Conceptual Design Document

HERMES

University of Colorado
Department of Aerospace Engineering Sciences
ASEN 4018

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1. Information

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Nomenclature

2WD	Two-Wheel Drive
4WD	Four-Wheel Drive
6WD	Six-Wheel Drive
AWD	All-Wheel Drive
CD	Child Drone
CD&H	Command Data and Handling
CHIMERA	CHIld drone deployment MEchanism and Retrieval Apparatus
COTS	Commercial Off the Shelf
CSR	Child Scout Rover
DRIFT	Drone-Rover Integrated Fire Tracker
FPS	Frames per Second
GPS	Global Positioning System
GS	Ground Station
HERMES	Hazard Examination and Reconnaissance Messenger for Extended Surveillance
INFERNO	INtegrated Flight Enabled Rover for Natural disaster Observation
Lidar	Laser Imaging Detection and Ranging
LOI	Location of Interest
MR	Mother Rover
V&V	Verification and Validation
DOF	Degree of Freedom
FOV	Field of View

2. Project Description

2.1. Purpose and Objectives

The effects of climate change include steadily increasing global temperatures, permanent changes in precipitation patterns, more frequent droughts and heat waves[1]. Year after year, these effects have extended the duration of the wildfire season in geographical locations with a dry climate, especially the western United States[2]. The wildfire prevention, suppression, and rehabilitation budget of the United States Forest Service has increased with this trend. In 1995, fire suppression costs made up 16% of the US Forest Services annual budget and in 2015, 50% of the budget was devoted to forest fires. Scientific statisticians estimate that in 2025, this number could exceed 67%[3]. The current method of wildfire prediction, identification, and rehabilitation will clearly not be cost-effective in the future, which motivates the development of the Jet Propulsion Laboratory's Fire Tracker System. This system aims to be a low-cost, hands-off approach to forest fire identification that will lead to earlier containment and elimination of forest fires.

The Fire Tracker System is composed of four distinct projects, with HERMES, the project sponsored for the 2018-2019 academic year, being the most recent in the continuum. The prior projects have consisted of INFERNO, CHIMERA, and the most recent DRIFT. INFERNO, the first in the series, was responsible for an autonomous flying child drone (CD) that drops a sensor package in an area prone to wildfires. CHIMERA's objective was to build the landing platform for INFERNO's CD, with the capabilities to secure and recharge INFERNO's CD. The most recent of the prior projects, DRIFT, built the mother rover (MR) and attached the landing platform, while integrating data processing and communication among the ground station (GS), the MR and the CD[4]. The MR is launched from the GS and has the ability to carry and level INFERNO's CD and the CHIMERA platform. However, the MR is large and bulky, which is not ideal given that the desired, searchable wildfire environment is characterized by dense forest, underbrush, and uneven terrain. This situation prevents the system from reaching critical areas of forests where the most scientific data can be accrued. Additionally, operating the large system in these tight spaces is a risk to the system's health and safety.

HERMES aims to improve the Fire Tracker System by assisting the MR to avoid potential risk of damage by large obstacles and uneven terrain while traversing the forested environment. The HERMES team will design and build a child scout rover (CSR) that will deploy on command, take images/video of its surroundings using an image capturing system, determine a viable path to a location of interest (LOI), send the LOI to the MR, and then and re-docked on the MR. The CSR will investigate these forested areas within a 250 meter (820 ft) radius from its deployment point from the MR, detect obstructions, and determine a viable path for the MR to travel to a location of interest (LOI), defined by an operator at the GS. It must perform these operations while navigating the dense environment with mobility and maneuverability. The specific actions it must perform are driving forward and reverse, executing a 360° turn, driving up and down slopes of 20°, and driving over discontinuities of 1 ft (0.30 m). With the success and integration of this mission, the full system can perform more effectively with less risk.

2.2. Concept Of Operations

The Concept of Operations specific to the HERMES project demonstrates the main functions and requirements the CSR must fulfill in order to guide the MR to a desired LOI. The MR is limited to traveling over a maximum incline of 20° and between obstacles no less than 5 ft (1.52 m) apart. The functions that the CSR will complete over this mission duration are displayed in the orange boxes and the requirements, detailed in later sections, are displayed in the blue boxes. Once the CSR is deployed from the MR, communications and functional checks will be made to ensure a successful mission. The CSR will receive the LOI from the GS, calculate a direct path to the LOI and proceed on said path. Once the CSR encounters an obstacle(defined in the Terrain Definition Table) that it cannot maneuver around, it will scan its environment to find a new path viable for the MR, record its current location as a waypoint, capture pictures and video, and send this time-stamped information back to the MR. Ideally, the CSR will be continuously sending GPS data back to the MR and not solely at the waypoint. Before proceeding on the new path, the CSR will confirm two-way communications with the GS and MR. If the CSR has lost connection with either the GS or the MR, the CSR will return to its last known coordinates. If the communication checks pass, the CSR will continue on its path until a new obstacle is encountered and the process will be repeated. Upon reaching the LOI, the CSR will confirm communications with the ground station and MR, confirm it is within ±5 m (16.4 ft) of the desired LOI, and send back its current location, pictures, and video to the MR. The MR will then have a list of recorded waypoints it will be able to travel along. The MR will then be able to travel to its LOI on a viable path based on its operational abilities. Once the MR and CSR are at the LOI, the CSR will complete the mission by re-docking.

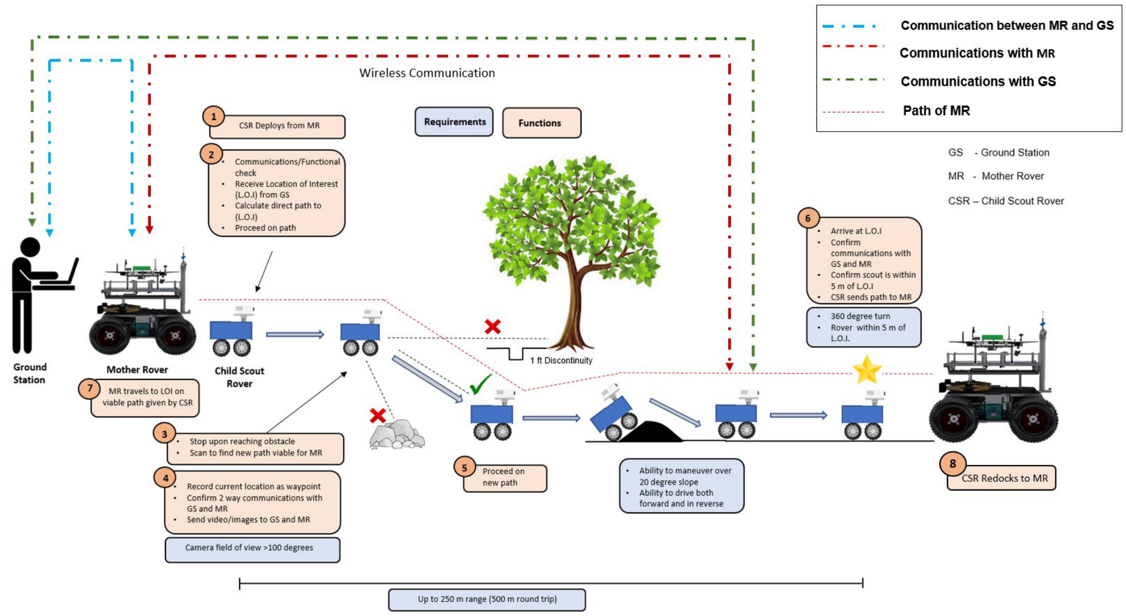

Figure 1. HERMES Mission Concept of Operations

The entire Concept of Operations of the Fire Tracker mission includes HERMES (CSR) and the projects completed in previous years: INFERNO, CHIMERA, and DRIFT. Figure 2 shows the flow of the entire mission and the CSR's involvement, displayed in steps 2 - 5. Due to the MR's limited maneuverability and range, the CSR will deploy to find a viable path to a LOI, (provided by the GS). After arriving to the LOI, the CSR will transmit the viable path to the MR. The MR will then travel to the LOI, and the CSR will dock. INFERNO will then be launched from CHIMERA through commands received from the MR. Once INFERNO deploys from CHIMERA, INFERNO will deploy a sensor package to collect and transmit temperature data to MR. The MR will be continuously transmitting data between the GS and INFERNO. After INFERNO completes it's mission, it will return to CHIMERA and the MR, receive a command to land from the MR, and use image processing to land on CHIMERA. CHIMERA's involvement is shown in steps 7 and 10 and INFERNO's involvement is shown in steps 8 and 9. Lastly, DRIFT's main steps involve departing from the GS (step 1), moving to the LOI found by the CSR (step 6), and returning to the GS (step 11).

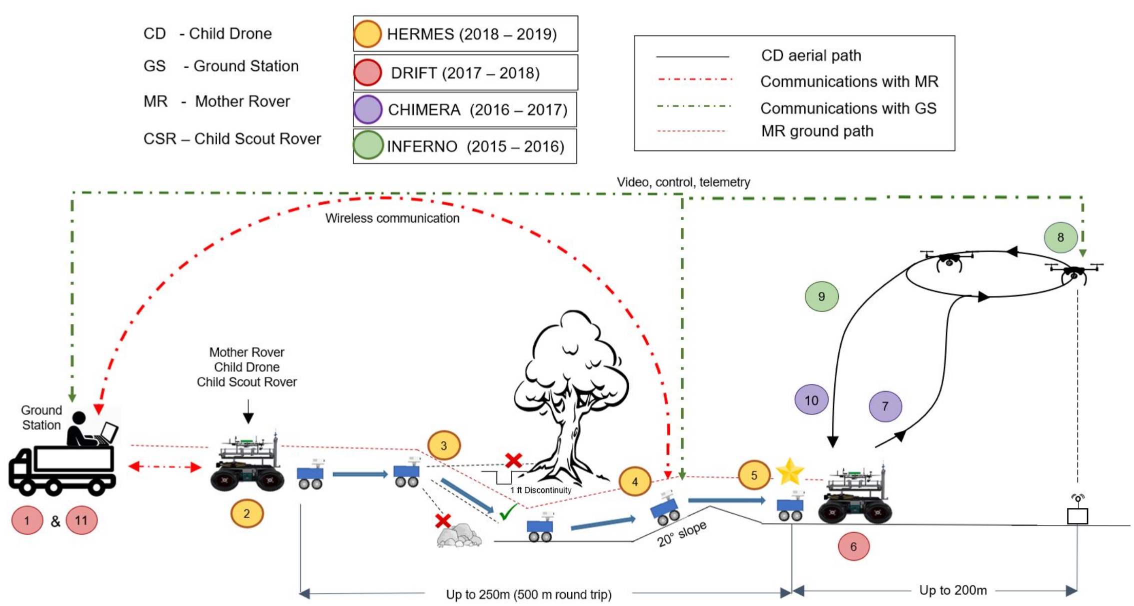

Figure 2. Overall Mission Concept of Operations

2.3. Functional Block Diagram

The following image, Figure 3, depicts the Functional Block Diagram for the Fire Tracker System, including DRIFT, and HERMES, and excluding INFERNO and CHIMERA since they do not interface with HERMES. While this project focuses on incorporating the CSR into the Fire Tracker System, the software and power as well as the structure on the MR will need to be modified to do so.

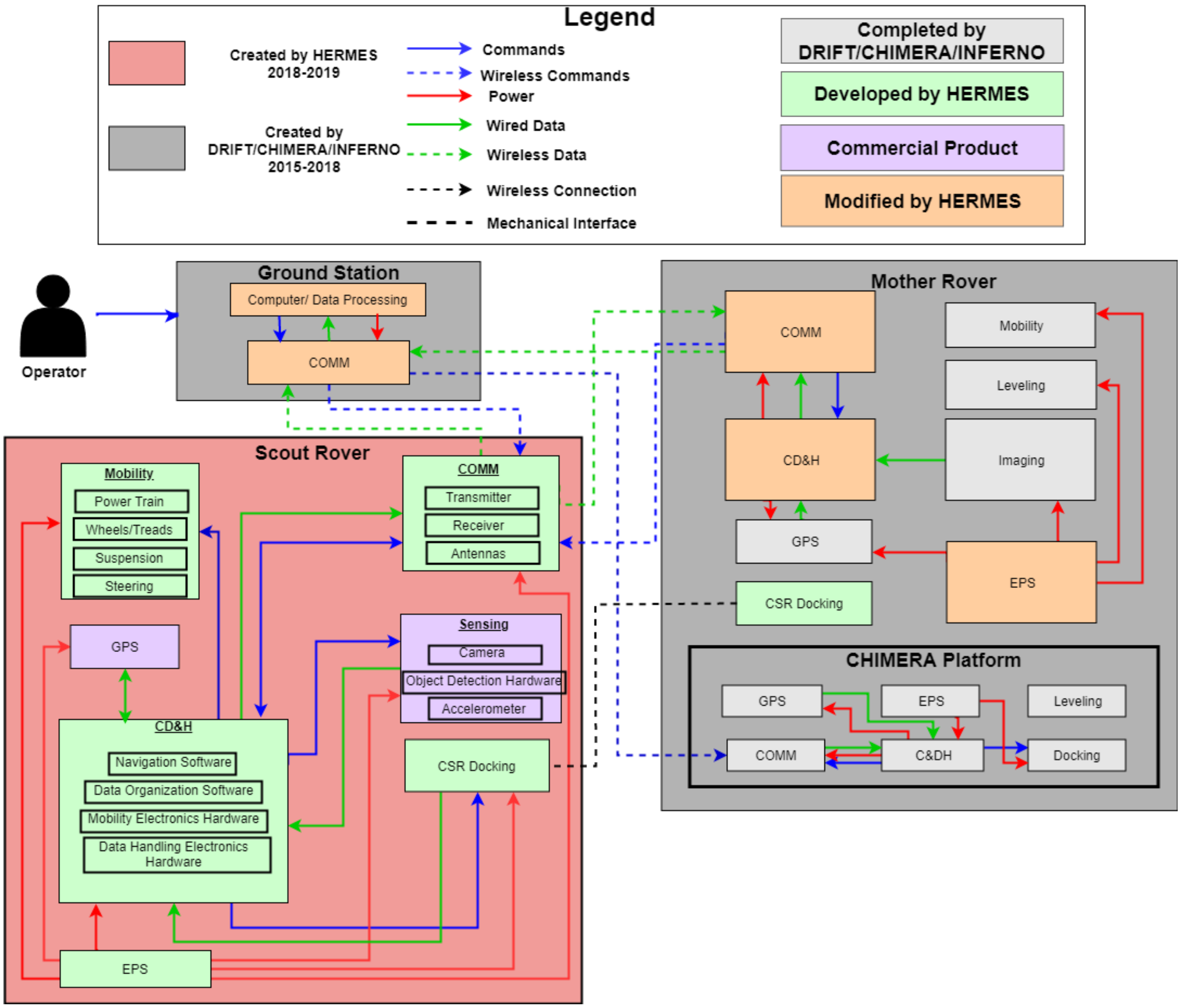

Figure 3. HERMES Project FBD

The scope of HERMES itself includes the CSR, portions of the MR, and the GS. The CSR is a ground based, motorized robot which mainly houses a camera to take images and video. The CSR contains its own power source so that it can be powered independently of the MR during operation as well as during testing. This power source will be dictated mainly by the CSR's range requirement and the CSR's mass. It can be further decomposed into a microcontroller(s), sensing system, docking mechanisms and software, communication hardware, GPS hardware, and a mobility system. The sensing system serves to collect obstacle positions from the environment with an obstacle detection device and images/video with a camera to ensure terrain navigation. HERMES also implements a docking mechanism system and software for the CSR so that it can interface with the MR when it is not on a mission. The communication hardware ensures that any data packets from the CSR or the MR are sent or received without the use of a wired connection. The GPS hardware is what ensures that the path taken by the CSR is recorded. The mobility system is composed of the wheels or treads, power train, suspension, and steering actuators. Mobility is responsible for driving the CSR to a desired location. Finally, the microcontroller(s) handles commands sent by the GS or MR, sends commands to the subsystems, and receives data (i.e. video, image, or sensor readings).

