University of Colorado
Department of Aerospace Engineering Sciences
ASEN 4018

Conceptual Design Document (CDD)

RAppelling Cave Exploration Rover (RACER)

Approvals

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1.0 INFORMATION

1.1 Project Customer

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2.0 PROJECT DESCRIPTION

2.1 Project Need and Objectives

Rovers and Unmanned Ground Systems (UGS) have been developed to replace high-risk human work in areas such as planetary exploration, military reconnaissance, and disaster relief. Steep and rocky terrain navigation is one of the biggest challenges for current UGS. For example, current rover systems lack the capability to descend vertical or near-vertical terrain. In light of this inability, this project aims to develop and demonstrate a rappelling rover system. This project will design, build, and test a child rover (CR) that can rappel a 90º vertical surface to a maximum depth of 5m.

RACER's mission is as follows: the CR will be transported to the terrain to be explored by a mother rover (MR) from which the CR can successfully undock and dock. The CR will be in communication with a ground station (GS) using the MR as a relay. Throughout this mission, the CR will receive movement and imaging commands sent by the GS. After rappelling down the vertical surface, the CR will explore 5m radially from the touchdown point over a horizontal surface with small rocks no larger than 3cm in diameter. While traversing this terrain, the CR will supply adequate lighting to take images with a minimum 10cm resolution at 5m from an object. The image will be transmitted to the GS. The CR will know its position within +/-10cm, horizontally and vertically, relative to the MR and transmit its position to the GS. After taking and transmitting at least 5 images, the CR will ascend the 5m 90º vertical surface and re-dock with the MR. In case communications with the MR/GS is not available, the CR will also be able to store the images locally. All components will be designed for an Earth-like environment between 0 and 40ºC. The entire mission duration will be less than 8 hours as this is a typical shift length for a ground station operator.

2.2 Definitions

Adequate Scene Lighting – Lighting bright enough so that a point of interest is clearly resolved from the image background.

Cave/pipe – A horizontal floor with a minimum of 5m radius area with small rocks no larger than 3cm in diameter on top of it. The MR will be fixed at the top of an up to 5m vertical surface above this floor.

Child Rover – A smaller rover designed to perform a specific task. The CR is constrained to interface with a larger MR that houses the CR for transportation. The CR can receive commands relayed from a GS through the MR. For this project, the TREADS rover will be used as the mother.

Explore – Descend the maximum 5 meter depth of the cave/pipe and then traverse a horizontal distance of 5 meters radially from the touchdown location. The CR must take pictures of a point of interest with specific resolution and Field of View (FOV) requirements described later in the document, and then transmit the image to the MR/GS. The CR must acquire at least 5 images within the 8 hour maximum mission duration. The point of interest must be illuminated with adequate scene lighting as mentioned above.

Point of Interest (POI) – An object of 10 cm diameter placed 5 meters away from the CR imaging system.

2.3 Objectives

In order to organize the functional objectives for RACER, they are separated into three levels based on their expected difficulty. The functional objectives for minimal success of RACER's mission are based on the customer's requirement for the CR to use the TREADS MR as well as being able to rappel into a cave/pipe and take/store/transmit images. The level one success criteria are as follows:

- The CR shall be able to undock from the TREADS CR bay.
- The CR shall be able to rappel a 90º incline to a maximum depth of 5m.
- The CR shall be able to transition from traversing a vertical surface to a horizontal surface.
- The CR shall be able to take and transmit/store at least 5 images.

Level two success includes everything from level one in addition to going further in depth to the functional objectives of the CR. The level two success criteria are as follows:

- The CR shall handle communication crop-outs with the MR/GS by halting its mission and waiting for communications to be re-established.
- The CR shall be able to traverse 5m radially from rappel touchdown point, controlled via movement commands from the GS.

- The CR shall be able to resolve a 10cm diameter POI from a 5m distance using its imaging system.
- The CR shall provide adequate scene lighting
- The imaging system on the CR shall have azimuth/elevation angular coverage of 180º and 90º, respectively.

Level three success criteria are functional objectives that, if achieved along with levels one and two, would mean total mission success for RACER. These objectives include the positioning accuracy tolerances as well as the ability to return to the MR after exploring the cave/pipe. These functional objectives are expected to be difficult to achieve, but would severely limit the real-world applications of RACER if they are not met. The level three success criteria are as follows:

- The CR shall know its depth within the cave/pipe accurate to +/- 10 cm.
- The CR shall know its horizontal distance travelled accurate to +/- 10 cm.
- The CR shall be able to transition from traversing a horizontal surface to a vertical surface.
- The CR shall be able to ascend a 90º incline from a maximum depth of 5m.
- The CR shall be able to re-dock with the TREADS MR.

2.4 Concept of Operations

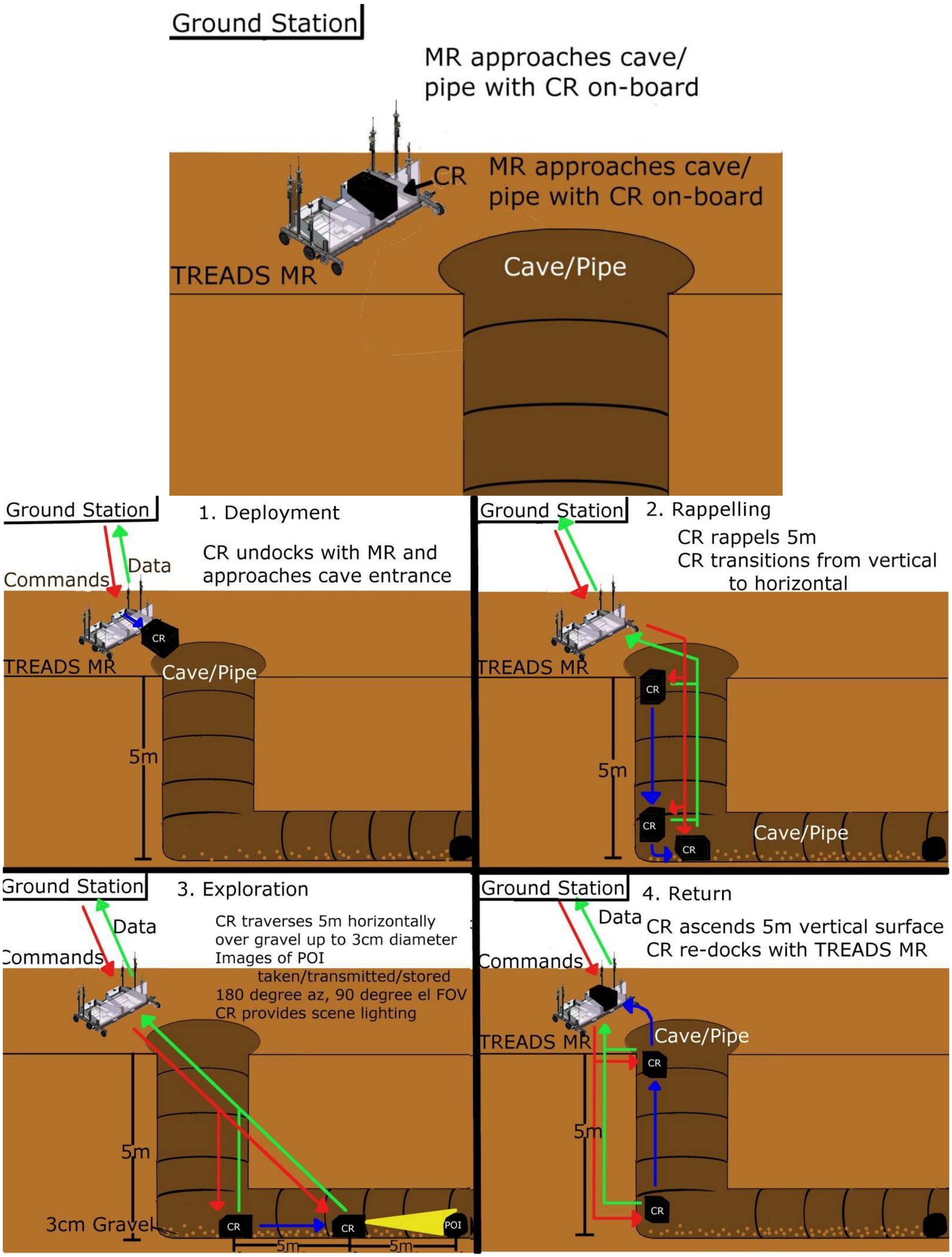

Figure 2.4.1: Concept of Operations for RACER

The Concept of Operations (CONOPS) shown in **Figure 2.4.1** describes the main functions and their respective system tests for the CR and its interfaces with the MR/GS. In the Deployment Stage, the operator will command the CR to undock with the stationary MR from the GS. During the Rappelling Stage, the CR will be commanded to descend a vertical face to a maximum of 5m. At the bottom of the face, the CR will transition from vertical to horizontal motion. Meanwhile, the CR will transmit images and positional data back to the GS via the MR. In the Exploration Stage, the CR will traverse up to 5 meters radially from the touchdown point over a horizontal surface with sparse 3 cm diameter gravel to a point of interest, as commanded by the GS. There, the GS will command the CR to record images with FOV, resolution, and lighting requirements that were previously defined. Additionally, the CR will transmit its position relative to the MR back to the GS to within +/- 10 cm accuracy. During the Return Stage, the operator will command the CR to ascend the vertical face and re-dock with the MR.

2.5 Functional Block Diagram

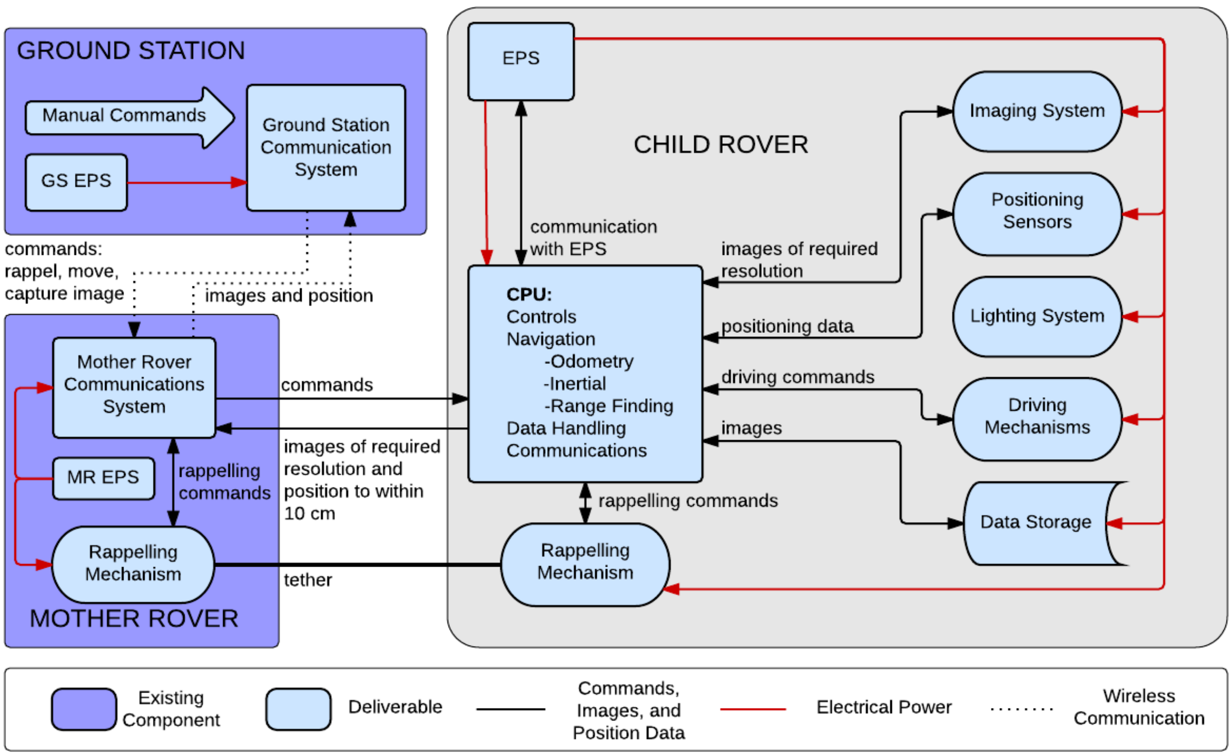

Figure 2.5.1: Functional Block Diagram for RACER

In the Functional Block Diagram (FBD) in **Figure 2.5.1**, operations begin when commands are manually input to the GS. These commands will include functions such as rappelling, moving, capturing images, etc. Commands are wirelessly transmitted from the GS to the MR, which then relays the commands to the CR. It has not yet been decided if the transmission will occur wirelessly between the MR and CR. If so, a transmitter/receiver component will need to be added to the CR. The commands are sent to the CR's CPU, which then sends the commands to their respective peripherals (rappelling mechanism, imaging system, etc.). The CPU will also receive information from sensors and the imaging system for the purpose of positioning and image storage/transmission, respectively. Finally, the CPU will transfer the CR's position and images to the MR to be relayed to the GS. There are electrical power systems (EPS) shown on both the MR and CR. This design decision is justified in Section 4.5.

3.0 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 and Inspection are shown below:

- Demonstration - The requirement will be verified by physical demonstration (e.g. the CR rappelling 5 m vertically)
- Inspection - The requirement will be proven true by a measurement of some sort: length, mass, power, etc.

The testing method for verifying and validating requirements includes a number of different tests that cover the requirements that involve testing. The tests can be seen below in **Table 3.1.1**. Many of the tests below also test more than one requirement. Also throughout each test, the power used will be measured to help determine how much power is needed for a complete mission.

Table 3.1.1: Verification & Validation Tests

Test	Test Description
Docking	The CR will undock from the MR and drive over a 90º edge as if beginning the rappelling stage of its mission. The CR will then be raised back up over the same edge and have to re-dock with the MR.
Communication	The CR will be sent commands from the GS (relayed through the MR) to perform desired tasks. The CR will transmit requested data (position and images) to the GS (relayed through the MR) or perform the movement task. The CR will then send task completion acknowledgements to the GS and receive transmission received acknowledgements from the GS, both relayed through the MR.
Communication Drop-outs	The CR will be commanded to perform several movement tasks. Then communication between the CR and GS will be manually dropped by turning off the MR. The CR will then reverse previous driving steps autonomously until communication is restored by turning the MR on.
Rappelling	The CR will be lowered by the rappelling system down 5m and will transition from a vertical to horizontal travel. The CR will be measuring its depth into the cave/pipe throughout this test.
Ascension	The CR transitions from a horizontal to a vertical surface and ascends the 5 m vertical surface using the rappelling mechanism. The CR will be measuring its depth into the cave/pipe throughout this test.
Exploration	The CR will traverse a horizontal surface inside a semicircle with a 5 m radius using pictures sent to the GS for navigation. The surface will consist of scattered rocks no larger than 3 cm in diameter. The CR will be measuring its distance travelled throughout this test.
Low-light Imaging	The imaging system will record images of a POI in a completely dark room. The POI will be re-positioned between images in order to verify that the resolution requirement is met for the entire FOV. The imaging system's light source will provide adequate scene lighting. The images will then be inspected to verify that the POI is resolved from the image background.

