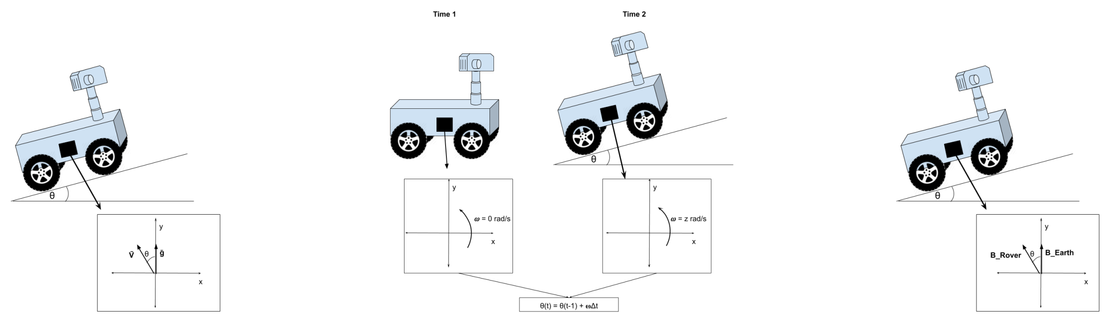
The pros and cons for this approach are listed below in Table 17.

Table 17: Pros and Cons Table for MEMS Gyroscope [6]

Condition	Pro	Con
3-axis measurements	X	
Low noise in the signal	X	
Signal processing required		X

Design Option 2: 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 18: Sensors Used in Determining Rover Inclination with IMU

As shown in figure 18, 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 18.

Table 18: Pros and Cons Table for IMU[8]

Condition	Pro	Con
Redundant measurements	X	
Highly accurate in all types of terrains	X	
Complex signal processing		X

Design Option 3: 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.

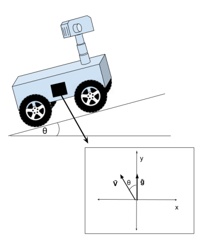


Figure 19: Diagram of Inclination as Measured by Accelerometer

As shown in the figure 19, 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 19.

Table 19: Pros and Cons Table for Accelerometer[7]

Condition	Pro	Con
3-axis measurements	X	
Simple signal processing	X	
Inaccurate measurements due to noise in signal		X

3.3.3 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.

Design Option 1: LiDAR

Light detecting and ranging (LiDAR) is a form of distance measuring where a near visual band of light is emitted from a laser, reflected off an object, and the reflection is then measured by a sensor. Often a LiDAR sensor used in robotics will scan a large range of angles and produce a point-cloud of the surrounding area. Figure 20 shows a diagram of the basic steps LiDAR uses to produce this point-cloud. The pros and cons of using LiDAR for obstacle avoidance are listed in table 20

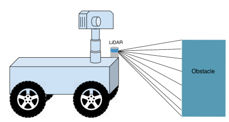


Figure 20: Diagram of LiDAR functionality.

Table 20: Pros and Cons Table for LiDAR [11]

Condition	Pro	Con
Accurate distance and shape measurement	X	
Significant cost especially for wide range LiDARs		X
Large field of view options available	X	
Can collect elevation data even in dense forests	X	
Accuracy effected by particulates in the air		X

Design Option 2: 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 21 shows an example diagram of the how a radar transmits and receives a radio signal. Table 21 shows a list of pros and cons for RADAR.

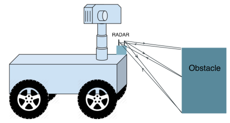


Figure 21: Diagram of RADAR functionality.

Table 21: Pros and Cons Table for RADAR [12]

Condition	Pro	Con
Can measure distance and some obstacle shape	X	
Affected by other communication signals		X
Large field of view options available	X	
Some shapes and materials can cause inaccuracies		X

Design Option 3: 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 22 shows a diagram of how an ultrasonic range finder is used to detect an object. Table 22 is a list of pros and cons for ultrasonic range finders.

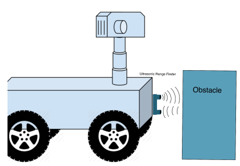


Figure 22: Diagram of ultrasonic range finder functionality.

Table 22: Pros and Cons Table for Ultrasonic range finder [13]

Condition	Pro	Con
Can measure obstacles at close distances	X	
Field of view is limited		X
Accuracy can be effected by object shape		X

Design Option 4: 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 23 shows a diagram of the view that an FPV camera would provide. Table 23 is a list of pros and cons for the FPV camera.

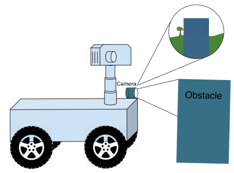


Figure 23: Diagram of FPV camera functionality.

Table 23: Pros and Cons Table for FPV Camera [16]

Condition	Pro	Con
Allows for direct feedback to a human operator	X	
Cameras are often very inexpensive	X	
There is no direct obstacle detection or measurement		X

Design Option 5: 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 24 shows a diagram of how the bumper sensor functions.

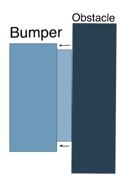


Figure 24: Diagram of bumper sensor functionality.