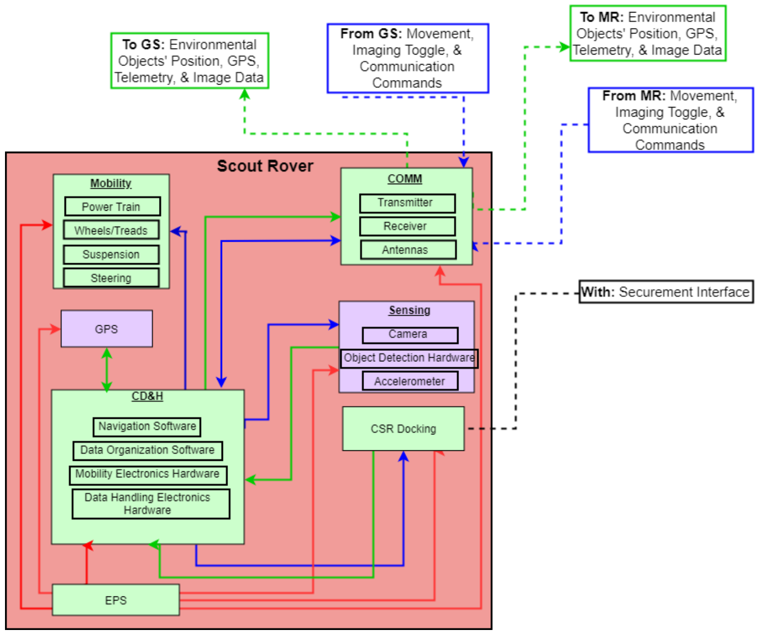

Figure 4. CSR Functional Block Diagram

The MR can be broken down from the full system functional block diagram. Aside from the CHIMERA platform the elements for the MR are the same as the CSR. In addition, unlike the CSR the MR does not contain an object detection device. Some additions to the MR will be docking hardware for the CSR to secure itself to, a modified power system to account for the docking mechanisms, and additional software to accommodate CSR communication. A large part of the modificaiton will be software since the MR will be the commands' middleman between the GS and CSR.

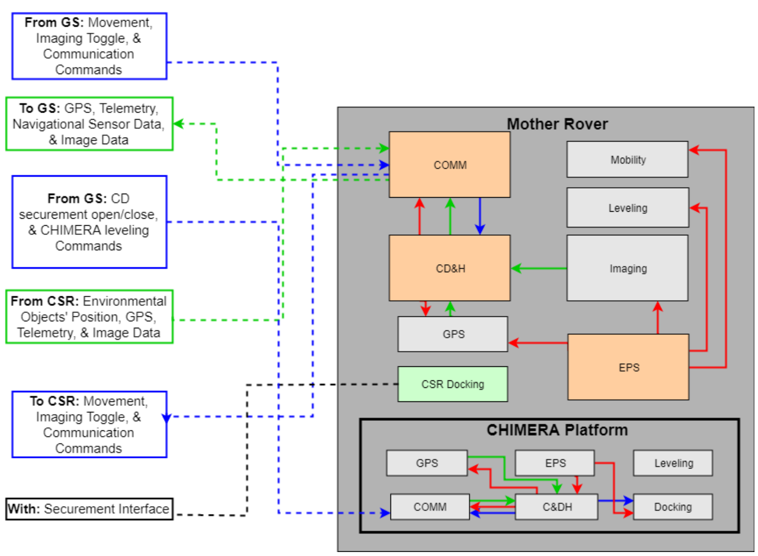

Figure 5. MR Functional Block Diagram

2.4. Functional Requirements

The functional requirements for the mission are displayed in the table below. Each requirement has been assigned a requirement ID which is used to identify the requirement easier, and assist in defining derived requirements.

Requirement ID	Description	Parent Requirement	V&V
CSR.1	The CSR shall be able to receive commands from the MR or the GS	Statement of Work	Test: Communication — Met if all CSR.1 derived requirements are met
CSR.2	The CSR shall be able to send image and positioning data to the GS	Statement of Work	Test: Communication — Met if all CSR.2 derived requirements are met
CSR.3	The CSR shall be able to travel to a location of interest	Statement of Work	Test: Path Finding — Met if all CSR.3 derived requirements are met
CSR.4	The CSR shall travel back to the last reported waypoint upon loss of communications with the MR	Statement of Work	Test: Off-Nominal Communication Navigation — Met if all CSR.4 derived requirements are met
CSR.5	The CSR shall be able to take video while driving or in position-hold	Statement of Work	Test: Camera Operation — Met if all CSR.5 derived requirements are met
CSR.6	The CSR shall be able to take pictures while driving or in position-hold	Statement of Work	Test: Camera Operation — Met if all CSR.6 derived requirements are met
CSR.7	The CSR shall be able to dock from the MR	Statement of Work	Test: Docking and Deploying — Met if all CSR.7 derived requirements are met
CSR.8	The CSR shall be able to deploy from the MR	Statement of Work	Test: Docking and Deploying — Met if all CSR.8 derived requirements are met
CSR.9	The MR shall travel to the CSR when a path is found	Heritage	Test: Final Path Validation

Table 1. CSR Functional Requirements

3. Design Requirements

3.1. Verification and Validation Method Definitions

Verification and validation methods are an important aspect of the requirements themselves. The three methods used for this project are: Demonstration, Inspection, and Testing. The definitions for Demonstration, Inspection, and Test are shown below:

Demonstration - The requirement will be verified/validated by a small activity which composes an operation. An example of a demonstration would be the CSR travelling up a 20 ^{o} incline successfully.

Inspection - The requirement will be verified/validated by satisfying a specified measurement. An example would be a measurement of length or mass.

Test - The requirement will be verified and/or validated by an operation. A formal compilation of a procedure will need to be written and reviewed. There will be multiple testing methods depending on the system, and these tests are shown in the table below, table 3.1.

Below are the tests that have been defined to validate the CSR against the required performance posed by the project.

Test	Test Description
Docking and Deploying	The CSR will be placed such that the docking hardware aboard the MR is within the FOV of the CSR's camera. The CSR will then be commanded to dock on the stationary MR autonomously. In addition the CSR will be placed in the stowed configuration aboard the MR and commanded to deploy autonomously.
Communication	The CSR will receive commands from the GS 250 meters away to perform desired tasks in multiple options of mission defined terrain (See Terrain Definition). The CSR will transmit requested data (position, images, and obstacle positions) to the GS and MR or perform the movement task. The CSR will then send task completion acknowledgements to both the GS and MR to then receive transmission acknowledgements from the GS.
Off-Nominal Communication Navigation	The CSR will be placed in a location where it can communicate with the MR and GS successfully. Then, the MR's communication system will be turned off to demonstrate that the CSR is able to return to it's last known location.
Obstacle Avoidance	The CSR will be placed such that a test defined location of interest is obstructed by obstacles. The CSR will be commanded to travel to the location and utilize the object detection device to navigate the obstacle(s).
Environmental Maneuverability	The CSR will be commanded to drive in various configurations of mission defined terrain (See Terrain Definition)
Camera Operation	The CSR will receive a toggle camera on command and a toggle off command. These commands will be received in two cases: when the CSR is in position hold and driving
Final Path Validation	A path will be transmitted to the MR as the final path and the MR will be commanded to navigate the path.
Range	The CSR will be placed on a treadmill and travel 250 meters at 0°. In a second case the CSR will do 5 continuous iterations of the previous stated case.
Inclinations	The CSR will be placed on a treadmill inclined at a 20 ° slope and show capability to travel up to 250 meters.

Table 2. Test Definition Table

3.2. Terrain Definition

To clarify what kind of terrain the CSR shall be able to operate in, various categories for forest, ground, and underbrush have been defined. These definitions are shown in the table below, Table 3.2. The CSR's operating conditions are constrained by the terrain that the MR can travel in (with the exception of a 1 ft discontinuity and the MR's range), and by the MR's dimensions (60 inches (1.524 meters) wide and 35 inches (0.889 meters) high). Due to this, the CSR will travel in the terrain defined in the table below, through areas the size of the MR, and in inclined slopes of 20 ^{o} or less. The forest and ground classifications are based off of existing classification metrics. Specifically, the forest was based off a classification found in an article on Basal Area on ThoughtCo.[5], while the ground classification is based off of the Wentworth Scale, which is a scale for classifying and describing sediments by grain size[6]. There was not an existing metric for underbrush, however the classification was based off of the CSR's estimated capabilities. It should be noted that an acre is equivalent to 43,560 ft^2 and 4046.86 m^2, and that the average tree diameter will be around 11 inches (roughly 28 centimeters). The height of the trees will not be considered in this classification because the average tree height of a tree is over 6 meters tall (around 20 ft)[7]. Another thing to note, is that the width of shrub is being defined .5 meters (1.6 ft) and the height being less than 2 meters in height (6.6 ft)[8]. The root diameter classification is based off of average root diameters measured at a distance 2-3 meters from the tree base[9]. Obstacles that the CSR may encounter are defined by 1 ft (0.3048 meter) discontinuities, any underbrush type, any ground type, and trees in any forest type.

Terrain	Forest	Ground	Underbrush
Type A	Open: 0 trees per acre	Mud: Grain size: 0.00006 - 0.0039 mm (< .0002 in)	Dirt with no vegetation: - Refer only to ground classification - Scattered leaves
Type B	Understocked: ~100 trees per acre	Silt: Grain Size: 0.0039 - 0.0625 mm (< .003 inch)	Grass, Fallen Leaves, and No shrubbery: - Full ground coverage by leaves - Grass between 2cm - 10cm height (.8 - 4 inches) - Small roots 1-2 cm (.4 - .8 inches) in diameter
Type C	Fully Stocked: ~170 trees per acre	Sand: Grain Size: 0.0625 - 2.00 mm (< .08 inch)	Grass, Fallen Leaves, and Scattered Shrubbery - Shrubbery spaced by at least 1 meter - Includes type A and B underbrush - Medium roots: 3-4 cm (1.2 - 1.6 inches) in diameter
Type D	Overstocked: ~200 trees per acre	Gravel: Grain Size: 2.00 - 4.096 mm (< .2 inch)	Grass, Fallen Leaves, and Dense Shrubbery - No spacing between shrubbery - Includes type A, B, and C underbrush - Large Roots: 5-6 cm (2 - 2.4 inches) in diameter

Table 3. Terrain Definition and Classifications

It should be noted that the terrain types (rows) and categories (columns) are not mutually exclusive. An example would be that the CSR could travel through a Type A forest, Type B ground, and Type C Underbrush at the same time. The categories can be combined depending on the test.

3.3. Requirements Flowdown

The flowdown requirements were derived from each subsystems shown in the CSR's FBD.This includes Mobility, Communication, CD&H, Sensing, Docking and Power. The requirement ID indicates which subsystem the flowdown requirement belongs to. MOB stands for mobility, COMM for communication, CDH for CD&H, SENS for sensing, DOCK for docking, and POW for power.

CSR.1 : The CSR shall be able to receive commands from the MR or the GS		
Requirement ID	**Description**	**V&V**
COMM.1.1	The CSR Communication system shall receive complete command packets up to 250 meters (820 ft) *Motivation - Since the CSR will be operating over large distances from the GS, it should be able to receive all commands from the maximum distance a mission will travel*	Test - Communication
CDH.1.1	The CSR CD&H system software shall distribute commands based on subsystem (i.e. Mobility, Sensing, CD&H, Power, and Communication) *Motivation - Since the CSR system will have multiple subsystems it is necessary that the CD&H subsystem distributes specific commands to the correct subsystems*	Demonstration
CDH.1.2	The CSR CD&H system hardware shall interface with the Communication system receiver *Motivation - In order for the commands received by the receiver to be issued to the rest of the system, the receiver must interface with the hardware that runs the command handling software*	Demonstration

Table 4. CSR.1 Design Requirements Flowdown

CSR.2 : The CSR shall be able to send image and positioning data to the GS		
Requirement ID	**Description**	**V&V**
COMM.2.1	The CSR Communication system shall send GPS data to the GS at a frequency between 1-20 Hz through mission defined terrain (See Terrain Definition) *Motivation - Depending on the COTS GPS component, the transmission frequency of the GPS data packets may vary between this range.*[10]	Test - Communications.
COMM.2.2	The CSR Communication system shall send obstacle position data to the GS through mission defined terrain (See Terrain Definition) *Motivation - The obstacle position must be known in order to determine if a viable path is possible.*	Test - Communications
COMM.2.3	The CSR Communication system shall send imaging data to the MR in packets of 6-30 kilobytes (TBR) through mission defined terrain (See Terrain Definition) *Motivation - Depending on the capability of the receiver on the MR the CSR transmitter can only send a limited size of imaging data packets*	Test - Communications
COMM.2.4	The CSR Communication system shall send GPS data from up to 250 meters (820 ft) to the GS *Motivation - The CSR will be operating at a maximum distance of 250 meters (820 ft) from the GS, so the CSR should be able to send GPS data packets up to this maximum distance.*	Demonstration
COMM.2.5	The CSR Communication system shall send obstacle positions data from up to 250 meters (820 ft) to the GS *Motivation - The CSR will be operating at a maximum distance of 250 meters (820 ft) from the GS, so the CSR should be able to send environmental position data packets up to this maximum distance.*	Demonstration
COMM.2.6	The CSR Communication system shall send imaging data from up to 250 meters (820 ft) to the GS *Motivation - The CSR will be operating at a maximum distance of 250 meters (820 ft) from the GS, so the CSR should be able to send imaging data packets up to this maximum distance.*	Demonstration
CDH.2.1	The CSR CD&H system software shall organize collected GPS, Environmental position, and imaging data by time *Motivation - Since the CSR will be collecting data over the duration of its mission it is necessary to organize the recorded data so that the mission can be understood*	Demonstration
CDH.2.2	The CSR CD&H system shall interface with the Communication system transmitter *Motivation - In order for the data collected by the CSR to be transmitted to the GS the transmitter must interface with the hardware that runs the data handling software*	Demonstration

Table 5. CSR.2 Design Requirements Flowdown

CSR.3 : The CSR shall be able to travel to a location of interest		
Requirement ID	**Description**	**V&V**

MOB.3.1	The CSR Mobility system shall be able to perform a 360 ^{o} turn *Motivation - In order for the CSR to maneuver around obstacles it needs to turn, so if it can perform the maximum reorientation it can re-orientate to any degree*	Demonstration
MOB.3.2	The CSR shall be able to go over discontinuities up to 1 foot (0.30 meters) *Motivation - While the MR can not go over 1 foot (0.30 m) discontinuities it is advantageous for the CSR to go over a discontinuity in the event that it encounters one while on mission*	Demonstration
MOB.3.3	The CSR shall be able to go up or down a slope of 20 ^{o} *Motivation - Since the MR can drive up slopes of this degree the CSR needs to have the capability to too*	Demonstration
MOB.3.4	The CSR shall be able to drive in underbrush (See Terrain Definition) *Motivation - The CSR will be operating in forest environment and will encounter varying levels of this type of vegetation*	Test - Environmental Maneuverability
MOB.3.5	The CSR Mobility system shall be able to drive the CSR chassis in the Mission defined terrain (See Terrain Definition) *Motivation - The CSR must be able to navigate through any terrain within the scope of the mission*	Test - Environmental Manueverability
MOB.3.6	The CSR Mobility subsystem shall operate for 5 missions(TBR) before needing maintenance *Motivation - The maintainability of the CSR is important for theuser so that it is not deployed on a mission when it can not per-form at its expected performance*	Test - Range
SENS.3.1	The CSR Sensing system shall include an object detection device *Motivation - In order for the CSR to navigate itself through an unknown environment it needs a way to sense obstacles*	Inspection
SENS.3.1.1	The CSR Sensing system shall report objects within the field of view (FOV) of the object detection device *Motivation - Depending on the FOV of the chosen object detection device, the CSR should be capable of reporting an object within its field of view*	Demonstration
SENS.3.1.2	The CSR Sensing system shall have a maximum range within 50 meters from the CSR *Motivation - Depending on the range of the object detection device, the CSR should be capable of reporting an object up to the object detection device's range*	Demonstration
SENS.3.2	The CSR Sensing system shall determine the grade/incline on which the CSR is travelling *Motivation - The CSR must map the terrain grades its traversing so that a viable path for the MR can be determined, because the MR has a 20 ^{o} terrain limitation*	Demonstration
POW.3.1	The CSR Power system shall provide power to mobility such that mobility can operate up to 250 meters in any direction from the CSR deployment, and 250 meters back to the deployment point. (500 meters total) *Motivation - For the mobility subsystem to operate for the duration of a mission the power system must be capable of providing the necessary power*	Test - Range