3.2 Requirements Flow Down

The functional requirements (FRs) for this project were derived from the project statement and are higher level compared to the design requirements (DRs) further down. These functional requirements are shown in **Table 3.2.1** below. For these requirements to be considered successful, all of the child requirements that are associated with the functional requirements must be met.

Table 3.2.1: Functional Requirements

Requirement Number	Requirement Description	Parent Requirement	Verification & Validation
FR.1	The CR shall use TREADS as the MR	Heritage requirement	Met if all DR.1 requirements are met
FR.2	The CR shall communicate with the GS via the MR	Derived from project heritage	Met if all DR.2 requirements are met
FR.3	The CR shall explore a cave/pipe	Derived from problem statement	Met if all DR. 3 requirements are met
FR.4	The CR shall contain a positioning system	Derived from problem statement	Met if all DR.4 requirements are met
FR.5	The CR shall capture photographic images	Derived from problem statement	Met if all DR.5 requirements are met
FR.6	The CR and MR systems shall contain their own electrical power sources	Heritage requirement	Met if all DR. 6 requirements are met

The first functional requirement goes into the physical requirements necessary for the CR to interact with the MR. The design requirements that go along with FR.1 are shown below in **Table 3.2.2**. The design requirements **DR.1.1.1** and **DR.1.1.2** were derived from last year's DARE project which also used TREADS as the MR.

Table 3.2.2: FR.1 Design Requirements Flow Down

FR.1 : The CR shall use TREADS as the MR			
Requirement Number	**Requirement Description**	**Parent Requirement**	**Verification & Validation**
DR.1.1	The CR shall fit within the TREADS CR bay	FR.1	Demonstration
DR.1.1.1	The CR shall have an area no greater than 0.483 m x 0.483 m	DR.1.1	Inspection
DR.1.1.2	The CR shall have a mass of no more than 9.8 kg [7]	DR.1.1	Inspection
DR.1.2	The CR shall un-dock and dock with the TREADS MR	FR.1	Demonstration
DR.1.2.1	The CR shall re-dock with the MR after completing its mission	Derived from problem statement	Inspection
DR.1.2.2	The CR shall exit/enter the MR bay within a +/-4.3 degree area from straight out	FR.1, see appendix A.3	Testing - Docking

The next functional requirement goes into the communication requirements necessary for the CR to meet the functional objectives given by the customer. Since the CR will be traversing out of line-of-sight from the MR, it is important for these design requirements to be met; particularly **DR.2.2.7** and **DR.2.3**. The CR will be in communication via the MR meaning that the MR is simply acting as a communications relay point. The full design requirements flow down for FR.2 is shown below in **Table 3.2.3**.

Table 3.2.3: FR.2 Design Requirements Flow Down

FR.2: The CR shall communicate with the GS via the MR			
Requirement Number	**Requirement Description**	**Parent Requirement**	**Verification & Validation**
DR.2.1	The GS shall be able to send commands to the CR via the MR	FR.2	Inspection
DR.2.2	The CR shall receive commands from the GS via the MR	FR.2	Met if all child requirements are met
DR.2.2.1	The CR shall receive rappelling commands	DR.2.2	Testing - Communication
DR.2.2.2	The CR shall receive commands to move a specific distance	DR.2.2	Testing - Communication
DR.2.2.3	The CR shall receive picture taking commands	DR.2.2	Testing - Communication
DR.2.2.4	The CR shall receive communication commands	DR.2.2	Testing - Communication
DR.2.2.5	The CR shall receive commands to turn on/off light source	DR.2.2	Testing - Communication
DR.2.2.6	The CR shall send data to the GS using the MR as a relay	DR.2.2	Testing - Communication
DR.2.2.7	The CR shall receive “transmission received” acknowledgements from the GS via the MR	DR.2.2	Testing - Communication & Communication Drop-outs
DR.2.3	The CR shall be able to detect if communication with the MR is not available	FR.2	Testing - Communication Drop-outs
DR.2.3.1	The CR shall retrace its previous driving steps until communications are reestablished	DR.2.3	Testing - Communication Drop-outs

The third functional requirement and subsequent design requirements are based on the functional objective of the CR to rappel into a cave/pipe and explore. It is important that these design requirements are met because they are vital to the mission purpose. **Table 3.2.4** lays out the design requirements flow down for FR.3.

Table 3.2.4: FR.3 Design Requirements Flow Down

FR.3: The CR shall explore a cave or pipe			
Requirement Number	**Requirement Description**	**Parent Requirement**	**Verification & Validation**
DR.3.1	The CR shall be able to rappel slopes of 90º inclination	FR.3	Testing (Rappelling) and Demonstration
DR.3.1.1	The CR shall be able to rappel to a maximum depth of 5m	DR.3.1	Inspection, Testing (Rappelling) and Demonstration
DR.3.2	The CR shall be able to transition from rappelling to travelling horizontally	FR.3	Testing (Rappelling) and Demonstration

DR.3.3	The CR shall be able to traverse a distance of up to 5m horizontally from the rappel touchdown point	FR.3	Testing - Exploration
DR.3.3.1	The CR shall be able to traverse a floor with small rocks no larger than 3cm in diameter	DR.3.3	Testing - Exploration
DR.3.4	The CR shall be able to go to a location of interest on cave terrain as commanded by the GS via the MR	FR.3	Testing - Exploration
DR.3.4.1	The location of interest shall be within a 5m radius of the CR's location	DR.3.4	Testing - Exploration

The next functional requirement goes into the positioning system the CR must have. The design requirements flow down for FR.4 that is shown in **Table 3.2.5** is based off of functional objectives defined by the customer.

Table 3.2.5: FR.4 Design Requirements Flow Down

FR.4: The CR shall contain a positioning system			
Requirement Number	**Requirement Description**	**Parent Requirement**	**Verification & Validation**
DR.4.1	The CR shall know its relative position to the MR	FR.4	Met if all child requirements are met
DR.4.1.1	The CR shall know its depth within ± 10 □□	DR.4.1	Testing - Communication
DR.4.1.2	The CR shall know its distance traveled within ± 10 □□	DR.4.1	Testing - Communication
DR.4.2	The CR shall be able to send position information to the GS via the MR	FR.4	Testing - Communication

The fifth functional requirement is for the imaging system that the CR must utilize. Again, these design requirements are vital to the success of RACER's mission. The design requirements that accompany the FR.5 are found in **Table 3.2.6** below. These requirements were defined from functional objectives provided by the customer.

Table 3.2.6: FR.5 Design Requirements Flow Down

FR.5: The CR shall capture photographic images			
Requirement Number	**Requirement Description**	**Parent Requirement**	**Verification & Validation**
R.5.1	The imaging system shall record images	FR.5	Testing - Low-Light Imaging
R.5.2	The CR shall be able to resolve objects of a 10cm diameter at 5m distance	Derived from problem statement	Testing - Low-Light Imaging
R.5.2.1	The imaging system shall have a minimum resolution of 50x50 pixels	R.5.2, see appendix A.4	Testing - Low-Light Imaging
R.5.3	The CR shall be able to take photos with an azimuthal angular coverage of 180 degrees	DR.5.3	Demonstration

R.5.4	The CR shall be able to take photos with an elevation angular coverage of 90 degrees	DR.5.3	Demonstration
R.5.5	The imaging system light source shall have a minimum 50 lumen brightness	FR.5, see appendix A.5	Testing - Low-Light Imaging
R.5.5	The CR shall be able to store at least 5 images	FR.5	Inspection
R.5.6	The CR shall be able to transmit images to the GS via the MR	FR.5	Testing - Communication

The final design requirement is for the CR and MR to carry their own power supplies. For the mission to be a success, the CR should have enough power to complete its mission without recharging. Therefore, the design requirement for FR.6 is shown in **Table 3.2.7**, below.

Table 3.2.7: FR.6 Design Requirements Flow Down

FR.6: The CR and MR systems shall contain their own electrical power sources			
Requirement Number	**Requirement Description**	**Parent Requirement**	**Verification & Validation**
DR.6.1	The power system shall provide enough power for the CR to complete its mission without recharging	FR.6	Testing - All types

4.0 KEY DESIGN OPTIONS CONSIDERED

For the purpose of coming up with a potential baseline design for the CR, different design options were explored for the critical subsystems. The six subsystems that were determined to be critical are the: rappelling, positioning, driving, imaging, power, and communication subsystems. The reason that these six subsystems were selected as critical subsystems is that the potential design solutions for each subsystem will drive the lower level design solutions later on.

The first four subsystems in this list (rappelling, positioning, driving, and imaging) have enough design alternatives to consider that trade studies must be conducted for each of them. The imaging subsystem is further broken up into a camera, an actuation method, and its light source. The different potential design solutions for each of these subsystems can be seen in **Figure 4.1** and more detailed overviews will be given in the following subsystem-specific sections.

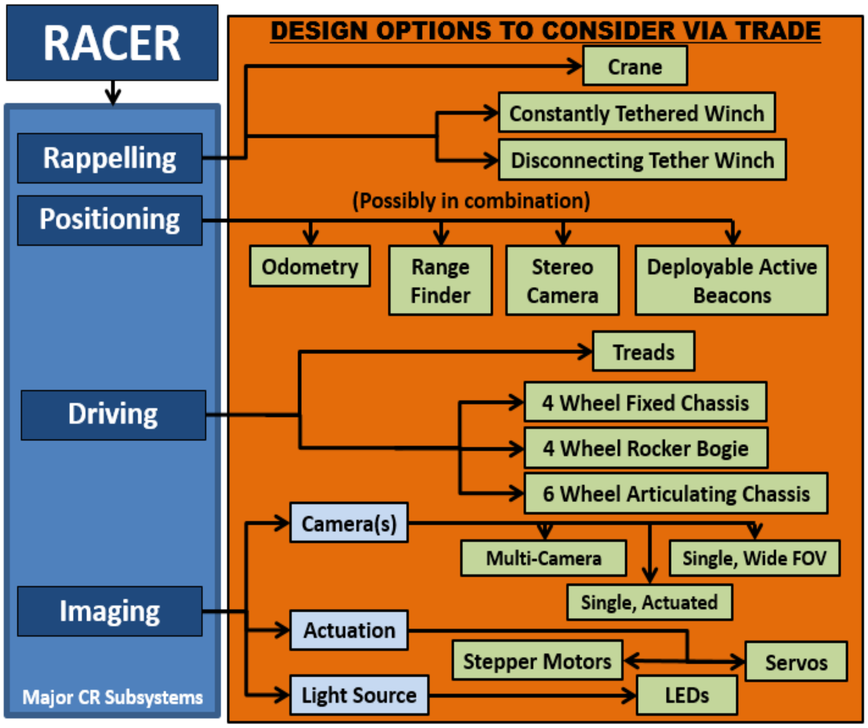

Figure 4.1: Design options to be considered using trade studies.

The last two major subsystems, power and communication, are different from the first four in that their design concepts do not require full trade studies to decide which solution is best. The options available given the functional requirements of this project as well as the setup of the legacy GS/MR make the decisions clear. The reasoning behind these decisions will be done via "mini-trades" which are performed using pros and cons and engineering judgement. The different potential design solutions for the power and communication subsystems can be seen in **Figure 4.2** and more detailed overviews will be given in the following subsystem-specific sections.

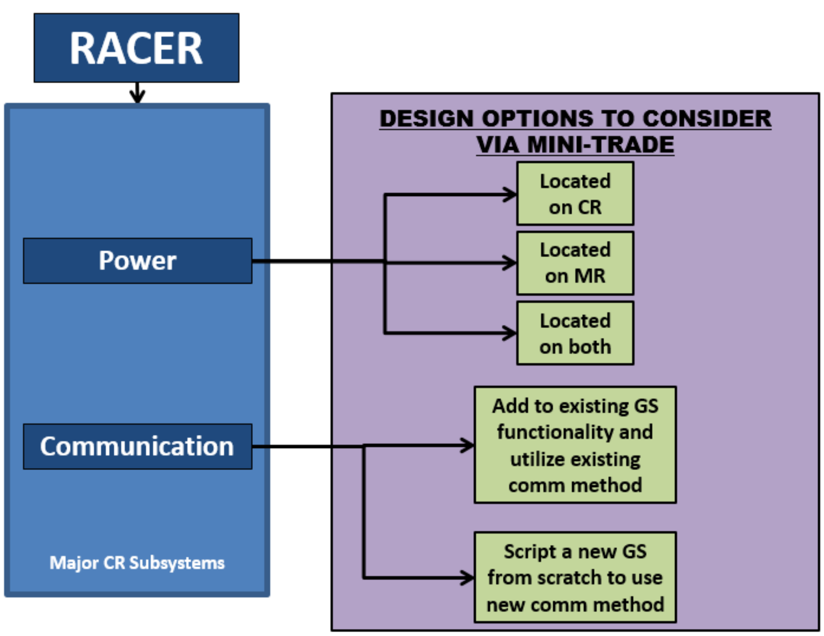

Figure 4.2: Design options to be considered using mini-trades.

4.1 Rappelling Subsystem

This subsystem's main requirement is to be able to rappel the CR system down into a cave/pipe and be able to bring the CR back up to the top of the cave/pipe. By considering and describing three different viable design solutions, a trade study can later be done to determine the optimal solutions for RACER. The following rappelling subsystem designs are considered:

- The MR and CR constantly tethered
- Detaching tether
- Crane

4.1.1 Constantly Tethered

This design concept uses a winch to rappel the CR via a tether of TBD material. The winch could theoretically be located on either the MR or CR, but this analysis is limited to the winch be mounted on the MR. This choice was made based on calculations shown in appendix **A.2** that show a large amount of work must be done by the rappelling system relative to driving work so minimizing CR mass is important.

The CR will be lowered to the bottom of the cave/pipe using the winch system, then the rover will be able to explore while connected to MR. When the CR exploration is finished, the CR will be commanded back to the base of the 5 m vertical face before being pulled back up to the MR with the winch system. **Figure 4.1.1.1- Figure 4.1.1.3** show the basic concept of the CR being constantly tethered for rappelling, and **Table 4.1.1.1** lists this systems pros and cons.