Table 24: Pros and Cons Table for Bumper Sensor [14]

Condition	Pro	Con
Can detect a wide variety of obstacles	X	
Has no range		X
Requires a collision with the obstacle		X

Design Option 6: 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 25 is a diagram of how IR transceivers detect an obstacle. Table 25 is a list of pros and cons for IR transceivers.

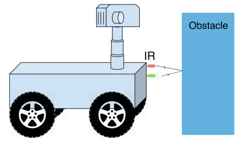


Figure 25: Diagram of IR transceiver functionality.

Table 25: Pros and Cons Table for IR Transceiver [15]

Condition	Pro	Con
Range is limited to short distances		X
System is fairly inexpensive	X	
Affected by obstacle size and shape		X

3.4 Mast Sensors

Mast sensors are the sensors that will sit atop the mast and help survey the fire line. They consist of a camera as well as distance sensors that measure the distances from the rover to the fire line as well as the flame front.

3.4.1 Mast Camera

First, the design options for the mast's camera are considered such as a DSLR camera, a thermal camera, a 360 degree camera, and an action camera.

Design Option 1: DSLR Camera
DSLR stands for Digital Single-Lens Reflex and is the typical consumer-grade type of camera used by professional photographers and amateur filmmakers. With 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.

Figure 26: DSLR Camera

Table 26: Pros and Cons Table for DSLR Camera

Condition	Pro	Con
High image quality	X	
Great optical zoom capability	X	
Good field of view	X	
Large lens means high weight		X
Fragile lens and exterior casing		X
High cost		X

Design Option 2: 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 27: 360 Degree Camera

Table 27: Pros and Cons Table for 360 Degree Camera

Condition	Pro	Con
Full 360 degree field of view	X	
Low weight	X	
Very large image distortion		X
Little to no optical zoom ability		X
High cost		X

Design Option 3: 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.

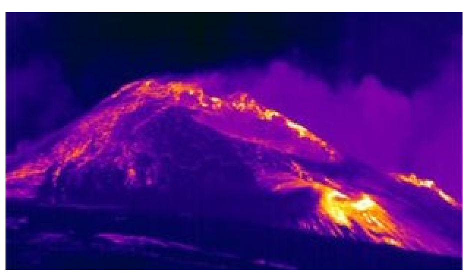


Figure 28: thermal Camera

Table 28: Pros and Cons Table for Thermal Camera

Condition	Pro	Con
High visibility of flame front	X	
Good optical zoom capability	X	
Good field of view	X	
Low visibility of environment surrounding fire		X
High cost		X

Design Option 4: 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 29: Action Camera

Table 29: Pros and Cons Table for Action Camera

Condition	Pro	Con
Resistant to damage	X	
Good field of view	X	
Low weight	X	
Low optical zoom capability		X
Lowered image quality		X

3.4.2 Distance Sensors

Next, the various design options for distance sensing are considered to help survey the fire line. The different design options that are reviewed are dual thermal camera, LiDAR rangefinders, RADAR, dual (optical) cameras, using selected object detection sensors, and passive rangefinding.

Design Option 1: Dual Thermal Cameras (stereoscopic)

Stereoscopic cameras are a set of two cameras placed offset from one another horizontally, such that the images can be combined and processed using geometry to determine the distance to a part of the images. This option uses thermal cameras to better highlight the flame front so that the distance to the flame front can be more accurate. This comes with the caveat that the fire line is more difficult to locate in a thermal image than an optical one.

Table 30: Pros and Cons Table for Thermal Camera

Condition	Pro	Con
High flame visibility	X	
High environmental reliabilty	X	
Low visibility of the fire line		X
Moderate image processing complexity		X
High cost		X

Design Option 2: LiDAR Rangefinder

See section 3.3.3 Design Option 1: LiDAR. This LiDAR sensor would be selected for its long distance functionality.

Table 31: Pros and Cons Table for Thermal Camera

Condition	Pro	Con
High accuracy at range	X	
Low data processing complexity	X	
Moderate environmental reliability		X
Moderate-to-low flame visibility		X

Design Option 3: RADAR

See section 3.3.3 Design Option 2: RADAR. This RADAR sensor also would be selected for its long distance functionality.

Table 32: Pros and Cons Table for Thermal Camera

Condition	Pro	Con
High accuracy at range	X	
High environmental reliability	X	
High cost		X
Moderate data processing complexity		X

Design Option 4: Dual Cameras (stereoscopic)

See Design Option 1. This is the same concept as the thermal cameras, but with better visibility of the fire line and worse visibility of the flame front.

Table 33: Pros and Cons Table for Thermal Camera

Condition	Pro	Con
High visibility of the fire line	X	
Moderate accuracy at range	X	
Moderate environmental reliability		X
Low visibility of flame front		X
High cost		X

Design Option 5: Use Object Detection Sensor(s)

The existing object detection sensors could be used for distance sensing as well by mounting one or multiple on the camera mast mount. This option would result in a lower cost for this sensor system and is weighted based on the sensor types that are chosen as a result of the object detection sensors trade study. Since that study resulted in three sensors being selected for the baseline design, this option is rated as a LiDAR sensor.