POW.3.2	The CSR Power system shall provide power to the Sensing system's object detection device such that it can operate over its maximum range *Motiviation - For the CSR to navigate and map its surroundings for the duration of a mission the power system must be capable of providing the necessary power*	Demonstration
CDH.3.1	The CSR CD&H system shall command the mobility systems power train to actuate *Motivation - For the CSR to drive at all commands must be sent to the power train*	Demonstration
CDH.3.2	The CSR CD&H system shall determine the relative distance between obstacles reported by the Sensing system *Motivation - The MR can only proceed down paths on which its width can fit, because the MR has a width limitation of 5 ft (roughly 1.524 meters)*	Test - Path Finding
CDH.3.3	The CSR CD&H system software shall store the Location of Interest's GPS coordinates in memory. *Motivation - In order for the CSR to remain on course with the LOI the location must be stored in memory*	Test - Path Finding
COMM.3.1	The CSR Communications system shall receive positioning data that composes a location of interest from the GS or MR. *Motivation - The CSR must be able to receive the location of interest positioning data in order to travel to the LOI*	Test - Communications

Table 6. CSR.3 Design Requirements Flowdown

CSR.4 : The CSR shall travel back to the last reported waypoint upon loss of communications with the MR		
Requirement ID	**Description**	**V&V**
MOB.4.1	The CSR Mobility system shall be able to perform a 360 deg turn *Motivation - If the mobility system can rotate the CSR to the max possible case it can roatate the CSR to any smaller angle*	Demonstration
CDH.4.1	The CSR CD&H shall store the last recorded waypoint *Motivation - To return to this position it must be stored in memory*	Demonstration

Table 7. CSR.4 Design Requirements Flowdown

CSR.5 : The CSR shall be able to take video while driving or in position-hold		
Requirement ID	**Description**	**V&V**
SENS.5.1	The CSR Sensing system shall include a camera which captures video *Motivation - A camera with video capability is required to take video*	Inspection

SENS.5.1.1	The CSR Sensing system shall take video at a rate of 30 fps (TBR) while the CSR is driving or in position-hold *Motivation - The quality of the video will is being based off of INFERNO's frame rate.* [11]	Demonstration
SENS.5.1.2	The CSR Sensing system shall take video at 720 pixel resolution (TBR) while the CSR is driving or in position-hold *Motivation - The video quality is being based off of INFERNO's frame rate.*	Demonstration
SENS.5.1.3	The CSR Sensing system video device shall have a FOV of 100 ^{o} *Motivation - Establishes the type of lens incorporated in the camera design*	Inspection
SENS.5.2	The CSR Sensing system video device shall operate for 5 missions (TBR) before needing maintenance *Motivation - This ensures that the CSR is not deployed when not all of its components can operate at expected performance.*	Test - Camera Operation
POW.5.1	The CSR Sensing system shall provide power to the video device such that it can capture video *Motivation - The video device can not perform if power is not distributed to it*	Demonstration

Table 8. CSR.5 Design Requirements Flowdown

CSR.6 : The CSR shall be able to take pictures while driving or in position-hold

Requirement ID	Description	V&V
SENS.6.1	The CSR Sensing system shall include a camera which captures pictures *Motivation - A camera with imaging capability is required to take pictures*	Inspection
SENS.6.1.1	The CSR Sensing system shall take pictures at an 8 MP (TBR) resolution while the CSR is driving or in position-hold *Motivation - A clear image will be needed to determine what the environment looks like. The resolution was based off of INFERNO's image resolution.* [11]	Demonstration
SENS.6.1.2	The CSR Sensing system imaging device shall have a FOV of 100 ^{o} (TBR) *Motivation - Establishes the type of lens incorporated in the camera design*	Demonstration
SENS.6.2	The CSR Sensing system image device shall operate for 5 missions (TBR) before needing maintenance *Motivation - This ensures that the CSR is not deployed when not all of its components can operate at expected performance.*	Test - Camera Operation
POW.6.1	The CSR Sensing system shall provide power to the imaging device such that it can capture images *Motivation - The imaging device can not operate if power is not distributed to it*	Demonstration

Table 9. CSR.6 Design Requirements Flowdown

CSR.7 : The CSR shall be able to dock to the MR		
Requirement ID	**Description**	**V&V**
SENS.7.1	The CSR Sensing system shall report the CSRs orientation with respect to the MR scout docking system *Motivation - The CSR can not dock with the MR if its relative position to the dock is unknown*	Test - Docking and Deploying
POW.7.1	The MR scout docking power system shall provide power to the MR scout docking mechanism to actuate for docking *Motivation - The CSR can not be secured to the MR if power is not supplied to the docking system actuators*	Demonstration
CDH.7.1	The CSR CD&H system shall compute the correction for the CSRs position with respect to the position of the MR scout docking mechanism *Motivation - For autonomous docking the CSR must correct its position on board*	Test - Docking and Deploying
CDH.7.2	The CSR CD&H system shall command the Mobility system to implement position corrections with respect to the MR scout docking mechanism *Motivation - For autonomous docking the CSR needs to distribute movement commands on board*	Test - Docking and Deploying
DOCK.7.1	The CSR docking mechanism shall secure to the MR scout docking mechanism *Motivation - Docking with the MR can not be completed if this is not done*	Demonstration

Table 10. CSR.7 Design Requirements Flowdown

CSR.8 : The CSR shall be able to deploy from the MR		
Requirement ID	**Description**	**V&V**
POW.8.1	The MR scout docking power system shall provide power to the MR scout docking mechanism to actuate for deployment *Motivation - The CSR can not deploy from the MR if power is not supplied to the deployment system actuators*	Demonstration
DOCK.8.1	The MR scout docking mechanism shall be capable of detaching from the CSR docking mechanism *Motivation - The CSR can not deploy if the corresponding docking system on the MR does not have this capability*	Test - Docking and Deploying

Table 11. CSR.8 Design Requirements Flowdown

4. Key Design Options Considered

4.1. Translational System

The translational system was chosen to be a key design parameter to be considered because of how critical its function is to the mission. The translational system relates directly to the mobility capabilities of the CSR, which in turn relate to the functional requirements CSR.3,CSR.4, CSR.7, and CSR.8. The CSR must be able to travel forward and backwards in forest fire prone areas and perform 360° turns. Otherwise it cannot navigate and would be unable to reach a LOI.

4.1.1. Rocker Bogie system

Rocker Bogie[12] system is a suspension system consisting two links on each side connected with six wheels with no springs used. On each side, there is a large link called a 'rocker' and a smaller link called a 'bogie'. The rockers on each side are connected by a differential for leveling purpose. Namely, when one side goes up relative to the main body, the other side goes down to help level the main body and avoid tipping. The 'bogies' are commonly used in the tank track as loading wheels. In the rocker bogie system, 'bogie' refers to the wheels on the small link which can distribute weights. However, in order to drive over 1 ft (0.30 m) discontinuity required by MOB.3.2., the stiffness of the axles must be increased, possibly through the use of torsion springs, such that the system does not fall into the gap. This required stiffness decreases the effectiveness of the rocker bogie suspension. Additionally, the moving linkages of the system add mechanical and manufacturing complexity to the system. An image of rocker-bogie system is shown below:

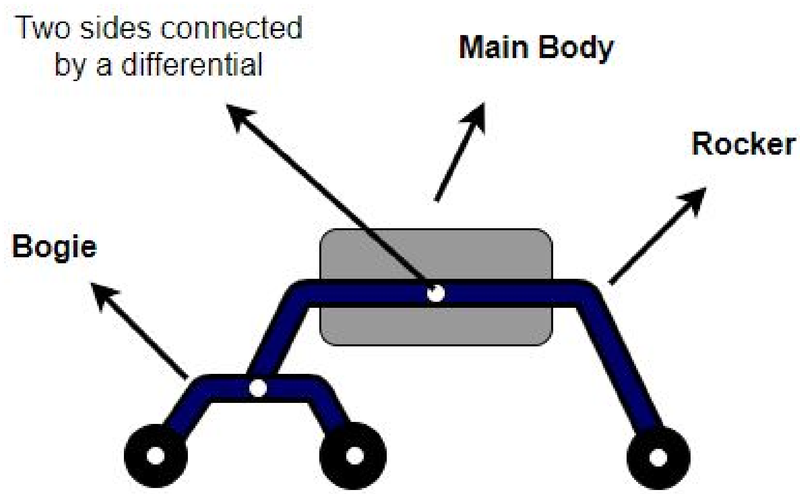

Figure 6. Rocker Bogie Configuration

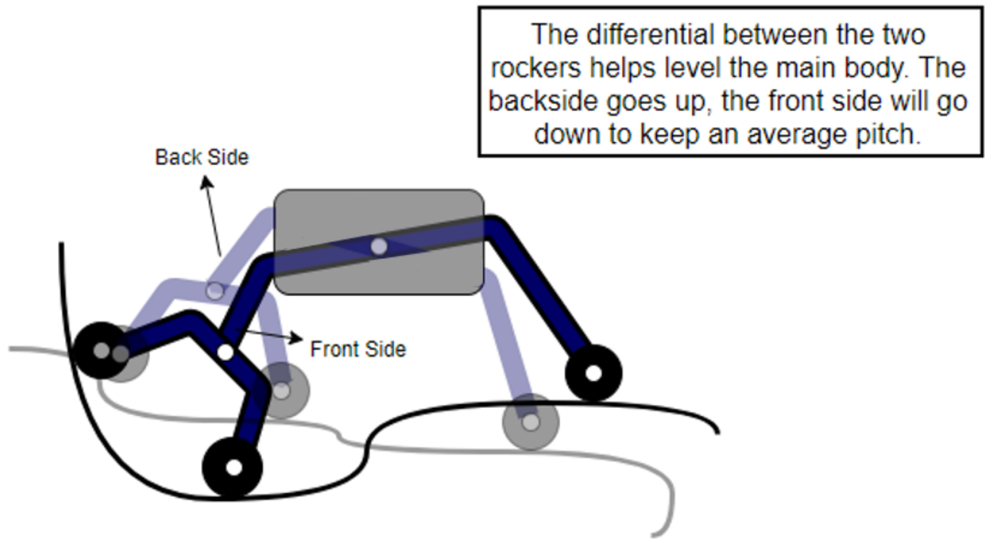

Figure 7. Rocker Bogie Differential Suspension

Description	Pro	Con
Can climb over obstacles up to twice its wheel size	**X**	
Reduces the motion of the main body	**X**	
Low potential of flipping over	**X**	
Gear damage caused by single differential		**X**
Unstable at high speed		**X**
Mechanically complex		**X**
Required axle stiffness reduces suspension effectiveness.		**X**

Table 12. Pros and Cons of the Rocker Bogie Suspension System

4.1.2. Tank Track System

The tank track system contains several wheels and a continuous track link on each side of the vehicle body. The continuous track link keeps the wheels from the potentially getting stuck and increases the traction. However, since the continuous track link is long and not flexible, there is a potential of tipping if the vehicle is trying to go over large obstacles as shown in the figure below. This system is mechanically complex and would be extremely difficult to manufacture without COTS parts, which are extremely expensive for treads longer than 2 ft (0.61 m), which is needed to meet the 1 ft (0.30 m) discontinuity requirement, MOB.3.2.

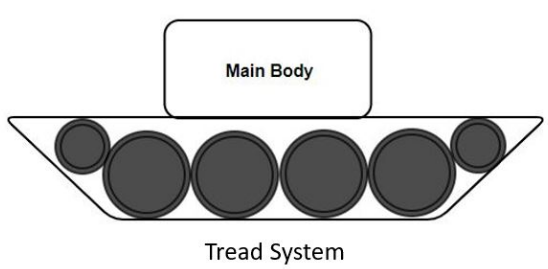

Figure 8. Tank Track System Configuration

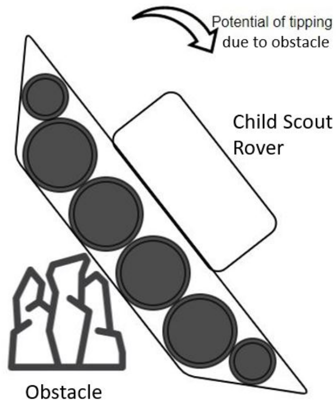

Figure 9. Tank Track System Tipping Risk

Description	Pro	Con
Mechanically complex		**X**
Significant traction	**X**	
Low contact pressure	**X**	
Capable of crossing 1 ft (0.30 m) discontinuity with a smaller profile.	**X**	
High potential of tipping		**X**
Expensive (>$1000) COTS parts required.		**X**

Table 13. Pros and Cons of the Tank Track Suspension System

4.1.3. Four Wheel Drive, Four Wheels

This system has four wheels fixed on the vehicle body, each being supplied power. This system is easier to design and manufacture while still meeting the design requirements. The main drawback with this design is that in order to cross the 1 ft (0.30 m) discontinuity, the wheel diameters must be greater than 1 ft (0.30 m). This results in a physically large, expensive system. The benefit of the large wheels is it provides more traction and suspension than smaller wheels. An all wheel drive design using two motors was considered; however, due to the added mechanical and manufacturing complexity it would require, it was deemed not worthy to be a key design consideration. Additionally, trading for system with an active suspension system was considered; however, due to the low travel speeds of the CSR, the existing suspension provided by the large wheels, and the mechanical and manufacturing complexity required to design active suspension, it was not considered for trading.

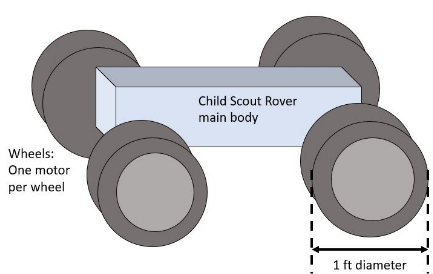

Figure 10. 4WD System Configuration

Description	Pro	Con
Mechanically Simple	X	
Relatively Simple to Manufacture	X	
Greater traction and suspension than small wheels	X	
Large required size of CSR		X
Expensive		X

Table 14. Pros and Cons of the Four-Wheel-Drive System

4.1.4. Six Wheel Chassis

Six wheel chassis is designed to go over 1 ft (0.30 m) discontinuity with minimal mechanical complexity. With the additional wheels at center as supports of center of mass, the vehicle could go over 1 ft (0.30 m) discontinuity with smaller wheels, as demonstrated by Figure 11. However, this design reduces the available room of the main body because the mass be centered over the chassis. Additionally, the smaller wheels result in even less suspension and traction than the four wheeled system. There are several potential configurations for a six-wheeled translational system.

The first is implementing active suspension versus having fixed wheels. Due to the mechanical and manufacturing complexity required to design a suspension system, and the low benefit it would have due to the low travel speeds and stiffness required to cross a 1 ft (0.30 m) discontinuity, it was decided that implementing an active suspension system would not be worth it, and is not considered in the trade study.

The next potential configuration is whether to drive the wheels directly through the motor, or to design an all wheel drive system, where there are less motors than wheels. Like with the four wheel system, it was decided that implementing a sophisticated power train would require too much manufacturing and mechanical complexity to be worth it. There is also the option to leave the middle two wheels un-powered; this would then only require the two front and two back wheels to be powered, while still providing the support required to cross the 1 ft (0.30 m) gap, avoiding a more sophisticated drive train, and reducing the control complexity required for six wheels. For the trade study, both the 6WD and 4WD configurations will be considered for the six-wheeled translational system. Their pro's and con's are tabulated in Tables 4.1.4 and 4.1.4, respectively.

