University of Colorado
Ann and HJ Smead Aerospace Engineering Sciences Department
ASEN 4028: Senior Projects

Project Final Report (PFR)

Range Extending System to Complement Underground Exploration (RESCUE)

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0.1 List of Acronyms

Acronym	Definition
ClearPath Husky	The ground robot used by MARBLE, on which the project's sensor system will be supporting
DARPA	The Defense Advanced Research Projects Agency. The agency organizing the Subterranean (SubT) Challenge.
FC	Functional category
FOV	Field of View.
GPIO	General Purpose Input/Output
FR	Functional requirement
I^{2}C	Inter-integrated circuit, a synchronous serial communication bus used by RESCUE for data transfer
IDE	Integrated development environment. This often describes a software application that provides comprehensive facilities to programmers for software development.
MARBLE	CU's team competing in the DARPA Subterranean Challenge, stands for Multi-agent Autonomy with Radar-Based Localization for Exploration
NASA	National Aeronautics and Space Administration
NFC	Nested Firing Command. Explained in section 0.2.
PWM	Pulse-width modulation, a square-wave command send to electronics such as motors
RESCUE	Range Extending System to Complement Underground Exploration
ROS	Robot Operating System
TDR	Technical Design Requirement
UGV	Unmanned Ground Vehicle, most often used to refer to the ClearPath Husky in this document.

0.2 Definitions

Due to the unique nature of this project, this section is intended to define terms appearing throughout the document with specific meanings to ensure mutual understanding.

- **Activation Command:** A command sent from the MARBLE team to the sensing system to transition from a standby state to an active state.
- **Active State:** The sensor system state after an activation command, where the system is ready to receive a firing command. For example, a drone sensor system in an active state would be unattached to the Husky and ready to take off as soon as a firing command was recieved.
- **Artifacts:** Set of objects with distinct characteristics confirmed by DARPA to be found in undisclosed locations within the cave. Points are awarded to competitors in the DARPA SubT challenge for locating and identifying artifacts accurately [1]. The exact details on each artifact are listed in appendix section A.

- **Customer acceptance test:** A validation method. Ensuring that the costumer is satisfied with the product and meets their expectations.

- **Deactivation Command:** A signal sent from the MARBLE rover to the sensing system to terminate its current activity and return to it standby state.

- **Deployment:** The process of the sensor system going from its active state to an operational state in a location or set of locations commanded by the MARBLE team with a firing command or a nested firing command.

- **Detect:** Recognizing an artifact from sensed data.

- **Final Competition Environment:** The physical environment the team's system is expected to be used in. The Final Competition course is selected by DARPA as an underground, enclosed environment including human-made tunnel networks, urban and municipal underground infrastructure, and natural cave networks [1]. Throughout this document, the words **"Cave"** and **"Final Competition Course"** generalize this environment.

- **Firing Command:** A signal sent from the MARBLE team to the sensor system to deploy to a specific location relative to the ground robot inside the sensor system's physical reach.

- **Nested Firing Command:** A command that comes after the main firing command to order the system to deploy to another location relative to the current location of the sensing system. Nested Firing Commands (NFCs) could be repeated as many times as the operator wants, however, in practical competition the NFCs effectiveness is limited by the sensor system's physical and sensing reach capabilities and competition time.

- **Obstruction:** Any terrain or object that can block the travel of the Husky or a sensor apparatus it deploys. For example, a partially blocked doorway in the urban portion of the completion environment would be considered an obstruction.

- **Operational Conditions:** Term used to indicate the terrain and ambient conditions expected in the final competition environment. According to DARPA's documentation, these conditions typically include hazards or obstacles such as darkness, dust, fog, mist, smoke, sudden changes in terrain elevation, confined or low ceiling clearance spaces, and water puddles [1].

- **Operational State:** The sensor system state when the system is deployed and sensing. This includes the process of deployment, gathering data, transmitting data, and returning to the standby state again.

- **Physical Reach:** How far the sensing system can move its sensors from where they are stowed on the Husky. For example, the physical reach of a drone would be the locations it could fly to after launching off the Husky.

- **Reusability:** The sensor system's ability to receive multiple firing commands to the system after the course of the mission. Each deployment is process has its own unique firing command. For example, a sensor system using a set of launched projectiles containing sensors is reusable if multiple sensor projectiles can be launched over the course of MARBLE's mission.

- **Sense:** To collect data from the environment a given sensor is operating within. The sensed data will change from sensor to sensor, for example a visual signature sensor might collect still images or color video.

- **Sensing Reach:** How far the sensing system can sense. For example, a robotic arm with an attached camera would have a physical reach only as far as the arm could extend from the Husky, but the sensing reach would be determined by how far the attached camera could sense artifacts successfully.

- **Sensor Apparatus:** The component of the sensor system moving a sensor into position, the sensor being the component that is actually sensing artifact signatures. For example, if the sensor system was a drone carrying a camera on a gimbal, the drone and gimbal would be sensor apparatus while the camera would be the sensor.

- **Standby State:** The state in which the sensor system is powered on and ready to receive firing commands from the MARBLE team, but is not currently being used and is in a stowed position where the MARBLE Husky can go about its regular mission.

- **Unobstructed:** Defined relative to sensor system mobility requirements. Unobstructed indicates a straight line radius from a mounting point on the MARBLE team's ground robot that is not physically blocked by impassible terrain, such a solid ground surface that cannot be maneuvered around, or components of the Clearpath Husky that cannot be traveled through.

- **Usability Test:** A validation method. A technique used in user-centered interaction design to evaluate a product by testing it on users. This can be seen as an irreplaceable usability practice, since it gives direct input on how real users interact with the system.

- **Validation:** The assurance that a product, service, or system meets the needs of the customer and other identified stakeholders. It often involves acceptance and suitability with external customers [2].

- **Verification:** The evaluation of whether or not a product, service, or system complies with a regulation, requirement, specification, or imposed condition. It is often an internal process [2].

- **PLA:** Polylactide 3D printed plastic. Note that all mass estimates for PLA plastic components were assumed to be printed at 100% infill density with a material density of 1.24 g/cm^3 [3].

1 Project Purpose

Author(s): Seth Krein

Range Extending System to Complement Underground Exploration (RESCUE) is centered around improving the University of Colorado Boulder's MARBLE team's performance in the DARPA Subterranean challenge. Running since 2018 and currently scheduled to conclude in August 2021, the purpose of the challenge is to improve semi-autonomous robotic capabilities for military and emergency response organizations operating in underground environments [1]. The primary objective of this competition is to correctly identify and report "artifacts," such as survivors (represented by thermal dummies), cell phones, tools, ingress and egress points, and gas leaks. The existing MARBLE sensing suite is bound to an unmanned ground vehicle (UGV), offering no sensing range beyond its immediate line of sight. As such, the purpose of RESCUE is to extend the sensing range of the MARBLE team's UGV in order to identify artifacts in hard-to-reach locations. This objective will be achieved through the development of a soft robotic arm that is capable of extending a sensor package over three meters from the ground vehicle. Soft robotics is a relatively novel technological advancement that has yet to be utilized in a mission such as this despite the fact that they offer a superior range to traditional robotic arms without added mass or volume when stowed.