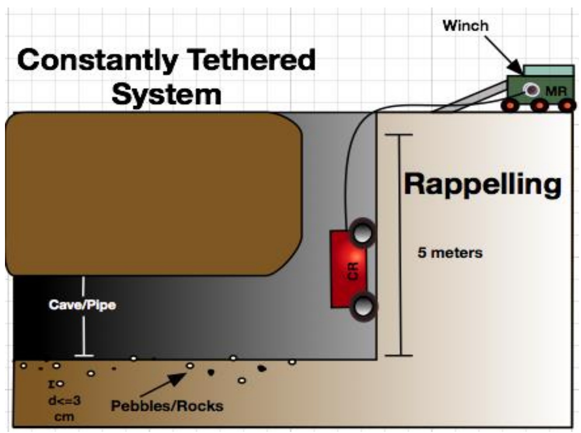

Figure 4.1.1.1: Rappelling with Tether

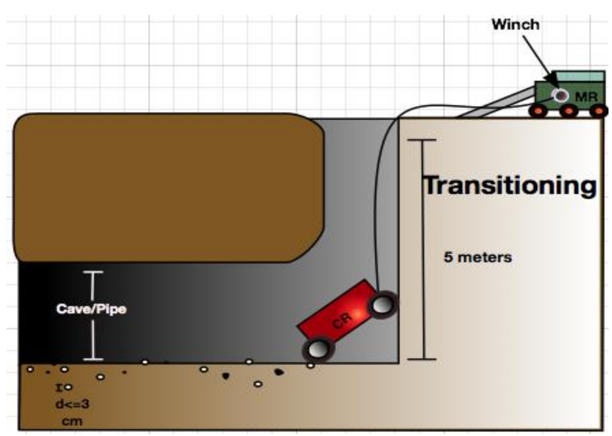

Figure 4.1.1.2: Constantly Tethered during Transition

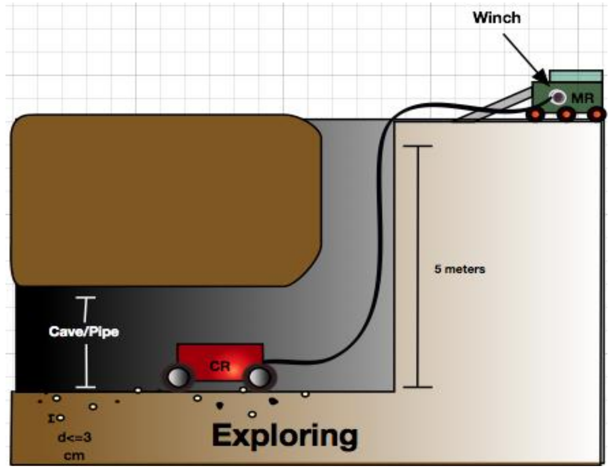

Figure 4.1.1.3: Exploring with Tether Connected

Table 4.1.1.1: Pros and cons of Constantly Tethered rappelling subsystem

Description	Pro	Con
Mechanical simplicity of connection that does not need to detach	X	
If CR fails, it can be retrieved by MR by retracting tether	X	
Tether tracking could be used to help determine position of the CR	X	
If the tether is not kept taught throughout the exploration it may become tangled or form a kink thus causing problems for return to the MR		X
Being constantly tethered requires a minimum of 10 m of wire. This increases the size and the weight of the system.		X

4.1.2 Detaching Tether

This design concept starts the mission with the CR connected to the MR by a tether that is released/retracted by a winch system mounted on the MR. The CR will be lowered by the winch system into the cave/pipe, shown in **Figure 4.1.2.1**. After the CR has completed its descent and transitioned from vertical to horizontal orientation, the mechanical clamping system on the back of the CR will be commanded to release its connection to the tether. This interaction is highlighted in **Figure 4.1.2.2** and **Figure 4.1.2.3**. After completion of its mission, the CR will connect back to the tether using the clamping system and guidance from an imaging system located on the back of the CR. Then the CR will be pulled back up to the MR using the winch system. **Table 4.1.2.1** shows the pros and cons of this design concept.

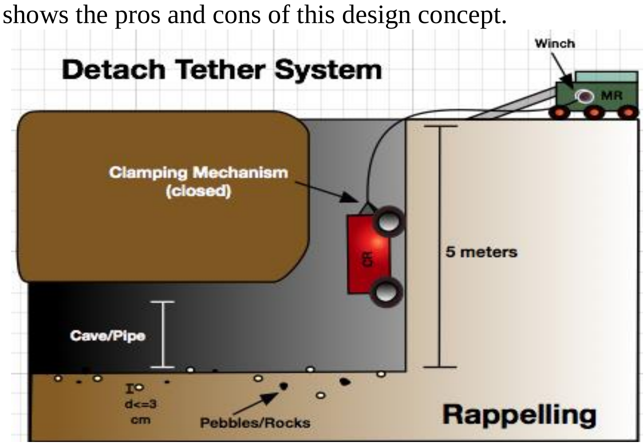

Figure 4.1.2.1: Connected during Rappel

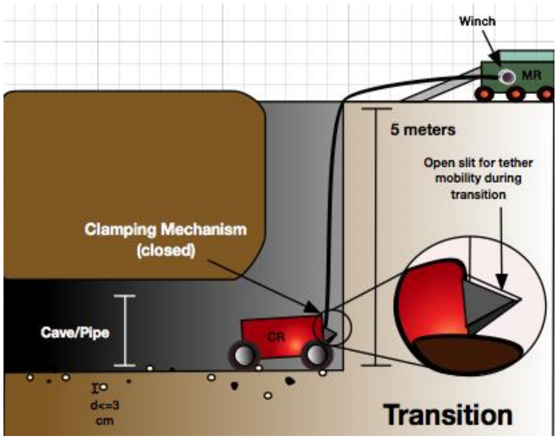

Figure 4.1.2.2: After the Transition

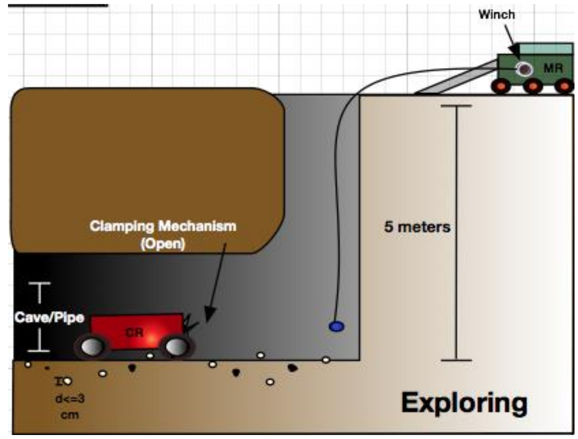

Figure 4.1.2.3: Detached for Exploration

Table 4.1.2.1: Pros and cons of Detaching Tether rappelling subsystem

Description	Pro	Con
Tether only needs to be long enough for CR to rappel 5 meters	X	
Less mechanical complexity involved with keeping a tether taught	X	
No tether tracking will be used once landed at base		X

4.1.3 Crane System

This system design is set up where two crane arms attached to the MR will lower the CR down to a maximum 5 m depth. One important difference between this and the basic winch system is the rover will be lowered flat and therefore not be required to transfer from a 90º vertical surface to a flat horizontal surface. The crane arms will both use a winch system where the two wires will be attached to the top side of the CR using a clamping system shown in **Figure 4.1.3.1**. This can ensure a smooth rappel down the vertical surface where the CR is unlikely to get twisted on the descent. Once the descent is complete the CR will detach from the wires as the clamping system is released, as seen in **Figure 4.1.3.2**, and begin the exploration process. The reason for disconnection is so the CR has full range of motion that will not tangle the wires through a series of turns. Once the CR completes the exploration mission it will return to the two connection points and attach back to the crane system where it will be raised back to the MR. **Table 4.1.3.1** shows the pros and cons of this design concept.

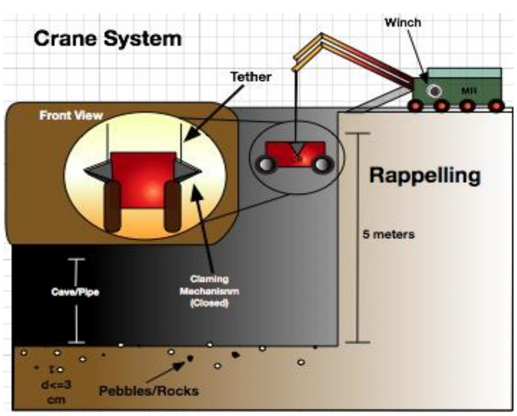

Figure 4.1.3.1: Crane Rappelling

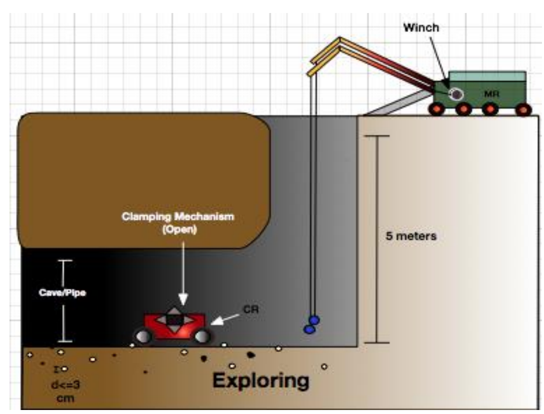

Figure 4.1.3.2: Detached from tethers, Exploration

Table 4.1.3.1: Pros and cons of Crane rappelling subsystem

Description	Pro	Con
Horizontal descent creates simple descent with no vertical to horizontal transition	X	
Mechanically complex to design two crane arms for the MR		X
CR will have to hold all power needed while exploring		X
Crane arms used for descent will have a high weight		X

4.2 Positioning Subsystem

RACER's primary positioning requirement is to determine the horizontal distance traveled by the CR as well as vertical depth within the cave/pipe within +/-10cm. In the following section, four positioning methods will be described and weighed. A trade study will then be conducted to determine the most adequate solution. The four positioning methods to be considered are as follows:

- Odometry and inertial navigation
- Range-finding utilizing sonar or lasers
- Range-finding with stereoscopic cameras
- Positioning with deployable active beacons
-

4.2.1 Odometry and Inertial Navigation

Odometry is the method of measuring the motion of a vehicle's wheels and using those measurements to calculate the position of the vehicle. Specifically, encoders can be used to calculate the distance each wheel has traveled. This information can then be used to determine both the change in position and change in orientation of the vehicle [4]. This method of positioning is inexpensive and can provide short term accuracy [5]. Another advantage of using this positioning technique is it would also be possible to place an encoder on the rappelling winch and measure the depth the rover has rappelled. This is significant because the total distance the rover has traveled includes the distance it has rappelled vertically. One of the odometry method's shortcomings is that there is a potential for an accumulation of error over time. One potential for error accumulation is that odometry assumes a no-slip condition. If any slippage occurs the system would compute the rover has traveled some distance when in fact it may not have moved. Another cause of the error accumulation is that any errors in orientation, however small, will yield an accumulation of errors in lateral position [P.2]. Because the functional requirement is total distance traveled this error build up in lateral position should not drastically impact the success of the rover's mission. However, the team must acknowledge these errors exist so an inertial back-up system is proposed to reduce error. The inertial navigation will be performed by double-integrating acceleration from an accelerometer and a gyroscope. The purpose of the accelerometer is to reduce errors related to slippage and the purpose of the gyroscope is to reduce error associated with orientation. **Figure 4.2.1.1** illustrates how this design option would be integrated with the CR. **Table 4.2.1.1** lists the pros and cons associated with this design option.

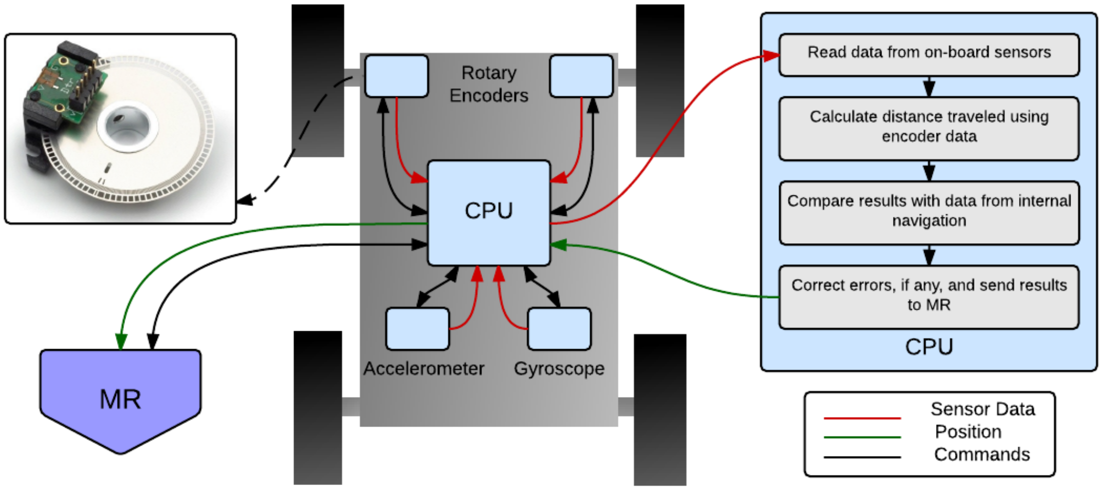

Figure 4.2.1.1: Odometry and inertial navigation positioning subsystem diagram

Table 4.2.1.1: Pros and cons of odometry and inertial navigation positioning subsystem

Description	**Pro**	**Con**
Engineering heritage from legacy JPL rover senior projects	**X**	
Cost-efficient for its accuracy	**X**	
Microcontrollers are available that have built-in accelerometers and gyroscopes	**X**	
Build-up of error over time		**X**
Accelerometers and gyroscopes do not provide positioning data when the CR is at constant velocity		**X**
This design would require an encoder on the winch. As the tether is unspooled from the winch, the diameter of the winch decreases. A model would have to be developed to account for this change.		**X**

4.2.2 Range-Finding with Stereoscopic Cameras

The basic principle behind this positioning method is to integrate two images of the same area that were taken by cameras separated by some distance d on the CR. In the same way having two eyes gives humans depth perception, integrating the two images, if done correctly, can allow one to compute the range between objects in the images and the CR. One of the issues surrounding this technique is the correspondence problem. This problem refers to determining what locations on the two images correspond with each other. Many factors contribute to this problem such as cameras that have different fields of view [p.4] and the resolution if the images. Solving this problem will require an extensive amount of both programming by the engineers and computational power from the CPU but if implemented correctly, could provide an acceptable positioning system design. **Figure 4.4.2** below shows how this technique could be integrated with the system. The object or “point of interest” is labeled P. **Table 4.2.2.1** lists the pros and cons associated with this design option.

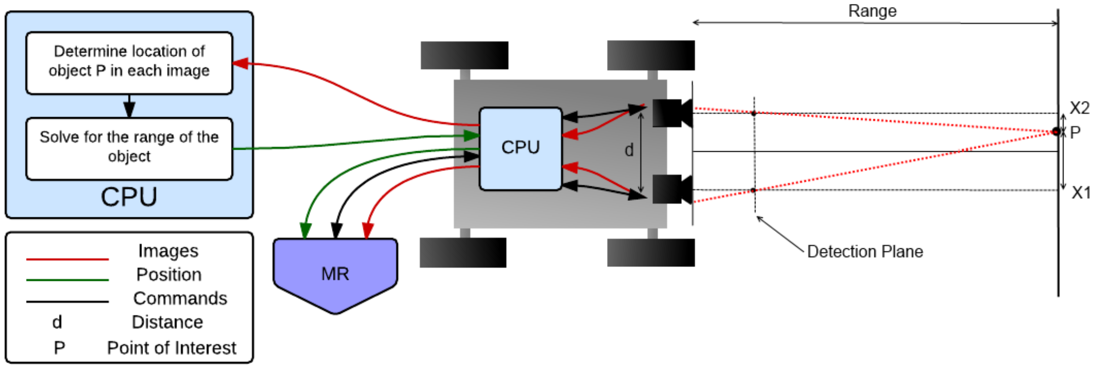

Figure 4.4.2: Stereo imaging diagram

Table 4.2.2.1: Pros and cons of Stereoscopic positioning subsystem

Description	Pro	Con
The positioning system could be integrated with RACER's required imaging system	X	
If configured properly the system can be very accurate	X	
Laser/sonar range finders are one-dimensional whereas a dual camera system provides the entire field of view for analysis	X	
The accuracy of the system is dependent on the distance between the cameras and is therefore limited by the size of the CR		X
The implementation of this design will require extensive image processing, a field that is foreign to the team		X
Will require a more powerful processor to handle image processing		X

4.2.3 Range-finding with 1-D range-finder devices

This concept involves using range-finding devices (laser, ultrasonic, etc.) to determine distance travelled. By monitoring the distance to the nearest object ahead of the rover, the total horizontal distance can be tracked. This offers the following three advantages: simplification of integration, accurate measurements along that axis, and the ability to determine depth while rappelling. There are two areas where this approach could potentially become problematic. One is when performing turns, the measurement axis would change. Finally, if there are no landmarks ahead of the robot for the range-finding device to detect, then this type of positioning is essentially useless. While this can be mitigated with scanning range-finder devices, it nevertheless still relies on having a populated environment in order to work. **Figure 4.2.3.1** illustrates this positioning concept and **Table 4.2.3.1** outlines the advantages and disadvantages.