Table 34: Pros and Cons Table for Thermal Camera

Condition	Pro	Con
No additional cost	X	
High accuracy at range	X	
Low data processing complexity	X	
Moderate-to-low flame visibility		X
Moderate environmental reliability		X

Design Option 6: Passive Rangefinding via Object Recognition
Object recognition can also be used for rangefinding with a reference object of known size. For example, by comparing trees in the camera view of the rover to a reference tree height, the pixel count of the camera can be used to determine the size of the object. This process only works at long ranges and has a questionable accuracy, dependent entirely on the variation in tree (or other reference object) size.

Table 35: Pros and Cons Table for Thermal Camera

Condition	Pro	Con
Very high range	X	
No additional cost	X	
Moderate image processing complexity	X	X
Low accuracy		X
Low visibility of flame front		X

3.5 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.

Design Option 1: 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.

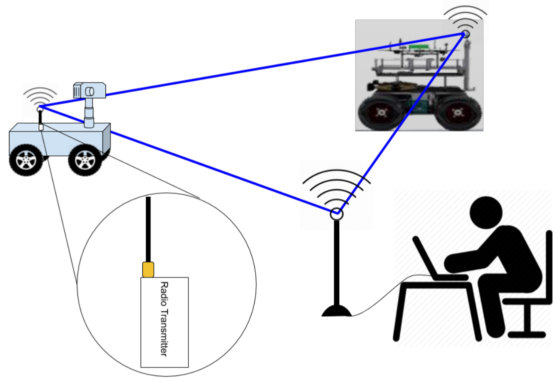


Figure 30: Radio Systems

Table 36: Pros and Cons Table for High-Band Radio

Condition	Pro	Con
High speed data transfer	X	
Large attenuation due to obstacles		X
Higher costs to increase range		X

Design Option 2: 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 37: Pros and Cons Table for Low-Band Radio

Condition	Pro	Con
Long range connectivity	X	
Less attenuation loss	X	
Less modifications to MR	X	
Slow data transfer rates		X

Design Option 3: 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.

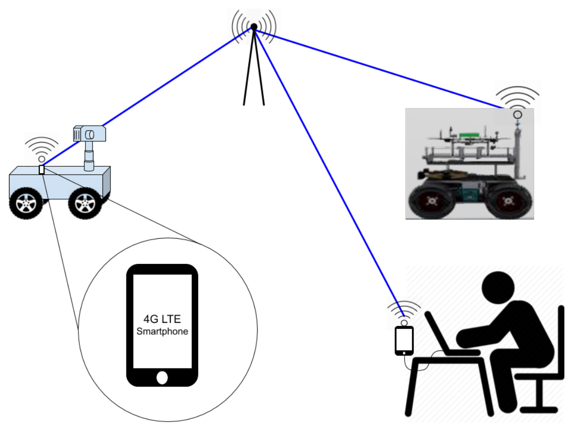


Figure 31: Cellular Data

Table 38: Pros and Cons Table for Cellular

Condition	Pro	Con
High speed data transfer	X	
Long range	X	
Could be costly		X
Dependant on the network provider		X

Design Option 4: 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.

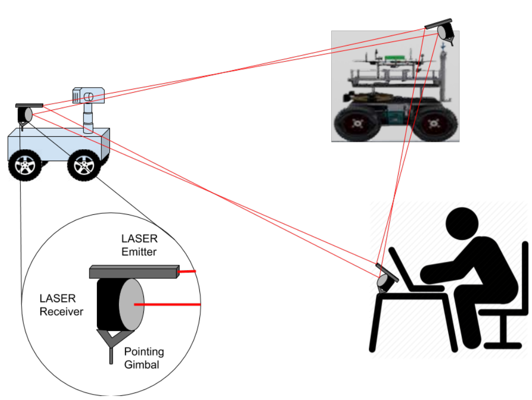


Figure 32: LASER

Table 39: Pros and Cons Table for LASER

Condition	Pro	Con
High rate of data transfer	X	
Difficult to maintain constant communications		X
Extremely complex for two-way communication		X

3.6 Software

Software plays a critical role in command and data handling as well as critical elements to the ARGOS mission such as autonomous navigation. The software category can split up into different platforms and different processing capabilities for the rover.

3.6.1 Platform

Design Option 1: ROS

The Robotic Operating System (ROS) is a widely used development platform for robotics. It structures scripts into different nodes which can send and receive messages to each other. The platform is designed to work with heterogeneous sensors and programming languages. Table 40 is a list of pros and cons for ROS.

Table 40: Pros and Cons Table for ROS [21] [22]

Condition	Pro	Con
Allows for different programming languages to be used simultaneously	X	
Numerous pre-built packages for motion planing and sensor integration	X	
Not optimized for a specific rover type		X

Design Option 2: YARP

Yet Another Robot Platform (YARP) is a newer robotics platform that is optimized for articulators and other multi-axis robots. It handles messaging between heterogeneous programs and sensors. Table 41 shows a list of pros and cons for YARP.