UGV's sensing capabilities are typically limited in comparison to airborne drones; however, they offer a far greater endurance, thus offering increased capability in long-duration missions. The inability of ground-based robots to sense environments blocked by hazards such as ledges, crevices, and holes is a weakness that this project will seek to overcome. When retrofitted with the RESCUE sensor system, ground-based robots, such as the MARBLE team's Clearpath Husky, will have the capability of visually sensing the entire environment within at least a three-meter hemisphere above the robot. This capability will provide a ground-based robot with an edge over airborne drones in a vast majority of subterranean missions. Whether that be the DARPA Subterranean challenge or military and/or emergency response applications.

2 Project Objectives and Functional Requirements

2.1 Levels of Project Success

The objectives of this project are outlined in the table below and the success of each will be measured by three levels that build upon each other. Achieving level two or three will imply success in the lower level(s). Each level demonstrates increasing difficulty of achievement and increased capability of the sensor system.

Table 1: *Levels of Success*

	Level 1	Level 2	Level 3
Sensing Range	All sensors can be utilized to effectively sense their respective artifacts within 3 meters of MARBLE's Husky in any given accessible direction.	All sensors can be utilized to effectively sense their respective artifacts within 4 meters of MARBLE's Husky in any given accessible direction.	All sensors can be utilized to effectively sense their respective artifacts within 5 meters of MARBLE's Husky in any given accessible direction.
Physical Reach	Sensor apparatus has the ability to physically reach a location that is along an unobstructed radial path at least 1 m, but not more than 5m from its mounting location.	Sensor apparatus has the ability to physically reach a location that is along an unobstructed radial path at least 2.5 m, but not more than 5m from its mounting location.	Once the sensor apparatus is re-positioned, the mechanical mount for the visual artifact signature sensor shall be capable of rotating $\geq 90°$ about at least one axis.
Artifact Sensing	The sensor suite shall be able to visually sense the following brightly colored artifacts: human survivor, backpack, fire extinguisher, and rope.	The sensor suite shall be able to sense and detect CO_2 at approximately 2000 parts per million concentration.	
System Position and Orientation	Sensor apparatus able to determine and report its position relative to the Husky within 1 meter accuracy of its ground truth location.	Sensor apparatus is capable of reporting its orientation relative to the Husky with $\leq 5°$ accuracy.	
Response to commands	The total time to go from standby state to active state shall be $\leq 30[s]$.	The time of responding to firing commands should be instantaneous $\leq 1[s]$	The time between receiving deactivation commands returning to standby state shall be $\leq 120[s]$
Usage	The sensor apparatus can be deployed and utilized $\leq$5 times.	The sensor apparatus can be deployed and utilized $\leq$10 times.	The sensor apparatus can be deployed and utilized $\leq$15 times.
Endurance	Sensor system is able to maintain an active state where it is sensing for 25% of MARBLE average competition operation (30 minutes) and a standby state for 100% average competition operation and setup time (135 minutes).	Sensor system is able to maintain an active state where it is sensing for 50% of MARBLE average competition operation (60 minutes).	Sensor system is able to maintain an active state where it is sensing for 75% of MARBLE average competition operation (90 minutes).
Communication	Communicate sensing data with MARBLE before next deployment. (1-Way)	Communicate sensing data with MARBLE upon request. (2-Way)	Communicate sensing data with MARBLE asynchronously as the sensor system operates. (2-Way continuous)

2.2 CONOPS

Author(s): Abdulla AlAmeri, Ryan Hughes

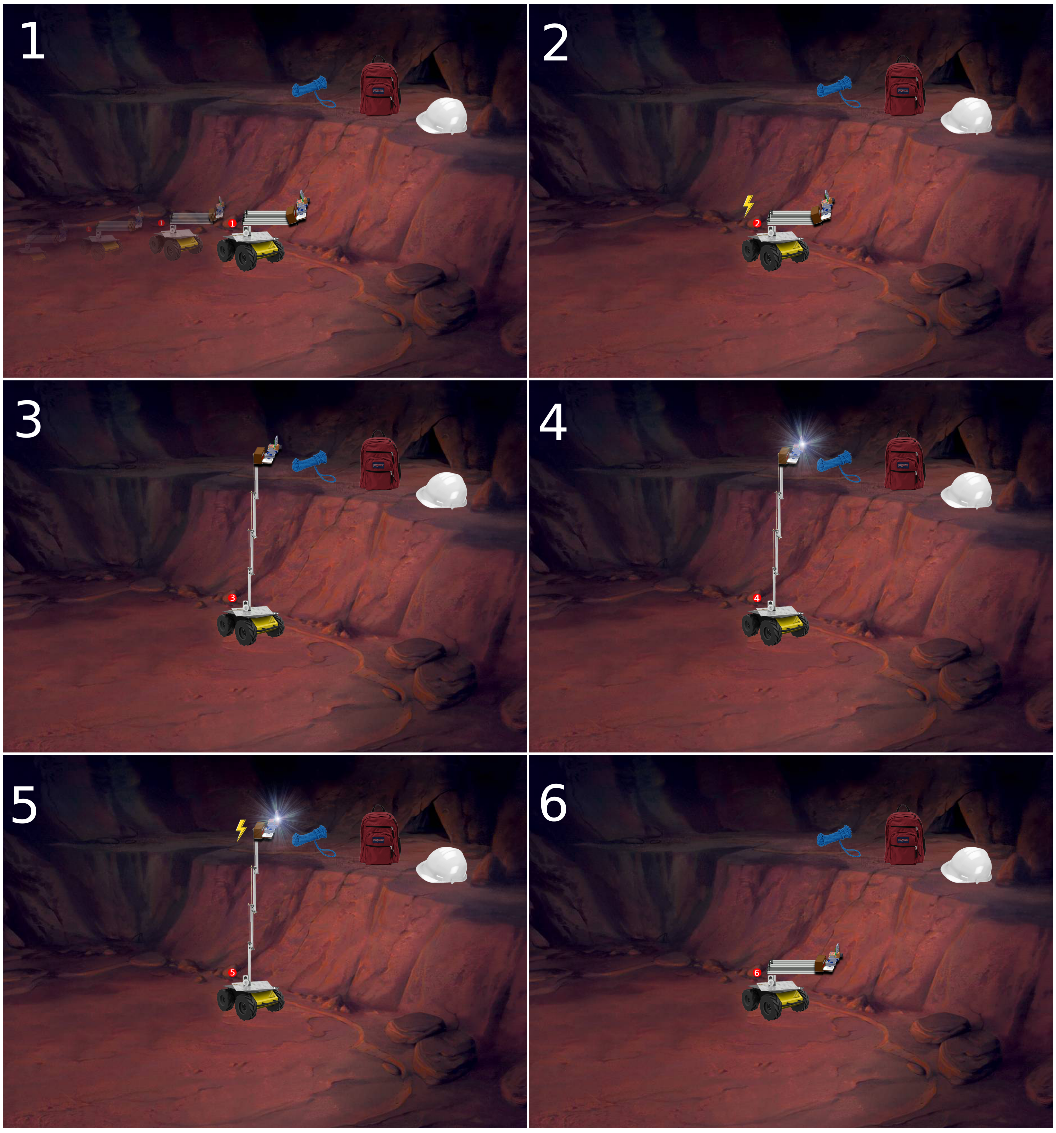


Figure 1: Concept of Operations (CONOPS)