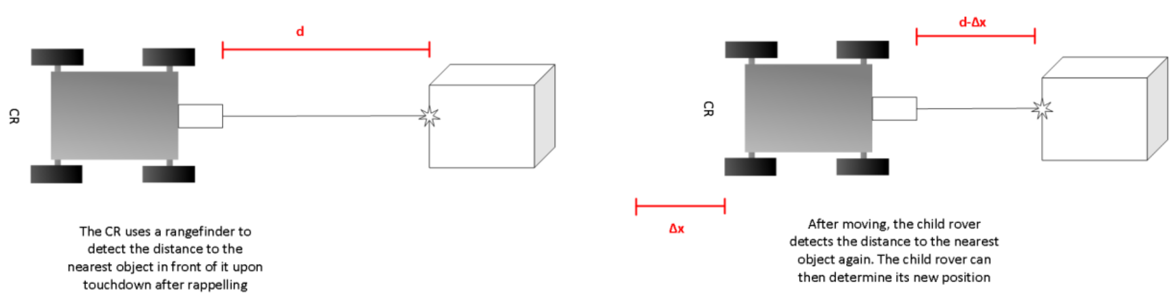

Figure 4.2.3.1: Range-Finding Positioning Concept

Table 4.2.3.1: Pros and cons of 1-D Range Finder positioning subsystem

Description	Pro	Con
Accurate in correct environment	X	
Easy integration with rover system	X	
Ability to determine depth while rappelling	X	
Managing turns requires extra positioning logic		X
Dependent on having a populated environment		X

4.2.4 Range-finding with deployable active beacons

This concept involves using active beaconing to determine the CR's position with respect to the beacons. This in turn can be used to determine the CR's position with respect to the mother rover. This system would work by having the MR/CR deploy beacons at known locations relative to the MR within the environment. Then, as the CR moves around, it would use the beacons' signals to triangulate its position. While this offers the advantage of offering an accurate positioning system that is entirely environment independent, the additional mass and mechanical complexity to make this system work could be prohibitive. Furthermore, the exact locations of each of the beacons would need to be known at the time of their deployment, which is not necessarily feasible. **Figure 4.2.4.1** illustrates this concept and how the triangulation would occur and **Table 4.2.4.1** outlines the advantages and disadvantages of this system.

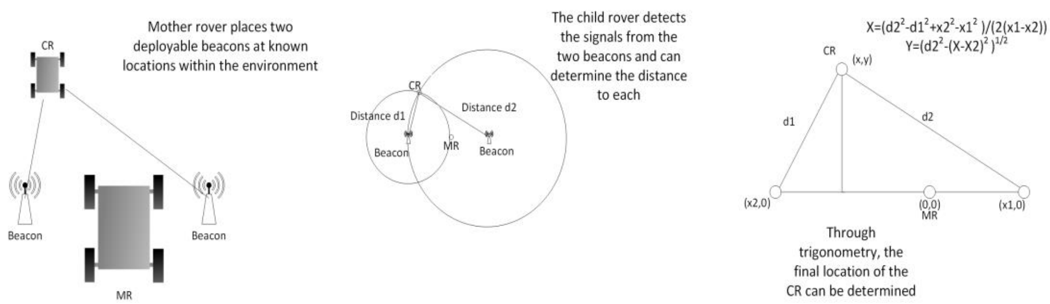

Figure 4.2.4.1: Deployable beacons positioning concept

Table 4.2.4.1: Pros and cons of Deployable Active Beacon positioning subsystem

Description	Pro	Con
Independent of environment if deployed properly	X	
Accurate positioning	X	
Extra mass		X
Exact location of beacon must be known		X
Requires designing beacon and beacon deployment subsystems		X
Beacon deployment is dependent on environment		X
Requires direct line-of-sight to beacons		X

4.3 Driving Subsystem

The driving subsystem will be used to propel the CR over a horizontal surface up to a distance of 5 m. The terrain will be flat but the rover will encounter sparse gravel up to 3 cm in diameter. The driving subsystem must also allow the rover to successfully transition from horizontal to vertical as the CR begins its rappel into the cave/pipe, and then back to horizontal as the CR reaches the bottom of the cave/pipe. An operator will be controlling the driving system remotely via the GS, so the driving system must have sufficient mobility to turn and maneuver wherever the operator specifies.

Four main driving system types were considered and are described below:

- Fixed wheels
- Articulating chassis with wheels
- Rocker-bogie suspension with wheels
- Treads

4.3.1 Fixed Wheels

The first concept for for the drive system configuration is a fixed chassis with 4 wheels. Two designs are discussed. The first is the the design that contains one large drive wheel and one small passive wheel shown in **Figure 4.3.1.1(A).** Its front wheels will be at least 6 cm in diameter to be able to traverse the 3 cm gravel. The large wheels will be used as a way to traverse from the horizontal surface at the top of the cave/pipe over the edge to the vertical wall and from the vertical wall to the horizontal floor without losing contact with the surface. The second design shown in **Figure 4.3.1.1(B)** has two large drive wheels and two large passive wheels. This design also contains a raised chassis so when it transverses from the horizontal surface to the vertical wall, the chassis will not hit the edge of the cave.. The 4-wheel system can transition from horizontal to vertical without the need for any additional moving parts so this is the simplest design in terms of minimized amount of moving parts and ease of manufacturing. This is a configuration that has been well proven to work in many other situations and is well documented. The pros and cons of these concepts are discussed in **Table 4.3.1.1**.

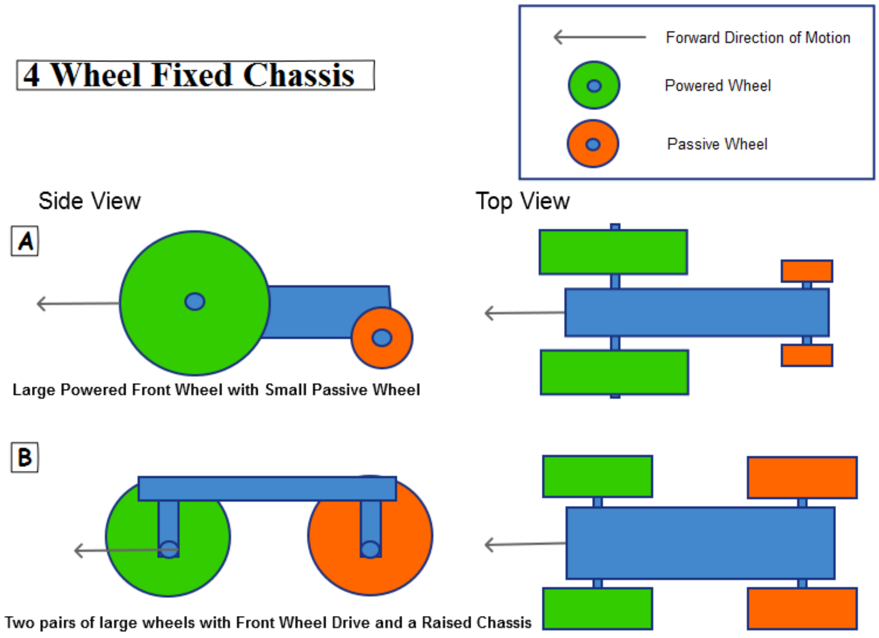

Figure 4.3.1.1: (A) Two large wheels and two small wheels (B) Four larger wheels with a raised chassis.

Table 4.3.1.1: Pros and cons of 4 Wheel Fixed Chassis driving subsystem

Description	Pro	Con
Single solid chassis means simple manufacturing and construction	X	
No ability to adapt to obstacles		X
Single solid chassis makes other subsystem integration simpler	X	

4.3.2 Articulating Chassis

The second driving system design concept is a 6 wheel articulating chassis. This design contains a pivot joint in the middle of the chassis to give the ability to mold to the surface with a combination of a servo and gravity to articulate the chassis will form to the surface it is in contact with. This will aid in the CR's transition between vertical and horizontal surfaces and help it to drive over the 3 cm gravel. This design was utilized in the SPIDAR[3] rover used for search and rescue operations for the specific reason stated above. The articulating chassis concept is shown is **Figure 4.3.2.1** and its pros and cons are discussed in **Table 4.3.2.1**.

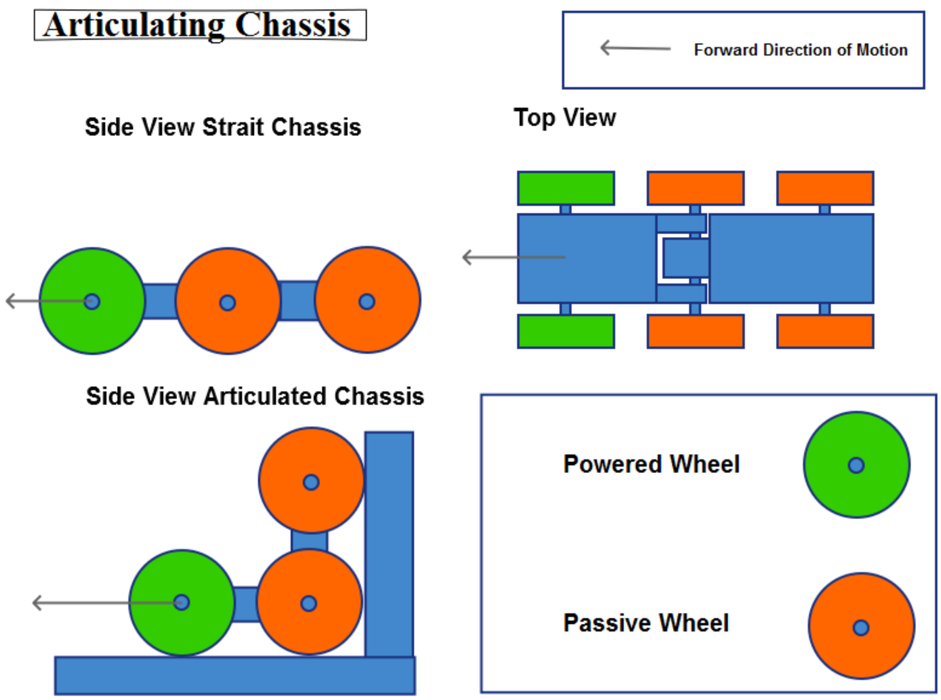

Figure 4.3.2.1: 6 wheel drive system with a two part articulating chassis.

Table 4.3.2.1: Pros and cons of 6 Wheel Articulating Chassis driving subsystem

Description	Pro	Con
Ability to modify shape in response to changing terrain	X	
Additional pair of wheels adds system weight		X
Increase in complexity to actuate chassis		X

4.3.3 Rocker-Bogie Suspension

A rocker-bogie suspension uses the mechanical motion of wheels and the arms to which they are connected as a suspension system. This design concept has a long heritage among NASA rovers, most notably on the Curiosity, Spirit, Opportunity, and Pathfinder missions. NASA rovers typically use a 6-wheel design,[8] but the RASC-AL rover team from the Worcester Polytechnic Institute successfully designed and manufactured a 4-wheel variant,[2] a representation of which is shown in **Figure 4.3.3.1.**

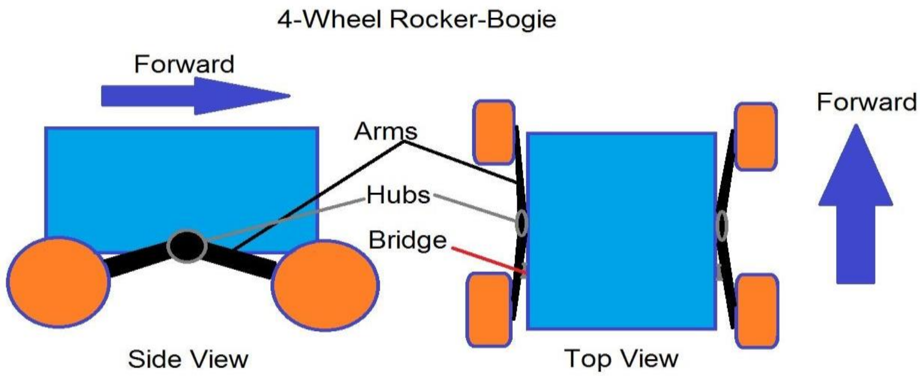

Figure 4.3.3.1 Rocker-Bogie system with 6 wheels

In this design, each of the four wheels is connected to the end of an arm. The two arms on each side meet at a pivot in the middle, about which they rotate. The rover body is connected to the rocker-bogie at the arm hubs and by a bridge that links the two arms underneath the chassis body.

The main advantage of using a rocker-bogie system over a fixed-wheel design is that it substantially increases rover mobility without significantly increasing weight or cost. When the rocker-bogie encounters an obstacle, a single wheel drives over it while the other wheels remain on the ground. This allows greater stability for the rover body as well as meaning that less work is done by the driving motors (see appendix **A.2**). The rocker-bogie suspension also has few moving parts, compared to the other considered designs, which increases reliability and durability. However, rocker-bogie systems are not widely available commercially and one would need to be manufactured for this project, which increases complexity. The pros and cons of this system are shown in **Table 4.3.3.1**.

Table 4.3.3.1: Pros and cons of Rocker-Bogie driving subsystem

Description	Pro	Con
Maintains 4 driving points of contact at all times, even while going over obstacles and horizontal-vertical transitions	X	
Design concept has engineering heritage within JPL rovers	X	
High precision manufacturing for rocker-bogie bridge and arms		X

4.3.4 Treads

Treads are tracks that run around a set of wheels, powered by a pair of driving wheels in the front. This design is commonly used on military tanks, and an example is shown below in **Figure 4.3.4.1**.