Table 41: Pros and Cons Table for YARP[21]

Condition	Pro	Con
Allows for different sensors and programming languages	X	
Some pre-bulit packages exist for motion planning	X	
Focused on articulators not rovers		X

Design Option 3: Custom Controller

A custom controller is a purpose build platform for the rover by the design team. This would handle all the messaging between the different sensors and motors. Table 42 is a list of pros and cons for a custom controller.

Table 42: Pros and Cons Table for Custom Controller [23]

Condition	Pro	Con
Optimized for the specific use case	X	
Requires a significant amount of time		X

3.6.2 Rover Processing Capabilities

Design Option 1: Microcontroller

Microcontrollers are a form of small computer that are designed for embedded systems. They often have limited processing ability but require little power and are inexpensive. Table 43 is a list of pros and cons for the microcontroller.

Table 43: Pros and Cons Table for Microcontroller [17]

Condition	Pro	Con
Low power usage	X	
Limited processing power		X
Inexpensive	X	

Design Option 2: Microcomputer

Microcomputers are small computers containing a microprocessor as their central processing unit. They have some amount of RAM and solid state storage. Microcomputers are affordable but lack much of the processing power of a full scale computer. Table 44 is a list of pros and cons for the microcomputer.

Table 44: Pros and Cons Table for Microcomputer[20]

Condition	Pro	Con
More processing power than a microcontroller	X	
Low power draw	X	
Often contain some IO	X	

Design Option 3: Minicomputer

A minicomputer is a small form factor computer with a full size processor and RAM. A minicomputer often allows for expandable storage and PCI connections graphics processors or GPUs. These computers' processors are comparable to those found in laptops. Table 45 is a list of pros and cons for a minicomputer.

Table 45: Pros and Cons Table for Minicomputer [18] [19]

Condition	Pro	Con
Fast processing capabilities	X	
High power draw at max load		X
Expandable ports for graphics cards and RAM	X	
Less affordable than other options		X

4 Trade Study Process and Results

4.1 Rover Drivetrain

4.1.1 Trade Criteria Selection

Stability: (MOV.1. , SENS.3.1.2) This 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: This 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: (MOV.1.1, MOV.1.3, MOV.1.4, SENS.3.1.2) This 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: (MOV.1. , SENS.3.1.2) This 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: (MOV.1.2) This 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: This 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.

4.1.2 Weighting Assignments and Rationale

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

4.1.3 Score Assignment

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 10 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

4.1.4 Trade Matrix

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	2	2
Obstacle Manueverablity	0.175	4	2	4	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	2	2
Cost	0.05	3	5	5	3	3
Total Weighted Score:	**1**	3.325	3.5	**4**	3.3	3.425

4.2 Rover 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 table below outlines the weight assigned to each criteria and the rationale based on the requirements and levels of success.

Table 47: 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 Assignments and Rationale

The following table outlines what each score means for each trade criteria.

Table 48: Score Assignments and Rational for Rover Mast

Criteria	**1**	**2**	**3**	**4**	**5**
Cost	The system is extremely over budget and will likely not be doable	The system is over budget but could be compensated for if other systems are under budget	The system is right around what is in budget for this system	The system is slightly under budget and not overpriced.	The system is significantly under budget and would give the team a margin.
Support Weight/ Stability	The support weight of the mast is much lower than should be acceptable in order to hold up a camera and other sensors. The stability of the mast is such that the team would have significant worry for the camera and other sensors stability. Winds at very low speeds or small perturbations could cause a failure.	The support weight of the mast is lower than would be necessary to support a camera and other sensors. The stability of the mast is such that the team would have worry for the camera and other sensors stability. Winds at low speeds or small perturbations could cause a failure.	The support weight of the mast is about what is necessary to support a camera and other sensors. The stability of the mast is such that the team would not have worry for the camera and other sensors stability. Winds at moderate speeds or moderate perturbations could cause a failure.	The support weight of the mast is higher than what is necessary to support a camera and other sensors. Other components can be considered to be added onto the mast. The stability of the mast is such that the team would have confidence for the camera and other sensors stability. Winds at moderately high speeds or moderately high perturbations could cause a failure.	The support weight of the mast is much higher than necessary to support a camera and other sensors. Other components can be added on without issue. The stability of the mast is such that the team would have significant confidence for the camera and other sensors stability. Winds at high speeds or high perturbations could cause a failure.
Complexity	The complexity of the mast is such that it would cause the team extreme difficulty in manufacturing and integration	The complexity of the mast is such that it would cause the team some difficulty in manufacturing and integration	The complexity of the mast is such that it would be about what the team would expect for manufacturing and integration	The complexity of the mast is such that it would be ideal for what the team would expect for manufacturing and integration	The complexity of the mast is such that it would be straightforward for what the team would expect for manufacturing and integration
Extendable Height/ Compactable Height	The mast takes up an unreasonable amount of room when fully contracted and/or the extension height is not adequate for data capture	The mast takes up slightly too much room when fully contracted and/or the extension height is not ideal for data capture	The mast takes up a reasonable amount of room when fully contracted and/or the extension height is adequate for data capture	The mast takes up little room when fully contracted and/or the extension height is more than adequate for data capture	The mast takes up an very little room when fully contracted and/or the extension height is more than adequate for data capture
Power Required	The power required to raise the mast is much higher than should be allocated to it	The power required to raise the mast is somewhat higher than should be allocated to it	The power required to raise the mast is on target for what should be allocated to it	The power required to raise the mast is lower than expected and some of that power can be allocated to other components	The power required to raise the mast is much lower than expected and most of that power can be allocated to other components
Speed of Retraction	The speed of retraction would severely limit the rover's mobility and range by requiring too much mission time to be allocated to raising/lowering the mast slowly enough so as to not cause damage to the camera	The speed of retraction would somewhat limit the rover's mobility and range by requiring extra mission time to be allocated to raising/lowering the mast slowly enough so as to not cause damage to the camera	The speed of retraction would be on target for the time allocated to raising/lowering the mast at a speed that doesn't cause damage to the camera	The speed of retraction is high enough that the rover's mobility and range will be increased above normal due to less mission time being allocated to raising/lowering the mast, without causing damage to the camera	The speed of retraction is very high such that the rover's mobility and range will be greatly increased above normal due to less mission time being allocated to raising/lowering the mast, without causing damage to the camera