Shown in Figure 1 is the Concept of Operations, or CONOPS, of RESCUE's designed functionality. The use process of the full RESCUE system can be described in 6 phases, as listed below:

1. The RESCUE system travels with the MARBLE Husky while in standby mode
2. RESCUE receives a firing command from MARBLE containing a target deployment location in relative coordinates
3. The RESCUE system switches to active mode and deploys to the target location
4. The sensor suite collects CO_2 and image data
5. Collected data is transmitted from the end effector to the RESCUE base module, then to the MARBLE Husky

6. If RESCUE receives no further commands, the system returns to standby mode until the next deployment

2.3 Project Deliverables

Author(s): Ryan Hughes

The project deliverables expected of the RESCUE team can be classified into two categories: Course Deliverables and Customer Deliverables. As the names suggest, the former is in regard to the Senior Projects course for which the RESCUE team was formed, and the latter is in regard to the customer who proposed the project and presented the MARBLE team's current challenge that this project aims to overcome. Course deliverables were also sent to the customer as a means of displaying progress on the project. Both deliverable categories and their contents are listed below.

Course Deliverables

- **Project Definition Document:** Document defining the project scope and specific objectives
- **Conceptual Design Document:** Document detailing specific project requirements and high level design solution, accompanied by a description of the selection process
- **Preliminary Design Review:** Presentation on the feasibility of the baseline design
- **Critical Design Review:** Presentation on the final design including design, analysis, logistical feasibility, as well as manufacturing and test plans
- **Fall Final Report:** Document detailing final proposed design solution including all necessary and relevant information
- **Manufacturing Status Review:** Presentation including a manufacturing status update as well as an integration plan
- **Test Readiness Review:** Presentation on plans for verification & validation, along with necessary safety measures
- **Senior Design Symposium:** Public presentation of final project conveying project highlights and results
- **Spring Final Review:** Presentation on the final project including verification & validation results addressing all requirements
- **Project Final Report:** Document detailing final project results and lessons learned, serving as a basis for future work

Customer Deliverables

- **Physical System:** All physical components of the system, including the base, extension mechanism, end effector, and sensor suite
- **Software:** Communications, controls, and data collection

- **Installation Guide:** Instructions and specifications for configuring and operating the RESCUE system
- **Firing Command Specifications:** Required format for firing command compatibility with RESCUE software

2.4 Functional Block Diagram

Author(s): Ryan Hughes

Shown in Figure 2 is the Functional Block Diagram (FBD) describing the interaction between RESCUE components and subsystems. The diagram is broken into 5 subsystems, denoted by colored boxes containing modules. As portrayed in the legend at right, the arrows between modules are color-coded by function (e.g. power supply or data/command transmission).

The MARBLE host system will be supplying power to required components of the RESCUE system, such as the servos, motors, and Raspberry Pi microcontroller. MARBLE will also provide firing commands containing a target end effector location to RESCUE in return for sensory data and status reports from deployment. Data exchange is executed using the Robot Operating System (ROS) architecture consisting of modules called 'nodes' that exchange information over channels called 'topics.' All data transfer between RESCUE and MARBLE will be executed over a Gigabit Ethernet cable from a designated port on the MARBLE UGV to a port on RESCUE's base Raspberry Pi.