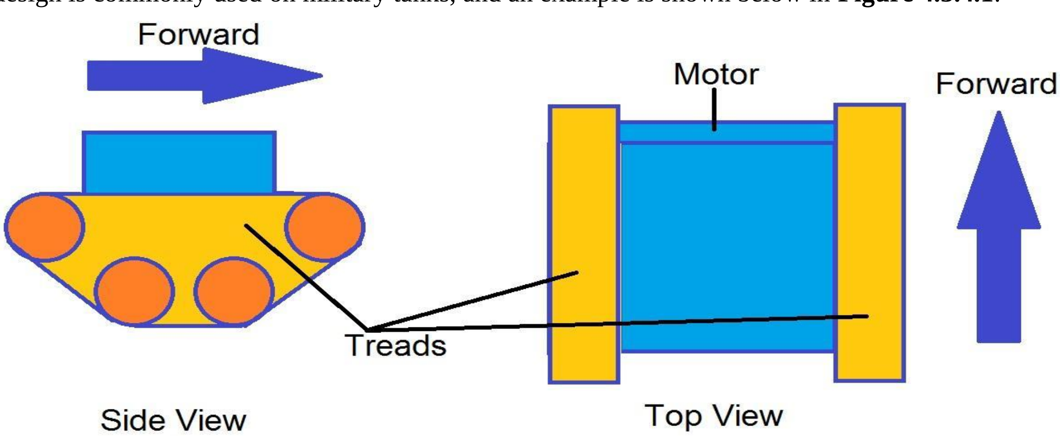

Figure 4.3.4.1:Treads Driving Option

Treads provide exceptional traction and are optimal for wet, slippery, or soft ground[1]. They decrease the pressure on the ground for heavy machines such as tanks by spreading their weight over a larger area. A treads configuration can also help with the transition from horizontal to vertical during the Return stage because the driving motor can run in reverse when the back of the CR is against the vertical wall. Since a treads-style driving system does not have a suspension, when it encounters an obstacle, the entire side of the rover will rise over the obstacle which increases work done by the driving system. Also, treads have higher internal friction due to the additional wheels and points of contact and so they require more power to operate. They are also heavier, more complex, and less reliable than the other considered designs because of their extra parts. These findings are compiled in **Table 4.3.4.1**.

Table 4.3.4.1: Pros and cons of Treads driving subsystem

Description	Pro	Con
Transition between horizontal and vertical can be assisted by driving motor	X	
Additional unpowered wheels and tread tracks are heavier than other design options		X
Additional wheels and equipment increase cost. Backup parts needed due to relative unreliability.		X
More moving parts increases difficulty to build and maintain. Increases risk of malfunction.		X

4.4 Imaging Subsystem

This subsystem's main requirement is to be able to take an image of a point of interest that is 10 cm diameter and 5 m away from the CR as seen in requirements **DR.5.1-DR.5.4**. The purpose of this sections is to weigh all the feasible options against each other so later a trade study can help determine what to use on the CR. The imaging subsystem is further broken down into a camera subsystem, an actuation subsystem (if required), and a light source subsystem. The following imaging camera subsystem designs are considered:

- Single Camera with Wide Angle Lens
- Actuated Single Camera
- Multiple Fixed Cameras

4.4.1 Single Camera with Wide Angle Lens

This concept involves using a single fixed camera with a wide and tall enough lens to be able to capture a single image with a 180° azimuthal and 90° elevational FOV. Furthermore, the image must have high enough resolution such that a POI can be resolved. This design concept is simple in that no moving parts are required and no extra image processing must be done. However, the main disadvantage of this solution is that the image would be distorted, especially around the edges. Correcting this effect with software is possible, but undermines the advantage of avoiding extra image processing. The other main issue with this solution is that most wide angle lenses are unable to encompass the entire required FOV so for the camera to remain fixed the rover would have to be moved in order to reposition the camera. One possible solution to this would be to use a fisheye lens to further increase the FOV, but this would also increase the distortion of the image. **Figure 4.1.1.1** shows a comparison of the same picture taken with and without this type of curved lens. Towards the outside of the image, the distortion is most visible but even in the middle it can be clearly seen that the POI would not be captured as intended. **Table 4.4.1.1** shows the pros and cons mentioned here.

Figure 4.4.1.1: Image distortion from wide FOV lens

Table 4.4.1.1: Pros and Cons of Single Camera with Wide Angle Lens imaging subsystem

Description	Pro	Con
No moving parts to break	X	
Low complexity of implementation with no moving parts	X	
Image distortion so resolution requirement cannot be guaranteed for entire picture		X
Unable to meet FOV requirements without moving CR		X

4.4.2 Actuated Single Camera

This design concept uses a single camera attached to two servos or stepper motors, one for vertical movement and one for horizontal movement that would allow the camera to be pointed towards the point of interest. Each image recorded would only capture a portion of the total FOV requirement, but would still meet the resolution requirement. The main advantage of this solution is that it eliminates the distortion of the fixed single camera with a wide field of view. The main disadvantage of this solution is that the servos or stepper motors would require additional software for their control. Moving parts have the potential to break, but these components are very reliable in general and are a widely used technology. **Table 4.4.2.1** shows the pros and cons mentioned here.

Table 4.4.2.1: Pros and Cons of Actuated Single Camera imaging subsystem

Description	Pro	Con
No added image distortion	X	
Low complexity of implementation with few moving parts	X	
Moving parts can break or not function as intended		X
Additional software complexity for camera pointing control		X

4.4.3 Multiple Fixed Cameras

This concept involves using multiple cameras that are fixed on the CR that each capture a portion of the total FOV. The main advantage of this solution is that it would not have any distortion like there is in the single fixed camera with a wide field of view solution and it would also not have any moving parts like the actuated single camera solution. However, by having so many cameras, it would be more complex mechanically to mount them all, find a microprocessor that you are able to attach that many cameras to, and transmit all of the images. Another disadvantage of this option is that if the POI spans multiple images, the images would have to be stitched together which would lead to distortion since they would be at points of view relative to the point of interest. The other option besides stitching the images together would be to reposition the CR such that the POI is captured in a single camera's image. **Figure 4.4.3.1** shows an example of a multiple camera system used on the SPIDAR rover. Pros and cons of this design concept are shown in **Table 4.4.3.1**.

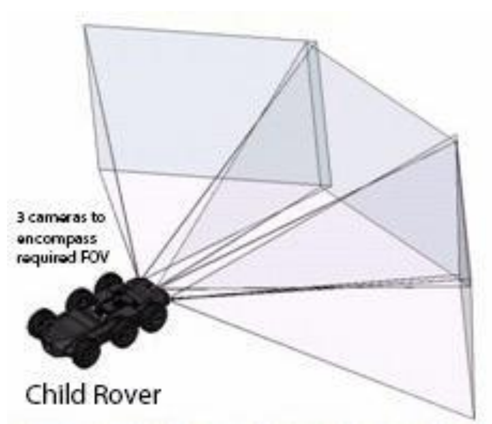

Figure 4.4.3.1: Possible implementation from another rover called SPIDAR [2]

Table 4.4.3.1: Pros and Cons of Multiple Fixed Cameras imaging subsystem

Description	Pro	Con
No added image distortion prior to image-stitching	X	
Low complexity of implementation with no moving parts	X	

Additional software complexity for image-stitching		**X**
Possibility of needing to reposition the CR to get a distortion-free image		**X**

4.4.4 Actuation

Regarding actuation, the two most practical options available are purchasing an off the shelf actuating camera that meets the requirements in **R.5.3** and **R.5.4** or designing an actuating system with servos or stepper motors. If a camera exists that meets these requirements that is within the project budget, the most practical option would be to purchase this camera and integrate it with the CR. However, a camera with the required specifications does not exist, the team will plan on developing an actuation system with servos or stepper motors.

One servo or stepper motor would be required for both vertical and horizontal actuation. In the case of using servos, a PWM signal would be supplied to the servos telling each to rotate a certain amount either vertically or horizontally. This movement is fairly accurate due to servos having built in feedback from encoders. For stepper motors, a full rotation is divided into a set number of steps. Then the user tells the motor how many steps to move at once thus allowing possibly very precise positioning depending on the specifications of the motor.

4.4.4 Lighting

The lighting subsystem addresses **DR.5.4** by providing adequate scene lighting to capture an image of a POI in low-light conditions. After some testing using a camera and different lumen bike lights, it was determined that the light source must have at minimum 50 lumens of brightness. Appendix **A.5** shows the results from the experiment. This level of brightness is attainable using commercial off-the-shelf LED light sources which are cheap, low mass, and use relatively low power.

4.5 Power Subsystem

RACER's power subsystem must fulfill FR.6 and all of its child requirements. By successfully meeting these requirements, RACER will be supplied with enough electrical power to complete its mission. The design of this subsystem entails many decisions such as the type of power source (i.e. solar cells, batteries, radioisotope thermoelectric generators (RTG), etc.), where the power source will be located (i.e. on the MR, CR, or both), and how power will be transported between the MR and CR if the power source is only located on one of the two.

Immediately, the type of power source can be decided. Solar cells would not work for RACER's application because of several reasons. The solar cells would have to be added to the existing TREADS MR which is a design outside the scope of this project. Also, solar cells would severely limit the applications this project to clear sunny days in open areas. RTGs are not a viable design solution because there is no commercial-off-the-shelf option within a $5,000 budget in addition to it being highly complicated and hazardous. Existing MR/CR systems in legacy JPL senior projects have used battery systems so the technology is proven for similar applications. Therefore, batteries will be used for RACER's power source.

Therefore, the limiting factor for this design is where the power source is located because the power transportation method is dependent on this decision. From **Figure 4.2** in Section 4.0, the design options considered for this choice are as follows:

- Power source solely on the MR
- Power source solely on the CR
- Power sources on both the MR and CR

4.5.1 Power source solely on MR

If the power source is located solely on the MR, the CR must be tethered to the MR throughout the mission and the tether must supply power to the CR. However, from the calculations shown in appendix **A.1**, the voltage drop across a 10m cable is significant (~4.0V for 20 AWG stranded copper wire). The voltage drop would be decreased to ~0.4V if 10 AWG copper wire was used, but this would increase the total weight of just the power cable in the tether to ~1kg. The total mass of the CR system cannot exceed 9.8 kg so having 10% of the total mass reside in just part of the rappelling system tether is prohibitive of this design option. **Table 4.5.1.1**, below, shows the pros and cons of the power source being located solely on the MR.

Table 4.5.1.1: Pros and Cons of the CR power source being located on solely the MR.

Description	Pro	Con
If the MR and CR are connected through a tether that carries power, transmitting communications through this tether would be a simple addition.	X	
CR mass would be reduced which means less work for the rappelling system.	X	
Having the power source located directly next to the rappelling mechanism is convenient.	X	
Either a large voltage drop across the tether or a large tether mass, neither of which is desirable.		X
Through operational wear-and-tear, the power cable may break which is a single point of failure for the mission.		X
Having batteries in the MR bay takes valuable space away from the CR.		X

4.5.2 Power source solely on CR

If the power source is located solely on the CR, the design suffers similar drawbacks to being located solely on the MR. The main difference between the two design concepts is that power for the rappelling subsystem must be transmitted through 10m of wire instead of power for the CR driving subsystem. As shown in the calculations in appendix **A.2**, the work done by the rappelling subsystem will be more than twice that of the driving subsystem. This means that the inefficiencies of transmitting power through a long wire are even more prohibitive. **Table 4.5.2.1**, below, shows the pros and cons of the power source being located solely on the CR.

Table 4.5.2.1: Pros and Cons of the CR power source being located on solely the CR.

Description	Pro	Con
If the MR and CR are connected through a tether that carries power, transmitting communications through this tether would be a simple addition.	X	
CR mass is increased by holding batteries for driving subsystem as well as rappelling subsystem.		X
Having the power source located directly next to the driving mechanisms is convenient.	X	
Either a large voltage drop across the tether or a large tether mass, neither of which is desirable.		X
Through operational wear-and-tear, the power cable may break which is a single point of failure for the mission.		X
More power must be transmitted through the tether for the rappelling mechanism		X

4.5.3 Power sources on both the MR and CR

By having power sources on both the MR and CR, cons from both single power source location designs are mitigated. There is no need to inefficiently transmit power to power-intensive subsystems, CR mass to be rappelled is minimized, and a major single point of failure for the mission is removed. **Table 4.5.3.1**, below, shows the pros and cons of having power sources on both the MR and CR. From the results of this table, it is clear that having separate power sources on the MR and CR is the optimal design solution for this project.

Table 4.5.3.1: Pros and Cons of the CR power source being located on both the MR and CR.

Description	Pro	Con
The CR tether does not need to be designed to avoid sharp bends and its material can be lightweight without metal.	X	
CR carried mass is minimized while avoiding inefficient power transmission.	X	
Having a power source located directly next to the driving mechanisms is convenient.	X	
Having a power source located directly next to the rappelling mechanism is convenient.	X	
Having batteries in the MR bay takes valuable space away from the CR.		X

4.6 Communication Subsystem

RACER's communication subsystem must fulfill FR.2 and all of its child requirements. By successfully meeting these requirements, RACER will be able to process all of the user input commands required to complete its mission. The design of this subsystem entails a single major decision between the following options: to modify the existing GS to add functionality required for this project or to script a new GS from scratch so that a new communication architecture can be utilized.

- Add to existing GS functionality and utilize existing comm method (Wi-Fi)
- Make a new GS from scratch to use a new communication and transmission method (RF)

4.6.1 Add to existing GS functionality and utilize existing comm method (Wi-Fi)

This option would allow for RACER to utilize the legacy GS by adding additional functionality to its communication system. In previous years, Wi-Fi has been used as the main wireless communication system between the GS, MR, and the CR. One advantage of using Wi-Fi is that it has a faster data transfer rate than other forms of RF transmission and it uses IP so there is some error checking built into the protocol. One of the disadvantages in this case is that there is no documentation readily available so many man hours will need to be devoted to reverse-engineering this subsystem. Another disadvantage of using Wi-Fi as a communication method is that the range is more limited than other RF options. Despite the scope of this project being well within the range of Wi-Fi, it would not work over much longer distances which decreases scalability.**Table 4.6.1.1** shows the pros and cons for this design.

Table 4.6.1.1: Pros and Cons of *using existing GS functionality and utilize existing comm method (Wi-Fi)*

Description	Pro	Con
Use existing and tested work from previous groups	X	
Faster data transmission rates vs other common RF communication methods	X	
Lack of documentation from previous groups means man-hours must be spent understanding the system not only to use it but to add required functionality		X

4.6.2 Make a new GS from scratch to use a new communication and transmission method (RF)

This option would require the team to create a new RF transmission method that would utilize a serial protocol for the transmission of data. This option would have slightly slower data transfer rates than using Wi-Fi. However, this option would be more customizable for RACER's specific communication requirements. Another advantage of using serial for wireless transmission is that most sensors and cameras that will be used will utilize serial for transmission so there will be no need to change protocols. Below in **Table 4.6.2.1** the pros and cons mentioned here are outlined.

Table 4.6.2.1: Pros and Cons making a new GS from scratch to use a new communication and transmission method (RF)

Description	Pro	Con
Longer range than Wi-Fi.	X	
Most cameras and sensors will already be utilizing serial.	X	
This team designs the system allowing for more design flexibility in both commands and data type priorities. Also, no reverse engineering due to lack of documentation for previous communication system.	X	
Slightly slower than Wi-Fi.		X

4.6.3 Legacy Equipment and Communication System [6]

The communication for the TREADS legacy system was tested last fall by the DARE team. They found that the GS and MR computer systems are operational. Both of the computers booted up and were determined viable. Testing was done last year by the DARE team to determine the functionality of the communication between MR and GS over the "Darkside" network, the results are shown below in **Table 4.6.1.1**.