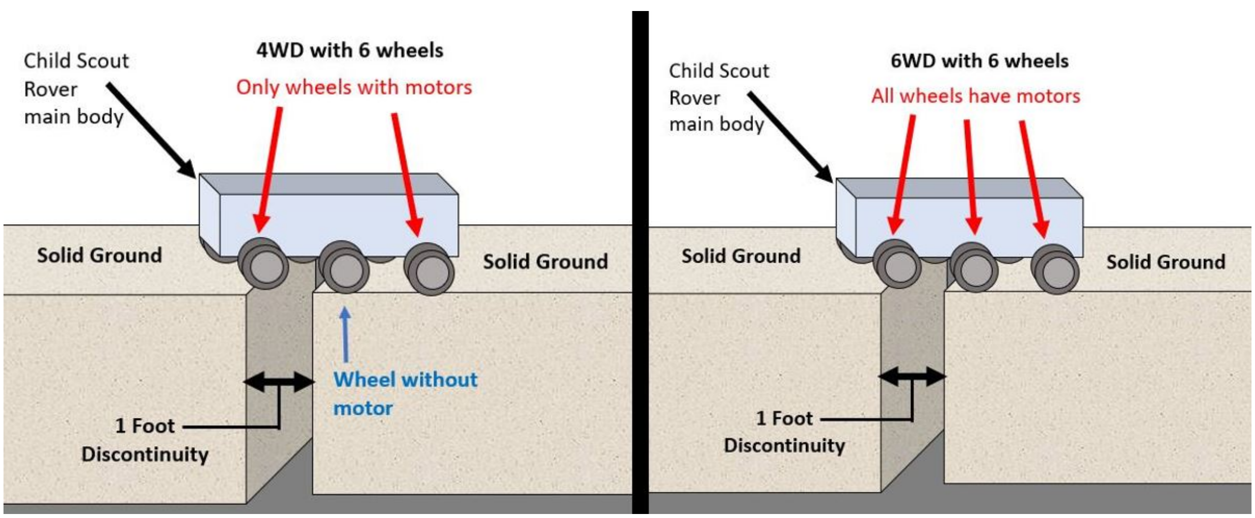

Figure 11. Six Wheel Chassis Configuration, fulfilling MOB.3.2 requirement

Description	Pro	Con
Mechanically simple	**X**	
Relatively simple to manufacture.	**X**	
Capable of crossing 1 ft (0.30 m) discontinuity with a smaller profile.	**X**	
Minimal suspension capability		**X**
Minimal traction		**X**
Limited CSR housing size to focus mass over the center wheel		**X**
Each wheel is powered	**X**	
Increased control complexity		**X**

Table 15. Pros and Cons of the 6WD Six Wheel Configuration

Description	Pro	Con
Mechanically simple	**X**	
Relatively simple to manufacture.	**X**	
Capable of crossing 1 ft (0.30 m) discontinuity with a smaller profile.	**X**	
Minimal suspension capability		**X**
Minimal traction		**X**
Limited CSR housing size to focus mass over the center wheel		**X**
Un-powered middle wheels increase chance of being stuck		**X**
Simpler control complexity	**X**	

Table 16. Pros and Cons of the 4WD Six Wheel Configuration

4.2. Object Detection

In order for the CSR to navigate to a particular LOI (Requirement CSR.3), the CSR must be capable of self-navigation through an outdoor area containing a number of obstacles, such as trees and rocks (See Terrain Definition). The key design option that enables this process to occur is object detection within this environment, or the ability for the CSR to sense obstacles in the terrain that lie in between the CSR and the LOI. Ideally, the CSR should be able to produce a terrain map and send it back to the MR and the GS, but the fundamental function of the CSR is purely detection of these obstacles. The following design alternatives have the ability to detect the existence of an object, but some are commonly used to develop terrain maps, depth maps, and categorize objects they have detected. The alternatives considered for this design option are lidar sensors, ultrasonic sensors, collision sensors, and image processing. It should be noted that the image capturing system for image processing is entirely separate and independent from the image capturing system that will fulfill requirements CSR.5 and CSR.6. In particular, the image processing alternative directly fulfills the SENS.3.1 derived requirement, along with the other object detection methods.

4.2.1. Lidar Sensor

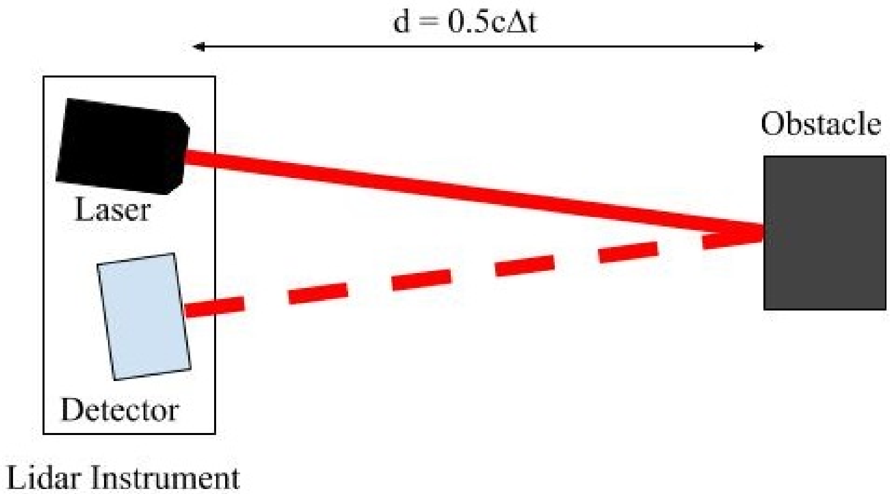

Figure 12. Lidar operation

Lidar (Light Detection and Ranging) sensors are used for remote sensing, creating environmental maps, and are able to accurately measure distances to objects within a given range. To measure distances, the lidar sensor emits quick consecutive laser pulses and makes calculations based on how fast those pulses reflect back to the sensor.[13] This process is depicted in Figure 12 along with the distance formula the instrument utilizes. Lidar would serve as a useful object detection method due to its high accuracy and large amounts of available software, making the system easier to integrate. It must be taken into account, however, that the system must be precisely calibrated and have a stable mounting system to limit measurement uncertainty.

Description	Pro	Con
Many software libraries available in a variety of common microprocessor languages	**X**	
Produce accurate environmental maps to clearly show where landscape objects lie	**X**	
Wide range of applications (can operate as a simple distance finder or a terrain map builder)	**X**	
Some lidar systems do not function outdoors (light-sensitive)		**X**
Must have stable mounting to limit pointing uncertainty		**X**

Table 17. Pros and Cons of Lidar Sensor

4.2.2. Ultrasonic Sensor

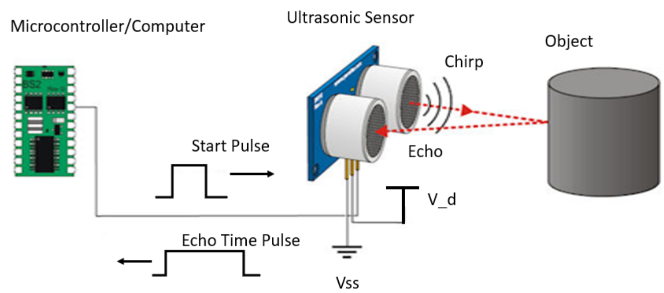

Figure 13. Ultrasonic detection operation [14]

Ultrasonic sensors are based off the use of sound for remote sensing. Typically these types of sensors are used for distance measurements and object detection. The method can be used to collect both types of data, however, boards are typically configured by the manufacturer to process either the distance or object detection data. To measure distances, the sensor emits a sound wave at a specific frequency. When the sound wave returns after colliding with an object, the distance can be computed since the sound wave travels at the speed of sound. Similarly, to detect objects an ultrasonic sensor sends out a sound wave and when the wave encounters an object it reflects (certain objects can absorb the sound wave). If the ultrasonic sensor receives a sound wave back then an object is in the direction of the source.

Description	Pro	Con
Available at different price ranges and fidelity levels	**X**	
Simple distance calculations	**X**	
Software is typically available for the ultrasonic sensor selected	**X**	
Material-dependent (some ultrasonic sensors give faulty data when sensing materials like wood)		**X**
Mapping can be difficult with lower fidelity hardware		**X**

Table 18. Pros and Cons of Ultrasonic Sensor

4.2.3. Collision Sensors

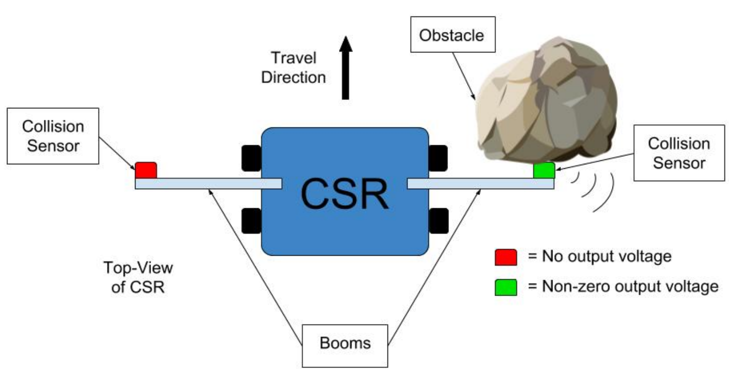

Figure 14. Collision sensor operation

For the purposes of the object detection trade study, collision sensors will be defined as any sensing system that is capable of detecting a direct impact of the CSR against an obstacle. Technically, other sensors such as lidar and ultrasonic sensors are capable of predicting an impact, but it should be noted that collision sensors functionally differ because they require an impact to occur in order for the sensor to produce meaningful data. The sensors that fall under this category are bump sensors, shock detectors, load cells, and accelerometers [15]. Bump sensors and shock detectors act as switches that output voltage when an impact occurs with a certain, calibrated force. A load cell measures the force of an impact and outputs a voltage relative to the force input, which is useful information for impact determination of various levels. An accelerometer detects changes in acceleration, typically in three axes. Although commonly used for vibration sensing, an accelerometer could be used to detect impacts, since an impact causes a rapid change in acceleration in a 3-axis coordinate system. A depiction of a collision sensor's operation is shown in Figure 14.

Description	Pro	Con
Easy integration with rover controls (behaves like a switch)	**X**	
Little back-end processing or data handling required	**X**	
Inaccurate method for detecting relative distances between objects		**X**
Any high speed collision may cause damage to rover		**X**
Very low range (requires impact so object avoidance is impossible)		**X**
Poor localization capability with respect to multiple obstacles		**X**

Table 19. Pros and Cons of Collision Sensors

4.2.4. Image Processing

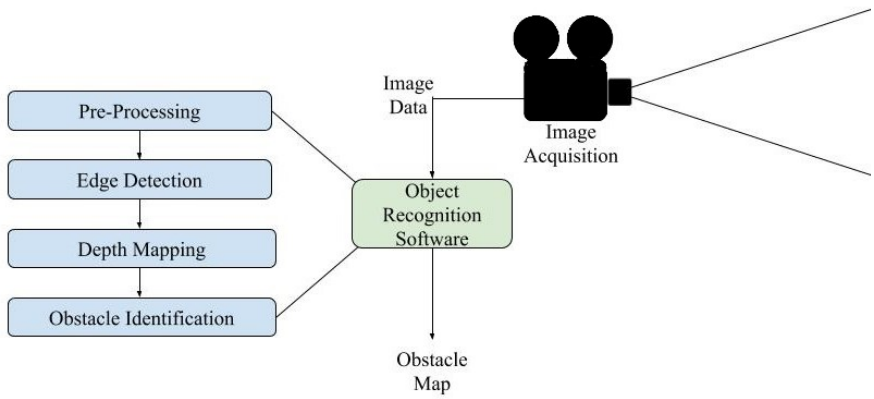

Figure 15. Vision processing flow chart

Image processing is the act of capturing an image and using computer-based algorithms to filter and enhance that image to extract useful data. Image processing techniques for object detection, for this study, refer to the hardware and software required to capture an image and gather relative distance information between a camera module and an obstacle. The two primary forms of image processing considered for this design alternative are traditional digital vision processing using a camera module with direct integration to a microcontroller and accurate depth map processing using an RGB-D camera.

Typically, microcontroller camera modules are capable of capturing images in several common formats including JPEG, PNG, Windows bitmap, RGB, and RGBA [16]. Many computer vision techniques exist in the industry today to perform the above procedure (Figure 15) to convert the images from raw image data to object maps that contain locations of determined objects in an environment. RGB-D camera modules are used in a stereo format and utilize an IR projected light pattern and an IR sensor to calculate and record relative depths [17]. These cameras are locked into the RGB format of images, but each pixel contains depth information, which is useful in determining relative distances between the camera module and an object.

Description	Pro	Con
Many software libraries available in a variety of common microprocessor languages	X	
Computationally heavy so may need an additional microprocessor		X
May struggle to determine accurate distances without multiple images or cameras		X
Large amounts of data must be processed per image		X

Table 20. Pros and Cons of Image Processing

4.3. Communication System

A critical element of our project is to have the CSR communicate to the MR and the GS. These pieces of equipment will need to establish strong connection links with each other to satisfy the functional requirements demanded being CSR.1, CSR.2, and CSR.4. Shown in Figure 16 is an aerial layout of the scenario the communications need to perform in. As shown, the CSR needs to be able to send and receive data from both the MR and GS. The max range needed across all these pieces of equipment needs to be 250 meters (820 ft). On top of the range, obstructions may be present including trees, brushes, boulders, and hills. The data that is being sent and received will consist of videos, pictures, GPS locations, and guidance, navigation, and control (GNC) commands. This amount of complex data demands high transmission rates and low latency to preserve data integrity. Our design options will all be compared to one other for best performance in both an ad-hoc or infrastructure network. An ad-hoc network is a form of point to point communication between devices directly whereas an infrastructure network is a form of indirect communication between devices through a wireless access point. It is also important to point out that the prior years work on communication led to minimal functionality but will still be considered. Final decision will be based on the most optimal method that creates the strongest data link between all pieces of equipment. Thus, the options of consideration consist of Wi-Fi, Zigbee, and Global System for Mobile Communications (GSM).

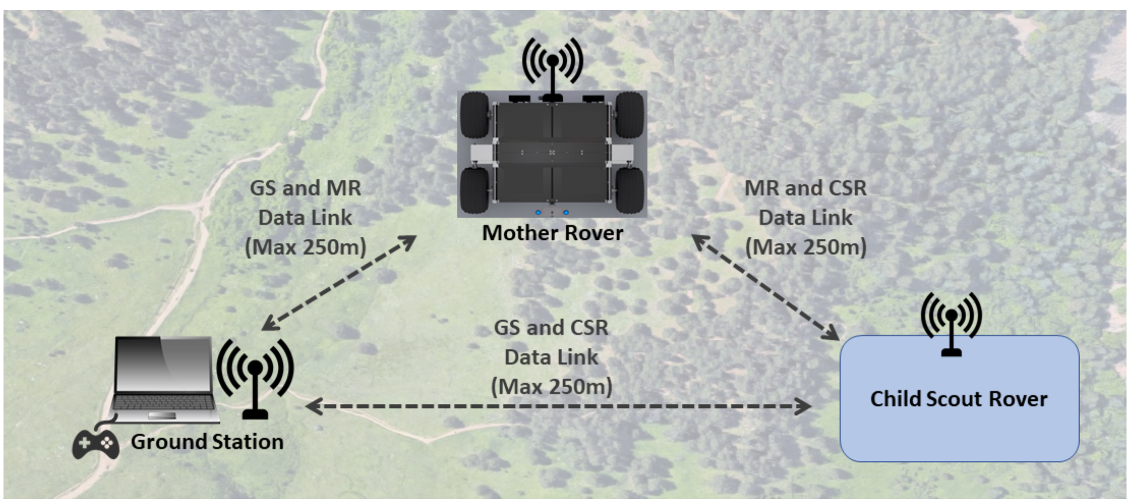

Figure 16. Communication system overview with an example of our communication node concept for the GS, MR, and CSR.

4.3.1. Wi-Fi

Wi-Fi being one of the most common communication protocols available, creates ease of usability and efficiency for incorporation into our communication system. This technology is based on the IEEE 802.11 standard which is the broadband reserved for wireless technology using the Industrial, Scientific, and Medical Radio (ISM) band. This band use has been widely incorporated into vast number of devices and modules that are readily available to ensure maximum compatibility across off the shelf devices. Wi-Fi also allows for large amounts of data transfer, but with the drawback of higher power consumption and low transmission range without external amplification. According to

Intel, data rates or throughput range from 2 to 450 Mbps[18]. For our implementation we need to design our Wi-Fi network with video transmission requirements in mind which require data rates from 600 to 800 Kbps for low quality streams and a minimum of 1.5 Mbps for medium quality streams[19]. Speed is easily achievable, but the matter of range proves to be the biggest challenge as it demands extensions including long-range antennas and power amplifiers. A schematic of implementation is shown in Figure 17 for both an ad-hoc and infrastructure implementation as well as an example of an off the shelf product that could be used as part of the communication node for each piece of equipment.