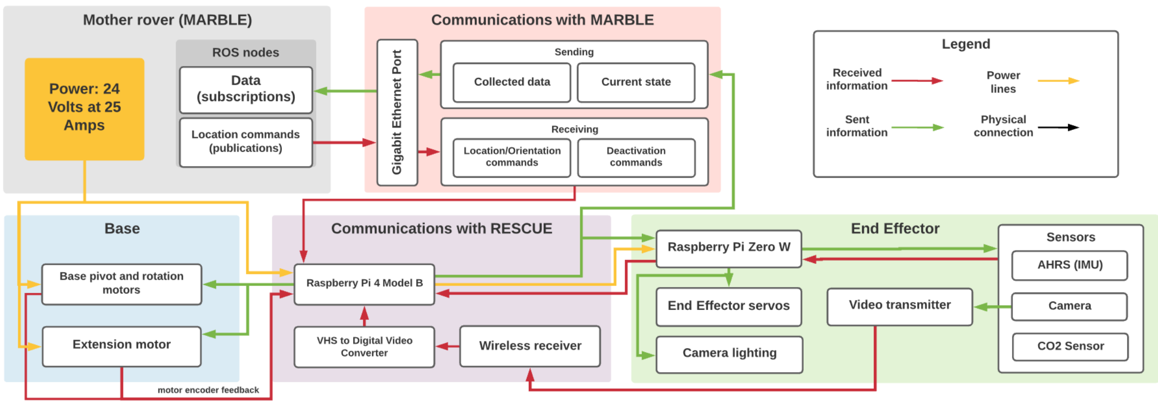


Figure 2: Simplified Functional Block Diagram

2.5 Functional Requirements

Author(s): Ryan Hughes, Abdulla AlAmeri, Michael Martinson

FRs	TDRs	Requirement
FR 1.1		RESCUE shall have the ability to physically reach a location along an unobstructed linear path that is at least 1 meter but not more than 5 meters away from RESCUE's stowing position on the MARBLE Clearpath Husky.
FR 2.1		The sensing system shall be able to sense DARPA subterranean challenge competition artifacts
	TDR 2.1.1	The sensing apparatus shall have the capability to visually sense the following brightly colored artifacts: human survivor, backpack, fire extinguisher, and rope. The visual sensing of these artifacts shall occur within the visual sensor's operational field of view
	TDR2.1.2	The sensing apparatus shall be able to sense and detect carbon dioxide (CO2) at 2000parts per million concentration.
	TDR2.1.3	Once RESCUE is repositioned, the mechanical mount for the visual artifact signature sensor shall be capable of rotating at least 90° or more about at least one axis.
	TDR2.1.4	RESCUE shall have enough lighting to perform all of its sensing operations in a possibly aphotic environment.
FR 3.1		RESCUE shall determine and report its location and orientation relative to the ground robot
	TDR 3.1.1	RESCUE shall be able to determine its position relative to the ClearPathHusky, within 0.1-0.5 meter accuracy of its ground truth location at all times
	TDR 3.1.2	RESCUE shall be able to determine its orientation to the ClearPath Huskywithin 5° accuracy of its ground truth orientation at all times.
FR 4.1		When in its standby configuration, RESCUE shall be compatible with the MARBLEteam's Clearpath Husky.
	TDR 4.1.1	When in its standby configuration, RESCUE shall not exceed a volume of 38 centimeters wide by 45 centimeters long by 30 centimeters tall.
	TDR 4.1.2	RESCUE shall not exceed a total mass of 10 kilograms
	TDR 4.1.3	If RESCUE is directly connected to the Husky, power drawn from the Husky robot shall be less than or equal to 24-30 Volts at 25 Amps.
	TDR 4.1.4	When RESCUE is deploying, in its active state, or in its operational state, the sensing apparatus shall not apply a force or moment that can unintentionally alter the position and/or orientation of or damage the MARBLE Clearpath Husky
FR 4.2		RESCUE's deployment operations shall be rapid enough to incur a minimal time cost toMARBLE's total mission time.
	TDR 4.2.1	Upon receiving an firing command from the MARBLE team when in standby configuration, RESCUE shall reach an active state in 30 seconds or less.
	TDR 4.2.2	Upon receiving a firing command from the MARBLE team when in its active configuration, RESCUE shall respond in an operational state as soon as (< 1 second) the command is received.
FR 5.1		RESCUE shall accomplish all other design requirements in an nominal thermal environment of 50-65°F.
FR 5.2		RESCUE shall have enough electrical power to maintain standby, active, and operational states fitting the MARBLE team's mission performance expectations.
	TDR 5.2.1	RESCUE shall have enough electrical power to maintain a standby state for at least 135 minutes.
	TDR 5.2.2	RESCUE shall have enough electrical power to maintain an operational state for at least 30 minutes.
FR 5.3		RESCUE shall withstand repeated deployments.
	TDR 5.3.1	The MARBLE team shall be able to deploy RESCUE at least 5 times during a competition run.
FR 6.1		RESCUE shall communicate its sensed data with MARBLE and this process shall not interfere with MARBLE's communication systems. RESCUE shall be able to receive firing commands, nested firing commands, and deactivation commands from MARBLE's team.
	TDR 6.1.1	RESCUE shall be capable of receiving firing commands from the ROS nodes in the existing MARBLE architecture.
	TDR 6.1.2	After deployment and retraction, RESCUE shall communicate sensing data with the MARBLE robot before its next deployment, or within approximately 60 seconds.
	TDR 6.1.3	RESCUE shall transmit data to the MARBLE robot through a wired connection that will remain securely attached and functional throughout the duration of competition use.
	TDR 6.1.4	RESCUE shall deliver frequent status reports to the MARBLE robot regarding deployment status and data collection

Figure 3: All functional/technical design requirements

3 Final Design

3.1 Final Design Overview

Author(s): Michael Martinson

The figures below provide an overview of RESCUE's complete form both in its stowed and extended states; note that fasteners are not included in the CAD models:

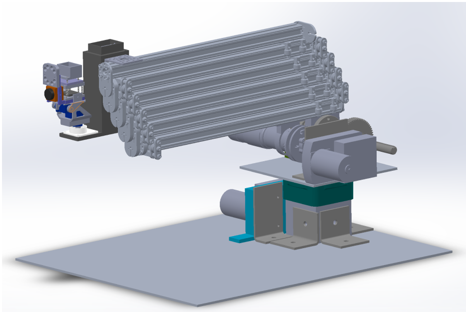
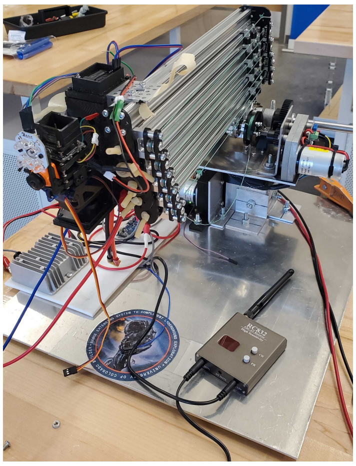
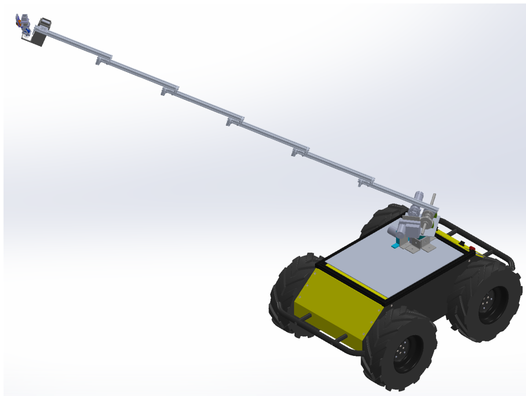


Figure 4: RESCUE Complete System CAD Model (Unmounted, Stowed)



(a) Complete System (Unmounted, Stowed)



(b) Complete System CAD Model (Mounted, Extended)

Figure 5: RESCUE Complete System Stowed and Extended

Table 2 indicates key system design parameters in relation to pertinent requirements:

Table 2: *System Overview Parameters*

Parameter	**Value**	**Requirement**
Sensor Package Extension Distance	1.89 m	1 m $\leq$ Distance $\leq$ 5 m (FR 1.1)
Stowed Volume	38.1 x 45.5 x 30.40 cm	38.1 x 45.72 x 30.48 cm (TDR 4.1.1)
Mass	6.6 kg, 8.09 kg with baseplate	10 kg (TDR 4.1.2)
Power Consumption	265.3 W	600 W (TDR 4.1.3)
Reusability	Up to 50 deployments	Up to 15 deployments (TDR 5.3.1)

RESCUE's subsystems, along with the functional requirements they primarily address, are identified in table 3 and discussed in subsequent subsections:

Table 3: *Subsystems List*

Subsystem	**Functional Requirements**
Extension	1.1, 4.1, 4.3, 5.3
Orientation	1.1, 4.1, 4.3, 5.3
End Effector	2.1, 3.1, 4.1, 4.3, 5.1
Base Electronics	2.1, 3.1, 4.2, 4.3, 5.2

3.2 Extension System: Structure

Author(s): Michael Martinson

In order to meet FR 1.1, RESCUE must be capable of extending its sensor package at least 1 m from its base along any unobstructed direction. To meet this requirement, the team designed a modified version of Servo City's Cascading X Rail Slide kit as RESCUE's "arm". The figure below diagrams the dimensions and structural elements of the arm. Note that the extension block, retraction mechanism, and pivot block are are discussed in later subsections.