Table 4.6.1.1: MR Command Test 1 [6]

Command Desired	Command Input to Computer	Command output by GS to MC	Command output by MC to MR	Pass/Fail
Drive Forward 2"	F	2-2-0	0-0-0	Fail
Drive Backward 2"	B	3-2-0	3-2-0	Pass
Turn Right 5°	R	4-5-0	4-5-0	Pass
Turn Left 5°	L	5-5-0	5-5-0	Pass
Ramp - Raise	A-1	N/A	N/A	"Ramp already raised"
Ramp - Lower	A-2	6-2-0	0-0-0	Fail
Request Telemetry	T	7-8-0	0-0-0	Fail
Ramp- Raise	A-1	6-1-0	6-1-0	Pass

Table 4.6.1.1 shows that the MR was able to drive backward and turn in either direction it was not able to drive forward. The MR ramp was able to raise but not lower and the request for telemetry does not function.

It is assumed that the functional condition of TREADS has not changed since last fall, so these results indicate that the communications system is functional enough to relay commands to the CR. For RACER's purposes, the MR's mobility failures will not affect mission completion as the MR will remain stationary with its ramp lowered.

5.0 TRADE STUDY PROCESS AND RESULTS

5.1 Rappelling Subsystem

5.1.1 Trade Metrics and Weighting Explanation

In order to complete a trade study on the different rappelling systems, the metrics used to measure how useful each system is must be understood. For the rappelling system the power consumed, mechanical complexity, software complexity, mass, size, and cost will all be used to measure the different design options. The metrics used are described below and given weights in **Table 5.1.1.1**.

Power Consumed: The rappelling system will have a large use of power in order to be able to allow the CR to descend and ascend. For this project the rappelling system will be mounted on the MR. The power for the rappel system will be added to the MR.

Software Complexity: In order to create a working rappelling system software must be created in order to send commands for the CR to use the rappelling system. This software must be incorporated into the designed GS software. It will also be required to be sent to the MR system, where the system will be connected. Software will be complicated because the legacy code must be understood before new software can be created and integrated.

Mechanical Complexity: The rappelling system will require a mechanical system, using the bare minimum of a winch and a motor, in order to be functional. How the mechanical system is built, attached to the MR, and integrated with the CR is a key design aspect for which rappelling system is chosen. The Mechanical systems being created include the rappelling system, the driving system, and the CR chassis.

System Mass: While the rappelling system will be on the MR it still has mass constraints. It cannot put strain on the current MR. This mass will include not just the winch and motor but also the wire system that is attached to the CR and the power required to use the rappel system. The mass of the entire system will be considered as part of the CR max weight of 9.8 kg. The reason for this is because the CR bay on the MR is what drives the maximum weight. Any weight added to the CR bay will take away from the total CR weight

System Size: Similar to the system mass the size is a derived requirement from the size of the MR. The rappelling system must fit onto the current MR while not interfering with any of the MR functions. This gives constraints in the size of the system.

Cost: Cost is always an important metric because the entire project has a maximum budget of $5,000. This cost will be distributed between the rappelling system, the positioning system, the driving system, the power system, the hardware system, and the imaging system. This means that the budget for the rappelling system has large constraints.

The following table shows how each metric is weighted and explains the reasoning behind assigned weights. The weights provided are derived from the minimum levels of success, the functional requirements, and engineering intuition.

Table 5.1.1.1: Design Metric Description and Weighting

Metrics	Percentages	Description
Mechanical Complexity	25 %	The rappelling system is primarily a mechanical system that will require multiple parts to allow the CR to descend and ascend a 90 degrees vertical surface. Rappelling into a cave/pipe is required for minimum success and to be able to complete FR.3. Because it is required for minimum success the mechanical system is the highest weighted metric at 25%
System Mass	20 %	While the mass will be mainly onboard the MR it is in the CR bay area. For this reason the mass of the system will be considered against the total mass of the CR. The CR has a maximum weight of 9.8 kg. This is a design driver of the entire system because the MR can only hold a

		maximum weight. The mass that the rappelling system can have must be minimal as to allow for the CR to have the other required systems
Software Complexity	20 %	To use the rappelling system from the GS, software commands must be created. These commands are required to be sent from the GS to the MR, where the system will be located. Then the commands will be relayed to the CR. FR.3 requires that the CR and GS are able to communicate. Because the GS already has completed software for legacy projects, the addition of software for the rappelling system is very important. The complexities in integrating into already created software make this metric weigh more than the power, size, and cost.
Cost	15 %	The project has a maximum budget of $5,000. This budget as described above is split between many different subsystems of the CR. This means that the cost plays a large factor into the design of each subsystem. Since there is a budget constraint and the rappelling system is required for minimal success the cost of the different systems is a key design metric.
Power Consumed	10 %	Because the rappelling system will be mounted on the MR the power for the system will also be on the MR. The MR has a large power supply as well as the ability to increase the power capacity with extra batteries. For this reason the power for the rappelling system is given the lowest weight since there is a larger power budget to work with than what the CR will have aboard its system.
System Size	10 %	Size is considered the least important metric for the rappelling system. The reason behind this is the amount of space to mount the rappelling system on the MR. Each CR bay on the MR have a width of 0.4826 m at the smallest point and a width of 0.635 m at the widest point. This provides more than ample space to mount the rappelling system. The only other consideration of space is any mechanical system that may be added to the CR for the rappelling system to function

5.1.2 Rappelling System Trade Study

With the metrics given weights based on the different functional requirements and levels of success a trade study can be completed. In order to perform a trade study score values must be designated to be assigned to the metrics for each system. For each metric a heuristic is developed in order to be able to understand what each score will mean for each specific metric. Below is a description of the heuristics that help determine how a metric is scored for each rappelling system and the score descriptions in **Table 5.1.2.1**.

Mechanical System Heuristic: The mechanical system is scored based on the difficulty to build the system and the time it takes to build. This includes the possibility of parts being machined, what material they are, and how it would integrate into the MR. Also, subsystem development should constitute less than 6 man-months, where a man-month is defined as the amount of work 1 person can do in a month, or 2 people can do in one half month. For a team of 2, 6 man-months of work would take 3 months to complete.

Software System Heuristic: The software system is scored based on the time it will take to create software to control the rappelling system and the ease of integration into the current GS software.

Cost Heuristic: The cost is scored based on the total project budget of $5,000.

System Mass Heuristic: The system mass is scored based on how much of the maximum CR mass of 9.8 kg the system will take up. As described in **Table 5.1.1.1** the mass of the rappelling system is considered to be part of the maximum CR weight. Therefore this must be minimized.

System Size Heuristic: The size of the CR bay on the MR, 0.635 m at widest, constrains the size of the rappelling system. The rappelling system size is scored based on the effect on the total size of the CR bay as this would take away from the maximum CR size

Power Consumed Heuristic: Power for the rappelling system is scored based on the additional power added to the MR and the mass of the required power to be added. As stated in section 5.1.1 the power added to the MR will be used all for the rappelling system and the mass of the additional power will take away from the CR maximum weight.

Table 5.1.2.1: Rappelling System Trade Study Heuristic Definitions

Metric	Value Assigned				
	1	2	3	4	5
Mechanical Complexity	Complex machined parts, more than 6 man months	Machined Parts, 5-6 man months	Machined Parts, 4-5 man months	Off the shelf part, 3-4 man months	Off the shelf parts, less than 3 man-month
Software Complexity	More than 5 man months	4-5 man months	3-4 man months	2-3 man months	Less than 2 months man hours
Cost	More than $1000	$750-$1000	$500-$750	$250-$500	Less than $250
System Mass	More than 40% total CR mass	30-40% total CR mass	20-30% total CR mass	10-20% total CR mass	Less than 10% CR total mass
System Size	More than 40% CR bay total size	30-40% CR bay total size	20-30% CR bay total size	10-20% CR bay total size	Less than 10% CR bay total size
Power Consumed	More than 20% CR total power	15-20% CR total power	10-15% CR total power	5-10% CR total power	Less than 5% CR total power

Once the trade study is complete by using the scoring method described above a more detailed explanation about the most important metrics will be given to analyze why each metric was given a specific score.

Table 5.1.2.2: Rappelling System Trade Study

		Constantly Tethered	**Detaching Tether**	**Crane**
Metric	**Weight**	**Score**	**Score**	**Score**
Mechanical Complexity	25%	**5**	**3**	**2**

System Mass	20%	**4**	**4**	**3**
Software Complexity Cost	20%	**5**	**4**	**3**
Cost	15%	**4**	**4**	**3**
Power Consumed	10%	**4**	**5**	**3**
System Size	10%	**4**	**4**	**2**
Weighted Total		**4.45**	3.85	2.65

5.1.3: Rappel System Trade Study Results

The trade study provides a numerical analysis of each rappel system. The final weighted total gives a general idea about which system will be the best for the required mission. These final weights can be seen in **Table 5.1.2.2.**

The first system analyzed was the constant tether. When analyzing this system it was realized that it was the simplest system in terms of the mechanical and software systems. It would only require three commands of power, lower, and raise. This means the software of the system is short and easy to create. The mechanical system also only requires a basic winch system. This means the required time to develop this system is minimal, which lead to the score of a five. For a constant tether system it would require a minimum of 10 m of cable wire. This is so the CR can complete the entire mission. The wire will add to the size and the mass of the entire system, which is the reason for the mass, size, and cost all receiving a score of four. With a constant tether system the power will have to remain on for the duration of the mission. This is to ensure that the tether wire never has slack, which could complicate the mobility issues of the CR. Since the power will always be on this system received a score of three. Overall this system seems to be the most useful from the trade study, the complexity factors from both the mechanical side and software side are easy to handle. The only issue with this system seems to be the power in order to keep the wire taught. The extra power will be minimal and can be countered by the addition of minimal power mass to the MR.

The second system analyzed was the disconnected tether. This system will require only five meters of wire as opposed to the 10 for the constant tether. But while the wire weight and size will be greatly reduced, an additional mechanical part on the CR must be created. This will be a clamp system that can disconnect and reconnect to the tether. This mechanical system will add to the mechanical complexity of the entire rappel system as well as increase the amount of commands the GS must be able to send to the CR. With this system the code process will take a larger amount of time to create and integrate into the MR system. The best part of a disconnected system is that the power use will be minimal. Since the wire does not have to be kept taught once the CR is on the horizontal cave/pipe floor the motor can be completely shut down until the CR must ascend back to the MR. The most complicated part of this system is that the CR will require a clamp mechanism in order to disconnect and reconnect to the rappel wire. This part will have to be machined and integrated with the CR to properly work. Overall this system would provide more mobility to the CR and use less power, but would take longer to construct and create working software for.

The final system analyze was the crane system. The crane system would make use of a winch system, but would allow the CR to rappel horizontally which would remove the need to be able to transfer from the 90 degree vertical surface to the flat horizontal surface. This would make the rappel system much easier and be a large design driver for the driving system of the CR. The issue with a crane system is the size and mass of the system. A crane would require two winch wire sets, two motors, and crane arms that can extend over the opening to the cave/pipe that are used to properly lower the CR. This would be mechanical complex to build as well as integrate into the MR. The biggest issue with this system is the size of the system simply because the crane arms must be large enough to support the entire CR and hold a motor and winch system. Overall this system, while it takes away the difficulty of the transfer between vertical and horizontal surfaces, is too large and mechanically complex to be used as the CR rappel system.

5.2 Positioning Subsystem

5.2.1 Positioning Trade Metrics and Weighting

Many factors contribute to a successful position system design. This section will describe each of these factors as trade metrics so that a trade study can be performed. The metrics to consider are mass, power consumption, cost, complexity, accuracy, size, and reliability. These metrics are described below and assigned weights in **Table 5.2.1.1.**

System Mass: Since the CR will be suspended by a tether of limited strength and that tether will likely be driven by a motor of limited power, the mass of each subsystem on the CR, including the positioning system, becomes significant. There are also mass requirements derived from being able to interface physically with the MR.

Power Consumption: It will be important to select a positioning system with low power consumption. A subsystem with a significant power consumption will require a larger power supply. For reasons such as mass and cost the size of the power supply will be limited. This will limit the available system power.

System Cost: Recall that the total project budget is only $5000. Taking this into account along with the fact that different positioning systems require different sensors of varying costs it is important to select a design that will not require expensive positioning sensors.

System Complexity: In the case of this subsystem complexity mostly refers to the software algorithms that will be associated with the positioning system. The team only has two semesters to complete this project. Because of this, the risk of not being able to develop a successful positioning algorithm within the required time must be considered.

Positioning Accuracy: DR 4.1 and its sub-requirements specify that the CR must know its position relative to the MR with errors less than 10 cm with regards to depth and distance traveled. This indicates that the accuracy of the positioning system is crucial to a successful mission.

System Size: In this case size refers to the geometry of the subsystem and its individual components. DR.1.1.1 states that the dimensions of the CR cannot exceed 0.483m x 0.483m. Therefore, the size of all subsystems must be considered when making a design selection.

System Reliability: System reliability refers to being able to complete the mission successive times with no complications. With regards to the positioning subsystem this refers to being able to meet all positioning requirements. The team must consider all factors that would affect a particular designs reliability. An example of this would be an environment that does not allow for successful CR positioning.

Table 5.2.1.1: Design Metric Description and Weighting

Metrics	Percentage	Description
System Mass	5%	Some examples of sensors that might be used in a positioning system are rotary encoders, gyroscopes, accelerometers, laser range-finders, and cameras. All of these, with the possible exception of cameras, have very low mass with respect to the 9.8 kg requirement. Another thing to consider when assigning a percentage to the system mass metric is that a large portion of the system is software, which doesn't have mass. For these reasons this metric was only assigned 5%.
Power Consumption	5%	Along with low mass, the possible sensors associated with a positioning system have relatively low power consumptions with respect to the rest of the CR subsystems. For this reason the power consumption metric was also given a 5%.
System Cost	15%	Although the masses and power consumptions of the possible positioning sensors are relatively low, the cost of some, such as laser range-finders and cameras, can be quite expensive if they are required to yield a certain accuracy. A technique such as stereo image range-finder will require

		image processing which will likely increase the required performance and cost of the CR onboard CPU.
System Complexity	20%	The complexities of the positioning system designs considered for the CR vary quite a bit. Certain designs come with a significant amount of heritage and can be designed and integrated with system within the allotted project time. Other designs will be much more difficult to develop and could be considered out of scope with regards to this project.
Positioning Accuracy	30%	Because the accuracy of the positioning system is directly correlated to a successful mission it was given the highest weight, 30%.
System Size	5%	Like the system mass metric, the system size metric is also given a 5% weight. This was done for similar reasons. The sizes of various sensors is very small relative to the rest of the system and a significant portion of the positioning system will be embedded software, which carries no size.
System Reliability	20%	Reliability of the positioning system is very important factor. A positioning system must be selected that can meet all mission requirements in various environments. For example, the geometry of the cave or pipe being explored should not drastically affect the accuracy of the positioning system to the point of mission failure.

5.2.2 Positioning System Trade Study

Now that each metric has been described and given weight, a trade study can be performed to select the most effective and appropriate positioning system for the CR. Recall that the four positioning design options are odometry with inertial navigation, one-dimensional range-finding, range-finding with stereoscopic imaging, and deployable active beacons. In the following trade study each design option will be assigned a score of 1 to 5 with regards to each metric described and weighted in the section above. The heuristics given to each trade metric are listed below and described in **Table 5.2.2.1.**

System Mass Heuristic: Positioning system mass is expected to be low compared to the total mass of the CR. An ideal positioning system would take up less than 5% of the CR mass whereas a bad design option would take up more than 25% of the CR mass.