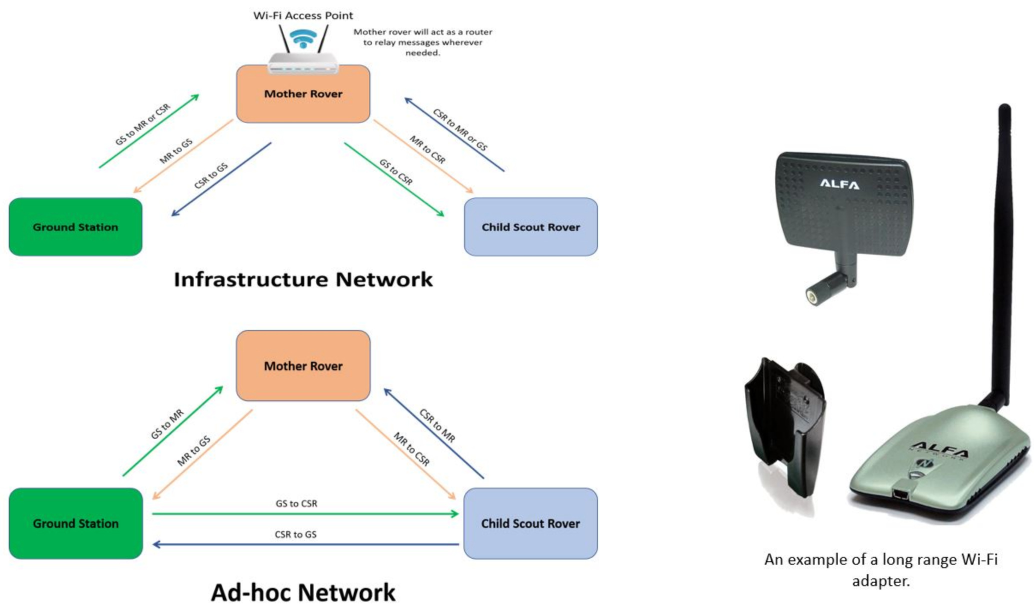

Figure 17. Wi-Fi method considering both an ad-hoc approach and an infrastructure approach with an example of a long range adapter that could be used.

Description	Pro	Con
High speed data rates	**X**	
Modular extension capabilities	**X**	
Ease of hardware and software integration	**X**	
Limited range requires additional hardware		**X**
Potential for higher costs to boost range		**X**
High power consumption		**X**

Table 21. Pros and Cons of Wi-Fi communication system

4.3.2. Zigbee

Zigbee is very similar to Wi-Fi in that it uses an IEEE standard with specifications defined under the 802.15.4 standard. This standard differs in that it specializes in low data rate, low power consumption, and low range wireless applications. According to Zigbee Alliance, data rates of 250 Kbps, 40 Kbps, and 20 Kbps can be achieved[20]. Video transmission will be unlikely to achieve with these rates; however, the data rates can be highly consistent for constant communication of sensor readings and signals being sent and received. This form of communication also allows ease of integration among off the shelf components and has been used in last years project. Last years project, DRIFT, used Xbee radio modules, which incorporate Zigbees based protocol, for their form of communication between the MR and the GS. These tested Xbee modules can transmit over long ranges, but only with clear line of sight and directionality for the path of transmission to the target. Using Zigbee will require the use of an ad-hoc infrastructure as the MR, GS, and CSR will each have one Zigbee radio module most likely incorporating last years Xbee radios with modifications. The schematic of implementation as well as the Xbee radios used last year are shown in Figure 18.

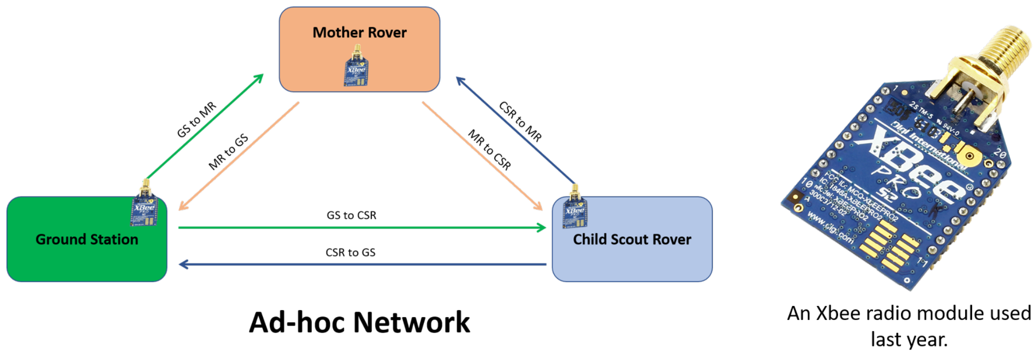

Figure 18. Zigbee method using an ad-hoc approach that shows the option of utilizing last year's Xbee radio modules.

Description	Pro	Con
Inexpensive	**X**	
Low power consumption	**X**	
Consistent data rates and connection with no obstructions	**X**	
Low speed data rates		**X**
Prone to small interferences		**X**

Table 22. Pros and Cons of Zigbee Communication System

4.3.3. Global System for Mobile Communications (GSM)

GSM is a more unique method to consider because it requires the use of cellular networks. The idea behind this method is to overcome the line of sight issues by utilizing cell towers near deployment. This method will allow each piece of equipment to have better path of transmission to the access point, being the cellular towers. According to Verizon, data rates of 5 to 12 Mbps can be achieved[21]. Speed and range can be easily achieved given the area of deployment has the right coverage. The drawback to using cellular modules is the fact that they are expensive. This is because our method would require the MR, GS, and CSR to have their own cellular module which ultimately requires a Subscriber Identification Module (SIM) card which brings along a paid service to the provider on top of the device itself. Nonetheless, a schematic of this approach is shown in Figure 19 as well as an example of a potential cellular module.

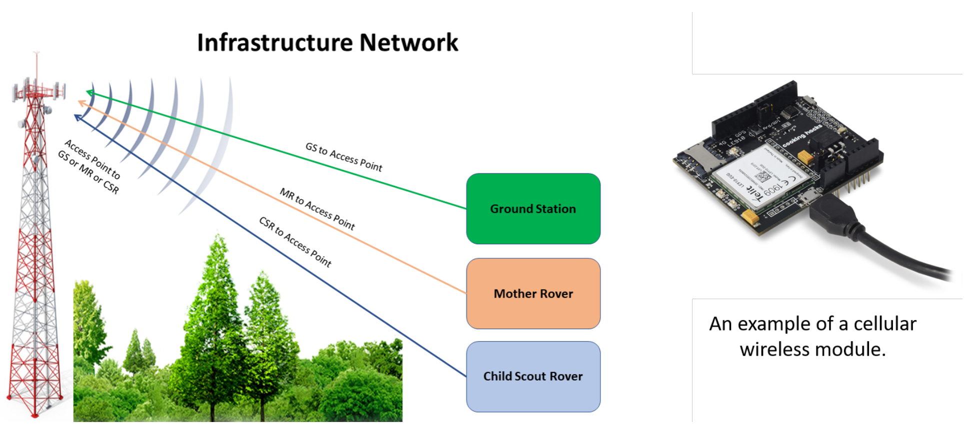

Figure 19. GSM method using an infrastructure approach by communicating through the cell tower.

Description	Pro	Con
High speed data rates	**X**	
Long range	**X**	
Connection contingent on network		**X**
Expensive		**X**

Table 23. Pros and Cons of Lidar Sensor

4.4. Docking/Deployment Mechanism

Another critical project element is the docking and deploying mechanism. In order to even be able to navigate to LOI, the CSR must be able to deploy from the MR's docking mechanism. Then after the CSR and the MR have reached an LOI, the CSR must be able to dock onto the MR in order to save power on the CSR and limit any risks the CSR may encounter if it were navigating through the terrain. This element also relates to requirements CSR.8 and CSR.9.

4.4.1. Hitch

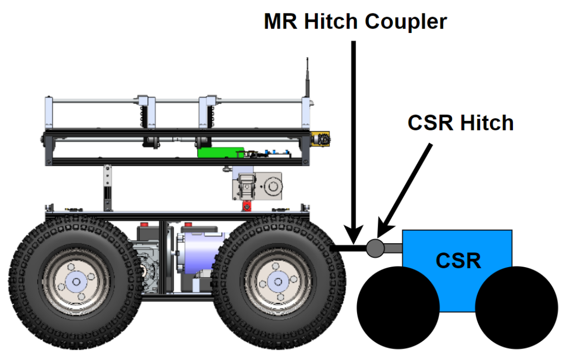

Figure 20. Hitch Docking Mechanism.

The Hitch design is comprised of a hitch on the CSR and an actuated coupler on the MR. To dock, the CSR would drive to the MR and align itself such that the MR's coupler can attach itself to the CSR hitch. To deploy, the MR coupling mechanism would decouple from the CSR hitch, and the CSR would drive away. This hitch design would be based off of the standard ball-hitch/coupler design used for towing and trailer attachments. While this design has been proven and is the standard for towing, it would require the use of two actuators and precise control. Other solutions which require less precise control would consist of the CSR driving into a locking mechanism with loose tolerances.

The main benefits of the hitch design are that it does not limit the size of the CSR, that COTS parts are available for a ball hitch design, and relatively minimal manufacturing would be required compared to the other designs. Additionally, it is unique in that if the automated docking control fails, the deploying mechanism could still function. Finally, the actuation would simply involve locking mechanisms, and no heavy components would be lifted by the actuators.

One of the drawbacks with the hitch design is that the docked CSR configuration would significantly reduce the maneuvering capabilities of the MR when the two are hitched together. This is due to the fact that the MR would no longer be able to rotate in place without possibly colliding with the CSR, and that the drag from the CSR would increase the power requirements for the MR to drive. This drag would also call for a requirement for the CSR to have a neutral gear. Another drawback with the hitch design is that the location control and imaging capabilities of the CSR would need to be precise to about 0.5" (1.27 cm).

Description	Pro	Con
Mechanically simple	**X**	
Low power load required for mechanism actuators	**X**	
Increases power required for MR to drive due to drag from the CSR		**X**
Reduces maneuverability of MR. Increases profile of MR when in the docked configuration, prevents in-place 360^o turns, and increases required power to drive.		**X**
COTS Parts Available.	**X**	
Does not constrain CSR Size	**X**	
Precise control required to align hitch and coupler.		**X**

Table 24. Pros and Cons of the Hitch Docking/Deployment Mechanism

4.4.2. Trailer Platform

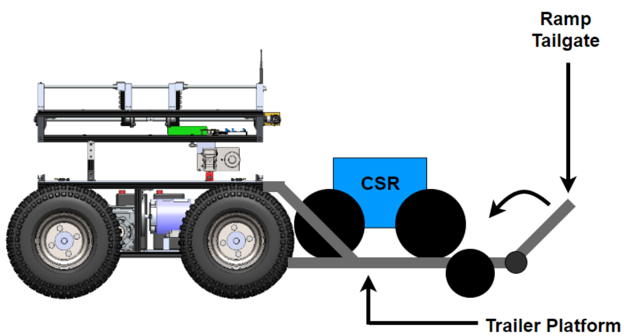

Figure 21. Trailer Docking Mechanism.

The trailer platform design consists of an extended trailer that is permanently fixed to the back of the MR which carries the stowed CSR. The trailer would have pivoting wheels to support the trailer as well as allow for in-place MR rotation. To deploy the CSR, the tailgate opens up as a ramp which the CSR drives down. Once the CSR is deployed, the tailgate is positioned upright using a motor. Likewise, to dock the CSR, the tailgate opens as a ramp which the CSR drives up on, then closes once the CSR is stowed on the platform.

The main benefit of the Trailer Platform design is that it does not constrain the size of the CSR. Additionally, the extended trailer also allows for greater maneuverability compared to the Hitch design, as the MR can still rotate in-place however the overall maneuverability is still decreased. Because the CSR would simply need to drive up the ramp, the control required would not need to be very accurate. However, the trailer platform requires a whole trailer to be manufactured, and it would decrease the maneuverability of the system as a whole due to the protrusion and extra drag.

Description	Pro	Con
Mechanically simple	**X**	
Structurally difficult		**X**
Low power load required	**X**	
Reduces maneuverability of MR		**X**
Costly (one 14” (0.36 m) pivot wheel costs over $300)		**X**
Does not constrain CSR Size	**X**	
Minimal MR Changes Required	**X**	

Table 25. Pros and Cons of the Trailer Platform Docking/Deployment Mechanism

4.4.3. On-Board Ramp, without Extended Side Platform

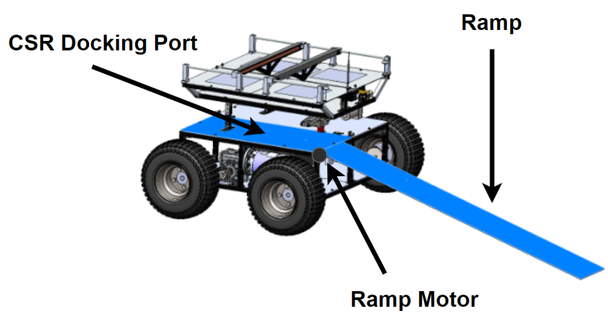

Figure 22. On-Board Ramp without Extended Side Platform Docking Mechanism.

The On-Board Ramp docking/deployment mechanism is comprised of a deployable ramp that is attached to the MR, such that the CSR may drive up or down the ramp to dock or deploy itself. This ramp would be actuated using a motor that can move the ramp from its deployed state or stowed state. To stow itself, the ramp would move up to a vertical position, insignificantly increasing the MR profile, and keeping the CSR in its stowed position. There are two main CSR stowing configurations for a ramp mechanism: on the top platform or on an extended side platform. This section discusses the non-extended platform.

This design is mechanically simple, as it is only comprised of an actuated ramp. Additionally, because the CSR would be stowed inside the MR, there would be no protrusions from the MR and no additional drag for the MR to carry; benefiting the maneuverability of the MR. Because the CSR would be stowed within existing platform space within the MR, there would be minimal structural modifications made to the MR.

The non-extended platform with a ramp’s main drawback is that it would significantly limit the length x width x height size of the CSR to 24”x9”x7.5” (0.61m x 0.23m x 0.19m). Additionally, due to the fact that the CSR must be stowed to the side of the MR, it shifts extra weight on that side’s wheels. This could create an imbalance of traction between the two sets of the MR’s wheels when the CSR is stowed. Finally, due to the fact that the ramp must stow the CSR on the top MR platform, the ramp must be at least 57.75” (1.47 m) long for the ramp to lie on a 20° slope. If the MR lies on a tilted slope and the ramp’s slope is increased, the CSR may not be able to dock. This large ramp would not only significantly increase the height of the CSR, but require a powerful enough motor to supply enough torque to lift the ramp.

Description	Pro	Con
Mechanically Simple	X	
Maintains maneuverability of MR	X	
Significantly limits CSR Size		X
Loads one side of MR wheels more when stowed		X
Large ramp required		X
CSR may not be able to dock with MR if MR is titled		X

Table 26. Pros and Cons of the On-Board Ramp Docking/Deployment Mechanism

4.4.4. On-Board Ramp, with Extended Side Platform

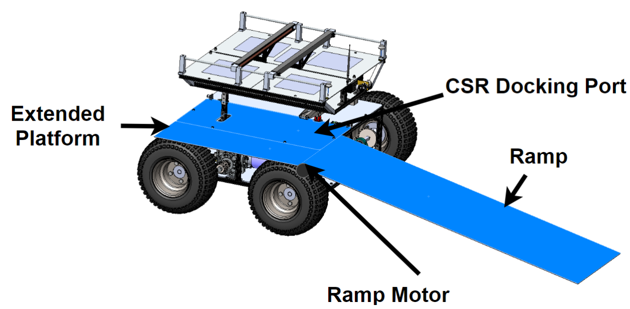

Figure 23. On-Board Ramp with Extended Side Platform Docking Mechanism.

The docking mechanism for this design option is the same as that of the on-board ramp with no side platform, except the MR has been modified to add an extended platform over the side of one of the wheel bases to allow for increased stow space for the CSR, effectively increasing its allowable size. The docking/deployment mechanism itself is the same; it is comprised of a deployable ramp, attached to the MR and the extended side platform that allows the CSR to deploy or dock with the MR. When the CSR is not actively being docked or deployed, the ramp is stowed in its vertical configuration.

This ramp is mechanically simple as it only requires an actuated ramp. Like the ramp with the non-extended platform, this design would not increase the profile of the MR and does add an element that must be dragged by the MR. Unlike the non-extended platform design, the allowed size of the CSR would be drastically larger. Although still limited to a size of 36”x16”x14” (0.91m x 0.41m x 0.36m), these dimensions are significantly easier to design around.

One main drawback is that the extended platform would require significant modifications to the MR’s chassis. Additionally, the platform and docked CSR would torque the MR, effectively increasing the load over the wheels below the platform. This would decrease the traction on the opposing sides wheels. Finally, like its non-extended version, the ramp would have to be at least 57.75” (1.47 m) long for a ramp slope of 20°.