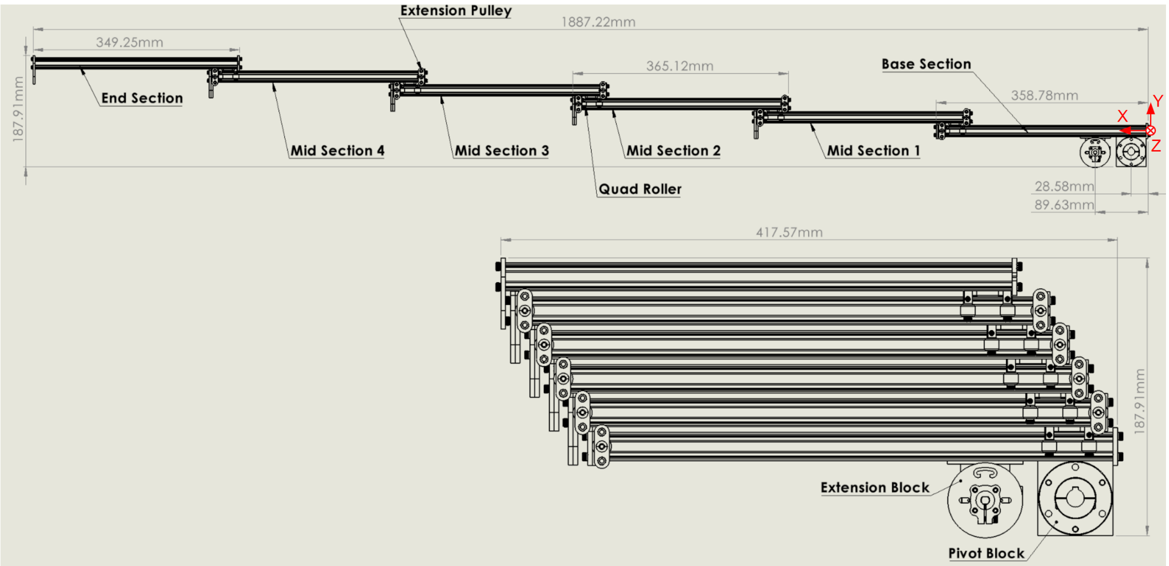


Figure 6: Extension System: Extended and Retracted Dimensions; Main Structural Elements

The arm consists of 6 aluminum rail sections connected using quad roller assemblies (fig. 7b) that allow each section to slide out once the extension system provides tension on the extension pulleys (fig. 7a). Middle (Mid), End, and Base sections all feature slightly different end hardware; the system was developed by modifying Servo City's COTS X Rail Slide kit by adding two additional middle sections.

(a) Extension Pulleys

(b) Quad Roller Assembly, Isometric CAD View

Figure 7: Extension System: Pulleys and Quad Roller

For purposes of designing the pivot and rotation system, the team modeled the entire assembly as 1060 Al alloy. Quad roller and pulley assemblies anchored to a segment were included in that segment's mass estimate. This strategy proved to be highly accurate: it results in a 630g mass estimate for a 4 section arm, whereas the actual mass of a 4 section segment is 640g. To simplify the moment of inertia computations, the team ignored the pivot block and assigned the Cartesian coordinates shown at the rear of the arm in fig. 6. The extension block was treated as a 450g point mass at the end of the arm, while the extension block was treated as a 520g point mass at +90mm in the X direction (mass values explained in later subsections). Moments of inertia of the 6 X rail sections were computed with the SolidWorks model. Pertinent values resulting from this approximation are as follows:

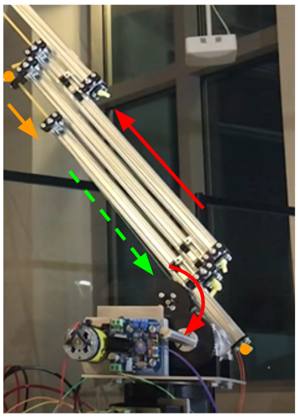
Table 4: *Extension System Structural Model Results*

Item	Value
Base Section Mass	138g
Mid Section Mass	176g
End Section Mass	143g
I_{zz}, Total System, Collapsed	0.149 kg m^2
I_{yy}, X Rail Segments, Extended	1.14 kg m^2

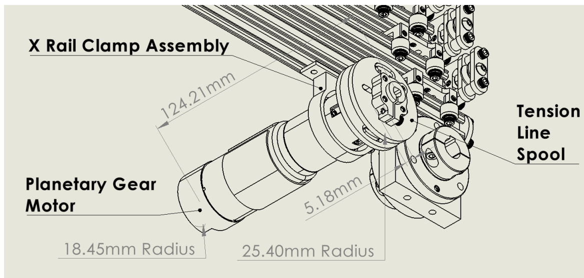
3.3 Extension System: Extension and Retraction Mechanisms

Author(s): Abdulla AlAmeri, Evan Welch, Michael Martinson

Paired with the reach requirement of FR 1.1, TDR 4.3.1 dictates that RESCUE shall fully deploy to any orientation within 30s. To meet these needs, the team developed the extension and retraction system diagrammed below:



(a) Extension/Retraction System Diagram



(b) Extension Motor Assembly

Figure 8: Extension/Retraction System: Functional Diagram and Extension Motor Assembly

Fig. 8a indicates key operational elements of the extension and retraction system. A motor with a connected winch (red curved arrow) puts tension on a 200lb test line (green arrow) that is connected to each sections' pulleys and causes them to force their section outward (red arrow). The extension motor mounting assembly is diagrammed in fig. 8b; a 5202 Series Yellow Jacket Planetary Gear motor provides 68.5 kg-cm of stall torque and 117 RPM unloaded at 12V [4]. This enables full extension in any orientation within ≈ 12s. All components of the extension system diagrammed in fig. 8b have a ≈ 520g mass.

Retraction is accomplished by reversing the extension winch's direction of rotation to spool in cabling as the surgical tubing connecting the X rail segments applies tension force (fig. 8a, orange arrow) to cascade the arm back to its stowed position. The team iteratively determined the required tension in each cable to ensure complete retraction from any orientation over the course of integrated system testing; the tension load in a given cable can be adjusted simply by adjusting each attachment knot's position (fig. 8a, orange dots).

3.4 Orientation System: Rotation Mechanism

Author(s): Jack Zeidlik, Michael Martinson

FR 2.1 states that the system shall be able to reach any location in a hemisphere located above MARBLE's Clearpath Husky, while TDR 4.3.1 requires the system to deploy to any sensing location within 30s. For the rotation portion of the orientation system, these requirements equate to a need for a system that can rapidly rotate across the entire 360° range required about an axis vertical relative to its base. This rotation was developed to act while the arm was collapsed; again the arm deploys in a "rotate - pivot - extend" order.

Developing the rotation system required the use of a modeled approximation of the worst-case scenario of rotating the arm while at full extension. The moment of inertia of the arm's X Rail sections about the y axis in fig. 6 (I_{yy}, X Rail Segments, Extended) was calculated utilizing the SolidWorks CAD model. The end effector and extension system were considered as point masses under the estimations described in section 3.2. Angular acceleration of 1 rad/s^2 was used and converted for the linear torque equation. Below is the equation used:

$$\tau = I_{yyext} * \alpha + m_{EE} * d_{ext} * (\alpha * d_{ext}) \tag{1}$$

The result of this calculation was 24.4 kgcm, which is much less than the 90 kgcm provided by the servo in Fig.9. With this being the worst case scenario and the arm being rotated before extension, there was an excess of torque from the motor so the rotation capacity could be focused on to enable full 360° rotation.