Trade Matrix

The table below outlines the scores each criteria received 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

4.3 Movement Sensors

4.3.1 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 49: 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 Assignments and Rationale

The following table outlines what each score means for each trade criteria.

Table 50: 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 51: 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

4.3.2 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 52: 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 Assignments and Rationale

The following table lists the score and reasoning for each trade criteria.

Table 53: 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 54: 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

4.3.3 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 55: 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 Assignments and Rationale

The following table lists the score and reasoning for each trade criteria.

Table 56: 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 57: Trade Matrix for Object Detection Sensors

Criteria	Weight	LiDAR	RADAR	Ultrasonic	FPV Camera	IR Transceiver	Bumper Sensor
Accuracy	0.25	4	3	3	3	1	2
Data Processing Complexity	0.25	3	3	4	2	4	5
Hardware Integration Complexity	0.2	4	3	4	5	4	3
Environmental Reliability	0.15	5	3	3	3	3	1
Range	0.05	5	3	1	3	4	5
Cost	0.1	1	2	4	5	3	1
Weighted Total	1	3.65	2.9	3.43	3.35	3.15	2.95

4.4 Camera and Distance Sensing

4.4.1 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 58: 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 Assignments

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 60: Trade Matrix for Mast Camera

Criteria	Weight	360 Camera	DSLR	Thermal Camera	Action Camera
Image Quality	0.2	3	5	1	4
Field of View	0.15	5	3	3	4
Video Transfer Time	0.15	3	2	3	4
Durability	0.1	3	2	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	3
Weighted Total	1	2.4	2.2	1.6	**2.8**

4.4.2 Distance Sensors

Trade Criteria Selection

Although not listed within the functional requirements, distance sensing was chosen to be included with the trade studies. This is because it was determined to be desirable for firefighters to know how far the flame front is from the fire line and how fast it is moving toward it, according to the team's firefighter contacts. In order to sense these distances and record distance data over time, the rover needs to include distance sensors at the same vantage point as the camera. The trade study criteria investigated for distance sensors are: accuracy at range, data processing complexity, mass, environmental reliability, cost and flame visibility.

Accuracy at range is defined as the accuracy of distance data at ranges greater than 10 meters. This was chosen as a starting point because it isn't likely that the rover will need to come closer than 10 meters to the flame front, so as not to risk heat damage. Data processing complexity refers to how quickly the on-board or ground station computer can parse the data into distances and speeds but also the time spent programming an algorithm to process the data. Mass refers to the mass added onto the rover from the distance sensor and is determined from average mass estimates of the sensor type in question. Environmental reliability is the ability for the sensor to sustain a high level of accuracy in conditions that aren't suitable to it, such as variable terrain or smoke in the air. Cost is also based on average estimates from the sensor type in question and also takes into account integration costs. The flame visibility is the sensor's (or its camera pairing's) ability to pick out flames in photo or video and largely accounts for each design alternative's ability to accurately sense the distance of the flame front in particular.

Weighting Assignments and Rationale

The following table lists rationale for weights given to criteria for distance sensors.

Criteria	Weight	Reasoning
Accuracy at Range (>10m)	0.25	To sense the distances accurately without coming directly up to the fire or fire line, a sensor system with good range is needed
Data Processing Complexity	0.2	In order for the ground station to receive effective data, the rate at which the sensor data can be processed, turned into distance data and sent to the ground station is crucial
Mass	0.1	To limit the potential tipping conditions when the mast is fully extended, the camera shouldn't be too heavy
Environmental Reliability	0.15	The distance sensor must be able to properly function in the environment surrounding a fire. This includes sensing through smoke and accurately sensing forest floors of varying roughness
Cost	0.1	To limit expenditures and remain within the budget of the project
Flame Visibility	0.2	To more easily identify the distance over time of the flame front, it is necessary to clearly see/sense the flame front in order to point the distance sensor at it

Table 61: Trade Criteria Weights and Rational for Distance Sensors

Score Assignments

The following table shows definitions of scores used in the trade matrix.