Description	Pro	Con
Mechanically Simple	X	
Maintains immediate maneuverability of MR	X	
Allows for a large CSR	X	
Significantly loads one side of the MR wheels		X
Significant structural changes to MR required		X
Large ramp required		X
CSR may not be able to dock with MR if MR is titled		X

Table 27. Pros and Cons of the On-Board Ramp Docking/Deployment Mechanism with Extended Platform

4.4.5. On-Board Lift, without Extended Side Platform

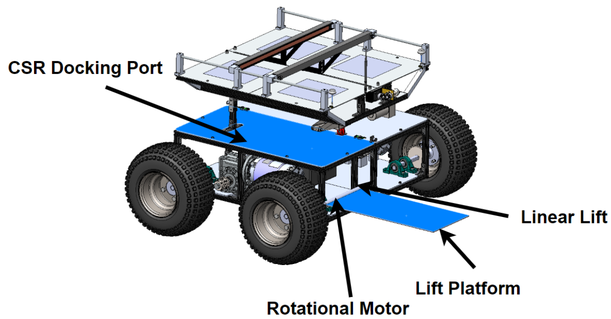

Figure 24. On-Board Lift without Extended Side Platform Docking Mechanism.

The On-Board Lift is another on-board docking deployment mechanism. This design option is comprised of a platform that is deployed horizontally onto the ground. In order for the CSR to dock or deploy, it would drive onto the lifting platform, and either be raised up to its docking port within the MR for docking, or be lowered to the ground for deployment. To stow itself, the lifting platform would rotate itself up to a vertical position such that the platform does not protrude from the MR and keep the CSR in its docking port in the MR. Like the on-board ramp, the lift has two possible CSR stow configurations: the top platform on the unmodified MR, or the extended side platform. This section discusses the pros and cons associated with the unmodified MR design.

The benefits of the on-board lift mechanism are similar to those of the on-board ramp mechanism; the profile of the MR would be unchanged, and there would be no additional power required to drag the CSR when driving the MR in the docked configuration. The on-board lift mechanism does improve on the on-board ramp in that it does not required as large of a platform; the ramp requires a length of at least 57.75” (1.47 m), whereas the lift only requires a platform the size of the CSR’s wheelbase. Additionally, it does not have the issue of potentially not working when the MR is tilted.

However, this design also has the same weaknesses as the on-board ramp design with no extension; the CSR is severely sized-limited to 24”x9”x7.5” (0.61m x 0.23m x 0.19m). Additionally, the docked CSR would load one side of the MR’s wheels more than the other. The on-board lift’s main weakness over the on-board ramp is that it would be more complex to model and manufacture due to the two degrees of freedom required: one to lift the platform, and the another to rotate the platform to its stow/deployment position. The lift actuators would also be required to supply enough power to lift both the platform and the CSR.

Description	Pro	Con
Mechanically Complex		**X**
Large power load required		**X**
Lift platform smaller than ramp platform	**X**	
Maintains maneuverability of MR	**X**	
Functions when MR is tilted	**X**	
Limits CSR Size		**X**
No significant changes to MR required	**X**	

Table 28. Pros and Cons of the On-Board Lift Docking/Deployment Mechanism

4.4.6. On-Board Lift, with Extended Side Platform

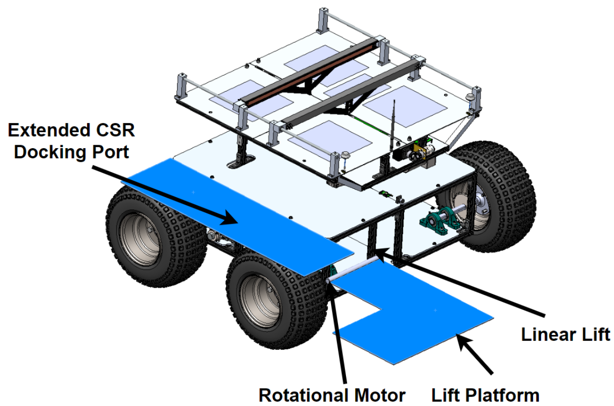

Figure 25. On-Board Lift with Extended Side Platform Docking Mechanism.

Like with on-board ramp design, the on-board lift has another possible stowing configuration: an extended side platform. This design has the same lifting mechanism as the non-extended on-board lift platform. An on-board lift can lift and lower a CSR to dock and deploy, respectively, and rotates vertically to stow itself and prevent the CSR from falling out when in the docked configuration. Unlike the unmodified on-board lift design, the extended side platform can support a much larger CSR.

The main advantages with this system are its ability to stow a CSR with dimensions of 36"x16"x14" (0.91m x 0.41m x 0.36m). Additionally, it has the benefits of the unmodified on-board lift platform: it does not increase the overall profile of the CSR, it does not significantly increase the power required to drive the MR, it allows for docking on slopes, and the platform size is relatively small compared to the ramp.

The on-board lift platform shares its weaknesses with the non-extended on-board lift platform and the extended on-board ramp. It is mechanical complexity due to the required two degrees of freedom, it requires significant MR structural modifications, the actuators must supply enough power to lift the platform and the CSR, and the offset docking port creates an unbalanced load on the MR.

Description	Pro	Con
Mechanically Complex		**X**
Large power load required		**X**
Lift platform smaller than ramp platform	**X**	
Maintains maneuverability of MR	**X**	
Functions when MR is tilted	**X**	
Limits CSR Size		**X**
Significant changes to MR required		**X**
Significantly loads only one side of the MR		**X**

Table 29. Pros and Cons of the On-Board Lift Docking/Deployment Mechanism with Extended Platform

4.5. Imaging System

The imaging system is a key component in the functionality of the CSR, and therefore a trade study is performed. The imaging system is the primary system for carrying out the functional requirement of sending data in the form of images and video to the GS and MR, specifically requirements CSR.2, CSR.5, and CSR.6. Moreover, this system will potentially assist in object detection and avoidance if the CSR does not reach a full level of autonomy. These images and video will relay important information about the environment back to the GS to get the CSR and MR to the LOI. In addition, the imaging system will be the key component of guiding the CSR to dock and deploy on the MS. With these critera in mind, four imaging system configurations were considered.

4.5.1. *Wide FOV Fixed Camera*

The option considered here is a wide FOV fixed camera. This camera will be fixed on the CSR with the capabilities of capturing a 100^o FOV. This is a simple case as no moving parts would be needed; however post processing may be needed. Due to the high FOV required, two options are considered. The first is a rectilinear lens with the capabilities to capture the full 100^o FOV; this would require a 15mm lens[22]. The second is a curvilinear lens, also known as a fish eye lens. With curvilinear, objects approaching the edge of an image become distorted. This poses an issue when trying to get an accurate representation on the size and location of obstacles and when the CSR is docking and deploying from the MR. This can be corrected with image processing, hence adding complexity to the system. A comparison of the two different type of lenses is shown in figure 26, and for this reason a rectilinear lens will be considered[23]. In this design option, there would only be one camera source from which to send images and video, which makes this option reliable, fast, and simple. In order to capture images and film video of other viewpoints outside the immediate FOV, the CSR must move the camera by moving the entire CSR in the desired direction. This would be done by commands from the GS and may become tedious, leading to issues in tight quarters where complete turning maneuvers may not be possible. Pros and cons to this design option are shown in table 4.5.1.

Figure 26. Curvilinear vs Rectilinear Images

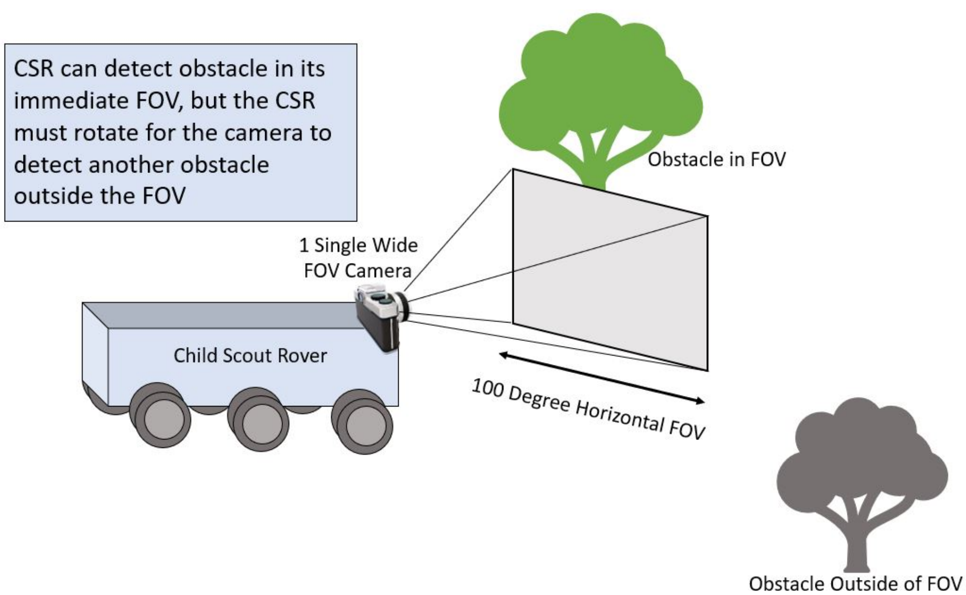

Figure 27. Wide FOV Fixed Camera Configuration

Condition	Pro	Con
The camera is able to capture the full required FOV	**X**	
Single camera source to communicate with the GS and MR	**X**	
Image distortion		**X**
Repositioning of the CSR required for expanded FOV		**X**

Table 30. Pros and Cons for Wide FOV Fixed Camera

4.5.2. Two Fixed Cameras

Here, two fixed cameras are considered to capture the full required FOV of 100^o. The greatest advantage here is that there would not be any distortion and no image processing would be needed for that aspect, however the images would have to be stitched together. Due to multiple cameras, there would now become two data sources that would have to communicate with the MR and GS. Two sources results in an increase in data to send and process and would increase the time duration and difficulty. There would be no need for moving parts which simplifies this design option, however again the CSR would now have to act as the pointing mechanism for the camera. This configuration involves placement of the two cameras side by side on the front of the topside of the CSR. The functional aspect of this configuration is reflected in the diagram below, with pros and cons following the diagram.

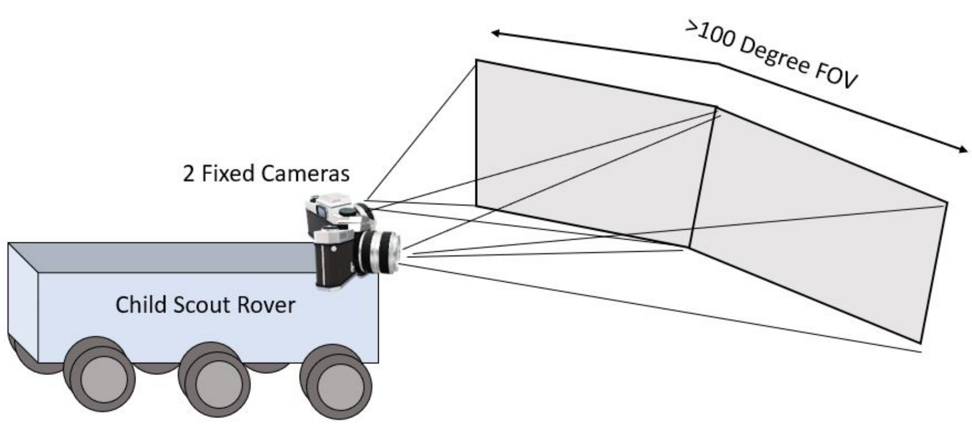

Figure 28. Two Fixed Cameras Configuration

Condition	Pro	Con
The camera is able to capture the full required FOV	**X**	
Two camera sources to communicate with the GS and MR		**X**
No image distortion	**X**	
Repositioning of the CSR required for expanded FOV		**X**
Image stitching required		**X**

Table 31. Pros and Cons: Two Fixed Cameras

4.5.3. Actuated Camera with 360^o FOV

This design concept is a single camera on a servo to rotate the camera 360^o. The actuated camera would have one degree-of-freedom (DOF) in yaw, rotating 360^o and giving full FOV. This would allow the GS to view the surrounding environment without moving the CSR, however additional commands would be required to turn the camera in the direction of interest. Additionally, this design requires mechanical implementation that increase the complexity and moving parts decrease reliability of the system. This mechanical implementation however is very popular and feasible for this case.

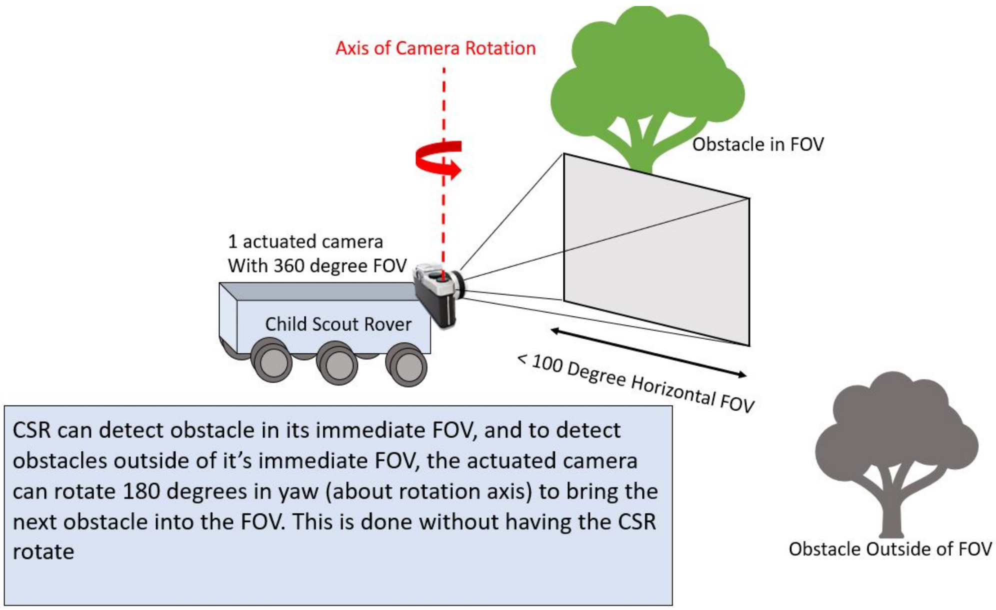

Figure 29. Actuated Camera with 360^o FOV Configuration

Condition	Pro	Con
The camera is able to capture the full required FOV	**X**	
Single imaging source to communicate with the GS and MR	**X**	
Limited image distortion	**X**	
Repositioning of the CSR is not needed for expanded FOV	**X**	
Complexity of mechanical integration for actuation of camera		**X**
Complexity of software integration for pointing control		**X**

Table 32. Pros and Cons: Actuated Camera with 360° FOV

4.5.4. 360^o 3 DOF Camera

The 360^o camera is a single camera with two lenses to capture images and video in all directions with its 3 DOF. This would potentially give an unlimited FOV; however with this distortion will arise. Image processing will again be needed for both distortion and to stitch images together. Depending on the camera chosen, the stitching can either happen instantaneously or is done in a post-processor. This can add difficulty as documentation to integrate and implement this software is sparse. Transmission rates would be significantly slower due to the expansive data collected by this camera, however there is again only one camera source sending data. A table of pros and cons can be seen in the table below.