Under these requirements, along with the base electronics' interface requirements, the team selected the ASMC-04B servo motor [5]:

(a) ASMC-04B Servo

Specification	Value
Nominal Operating Voltage	12 V
Stall Torque	90 kg cm
Max. Speed	60°/s
Max. Rotation Angle	300°
Voltage Signal Input	0 to +5V
Mass	530 g

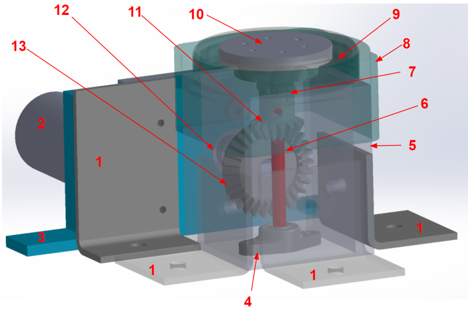
(b) Specifications

Figure 9: ASMC-04B Servo Specifications

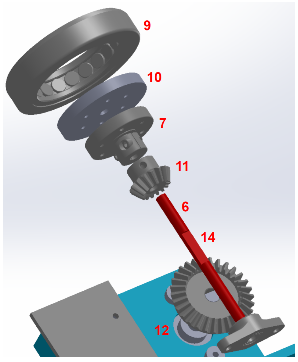
In order to achieve this torque requirement, allow for at least a 360° rotation, and minimize the vertical height of the rotation system, the team selected a 30 tooth, 45mm pitch diameter bevel driver gear meshed at 90° with a 15 tooth, 23mm pitch diameter pinion driver gear. Both gears have a 20° pressure angle; their assembly into the pivot system is captured in fig. 10. The driver gear is connected to the ASMC-04B's 8mm diameter D shaft using a M4x0.7mm, 10mm steel set screw, while the driven gear is connected to the 6mm, 89.4mm long 1566 carbon steel shaft's 20mm flat section with the same type of set screw.

This gearing selection allows for a 1:2 gear ratio and a theoretical output of 45 kg-cm with a 600° maximum rotation angle at 12V. Testing indicated that the system was capable of a full 360° rotation in ≈ 3s operating at a reduced 8V to prevent gear slippage.

Fig. 10a features a transparent diagram of the final rotation system's main components, while fig. 10b provides an exploded view of the rotation shaft assembly. The indicators in fig. 10 correspond to the list below:



(a) Components



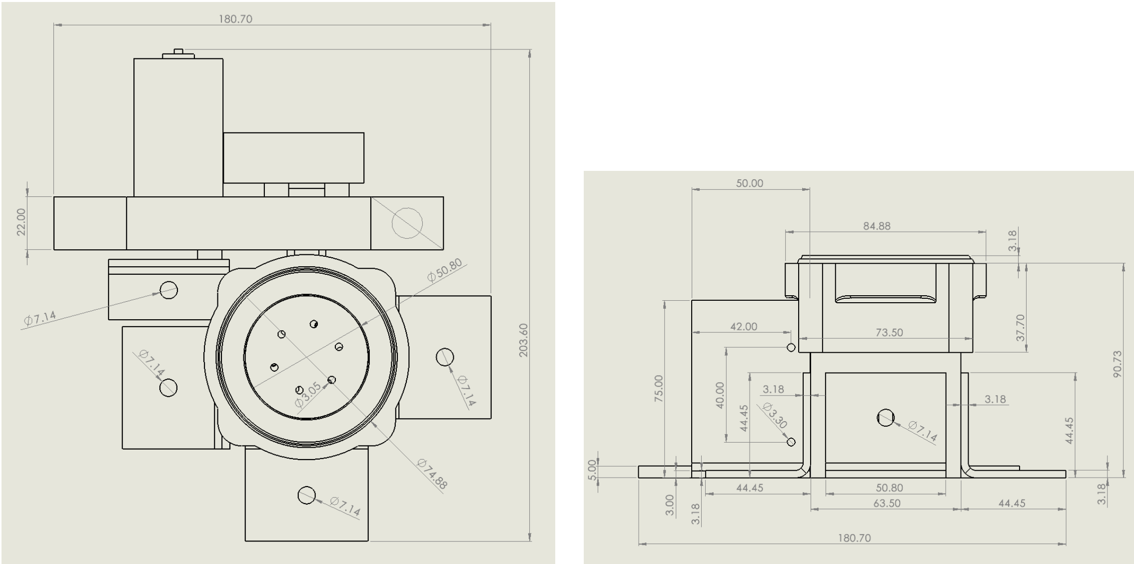
(b) Rotation Shaft Assembly, Exploded View

Figure 10: Rotation System Components

Table 5: *Rotation System Components*

1	Custom Aluminum L Brackets
2	ASMC 04B Servo
3	Custom 3D Printed Servo Mount
4	6mm Shaft Oil Bearing
5	78.03mm Square Aluminum Tube, 6.35mm thick
6	6mm Diameter, 89.4mm 1566 Carbon Steel Shaft
7	Aluminum 6mm Flange-Mount Shaft Collar
8	Custom 3D Printed Bearing Support
9	Tapered-Roller Thrust Bearing, 50.8mm ID
10	50.8mm Diameter, 6.35mm thick Aluminum Disk Shaft Connector
11	1045 Carbon Steel Pinion Driven Gear 23mm pitch diameter
12	25.4mm Diameter Hole For Motor Shaft
13	1045 Carbon Steel Bevel Driver Gear, 45mm pitch diameter
14	20mm, 2mm deep Flat Spot on 6mm Shaft

Fig. 11 indicates the key dimensions of the rotation system:



(a) Top (b) Left Side

Figure 11: Rotation System Dimensions (mm)

As visible in fig. 10, the rotation system operates by initially having the ASMC 04B supply torque to the driving gear, which fits inside the aluminum tower through a 25.4mm diameter hole. The servo mount and leftmost aluminum L bracket in fig. 10a anchor the motor to the base plate during operation using 3 6.35 mm bolts. The driver gear is meshed to the driven gear as discussed earlier. The 6mm shaft uses the 6mm oil bearing to rotate smoothly in the correct orientation at its base. At the top of the shaft, the flange mount shaft collar anchors the shaft to the custom disk shaft connector, which includes a 5mm deep, 6mm diameter hole (fig. 10b) to lock the shaft in place. A set of 5 M3x0.5mm, 22mm and 1 M3x0.5mm, 55mm steel socket head screws are screwed through the aligned holes in the flange mount collar and the disk connector before being anchored to the pivot system as described in the next section. The tower supports the PLA bearing support, which provides a ring to hold the tapered roller thrust bearing in place. The pivot system's baseplate rotates on top of the thrust bearing while torque is transmitted to it through its screwed connection with the disk connector. The thrust bearing also keeps the disk connector aligned while rotating.