Criteria	1	2	3	4	5
Accuracy at Range (>10m)	Accuracy is very low at range and could result in extreme error in distance readings	Accuracy is low at range and could result in large error in distance readings	Accuracy is acceptable at range but could result in some error in distance readings	Accuracy is high at range and results in minimal error in distance readings	Accuracy is very high at range and results in little to no error in distance readings
Data Processing Complexity	Data is too complex to be analyzed on rover	Data can be analyzed but with performance loss	Data can be analyzed on rover but at slower speeds	Data can be analyzed on rover in real time	Rover has no trouble analyzing data

Mass	The mast imaging system is very heavy and will likely not be able to be supported by the mast system a nd 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	The mast imaging system is lightweight and will not cause any difficulties with mast extension or rover speed
Environmental Reliability	System cannot be operated in smoke or forest environment	System can operate in environment but with a huge drop in performance or accuracy	System can operate with reasonable accuracy		System can operate with great accuracy regardless of smoke or forest environment
Cost	Extremely over budget	Somewhat over budget	In budget but still generally overpriced		Well within budget
Flame Visibility	Impossible to recognize fire area from data provided by system	Possible to identify fire but with low accuracy with operator	Possible to identify fire with human operator		System can collect data in which the rover can autonomously identify fire

Trade Matrix

The following table assigns the scores for each design alternative.

table[H]

Criteria	Weight	Dual Thermal Cameras (stereoscopic)	LiDAR Rangefinder	LiDAR Rangefinder + Thermal Camera	RADAR	Dual Cameras (stereoscopic)	Use Object Detection Sensors	Passive Rangefinding via Object Recognition
Accuracy at Range (>10m)	0.35	3	5	5	4	3	5	4
Data Processing Complexity	0.2	3	4	4	3	3	4	3
Mass	0.1	2	4	3	3	2	5	5
Environmental Reliability	0.15	5	3	5	5	3	3	2
Cost	0.1	1	3	2	1	1	5	5
Flame Visibility	0.1	5	2	5	2	3	2	1
Weighted Total	1	3.2	3.9	**4.3**	3.4	2.7	4.2	3.4

4.5 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 63: 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 Assignments and Rationale

The following table outlines what each score means for each trade criteria.

Table 64: 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 65: 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

4.6 Software

4.6.1 Platform

Trade Criteria Selection

The platform will serve as the backbone to all of the software packages built for the rover. Therefore, picking a platform that is integrates well with the rover is important. Three trade criteria were decided upon: compatibility, reliability, and integration complexity. Compatibility serves to study how well the platform will work with the rover and the sensors being considered. Reliability is studied as the platform will support all most all of the rover's functionality, so an unexpected failure in the platform would likely result in a failure of the mission. Finally, integration complexity represents how difficult it will be for the project team to begin using the platform.

Weighting Assignments and Rationale

Table 66 gives the weighting assignments and rationale for the platform trade criteria.

Table 66: Weighting Assignments and Rational for Platform

Criteria	Weight	Rationale
Compatibility	0.4	The rover's platform must be compatible with the hardware being considered. With limited or no compatibility the software becomes a hindrance to the success of the rover. This will help satisfy CDH 1.1 and MOV 1.2.
Reliability	0.2	The platform must be reliable. A history of use with rovers is preferred but otherwise reliability can be achieved by making a tailor made custom system.
Integration Complexity	0.4	The platform must be easily integrated with the sensors, various coding languages, and with the skills that the group possesses. A platform that is too complex will become a hindrance to the success of the rover. This will help satisfy SURV.3.1.2.

Score Assignments and Rationale

Table 67 gives the score assignments and rationale.

Table 67: Trade Criteria Weights and Rational for Platform

Criteria	1	2	3	4	5
Compatibility	Platform is not compatible with components being considered.		Platform is compatible with components but requires a moderate amount of effort to integrate.		Platform is easy to integrate with rover components. Many code bases relevant to the rover exist.
Reliability	Platform is unproven or has a history of not functioning correctly		Platform functions moderately well and has a history of successful use cases.		Platform is very reliable and has a strong history of success.
Integration Complexity	Platform requires a level of expertise not achievable by the group in a timely manor.	Platform requires a significant learning curve and complex tasks may no be achievable in the time allotted.	Platform requires a significant learning curve but is achievable in the time allotted.	Platform requires some learning and one or more members of the group have worked with it before.	Platform requires little to no additional learning, multiple members of the group are well versed with it.

Trade Matrix

Table 68 gives the trade matrix for platform.

Table 68: Trade Matrix for Platform

Criteria	Weight	R.O.S.	Y.A.R.P.	Custom Controller
Compatibility	0.4	4	3	5
Reliability	0.2	5	4	3
Integration Complexity	0.4	4	4	2
Weighted Total	1	4.2	3.6	3.4

4.6.2 Rover Processing Capabilities

Trade Criteria Selection

The on-board processor will serve to perform all the necessary computations the rover requires to achieve success such as fire detection and obstacle avoidance. Five trade criteria were chosen to asses the various processor types. Compute power encapsulates the main purpose of the processor. Significant compute power will be needed to achieve some higher levels of success. Power consumption must be accounted for as processors are not always designed with power efficiency in mind. Reliability is important as a processor failure would likely result in a total mission failure. Integration complexity represents the compatibility of the processor with the rest of the rover. Finally, the cost must be accounted for as some high performance processors can be extremely expensive.