Power Consumption Heuristic: Positioning system power consumption is also expected to be low compared to the total power required by the CR. An ideal positioning system would take up less than 5% of the CR power budget whereas a bad design option would take up more than 25% of the CR power budget.

System Cost: The total budget of the project is $5000. All subsystems will require a portion of this budget. Therefore, it would be unacceptable if the positioning system took up more than $1000. Ideally this system would only cost around $250 or less.

System Complexity: The time to develop a positioning system must at a minimum take less than the allotted time set by the course deadlines. Ideally this design would take less than 3 man months to successfully develop.

Positioning Accuracy: The positioning system must at a minimum meet the accuracy requirements in DR.1.4 A good positioning system design should be much more accurate to avoid mission failure.

System Size: Like mass, the size of the positioning system is expected to be much lower than the total size of the CR. An ideal positioning system would take up less than 5% of the CR size whereas a bad design option would take up more than 25% of the CR size.

System Reliability: Ideally, the success of the positioning system must be completely independent of the CR's surrounding environment. A poor design option would be entirely dependent on the CR's surroundings and environment.

Table 5.2.2.1: Positioning System Trade Study Heuristic Definitions

Metric	**Value Assigned**				
	1	2	3	4	5
System Mass	More than 25% CR mass	20% CR mass	15% CR mass	10% CR mass	Less than 5% CR mass
Power Consumption	Consumes more than 25% of CR power	Consumes 20% CR power	Consumes 15% CR power	Consumes 10% CR power	Consumes less than 5% CR power
System Cost	More than $1000	$750-$1000	$500-750	$250-$500	Less than $250
System Complexity	More than 6 man months to develop	5-6 man months	4-5 man months	3-4 man months	Less than 3 man-months to develop
Positioning Accuracy	More than 10 cm of error				Less than 1 cm of error
System Size	More than 25% system size	20% system size	15% system size	10% system size	Less than 5% system size
System Reliability	Positioning method is fully dependent on environment (e.g. landmarks)				Positioning method Completely independent of environment

Table 5.2.2.2: Positioning System Trade Study

		Odometry with Inertial Navigation	**1-D Range-finding**	**Range-finding with Stereoscopic Cameras**	**Deployable Active Beacons**
Metric	**Weight**	**Score**	**Score**	**Score**	**Score**
System Mass	5%	**5**	**5**	**4**	**2**
Power Consumption	5%	**5**	**5**	**4**	**5**
System Cost	15%	**5**	**4**	**4**	**4**
System Complexity	20%	**4**	**4**	**2**	**3**

Positioning Accuracy	30%	**4**	**5**	**5**	**4**
System Size	5%	**5**	**4**	**4**	**3**
System Reliability	20%	**4**	**3**	**4**	**1**
Weighted Total		**4.3**	4.2	3.85	3.1

5.2.3: Positioning System Trade Study Results

As shown in **Table 5.2.2.2** the design with the highest score after the trade study was positioning via odometry and inertial navigation. Before moving on it is important to discuss why this design won the trade study. This will be done by analyzing and justifying the scores given to each design.

Notice that one-dimensional range-finding was a close second choice. The laser range-finders that would be used on the CR for positioning are lightweight and have low power consumption. For this reason they were given 5's. The price was given a 4 because an individual range-finder can cost over $100. When considering that more than one range-finder may be necessary for a successful design it is easy to see the system could cost several hundred dollars. That being said, cheaper range-finders that use sonar as opposed to lasers do exist. Since range-finders will ideally return position directly to the CPU the system is expected to take approximately a month to develop. Range-finders are both accurate and small so they were given a 5 and 4 in those categories respectively. The main reason this method did not win the trade study is its dependencies on the surrounding of the CR. For example, obstacles would cause potentially large errors when the laser passes from the measuring point to the obstacle that are some distance apart. Another issue would be range-finding in a very long pipe. For these reasons it was given a 3 in reliability.

The score for range-finding with stereoscopic cameras was only slightly lower than the top two designs. The factors that significantly lowered this designs score was complexity. Even though this design scored 4's and 5's in all other categories, the 2 in complexity caused this design to lose the trade study. The reason the design is so complex is because of the complex image processing algorithm that would be required to extract the range of an object from multiple images.

The design with the lowest score was positioning via active deployable beacons. This design fell short in most categories but the two metrics that were given the lowest scores were mass and reliability. Mass was given a 2 because the beacons would have to rappel down the cave/pipe with the CR before being deployed and it is conceivable that these beacons could take up more than 15% the mass of the CR. The design was given a 1 in reliability because the success of the system is entirely dependent on the CR's surroundings. Recall that these beacons would have to be deployed to a known location to be effective. If the CR was in an environment such as a narrow pipe it would not be possible to deploy these beacons to their proper locations.

This leaves the winning design option, positioning with odometry and inertial navigation. This design received 4's and 5's for all design metrics. All sensors required for this design are small, lightweight, inexpensive, and have low power consumption. Because the design is a combination of two existing positioning techniques that could be effective solutions on their own it is no surprise that this design has the potential to be very accurate. This is also a very popular positioning technique used in robot applications so even though the team may not have experience with this technique there are a sufficient number of resources available to assist the team in developing this design. This is why the system was given a 4 for the complexity metric. Finally, the design was given a 4 in reliability because besides the possibility of slippage the design is mostly independent of the CR's surroundings.

Although odometry won the trade study the team has determined that while a combination of odometry and inertial navigation may be the best design for determining the distance the CR has traveled, one dimensional range-finding would be a more appropriate solution to determining the CR's depth. As stated in section 4.2.2, using odometry to determine depth would require tracking the rotations of the winch. This is a problem because as the CR rappels the radius of the winch decreases as the tether is unspooled. Range-finding would directly allow depth determination and would only require one range-finder.

5.3 Driving Subsystem

5.3.1 Trade Metrics and Weighting Explanation

Six metrics were analyzed to determine the optimal design choice for the Driving Subsystem. These are listed below and summarized in **Table 5.3.1.1.**

Mobility: refers to the CR's ability to traverse the required terrain. The CR must traverse over 3 cm diameter gravel (DR.3.3.1) and transition from vertical rappelling to horizontal movement (**DR.3.2**). Both of these derived requirements are included in mobility. Since this is the primary requirement of the Driving Subsystem, it has the highest weight.

Power Consumption: Once the CR has reached the cave floor, the main source of power consumption will be the driving subsystem. The functional requirements for the project require the CR to be able to determine its position, take photographs, and communicate with the GS continually. These all require power as well, so it is best for the driving system to use as little power as possible. Since Power Consumption relates back to three functional requirements, it is also highly weighted.

Complexity: This project will be completed by May 2015. To reach this goal, the Driving Subsystem must not be overly complex. Furthermore, additional complexity increases the likelihood of a system malfunction and increases the difficulty of any necessary repairs. For these reasons, complexity is the next-highest weighted metric.

Mass: DR.3.1.1 states that the CR must rappel 5m down a vertical face. The rappelling system will consume a large amount of power during its operation. The required power for the rappelling system is largely dependent on CR mass, as shown in appendix **A.1**. The driving subsystem will have a relatively large mass compared to the other subsystems on the CR. Therefore, a lower driving subsystem mass will help ameliorate the demands on the rappelling system, in accordance with **DR.3.1.1**. This metric is weighted relatively low because all of the investigated design options have comparable masses.

Cost: The entire project will cost less than \$5000, so cost for all subsystems must be considered. Cost is weighted low for the Driving Subsystem because all considered design options have a relatively low cost and the entire subsystem should cost less than \$500.

Size was not considered for this subsystem because any option chosen could be scaled to meet the design requirements. Durability was not considered because it is dependent on complexity and considering durability would give complexity an artificially high weight. The horizontal terrain to be traversed is also relatively benign so wear-and-tear on the driving mechanism will be minimal.

The weights for the five metrics were chosen by prioritizing the metrics and then scaling the weights so that the sum of the weights was 100%

Table 5.3.1.1: Design Metric Description and Weighting

Metric	Weight (%)	Explanation
Mobility	30	Project success depends on CR moving horizontally as directed and transitioning from vertical to horizontal. Odometry may also depend on reliable measurements.
Power Consumption	25	Taxes critical system utilized by the other subsystems. Limited power available.
Complexity	20	Project requirement to complete CR in a year. Simpler designs are less prone to error.
Mass	15	Maximum allowable weight defined by MR. Increased weight causes additional strain on rappelling system. Less important because all considered systems are of similar weight.

Cost	10	Low because of comparable and relatively low cost of considered design options

5.3.2 Driving System Trade Study

Using these weights, a trade study can be conducted to select a Driving Subsystem from the 4 options: 4-Wheel Fixed Chassis, 6-Wheel Articulated Chassis, 4-Wheel Rocker-Bogie, and Treads. In this trade study, each option will be scored on each metric according to the heuristics listed below and described in **Table 5.3.2.1.** For each of these heuristics, a score of 2 indicates that the design option meets the minimum requirements set by the heuristic.

Mobility Heuristic: The CR should drive over obstacles with constant speed

Power Heuristic: The Driving Subsystem should consume less than 60% of the total CR power after it has transitioned from rappelling to driving

Complexity Heuristic: Subsystem construction and maintenance should constitute less than 6 man-months.

Mass Heuristic: The Driving Subsystem should be less than 50% of the total CR mass

Cost Heuristic: The Driving Subsystem should cost less than $1000.

Table 5.3.2.1: Trade Study Heuristic Definitions

Metric	**Value Assigned**				
	1	2	3	4	5
Mobility	Does not clear obstacles	Clears obstacles at 0-25% speed	Clears obstacles at 25-50% speed	Clears obstacles at 50-75% speed	Clears obstacles at greater than 75% speed
Power	Consumes more than 60% of CR power	Consumes 50-60% CR power	Consumes 40-50% CR power	Consumes 30-40% CR power	Consumes less than 30% CR power
Complexity	Takes more than 6 man-months	Takes 5-6 man-months	Takes 4-5 man-months	Takes 3-4 man-months	Takes less than 3 man-months
System Mass	More than 50% of total CR mass	45-50% CR mass	40-45% CR mass	35-40% CR mass	Less than 35% CR mass
Cost	More than $1000	$750-$1000	$500-$750	$250-$500	Less than $250

The full trade study based on these metrics' weight and heuristics is shown in the table below.

Table 5.3.2.2: Drive System Trade Study

		4W Fixed	Articulated Chassis	Rocker-Bogie	Treads
Metric	**Weight**	**Score**	**Score**	**Score**	
Mobility	30%	**3**	**4**	**5**	**4**
Power	25%	**3**	**3**	**3**	**2**
Complexity	20%	**4**	**2**	**3**	**1**
Mass	15%	**4**	**3**	**3**	**2**
Cost	10%	**4**	**3**	**3**	**2**
Weighted Total		3.45	3.1	**3.6**	2.6

The rocker-bogie emerges as the optimal design choice based on its excellence in traversing the required terrain and obstacles. It achieved the highest score in the two highest metrics, mobility and power, and acceptable scores for the other metrics as well. The 4W Fixed design excels due to its simplicity, but it raises concerns regarding its ability to transverse the 3 cm gravel and to transition from rappelling to horizontal motion. Since mobility is the driving requirement for this subsystem, the Rocker-Bogie is the preferred option, despite the relatively close scores. Although the treads and articulated chassis options scored well in mobility, they fell short in other areas, particularly complexity.

The Rocker-Bogie has excellent mobility and good scores in all considered metrics. It is light and as power and cost efficient as the other considered systems. Furthermore, it has extensive heritage in rover systems, both at NASA and within the JPL legacy project at CU. For these reasons, the Rocker-Bogie is the recommended Driving Subsystem for this project.

5.4 Imaging Subsystem

5.4.1 Positioning Trade Metrics and Weighting

Many factors contribute to a successful imaging system design. This section will describe each of these factors as trade metrics so that a trade study can be performed. The metrics to consider are mass, power, cost, complexity, resolution/visibility, reliability, and size. These metrics are outlined in **Table 5.4.1.1** as well as the metric's percentage of importance to the subsystem.

Mass: Since the CR will be suspended by a tether of limited strength and that tether will likely be driven by a motor of limited power, the mass of each subsystem on the CR, including the imaging system, becomes significant. There are also mass requirements derived from being able to interface physically with the MR.

Power: It will be important to select an imaging system with low power consumption. A subsystem with a significant power consumption will require a larger power supply. For reasons such as mass and cost the size of the power supply will be limited.

Cost: The total project budget is $5,000. Taking this into account along with the fact that different imaging systems require different types of cameras and possibly motors of varying costs it's important to select a design that will not require expensive components.

Complexity: The complexity of this subsystem comes from having such a large FOV requirement. The subsystem must be able to in some way image within a much larger FOV than a standard fixed camera would be able to do.

Resolution/Visibility: The POI must be captured in the image. This means that the resolution must be great enough to at least capture the POI in at least one pixel of the image. However, this would not yield much more than the predominant color and general position of the POI so ideally the resolution will be great enough such that the image is clearly able to be distinguished.

Reliability: System reliability refers to being able to complete the mission successive times with no complications. With regards to the imaging subsystem this refers to being able to take an image of a POI with no complications every mission.

Size: System size refers to how much of the CR the imaging subsystem will take up. Ideally, this will be as small as possible to allow for other subsystems to have room on the CR.

Table 5.4.1.1: Design Metric Description and Weighting

Metrics	Percentage	Description
Mass	5%	There are very few parts of this subsystem that will have much mass. Some systems will have higher mass than others due to having additions cameras or motors but all these components have a very low relative mass to other subsystems.
Power Consumption	15%	The main component that will use power in this subsystem is the processor that will handle the images and possibly any motors that control positioning.
Cost	20%	Cost of cameras, motors and processors can become expensive.
Complexity	15%	Each variation of the subsystem will have their own added complexities. Some will be more than others and the idea of the study is to weigh if it's worth the added complexity of the system for an improved result over other proposed variations.
Resolution and Visibility	25%	The image taken of the POI must have at least one pixel that captures the POI as a whole. However ideally, the subsystem will have a high enough resolution and be able to capture the POI in low-light conditions while being able to clearly distinguish the POI.
Reliability	15%	The more complex the subsystem is, the more parts there are to have problems with especially over multiple missions.
Size	5%	The size of all components of this subsystem are relatively small in size compared to other subsystems on the CR.

5.4.2 Imaging System Trade Study

Now that each metric has been described and given a weighting, a trade study can be performed to select the most effective and appropriate imaging system for the CR. Recall that the three imaging design options are a single fixed camera with a wide angle lens, an actuated single camera, and multiple fixed cameras. In the following trade study each design option will be assigned a score of 1 to 5 with regards to each metric described and weighted in the section above. The heuristics given to each trade metric are shown below. The results are listed below in general and then further outlined in **Table 5.4.2.1**.

Mass Heuristic: Imaging system mass is expected to be low compared to the total mass of the CR. An ideal imaging system would take up less than 5% of the CR mass whereas a bad design option would take up more than 25% of the CR mass.