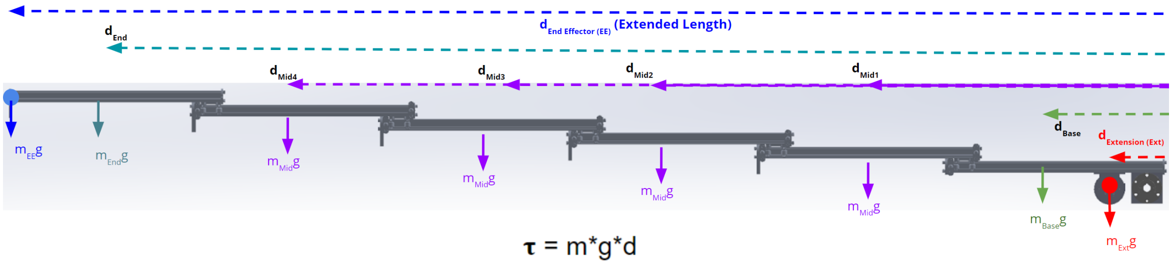
As shown in fig. 5a, the pivot assembly is anchored to a 381x457.2x3.175 mm aluminum plate to replicate the allowed stowed volume on the Husky. The aluminum L brackets and the 3D printed servo mount are bolted to the base using 6.35mm grade 2 bolts, while the 6mm shaft oil bearing is bolted to the plate using a pair of M4x0.7mm, 16mm steel socket head screws.

3.5 Orientation System: Pivot Mechanism

Author(s): Michael Martinson

FR 1.1 requires RESCUE's arm to have at least a 1m reach along any unobstructed direction from its base, while TDR 4.3.1 requires the system to deploy to any sensing location within 30s. For the pivot portion of the orientation system, these requirements equate to a need for a system that can quickly pivot the retracted arm upward from its horizontal stowed position to any angle from 0° to 90° and then hold it in that position while it is fully extended to 1.89 m.

Developing the pivot subsystem required using the modeled approximation of the extension system from section 3.2. The team started by determining the 'worst case' static scenario from a torque perspective: when the arm is being held fully extended in a horizontal, 0° pivot orientation. Assuming the point mass approximations for the end effector and extension system from subsection 3.2 and assuming that gravity acts on the center of each rail segment, the following model diagrams this scenario and how its torque can be computed:



$$\tau_{Total} = (m_{Ext}d_{Ext} + m_{Base}d_{Base} + m_{Mid}d_{Mid1} + m_{Mid}d_{Mid2} + m_{Mid}d_{Mid3} + m_{Mid}d_{Mid4} + m_{End}d_{End} + m_{EE}d_{EE})*g$$

Figure 12: Pivot System Design: Torque Modeling

Using this model and SolidWorks CAD to understand component positions during extension, it is possible to estimate how the pivot motor's required torque increases as the arm segments extend in the cascade extension process. Note that the 'extended length' axis represents the position of the end effector point mass relative to the back end of the base rail segment:

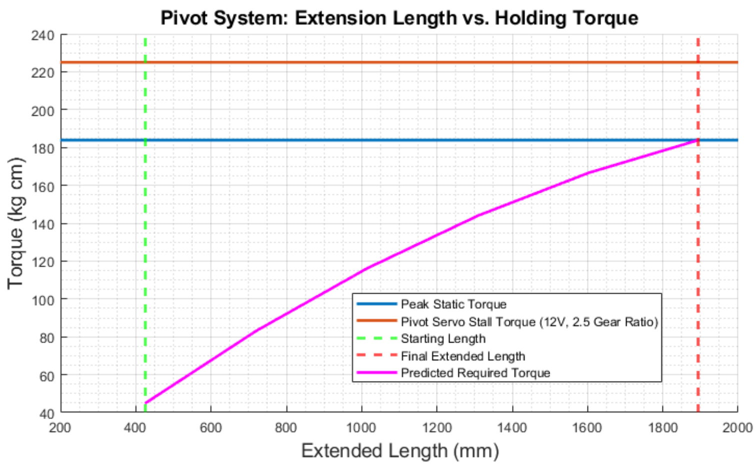


Figure 13: Pivot System Design: Static Torque vs. Extension Length Model

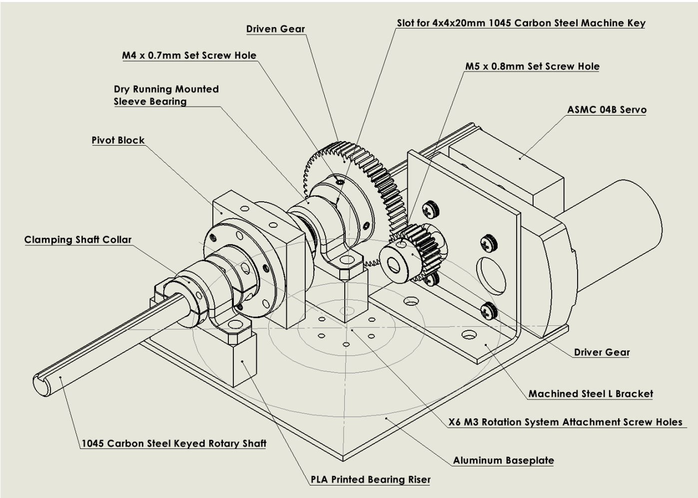
RESCUE deploys in a "pivot - rotate - extend" order. To evaluate the system's torque requirement for pivoting the arm in its retracted configuration, the team first applied the same strategy shown in fig. 12 along with the data from table 4 and SolidWorks model measurements of the arm in its retracted state to compute the "static" torque of the retracted arm at 0 ° pivot. For the additional "dynamic" torque output required to pivot the arm, the team assumed an angular acceleration of $\alpha = 1$ rad/s^2. Therefore, the pivot torque requirement was computed as:

$$\tau_{Pivot} = \tau_{'Static'} + \tau_{'Dynamic'} = 40.04kgcm + (I_{zzTotalSystem,Collapsed}) * (\alpha) \qquad (2)$$

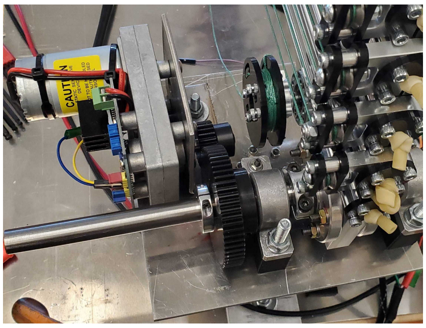
$$\tau_{Pivot} = \tau_{'Static'} + \tau_{'Dynamic'} = 40.04kgcm + 1.51kgcm = 41.55kgcm \quad (3)$$

Under this torque and speed requirement, the team again selected the ASMC-04B servo (9a). In order to meet the 184 kg cm maximum torque required for the pivot system, the servo was outfitted with a 2.5:1 gear ratio using a pair of 20° pressure angle gears with a 24 tooth, 24mm pitch diameter round bore gear as the driver gear and a 60 tooth, 62 mm pitch diameter, 4mm keyed bore gear as the driven gear keyed to the system's main pivot axle. Theoretically, this system results in a 90° rotation in 3s and a 225 kg cm torque output at the ASMC-04B's nominal operating 12V. Through system testing the team determined that the pivot system can support the fully extended arm in any orientation, and can accomplish a 90° pivot in ≈ 3s.