Weighting Assignments and Rationale

Table 69 describes the weighting assignments and rationale for each trade criteria.

Table 69: Weighting Assignments and Rational for Processing Capabilities

Criteria	Weight	Rationale
Compute Power	0.3	The processor must have enough compute power to handle image processing, communications, and some level of obstacle avoidance. Picking a processor that is too limited will result in some higher levels of success becoming achievable, especially when it comes to autonomous obstacle avoidance and fire jump detection. This will help satisfy SURV.3.1.2 and CDH.2.2.
Power Consumption	0.1	It is important to factor in the power consumption of processors as some more complex systems will require a significant amount of power that may lead to an unreasonably large battery being needed.
Reliability	0.2	The processor must be able to function reliably as it serves to coordinate all the actions that the rover will take. Without a functional processor the rover will be unable to complete even the most basic tasks.
Integration Complexity	0.2	The processor must integrate with the platform and the sensors. It's also important to consider the difficulty of integration.
Cost	0.2	The cost must be factored in to account for trade-offs between cost and compute power. Many high performance systems exist but their cost can quickly grow.

Score Assignments and Rationale

Table 70 gives the score assignments and rationale.

Table 70: Trade Criteria Weights and Rational for Processing Capabilities

Criteria	1	2	3	4	5
Compute Power	Processor does not provide enough compile power to fulfill basic functions	Processor provides compute power to fulfill some basic functions but more complex tasks are unachievable.	Processor can handle basic functions as well as some higher level tasks such as image processing, but not at the same time.	Processor can handle all basic functions as well as performing one or more higher level tasks at the same time.	Processor can handle basic functions and all higher level tasks simultaneously.
Power Consumption	Requires >100W at full load	Requires 75-100W at full load	Requires 50-75W at full load	Requires 25-50W at full load	Requires <25W at full load
Reliability	Processor is prone to failure in even moderate environmental conditions. Processor has a history of not functioning correctly.		Processor can handle more extreme environmental conditions and has a history of functioning well.		Processor can handle a wide variety of environmental conditions and is proven to not suffer from reliability issues.
Integration Complexity	Processor does not integrate with platforms and components being considered.	Processor integrates with some platforms being considered. Integration requires a significant amount of time.	Processor integrates with platforms and sensors being considered. Integration is achievable in the time allotted.	Processor integrates with platforms and sensors. Integration is moderately difficult with some history of use with rovers.	Processor integrates well with platforms and sensors. There is a proven history of use and documentation.
Cost	> \$100.	\$75 – \$99.99	0 – \$74.99	5 – \$49.99	less than \$25

Trade Matrix

Table 71 gives the trade matrix for processing capabilities.

Table 71: Trade Matrix for Processing Capabilities

Criteria	Weight	Microcontroller	Microcomputer	Mini Computer
Compute Power	0.3	2	4	5
Power Consumption	0.1	5	5	2
Reliability	0.2	3	3	5
Integration Complexity	0.2	3	4	5
Cost	0.2	4	3	1
Weighted Total	1	3.1	3.7	3.9

5 Selection of Baseline Design

5.1 Rover Drive Train Results

The winner of the drive train trade study was the 6 wheel configuration with the middle wheels being unpowered (according to table 4.1.4) with a score of 4 out of 5 (5 being the max score) correlating with the respected weights for each category. This was an obvious win because this of this configurations ability to maneuver over obstacles with great stability while using an optimal amount of power.

5.2 Rover Mast Results

The winner of the rover mast trade study was the telescoping mast however the scissor lift was only 0.1 behind it with scores of 3.7 and 3.6 respectively. Both masts advantages were very similar as seen in the key design option tables 7 and 9 while their drawbacks differed in complexity and potential failure points. Therefore, it was decided that both would be brought along as possible design options and further research would be conducted to make a final decision. Possible modelling and simulations will need to be done to hone in on a final design.

5.3 Movement Sensors Results

5.3.1 Translational Movement Sensors

There was not one clear winner because the GPS score and the stepper motor score both came out to be within 0.5 of each other. The wheel odometer did not score as high as the other two options mainly because assumptions will be made like no-slip which will almost certainly occur in underbrush and there would be no way to integrate the hardware such that the Command and Data Handling subsystem could use the distance traveled measurement and communicate that data to other subsystems.

It is decided that both GPS and the stepper motor can be used to calculate distance traveled because both designs will already be used for other purposes. In addition, having two values from different sources will be a good way to check the calculations, improve accuracy, and provide redundancy.

5.3.2 Rotational Movement Sensors

From the trade study there was no clear winner since the three sensors scored within 0.3 of each other. However, the IMU includes both the MEMS gyroscope and the accelerometer within its design. Therefore, the redundancy that the IMU provides increases the overall accuracy determination of the inclination angle calculation of the rover. Due to this the IMU is chosen as the rotational movement sensor, since the IMU provides three values to compare the angle at which the rover is currently at.