Power Consumption Heuristic: Imaging system power consumption is also expected to be low compared to the total power on the CR. Ideally, this subsystem would take up less than 5% of the total power on the CR but bad designs could require as much as 25% of the power on the CR.

Cost Heuristic: Given the budget of the project of $5,000 we need to keep this subsystem as cheap as possible. Ideally, the total cost would be under $250 but undesirable designs would be upwards of $1,000.

Complexity Heuristic: This must be simple enough to be completed in the given time for the project. Ideally, this would be done in under one month.

Resolution/Visibility Heuristic: The image taken of the POI must have at least one pixel that captures the POI as a whole. Ideally under low light conditions, this subsystem will be able to take an image in which the object is clearly able to be seen and distinguished. For a design to receive a 5 there should be not distortion within the image.

Reliability Heuristic: Ideally, all components used will not stop functioning at any point.

Size Heuristic: The size of components for this subsystem are relatively small. Ideally, the entire subsystem would not take up more than 5% of the CR however it could take up as much as 25% of the CR if designed improperly or less efficiently.

Table 5.4.2.1: Trade Study Heuristic Definitions

Metric	**Value Assigned**				
	1	2	3	4	5
Mass	More than 25% CR mass	20% CR mass	15% CR mass	10% CR mass	Less than 5% CR mass
Power Consumption	Consumes more than 25% of CR power	Consumes 20% CR power	Consumes 15% CR power	Consumes 10% CR power	Consumes less than 5% CR power
Cost	More than $1000	$750-$1000	$500-750	$250-$500	Less than $250
Complexity	More than 4 man months to develop	3-4 man months	2-3 man months	1-2 man months	Less than 1 man-months to develop
Resolution and Visibility	Image only captures POI in one pixel and possible distortion				POI is clearly visible in low-light conditions with no distortion
Reliability	Failure of components is more than 25% likely	Failure of components is 20% likely	Failure of components is 15% likely	Failure of components is 10% likely	Failure of components is 5% likely
Size	More than 25% of CR size	20% of CR size	15% of CR size	10% of CR size	Less than 5% of CR size

Table 5.4.2.2: Imaging System Trade Study

		Single Fixed Camera with Wide Angle Lens	**Actuated Single Camera**	**Multiple Fixed Cameras**

Metric	Weight	Score	Score	Score
Mass	5%	**5**	**4**	**4**
Power Consumption	15%	**5**	**4**	**4**
Cost	20%	**5**	**4**	**4**
Complexity	15%	**5**	**4**	**3**
Resolution and Visibility	25%	**2**	**5**	**4**
Reliability	15%	**4**	**4**	**4**
Size	5%	**5**	**5**	**4**
Weighted Total		4.1	**4.3**	3.85

5.4.3: Imaging System Trade Study Results

As shown in **Table 5.4.2.2** the design with the highest score after the trade study was actuated single camera. This is because it's able best image the POI while still not being very heavy, not using a lot of power, won't cost much, isn't very complex, is very reliable, and will be small. This solution will allow for the CR to take an image in which the POI is not distorted and will not require the CR to move as long as the POI is within the required FOV.

6.0 SELECTION OF BASELINE DESIGN

To decide on a baseline design, Team RACER used the results of trade studies that were conducted in addition to engineering intuition. By determining design solutions for each individual critical project element, the baseline design as a whole is created. This baseline design is as follows:

The CR rappelling system will consist of a winch on the MR and a tether that remains connected to the CR throughout the entire mission. The CR will determine its distance traveled through a combination of odometry and inertial navigation. One dimensional range-finding may also be used to determine the depth of the CR. The CR driving system will be a 4-wheel design on a rocker-bogie suspension system. The imaging system will consist of a single, actuated camera with resolution greater than 50x50 pixels. The system will have power sources on both the MR and CR. The power supply on the MR will be used to power the rappelling system and the power supply on the CR will power the remaining subsystems such as driving, imaging, and positioning. Regarding the communications system, the goal will be to interface RACER with the existing Wi-Fi system on the TREADS MR. However, if this goal is determined to be unattainable within the allowed design period of the course: the team will be forced to design a temporary communications system from scratch that will use RF communication. **Table 6.0.1** below shows each subsystem design that was selected along with a description of why it was selected and how it will be used to meet project requirements.

Table 6.0.1: Baseline Design Selections

Subsystem	Design Selected	Description
Rappelling System	**Winch on MR with a Constant Tether**	Performing the mission with a tether attached at all times was the most practical design option. This design option was the least complex with regards to both software and mechanics. Using a constant tether also helps ensure a completed mission and if

		something were to go wrong the MR could simply pull back the CR with the winch.
Positioning System	**Odometry and Inertial Navigation**	Using odometry and inertial navigation was determined to be both the most effective and practical design solution for positioning do to its inexpensiveness, low power consumption, accuracy, and lightweight nature. Odometry will be used to track the distance traveled and the inertial navigation components will make it possible to eliminate errors.
Driving System and Chassis	**4-Wheel with Rocker-Bogie Suspension**	This chassis came out on top during the trade study closely followed by the 4 wheel fixed chassis design. Each of these will be explored further through research and conceptual prototypes but the 4 wheel design provides optimal in both cases.
Imaging System	**Single, Actuated Camera**	Using a single actuated camera is inexpensive, can provide an image with greater than 50x50 resolution, and has low power requirements. It will also provide an image without distortion. For these reasons it won the trade study and was determined to be the best imaging system option.
Power System	**Power Supply on both MR and CR**	Putting a power supply on both the MR and the CR was the power systems design that came with the most advantages. This configuration allow one power supply to power the winch on the MR and a separate power supply to power the subsystems on the CR.
Communication	**Wi-Fi interface with TREADS**	Although this may not be the optimal design choice requirements **DR.2.1** state that the MR will be used to receive commands from the GS and send commands to the CR. This implies that the legacy Wi-Fi communication system will be used.

7.0 REFERENCES

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APPENDIX

A.1 Voltage Drop across 10m of Stranded 20AWG Wire @ 12A

Because of the 5m vertical and 5m horizontal travel requirements, 10m of total required wire is reasonable if power is being transmitted through a tether between the MR and CR. The current value of 12A was picked because a standard DC motor draws approximately 6A and all driving subsystem designs considered use two-wheel drive.

From George Washington University, the DC resistance per km of stranded 20AWG copper wire is ~33Ω/km. With a 10m length of wire, the total resistance R_c=0.33Ω. Using Ohm's law to calculate the voltage drop, V_C, we find:

$$V_C = IR_C = 3.96V$$

Using the electrical power equation P = IV, it is found that the power loss through the cable would be approximately 47.5 watts for stranded copper wire.

If 20AWG stranded aluminum wire is used instead to save on cost as well as weight, all values would increase by a factor of 1.54 due to the larger resistivity of aluminum (from the Engineering Toolbox website).

If 10 AWG stranded wire was used instead of 20AWG, the voltage drop and power loss for the wire would decrease to a 10th of what was calculated. However, the total mass of the cable would be approximately a 1kg (0.5kg for 10m, but two wires are needed for the positive and negative voltage lines). The total mass of an aluminum cable would only be approximately 0.3kg based on the relative density of aluminum to copper.

A.2 Work Modeling for Rappelling and Driving

In order to model the work done during rappelling, a free body diagram was set up as shown in **Figure A.2.1**. Because the CR will rappel at a constant velocity, the tension force, $\vec{F}_T$, and weight, $\overrightarrow{W}$, balance so there is no net force on the CR. The CR's mass is known to be at maximum 9.8 kg and the acceleration due to gravity is 9.81 m/s^2. Therefore, the rappelling subsystem must exert 96.1 N of force on the CR throughout lowering and raising the CR 5 meters (10 meters total). The work calculation for rappelling is shown below:

$$Work_{rappelling} = W * d = 96.1N * 10m = 961\,Joules$$

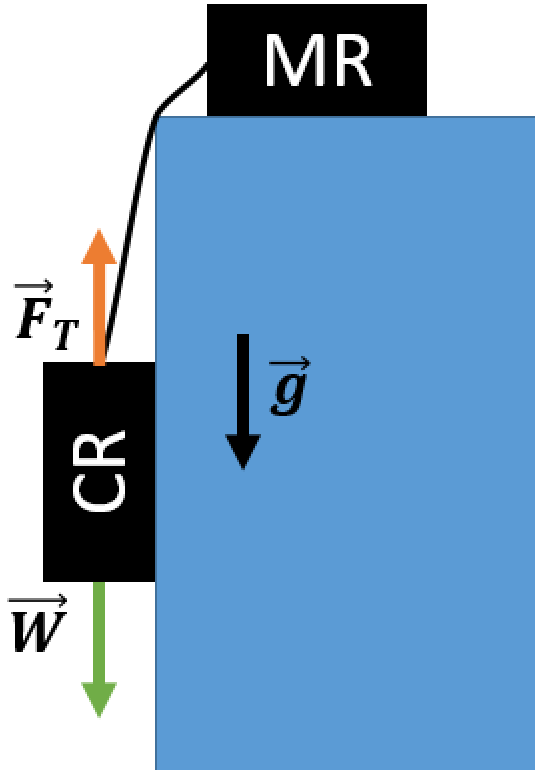

Figure A.2.1: Free body diagram for the CR during rappelling.

To model the work done while driving, conservation of energy is applied to the CR as it moves over small rocks with 3 cm diameters. The work done to raise the CR's mass is simply its weight in Newtons multiplied by the height it is raised (3 cm). Because the CR's driving subsystem will not be designed to recover un-powered wheel rotation as electrical energy, the work done by gravity as the CR rolls down the other side of the pebble has no effect on the work required to drive. The floor that the CR will drive over will only be sparsely covered by small rocks. If a 5 cm wheel diameter and constant 3 cm rock diameter is assumed, the maximum number of rocks encountered per meter of distance traveled is 100/(5+3) =12.5 (so that the wheel can fully return to the ground before climbing the next rock). Assuming zero wheel slip as well, the work done to drive 10 meters (5 meters out and back) is shown below:

$$Work_{driving} = (96.1N)(0.03m)\left(\frac{1}{rocks}\right) * \left(\frac{12.5rocks}{m}\right) * (10m) = 360\,Joules$$

If a non-fixed suspension design is used such as a rocker-bogie, the driving work is significantly reduced because the entire CR mass is not raised over each obstacle encountered.

Typical commercial-off-the-shelf brushless DC motors have efficiencies ranging from ~80-85%, but both the rappelling and driving subsystems will be affected equally by these inefficiencies so their relative magnitudes will remain approximately the same ($Work_{rappelling}/Work_{driving}$=2.7).

A.3 Model for determining maximum allowable tether deviation upon docking

Figure A.3.1 below shows the dimensions of the MR as well as the maximum allowable tether deviation upon docking with the MR. Note that several assumption were made for this calculation. The size of the CR was set as the maximum allowable size, 19". It is also assumed the tethers point of contact to the MR is at the center of the back of the docking bay and that the point of contact on the CR is at the center of the rear end of the CR. The calculations are shown below.

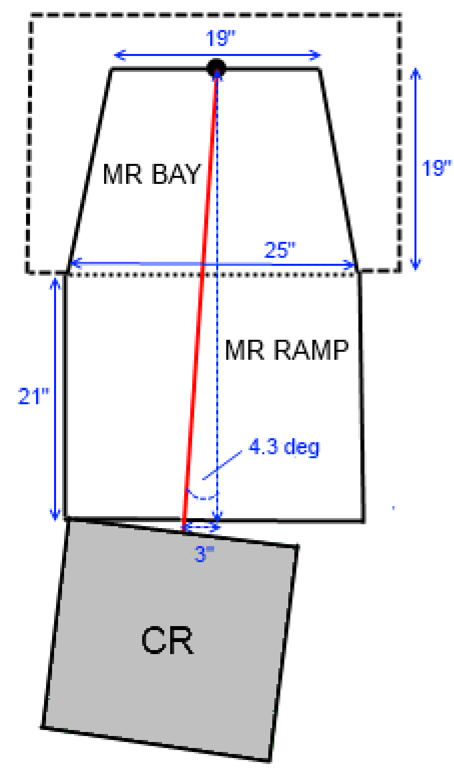

Figure A.3.1: MR dimensions used for docking angle allowable deviation calculations

*Distance from back center of the MR bay to the end of ramp **d** = 40".*

*Horizontal distance between center of ramp and CR point of contact **h** = 25"/2 - 19"/2 = 3"*

Max deviation = arctan(3/40) = 4.3 degrees.

Requirement: Upon approach for docking the tether deviation angle must be less than 4.3 degrees when the CR reaches the edge of the MR ramp.

A.4 Model for determining minimum pixels needed to capture POI with at least one pixel

The diagram below (**Fig A.4.1**) depicts how to determine the minimum number of pixels required by the imaging subsystem in order to capture the POI in at least one pixel.

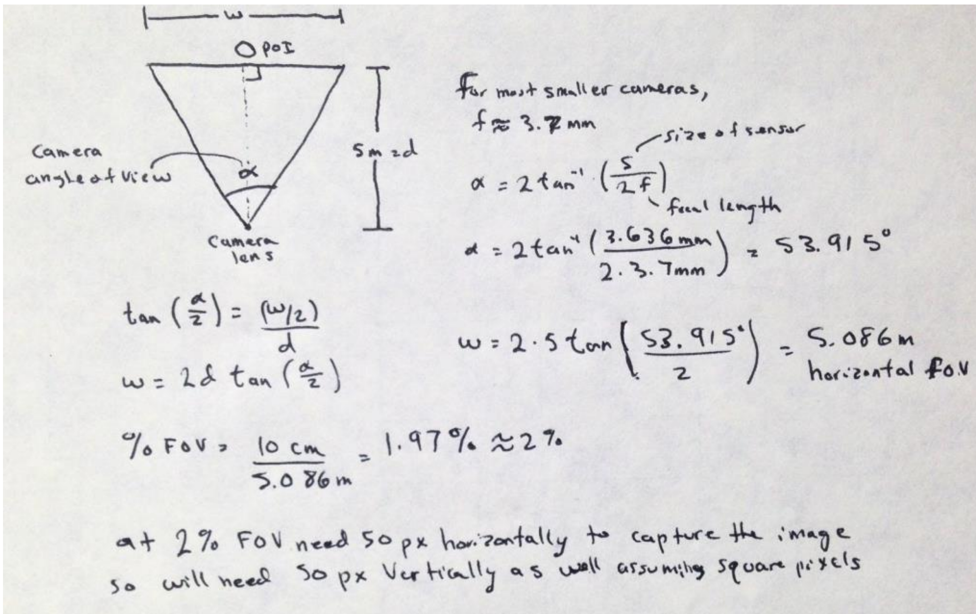

Figure A.4.1: Diagram for minimum required resolution

A.5 Definition of Adequate Scene Lighting

The images below were taken to estimate the lighting level required to see an object from 5m away in a low lighting setting. Notice in **Figure A.5.2** the rock can just barely be seen at a 50 lumen setting. From this experiment it was determined the CR will need a light that supplies at least 50 lumens.

a. Rock *b. Yellow Cup*

Figure A.5.1: 25 lumens from a light 16" above the ground and 5m away from POI

b. Rock *b. Yellow Cup*

Figure A.5.2: 50 lumens from a light 16" above the ground and 5m away from POI