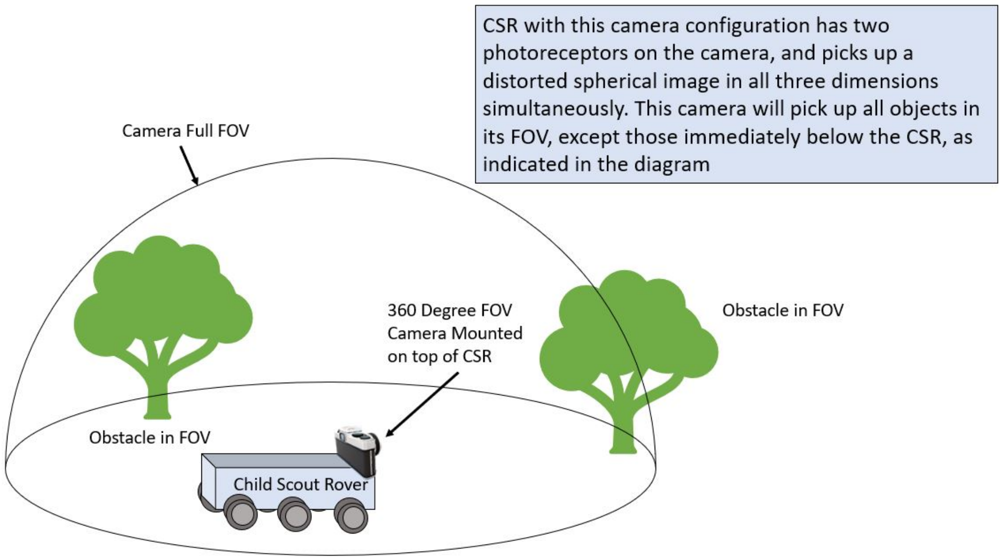

Figure 30. 360^o 3 DOF Configuration

Condition	Pro	Con
The camera is able to capture the full required FOV	**X**	
Single imaging source to communicate with the GS and MR	**X**	
No image distortion	**X**	
Repositioning of the CSR is not needed for expanded FOV	**X**	
Significantly more data to be transmitted to GS and MR, long transmission times		**X**
Image stitching required		**X**

Table 33. Pros and Cons: 360° 3 DOF Camera

5. Trade Study Process and Results

5.1. Translational System

5.1.1. Trade Criteria Selection

There are many factors to consider when choosing a translational system that is capable of meeting the terrain capability requirements. The criteria chosen for the translational system's trade study are Suspension Capability, Cost, Traction, Size, Control Complexity, Manufacturing Complexity, and Mechanical Complexity. The suspension capability was selected as a trade criterion, as the CSR will travel over rough terrain that could cause the CSR to get stuck or tipped over. The systems cost was considered due to the fact that the entire project should not exceed the provided budget of $5000, and the translational system will command a significant percentage of the total budget. The traction of the CSR is important to consider, as it must be able to travel through dirt, underbrush, and slopes without slipping. The size of the system will be a driving design parameter, hence its selection as a trade criterion. The goal should be to minimize the size of the rover, while still allowing it to meet the terrain requirements, namely the ability to cross a 1 foot (0.30 m) discontinuity. The complexity of controlling the motors must also be considered such that the CSR can be successfully maneuvered, and be precise enough to allow for docking with the MR. The manufacturing complexity must also be considered, as the translational system will require significant manufacturing. The system must be designed for manufacturability to minimize the time and financial cost required. The last trade criterion selected is the mechanical complexity of the design. In order to simplify the analysis required and to reduce the risk of mechanical failure, the system should aim to be as mechanically simple as possible. Another important criterion that was taken to consideration is the required power output of the translational system. However, all of the translational system will have approximately the same power output depending on the power input. While each individual motor may draw more or less power depending on the system, the overall power draw will be approximately the same, assuming similar efficiencies. The desired speed, mass, and range of the CSR will drive the power requirements much more than the translational system configuration. Further rationale behind the weight selection of the criteria is explained in Table 5.1.2 below.

5.1.2. *Weighting Assignment*

Criteria	**Weight** (%)	**Rationale**
Suspension Capability	5	Suspension helps improve the performance of the CSR on rough terrains and reduces the risk of tipping. However, as the CSR must be stiff enough to cross a 1 ft (0.30 m) discontinuity and will travel relatively slow, suspension will not be the a significant trade factor.
Cost	10	Ensuring the financial scope of the design lies within our given budget of $5000 is critical, as there are many other subsystems that will require part of this funding. However, while it will not likely command over $600 dollars, it is possible to purchase expensive COTS chassis. While significant, this is not the most significant trade criterion, at 10%.
Traction	10	The wheels of the CSR must have sufficient traction in order to travel through the rough terrain of the operating environment, such as slopes and underbrush. Although traction is important, the operating environment is mainly dry, thus traction is not the most significant design driver.
Size	15	The size of the CSR drives the design of the other subsystems, and because the CSR should ideally be smaller than the MR. However, as the lengths of the systems will be relatively similar, and the possibility of a trailer docking platform, it is not mission critical. This criteria earns a weight of 15%.
Control Complexity	15	The more motors the CSR contains, the more complex the CSR will be to control. By increasing the number of motors, thus control complexity, the risk of failure increases. Therefore, this criterion has 15% of the weight.
Manufacturing Complexity	20	In order to be a successful project, the manufacturing process has to be done thoroughly with limited time, money and resources available. Due to the mission critical aspect of this criteria, it was given a higher weight at 20%.
Mechanical Complexity	25	Mechanical complexity can be defined by several different aspects such as the drive train, suspension, moving wheel linkages, etc. Increasing the mechanical complexity of the system increases the difficulty of modelling and analyzing the system, and introduces increased risk of CSR failure. Due to the critical nature of this criteria, it is weighted the highest at 25%.

Table 34. Translational System Weighting Criteria and Rationale

5.1.3. *Scale Assignment*

Criteria	1	2	3	4	5

Cost	> $900	$700 - $900	$500 - $700	$300 - $500	< $300
Suspension Capability	No suspension and high potential of tipping	N/A	No suspension	N/A	With suspension
Traction	Minimal contact with the ground	N/A	Medium contact with the ground	N/A	Significant contact with the ground
Control Complexity	6 motors to control	N/A	4 motors to control	N/A	2 motors to control
Manufacturing Complexity	Too hard to manufacture. Component manufacturing must be outsourced	All in-house manufactured	Primarily in-house manufactured with some parts COTS	Significant COTS and in-house manufactured	Primarily COTS
Size (length x width x height)	>3ft x >3ft x >3ft	(2.5ft - 3ft) x (1ft - 2ft) x (1ft - 2ft)	(2.5ft - 3ft) x ≤1ft x ≤1ft	(2ft - 2.5ft) x ≤1ft x ≤1ft	≤2ft x ≤1ft x ≤1 ft
Mechanical Complexity	• Sophisticated Power Train	• Simple Power Train • Complex Tread System	• Simple Power Train • Simple Wheels • Moving wheel linkages	• Simple Power Train • Simple Wheels • Fixed wheel linkages • Suspension	• Simple Power Train • Simple Wheels • Fixed wheel linkages • No added suspension

Table 35. Translational System Scale Assignment and Ranges

5.1.4. Trade Matrix

Criteria	**Weight(%)**	**Options**				
		Rocker Bogie	Tank Track	4WD 4 wheels	6WD 6 wheels	4WD 6 wheels
Suspension Capability	5	5	1	1	3	3
Cost	10	4	1	4	4	4
Traction	10	3	5	3	1	1
Size	20	4	5	2	3	3
Control Complexity	15	1	5	3	1	3
Manufacturing Complexity	20	2	3	2	3	3
Mechanical Complexity	25	3	1	5	5	5
Weighted Total	100	2.85	3	3.15	3.1	3.4

Table 36. Translational Trade Matrix

5.2. Object Detection

5.2.1. Trade Criteria Selection

The trade criteria chosen for object detection include cost, range, hardware integration, computational difficulty, environmental vulnerability, and relative position detection. The rationale for these choices are clearly explained in the table within section 5.2.2. The most important criteria, however, are computational difficulty, environmental vulnerability, and relative position detection. Computational difficulty is largely important as complex analysis of data may lead to slower performance of the rover leading to significantly longer mission times as well as interfering with other functions the microcontroller must perform. Additionally, complicated computations greatly increase the complexity of required software and may cause lengthy development times which may not be available in the time allowed. The other two criteria deemed as being highly critical were chosen as the rover must be able to traverse complex areas in which large number of irregular obstacles may be encountered. The chosen object detection sensor must be able to remain accurate within these conditions or else the system will be unable to determine a viable path.

A design factor not taken into account in the trade criteria is power. Although power plays an important role in this project, the chosen object detection systems were found to consume little power in comparison to that of the translational system. Thus, with the criteria that has been chosen for this trade study, it has been determined all critical aspects for each system can be evaluated fairly.

5.2.2. Weighting Criteria with Rationale

Criteria	**Weight** (%)	**Rationale**
Cost	5	Accurate sensor systems can be expensive, so the cost must be taken into account in order to maintain a reasonable project budget.
Range	10	The range of the sensor dictates its maximum capabilities. A sensor with a shorter range will not be able to detect distant obstacles.
Hardware Integration	15	Hardware integration can be difficult if the chosen system has outputs that can only be read by atypical processors. Additionally, if the device requires uniquely designed mechanical and electrical interfaces, this integration process can become time consuming.
Environmental Vulnerability	20	The rover will be in complicated terrain with variable conditions such as changing lighting and complicated surface materials and geometries, and potentially damaging collisions. If the sensors data is made erroneous due to environmental obstacles then the rover will be unable to accurately navigate and determine a viable path.
Computational Difficulty	25	Some methods may be extremely computationally intense and thus may interrupt other programs within the software controlling the rover. Additionally, complex on-board computations may take a long amount of time to perform and thus may impact efficiency of the rover. Furthermore, object detection software is very complex and difficult to write, so it will be optimal to have a variety of available softwares for the chosen system. The desired use of these softwares will be to measure distances to obstacles and distances between objects.

Relative Position Detection	25	A large part of the scout rovers mission is to present a path that is viable for the mother rover to travel. Due to the size of the Mother Rover a key aspect of the path will be the distance between obstacles along it. If the detection systems measurements cannot provide this distance or enough information to allow for an accurate calculation this distance then a viable path cannot effectively be determined.

Table 37. Object Detection Weighting Criteria and Rationale

5.2.3. Scale Assignment

Criteria	1	2	3	4	5
Cost	> $550	$350 - $550	$150 - $350	$50 - $150	< $50
Range	max range 0 m - 5 m	max range 5 m - 15 m	max range 15 m - 25 m	max range 25 m - 35 m	max range > 35 m
Hardware Integration	Too difficult and time consuming to implement over the span of the project	Low possibility of fully finishing the system integration over the span of the project	Integration is challenging, but not too time consuming for project timeline	Integration difficulty is average and efficient for project timeline	Integration is easy and efficient for project timeline
Environmental Vulnerability	Extremely vulnerable to light, material types, surface geometry, or collisions	Highly vulnerable to light, material types, surface geometry, or collisions	Moderately vulnerable to light, material types, surface geometry, or collisions	Low vulnerability to light, material types, surface geometry, or collisions	Not vulnerable to environmental factors
Computational Difficulty	Extremely slow on-board computations. Little to no available software that is difficult to access or find and is poorly documented	Slow on-board computation time. Some available software but difficult to access or find	Moderate on-board computation time. An average amount of available software with average documentation	Moderate on-board computation time. Large amounts of software that is easy to access and has average documentation	Quick on-board computations. Many software libraries available that are easy to access and are well documented, or has product specific software tailored for the device.
Relative Position Detection	Not able to detect the relative position between obstacles	N/A	Ability to detect the relative position between obstacles with additional hardware integration and computational efforts	N/A	Able to detect the relative position between obstacles

Table 38. Object Detection Scale Assignment and Ranges

5.2.4. Trade Matrix

Criteria	Weight(%)	Options			
		Lidar	Ultrasonic	Collision Sensors	Image Processing
Cost	5	3	3	5	4
Range	10	5	5	1	5
Hardware Integration	15	3	3	3	4
Environmental Vulnerability	20	4	3	4	3
Computational Difficulty	25	4	3	4	1
Relative Position Detection	25	5	5	1	3
Weighted Total	100	4.15	3.7	2.85	2.9

Table 39. Object Detection Trade Matrix

5.3. Communication System

5.3.1. Trade Criteria Selection

The trade criteria chosen for the communication system are Signal Attenuation, Bandwidth(Speed), Range, Integration complexity, Size, and Cost. The rationale for choosing these criteria are shown in the Table under section 5.3.2. The most important criteria is signal attenuation, bandwidth, and range. Knowing a communication system's signal attenuation is vital as this mission's environment has terrain containing numerous obstructions. Signal attenuation is the reduction of signal strength during transmission. The signal needs to travel at least 250m (820 ft) to meet the requirements while dealing with signal loss from obstructions and from the path of transmission. There is also small levels of interference that can be caused by the amount of devices in the area. Hence the signal attenuation needs to be rated properly to consider transmitting the signal efficiently. During the mission, a lot of data will take place between the GS, MR, and the CSR. This data includes images, videos, GPS data, and etc. Therefore, it is important to analyze a system's speed capability to transmit all data successfully. Examining a communication system's range is also of great importance to ensure successful communication between the GS, MR, and the CSR. The other criteria is integration complexity, size, and cost. Since this project has to be completed within a year, it is crucial to examine the complexity of each system to ensure that the system can be integrated on time. The factors considered were the amount of documentation available, hardware complexity as well as software complexity. In order to communicate at a large distance, antennas will be required for extended range. The size of the antennas for each system had to be assessed to verify that the CSR can dock and deploy to the MR without interference. The last criteria was cost. Since this project has to be completed on a limited budget, it is critical to examine the cost of each system.

5.3.2. Weighting Criteria with Rationale

Criteria	Weight (%)	Rationale
Cost	5	Communication systems are more of a time requirement and a software challenge to establish. However, communication systems can be expensive therefore cost must be taken into account to maintain a reasonable project budget.
Size	10	Size of the communication system needs to fall under the design requirements (Size of the CSR). Since communication options include external antennas, this may present a problem for docking.

Integration Complexity	15	Integration includes hardware/software complexity and the documentation available for the communication system.These factors will directly affect the time (man hour) needed to make a working communication system. Since this project has a time-limit of one year, it is critical to analyze the integration complexity of the system.
Speed/Bandwidth	20	During the mission numerous types of data (images, video, gps, etc) will be transmitted and received between GS,MR, and the CSR. Thus, it is essential that the communication system in place has enough bandwidth for the communication to function smoothly.
Range	20	The communication range needs to be at least 250 meters (820 ft) for the functional requirement to be met. For the worst case scenario, we need to aim for a greater range of communication for a factor of a safety buffer.
Signal Attenuation	30	For the mission to be successful, the communication system needs to work at all time during the entirety of the mission without significant reduction of signal strength during transmission or signal attenuation. For a communication system to be reliable, it must transmit and receive the required data consistently with a minimal chance of failure and latency. Communication must also be available through hills, trees, boulders, and brushes. Thus, a reliable source of communication is essential for the success of the mission.

Table 40. Communcation Weighting Criteria and Rationale

5.3.3. Scale Assignment

Criteria	1	2	3	4	5
Cost	>$500	$250 - $500	$100 - $250	< $100	Free
Size (Height)	> 12” (0.30 m)	10-12” (0.25-0.30 m)	7-10” (0.18-0.25 m)	4-7” (0.1-0.18 m)	< 4” (0.1 m)
Integration Complexity (Man hour required)	> 280 hours	210-280 hours	140-210 hours	70-140 hours	< 70 hours
Speed	< 250 Kbps	250 Kpbs-1 Mbps	1 Mbps-10 Mbps	10-50 Mbps	> 50 Mbps
Range	< 250 m (820 ft)	250-275 m (820-902 ft)	275-300 m (902-984 ft)	300-325 m (984-1066 ft)	> 325 m (1066 ft)
Signal Attenuation	System has high loss from obstruction and path of transmission	System has some loss from obstruction and path of transmission	System has some loss from obstruction but minimal loss from path of transmission	System has minimal loss from obstruction and minimal loss from path of transmission	System’s only loss is due to free-space path loss

Table 41. Communication Scale Assignment and Ranges

5.3.4. *Trade Matrix*

Criteria	Weight(%)	Options		
		Wi-Fi	Zigbee	GSM
Cost	5	3	4	1
Size	10	4	5	4
Complexity	15	5	4	4
Speed/Bandwidth	20	5	2	3
Range	20	3	5	5
Signal Attenuation	30	4	2	4
Weighted Total	100	4.1	3.3	3.85

Table 42. Communication Trade Matrix

5.4. Docking/Deployment Mechanism

5.4.1. *Trade Criteria Selection*

The trade criteria selected are the Allowable Size of the CSR, the Docked Maneuverability, Manufacturing Complexity, Modification of MR, CSR Integration, Mechanical Complexity, Power, and Cost. Depending on the docking/deployment mechanism design, the CSR size may be severely constrained due to the limited space on-board the MR. The size of the CSR drives many further design decisions, hence the selection of this criterion. The maneuverability of the MR may be significantly impaired by the docking/deployment mechanism due to large protrusions, significant weight imbalances due to CSR stowing position, and dragged trailers. This criterion was selected such that design minimizes the impact on the MR's maneuverability. The manufacturability of the mechanism was selected, as the design must allow for the mechanism to be manufactured given the cost, time, skill, and resource constraints of the project. The modification of the MR was selected as a trade criterion due to the fact that the MR chassis may need to be significantly modified to integrate with certain docking/deployment mechanism designs. As the structural design of the MR was part of a heritage project, modifying it would require significant structural analysis and increase risk of structural failure. The integration of the CSR must also be considered. Different design options require differing levels of control precision for the CSR to dock. Additionally, the CSR may be required to implement a neutral gear depending on the design. The mechanical complexity of the docking/deployment mechanism was chosen as another trade criteria. The more moving and actuated parts, the more difficult the analysis and the greater the risk of mechanical failure. The required power is considered for the trades, as different systems will require more power for actuation. Due to the limited power budget of the MR, the design should aim to minimize the power required. The final trade criteria, cost, is considered due to the limited financial budget provided.