5.3.3 Object Detection Sensors

Three sensors were selected for the baseline design: LiDAR, ultrasonic range finder, and a first-person view camera. These sensors were the highest scoring and also complement each other well. LiDAR has significant benefits when it comes to accuracy and range. However, LiDAR falls short at very close distances. Ultrasonic range finders fill in the short range sensing to make the rover have a complete picture of its surroundings. The FPV camera was also chosen to better allow a human to control the rover in case of a situation where the autonomy fails. The combination of these three sensors means the rover has a wide array of obstacle sensing abilities.

5.4 Camera and Distance Sensing

5.4.1 Camera

From the camera trade study completed, the option chosen was the action camera. With a weighted total of 2.8 it beat the other options. Action camera quality has improved, while the prices have dropped. This is mainly due to the improvements in smartphone camera technology. The rover will be able to benefit from this by incorporating one on its mast.

5.4.2 Distance Sensing

From the camera trade study completed, the design with the highest score was the laser rangefinder with a thermal camera. With an overall score of 4.3, it beat all other options. In order to complete all the levels of success, the rover will have to identify and find the distance of a fire front. Having a laser rangefinder with a thermal camera is the best option for this. This design beat out the other options mainly due to its superior range accuracy and fire identification.

5.5 Communications Results

From the trade study process that was conducted in section 4.5, with highest overall weight of 4.2/5, the low-band radio was determined to be the best suited form of communications. Operating at roughly 900 MHz, the same frequency of past projects, will enable ARGOS to communicate with the ground station and the mother rover without installing new hardware on their systems. Point-to-point network will most likely be necessary instead of an omnidirectional antenna to ease integration between the mother rover and ground station. Low-band radio has lower attenuation, longer range, low power consumption, and provide enough bandwidth to ensure that all the necessary data is transmitted/received. The other options considered would most likely create more problems due to changes out components on the MR and GS, which would require countless man-hours and increased costs that could give us a non-functional final product and/or over budget.

5.6 Software Results

5.6.1 Platform

The Robotic Operating System or ROS was chosen as the baseline design platform. ROS is commonly used in industry and research as a rapid development platform for robots. It's history of use gave it a high score in reliability, higher than Yet Another Robot Platform or YARP which also has a history of use but is more focused on articulators rather than rovers. ROS serves as a messaging system to integrate a diversity of sensors and programming languages, giving it a high score in compatibility. ROS also has a large code base of open source packages that solve complex tasks such as simultaneous localization and mapping (SLAM) and motion planning. These packages will help contribute to higher levels of success in obstacle avoidance.

5.6.2 Rover Processing Capabilities

A mini computer was chosen as the on-board processor type to be used. Mini computers such as the Intel Nuc or O-droid have similar processing capabilities to those in many modern full sized laptops. Micro computers such as the Raspberry Pi require less power at full load but under moderate use the mini computers have comparable power usages. Mini computers also benefit from more in-board IO, decreasing latency and increasing the amount of possible high speed connections. Moreover, with the rise of powerful smartphone processors, the cost of mini computers that use smartphone chip sets have come down to a comparable level to microcomputers.

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Appendix

5.6.3 Image Processing

Design Option 1

The fourth level of success under surveillance has the rover being able to process data from cameras and available sensors in order to determine if the fire has breached the fire line. In order to do this, software will have to be used in order to analyze the provided data. Below is a example of field of view from one of the on board camera.

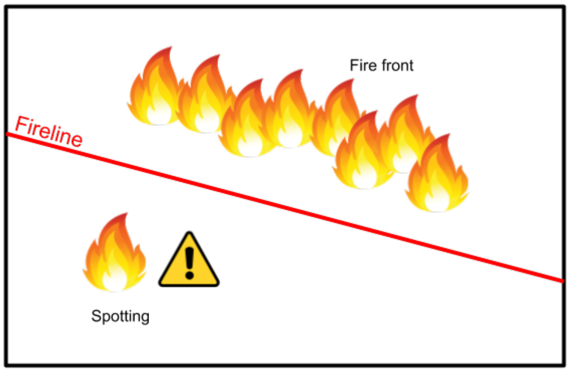

Figure 33: Surveillance camera field of view

To serve as an automated surveillance system you can use a image analysis. Taking an image, such as the one above, looping though all pixels beneath the fire line and insuring that there are no areas above a certain heat threshold you can insurhttps://www.embedded-computing.com/embedded-computing-design/e

Table 72: Pros and Cons Table for Matlab

Condition	Pro	Con
ROS compatibility	X	
Pre-built image and video analysis packages	X	
Team comfortability	X	
Slower processing speeds		X

Table 73: Pros and Cons Table for Python

Condition	Pro	Con
ROS compatibility	X	
Pre-built image and video analysis packages	X	

Table 74: Pros and Cons Table for C/C++

Condition	**Pro**	**Con**
ROS compatibility	X	
Superior processing speed	X	
Difficult learning curve		X

As seen in the tables above, all languages are compatible with ROS. All of the options have the ability to deliver the functionality that the rover requires. (Add something about processing speed not being as important). The factor that weighs heaviest in this decision is the comfortability of the language with the design team members. Choosing a language known by most of the memebers will lessen time needed to write code and debug. Matlab is known by all members and will be the language of choice going forward for image processing.