5.4.2. *Weighting Criteria with Rationale*

Criteria	**Weight** (%)	**Rationale**
Cost	5	While the cost of the system is significant, most design options will cost a similar amount, and the highest priority is to design a working system rather than saving money. This is the least important criteria at 5%.
CSR Integration	10	The complexity of the integration required with the CSR may make the design requirements more stringent; however, it does not significantly drive the design or risk total mission failure. Therefore, this criteria is given a 10% weight.
Mechanical Complexity	10	The design should aim to have as few moving parts and complex mechanical components to reduce to risk of failure and simplify dynamic and kinematic analysis. However, due to the relatively few moving parts and actuators, and thus overall mechanical complexity for this system, it is given a weight of 10%.
Power	10	Although the system should aim to minimize its required power, it should not require significant power such that power is a primary driving design factor. While a large power load may increase the risk and complexity of the system, it is not as significant of a design driver. This criteria is weighted at 10%.
Docked Maneuverability	15	If the docked maneuverability is impaired, it complicates the MR control and CSR path finding requirements. Additionally, worsening the MR's maneuverability increases risk of mission failure, as the MR could get stuck or possibly collide with the CSR depending on the design. To minimize the risk of mission failure, the docked maneuverability was ranked as one of the next most important criteria at 15%.
Manufacturing Complexity	15	Due to the limited monetary and time budget available, as well as the limited manufacturing experience of the team's personnel, the design should be as simple to manufacture as possible. Manufacturing cost and time overflow can easily result in mission failure; therefore, the manufacturing complexity is also ranked as the second most important criteria at 15%.
Modification of MR	15	As significant modifications made to heritage equipment both increases the risk of MR structural and electrical failure, and lies outside the scope of the project, minimizing the modifications made to the MR is also ranked as the second most important criteria at 15%.
Allowed Size of CSR	20	Due to the fact that the allowable size of the CSR significantly drives its overall design, this criteria was weighted the highest at 20%. Additionally, as the CSR is required to cross a 1 ft (0.30 m) discontinuity, the CSR must be at least 2 ft (0.61 m) long. By allowing the CSR to be larger, the design space for the translational system opens up.

Table 43. Docking/Deployment Mechanism Weighting Criteria and Rationale

5.4.3. *Scale Assignment*

Criteria	1	2	3	4	5
Cost	> $800	$800-600	$600-400	$400-200	< $200
CSR Integration	CSR must have a neutral gear.	Docking control accurate to ± 0.5" (1.27 cm). CSR does not need a neutral gear.	Docking control accurate to ± 1" (2.54 cm). CSR does not need a neutral gear.	Docking control accurate to ± 2" (5.08 cm). CSR does not need a neutral gear.	Docking control accurate to ± 4" (10.2 cm). CSR does not need a neutral gear.

Mechanical Complexity	Requires 3 actuators and 2 or more other moving parts.	Requires 2 actuators and 2 or more other moving parts.	Requires 1 actuators and 2 or more other moving parts.	Requires 1 actuator and 1 other moving part.	Requires 1 actuator and no other moving parts.
Power	Actuators must supply sufficient power to support over 40 kg.	Actuators must supply sufficient power to support 40-20 kg.	Actuators must supply enough power to support 20-10 kg.	Actuators must supply enough power to support 10-5 kg.	Actuators must supply enough power to support 5-0 kg.
Docked Maneuverability	MR and CSR in the docked configuration cannot make in-place 360° turns.	MR is capable of in-place 360° turning capability. Offset CoM in docked configuration.	Docking mechanism adds protrusion longer than CSR length. MR is capable of in-place 360° turning capability. Extra power required to drive CSR. Semi-offset CoM in docked configuration.	Docking mechanism adds protrusion smaller than CSR length. MR is capable of in-place 360° turning capability. Mechanism does not increase required driving power. Balanced CoM in docked configuration.	Docking Mechanism does not add a protrusion to the MR. MR is capable of in-place 360° turning capability. Mechanism does not increase required driving power. Balanced CoM in docked configuration.
Manufacturing Complexity	Too complex to manufacture in-house, outsourced machining required.	Minimal COTS parts, almost all components manufactured in house.	Few COTS parts, primarily manufactured in house.	Approximately half of components are COTS, but significant in-house manufacturing is required.	Primarily COTS parts with minimal in-house manufacturing.
Modification of MR	Significant machining and re-configuring of current MR structure required. Electronics configuration may be changed.	Significant machining of current MR housing or chassis required. Minor changes to MR structure required. Electronics configuration may be changed.	Significant machining of MR housing required. Electronics configuration may be changed.	Light machining of MR housing. Electronics configuration may be changed.	Trivial modifications to the MR are required. No electronics configuration changes required.
Allowed Size of CSR	CSR is limited to a size of 24"x10"x6" (0.61x0.25x0.15 m) or smaller	CSR is limited to a size of 28"x12"x9" (0.71x0.30x0.23 m) or smaller	CSR is limited to a size of 32"x14"x12" (0.81x0.36x0.30 m) or smaller	CSR is limited to a size of 36"x16"x14" (0.91x0.41x0.36 m) or smaller	Deployment mechanism does not limit the size of the CSR

Table 44. Docking/Deployment Scale Assignment and Ranges

5.4.4. Trade Matrix

Criteria	Weight(%)	Options					
		Hitch	Trailer Platform	On-board Ramp	On-board Ramp, Extended Platform	On-board Lift	On-board Lift, Extended Platform
Cost	5	4	3	4	4	4	4
CSR Integration	10	1	5	4	5	4	5
Mechanical Complexity	10	4	3	4	4	2	2
Power	10	5	4	2	2	2	2
Docked Maneuverability	15	1	3	4	2	5	2
Manufacturing Complexity	15	4	3	3	3	2	2
Modification of MR	15	4	3	3	2	3	2
Allowed Size of CSR	20	5	5	1	4	1	4
Weighted Total	100	3.55	3.7	2.9	3.15	2.7	2.8

Table 45. Docking/Deployment Mechanism Trade Matrix

5.5. Imaging System Configuration

5.5.1. Trade Criteria Selection

Many factors contribute to choosing an imaging system to meet all requirements. FOV Performance was chosen as a trade criteria, in order to examine the advantage and disadvantages for a camera configurations with different FOVs. FOV directly impacts the performance of the CSR, and how efficiently a path can be found for the MR. The second trade criteria chosen was Effect of Actuation. Effect of Actuation was considered to look at which design options required movement of the CSR to get additional viewpoints outside of the initial FOV captured, and which configurations could do this independently. It is easier for the camera system to do this on its own than to have the CSR re-position the camera to capture a new FOV, especially with obstacles present. Speed was defined as the percentage of the overall bandwidth of the system the cameras would use, as some cameras had a significant amount of data to send relative to other configurations. These roughly quantitative measures were determined by assuming a 10 Mbps bandwidth. This bandwidth is a reasonable estimate for a Wi-Fi communication system that was chosen in section 5.3.4. This category depends on frame rates associated with the specific camera used on CSR. However,it is intuitive that multiple cameras or a 360^o camera consume more bandwidth than other setups. Hardware/ Mechanical integration was also considered as the system needs to integrate with the CSR, and the amount of actuation and existing documentation for the devices were considered. Image processing was selected as another trade criteria; this category compares and contrasts the quality of the outputs of different imaging configurations, specifically compromising on distortion of the image, which will require extra image processing, as well as stitching images together. Cost was selected as a trade criteria in order to ensure the team was taking into account the cost of the imaging system, and weighing this cost against the advantages that each configuration provided. It can be noted that image processing for object detection is not considered in this trade, as an entire trade is devoted to this category. Image processing is considered for removing distortion from images and stitching images together, along with the image processing necessary to dock/deploy from the MR. Power was also not considered here because the power required for any camera configuration is significantly lower than the power required for other components; hence, the imaging system configuration will have a minimal effect on the power budget relative to the motors/communications.

5.5.2. *Weighting Criteria with Rationale*

Criteria	Weight (%)	Rationale
Cost	5	Cost includes any cost for the cameras, wires, rotation devices, and software integration. The higher the cost, the lower the score for the category due to the projects maximum budget of $5,000. Cost was rated as the lowest weighted category because the maximum amount the team will spend on a camera system is approximately $1,000, which is only 20% of the overall budget.
Image Processing	15	This category is essential for docking and deploying from the MR. Image processing required by image distortion (from wide FOV) and stitching of images is required for accurate environment, but will hinder performance by taking time. This category is weighted quite high due to the missions dependency on the data received concerning the CSR's surroundings.
Hardware/ Mechanical Integration	15	Hardware Integration can be difficult if the device does not have detailed documentation to be able to integrate the camera with the CSR. This criteria is important if also the device requires uniquely designed mechanical parts as this integration process can become time consuming.
Effect of Actuation	20	Effect of Actuation is defined as the effect of the camera's actuating abilities on the CSR's performance. The CSR's performance will increase with the ability of the camera to actuate independently of the CSR, gaining viewpoints outside of the immediate FOV. This is essential, as it would be much easier to rotate the camera to scan the environment than to have the CSR maneuver, resulting in faster determination of objects and waypoints. This is especially the case when obstacles are close in proximity.
Speed	20	Speed is a percentage approximation of the total communications bandwidth required to send images/video to the GS and MR. This category is weighted heavily because a key functional requirement is to send data in the form of images and video to the GS and MR. The design options considered vary on the amount of data that needs to be sent, and therefore the bandwidth that would be required to do so.
FOV Performance	25	FOV Performance is the capability of the camera system to perform the imaging objectives of the mission. The image/video FOV is the biggest driver of performance, because the performance of the CSR will increase with the camera systems capacity to pick up as many objects/obstacles as possible in a given FOV. FOV Performance was rated as the highest weighted category because the imaging system is crucial for mission success of sending images to the GS and MR.

Table 46. Imaging System Weighting Criteria and Rationale

5.5.3. *Scale Assignment*

Criteria	1	2	3	4	5
Cost	>$600	$400-$600	$200-$400	$100-$200	<$100
Image Processing	Image processing required due to image distortion and stitching of images	Image processing required due to image distortion	Image processing required to stitch images together, no distortion in images	No image processing is needed, image distortion present but is not extreme	No image processing due to distortion is needed

Hardware/ Mechanical Integration	Poor documentation, mechanical integration required including moving parts in > 1 DOF	Poor documentation, mechanical integration required including moving parts in 1 DOF	Poor documentation, mechanical integration relatively simple	Good documentation, mechanical integration required including moving parts in 1 DOF	Mechanical integration for moving parts not required
Effect of Actuation	Motion of CSR needed to gain additional FOV's	N/A	N/A	N/A	No motion of CSR needed to gain additional FOV's
Speed	>50% Bandwidth	40%-50% Bandwidth	30%-40% Bandwidth	20%-30% Bandwidth	<20% Bandwidth
FOV Performance	100^o FOV is never attained	100^o FOV is attained by camera actuation	100^o FOV is attained with no actuation	360^o FOV is attained with camera actuation	360^o FOV is attained at all times

Table 47. Imaging System Scale Assignment and Ranges

5.5.4. Trade Matrix

Criteria	Weight(%)	Options			
		Single Fixed Wide FOV Camera	Two Fixed Wide FOV Cameras	Single Actuated Camera	360°3 DOF Camera
Cost	5	5	4	4	1
Image Processing	15	2	3	5	1
Hardware/ Mechanical Integration	15	5	5	4	3
Effect of Actuation	20	1	1	5	5
Speed	20	5	4	4	2
FOV Performance	25	3	3	4	5
Weighted Total	100	3.25	3.15	4.35	3.30

Table 48. Imaging System Trade Matrix

6. Selection of Baseline Design

6.1. Translational System Result

The results of the trade study concludes that a Four Wheel Drive system with Six Wheels is the optimal design at 3.4/5. The next closest designs are the Four Wheel Drive with Four Wheels and Six Wheel Drive with Six Wheels systems, ranked at 3.15 and 3.1 respectively. The FWD with Six wheel system has the benefits of both the FWD with Four Wheel system and the 6WD with Four Wheel system; it is able to retain a relatively low profile and use small wheels to cross the 1 ft (0.30 m) discontinuity, while remaining less complex to control, model, and analyze compared to the 6WD system. Due to these benefits, the Four Wheel Drive with 6 Wheel system is the optimal translational system design option.

6.2. Object Detection Result

After performing the trade study in the previous section, it was found that a lidar sensor will be the most optimal object detection system. Lidar is capable of providing detailed maps of the surrounding terrain and accurate distance measurements to obstacles and between obstacles. This relative position detection aspect is extremely important as it allows the CSR to determine a viable path for the MR and is one of the main reasons why the collision sensors and image processing options were found to be sub-optimal. The lidar sensor will be able to accurately detect the relative position of obstacles, will typically have a maximum range greater than 35 meters (115 ft) and will be reasonably priced between \$150 - \$350. Furthermore, it was found that there is a large amount of available software which is both easy to access and integrate with the lidar system. Although the ultrasonic sensor was ranked rather similarly to the lidar sensor, it was found to be vulnerable to different material types and surface geometries which could greatly effect the accuracy of distance measurements. Hence, this is another reason why the lidar system was determined to be the most optimal sensor.

6.3. Communication System Result

From the trade study conducted under section 5.3.4, it was concluded that the Wi-Fi communication system was the best design option. Wi-Fi communication meets all the functional requirements of range shown in Table 1, the design requirements shown in Table 2, and can be easily integrated. It had the highest bandwidth when compared to all the design options as well as a low signal attenuation which enables the GS, MR, and the CSR to communicate successfully at the required range. The main concern with Wi-Fi is the additional hardware such as antennas and power amplifiers needed to increase the range of transmission. However, this is a reasonable solution to gain range as the extension can be integrated without much difficulty and consuming little additional power.

The main concern with the Zigbee communication system was its signal attenuation and low bandwidth. Since these were the two most important criteria for out trade study, Zigbee was the lowest rated design option. Although the GSM communication system was rated relatively close to the Wi-Fi communication system in the trade study, it was the most unreliable option. The communication through GSM completely depends on the network connection from the provider and is more costly to obtain. Since there is no way to accurately predict network connection, it would be a great risk to select the GSM communication system.

6.4. Docking/Deployment Mechanism Result

The trade study shows the trailer platform ranked the highest amongst the six trade options at 3.7/5. The next highest ranking option was the hitch design at 3.55/5. Both designs were external trailer designs, which provide a large design space for the CSR size compared to the other trade options, while minimizing any required modifications made to the MR. Additionally, the trailer designs balance the load of the CSR and docking mechanism across the MR's plane of symmetry, thus both wheels will be loaded similarly, unlike the on-board docking methods. The trailer platform benefits over the hitch design due to its simpler CSR integration and improved MR maneuverability. The trailer platform will not require precise CSR control to properly align the CSR and the docking mechanism, as it only needs to drive onto a platform that may be larger than the CSR. Additionally, the trailer platform will not require a neutral gear to be implemented into the CSR. Finally, the trailer platform benefits over the hitch design, as it allows for the MR to maintain its in-place turning capability, and removes the risk of the MR colliding with the CSR in the docked configuration. Due to its simpler integration and lower risks, the trailer platform is the best option for the baseline design.

6.5. Imaging System Configuration Result

As a result from analyzing the trade study outcomes, the actuated single camera was the design option chosen. This option was found to be the best fit in regards to the overall mission. The design is able to meet the required FOV, capture viewpoints outside of the immediate FOV much more readily than maneuvering the CSR, does not have distortion, and is relatively easy to integrate with the CSR. This camera will need an actuation system, however this is a reasonable task for the team to execute. The single actuated camera is ranked highly in all categories and exceeds all other options by a considerable margin. The other options each exceeded in individual categories such as meeting the FOV requirement and the simplicity of the design, however the other three cameras did not score high enough in all of the trade study's categories. All three other designs lacked important critera that could not be dismissed. The single actuated camera is the best design for success in the fundamental requirements of sending data in the form of images and video to the GS and MR, and all other requirements stemming from this primary requirement.

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