Fig. 14a shows an isometric CAD view of the pivot system with its primary components labeled (fasteners are not included), Fig. 14b shows an overhead view of the pivot system assembled:



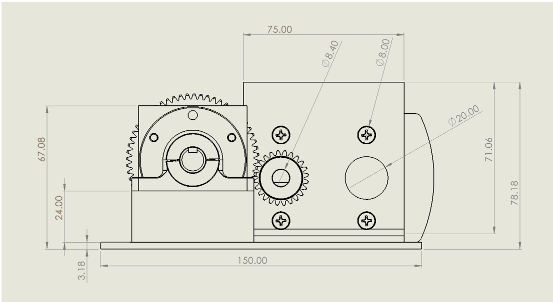
(a) Pivot System Components



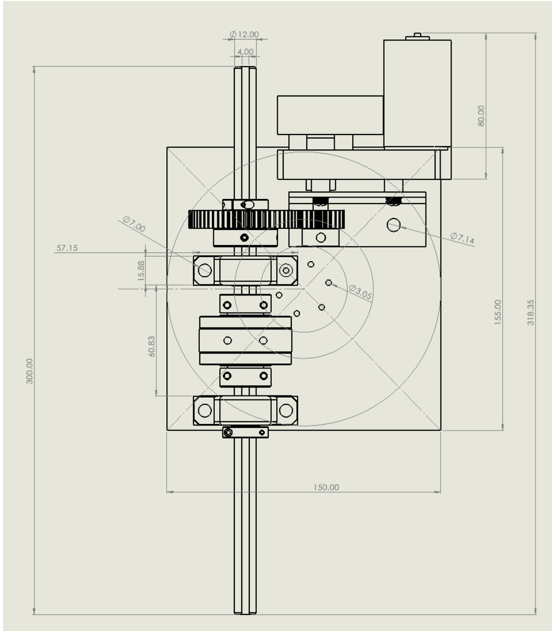
(b) Assembled Pivot System

Figure 14: ASMC-04B Servo Specifications

The pivot system's key dimensions are shown in fig. 15:



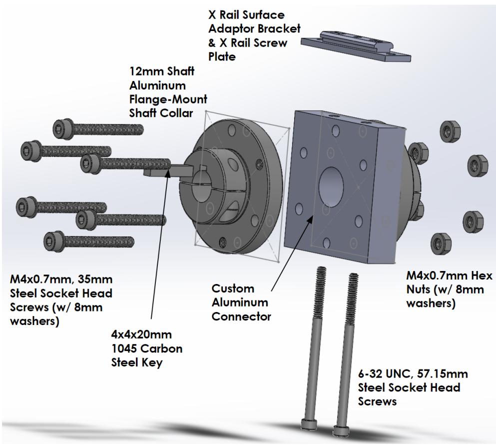
(a) Side View



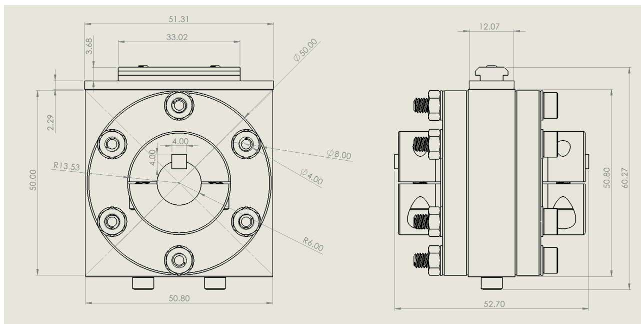
(b) Top View

Figure 15: Pivot System Dimensions (mm)

The pivot block assembly, including the hardware used to attach the X rail, is shown below:



(a) Components



(b) Dimensions (mm)

Figure 16: Pivot Block: Components and Dimensions

As shown in fig. 15, the entire pivot assembly is mounted to a 150x155x3.18 mm aluminum base plate featuring a set of 6 M3 holes that allow the assembly to be attached to the rotation system with a set of 5 M3x0.5mm, 22mm and 1 M3x0.5mm, 55mm steel socket head screws. A custom machined steel L bracket is used to mount the ASMC 04B servo to the baseplate with a 6.35mm bolt and includes a 20mm diameter hole that the servo's axle passes through. The driver gear transmits torque to the driven gear, which is keyed to a 300mm, 12mm diameter 1045 carbon steel shaft using a 4x4x20mm 1045 carbon steel machine key. The pivot shaft is held in place using two-piece clamping shaft collars and a pair of dry running mounted sleeve bearings, which are held to the baseplate using a set of 3D printed risers and 6.35mm bolts.

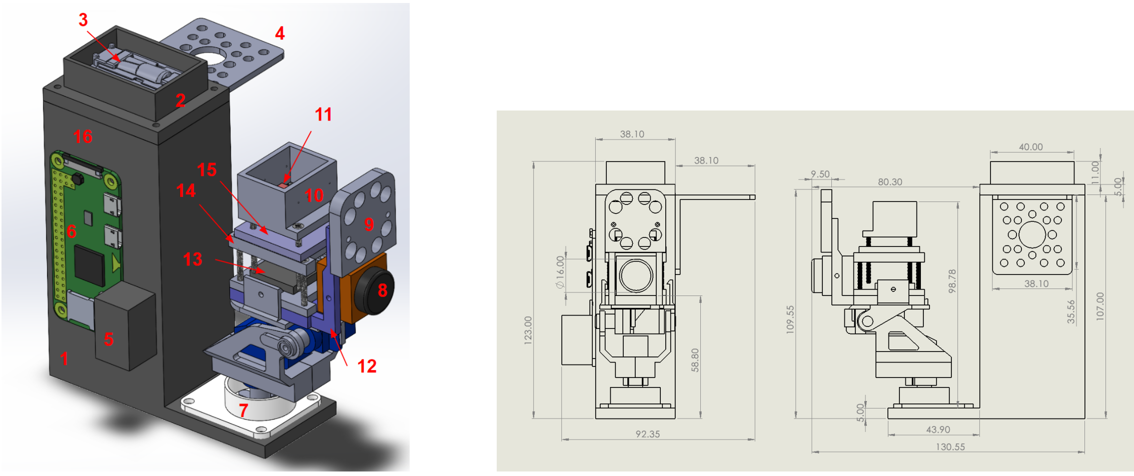
As diagrammed in fig. 16, the pivot block connects to the 12mm shaft using a pair of keyed aluminum flange mount collars that also use 4x4x20mm 1045 carbon steel machine keys. A custom machined 50x50.8x12.7mm aluminum block anchors these shaft connections to the X Rail Screw plate and surface adaptor bracket that compress the bottom of the base X rail section to the block using a pair of 6-32 UNC, 57.15mm steel socket head screws.

3.6 End Effector System

Author(s): Michael Martinson, Johnathan Tucker, Riley Swift

3.6.1 End Effector: Main Components

The figure below captures the main components of the End Effector system and its key dimensions; note that fasteners, the lighting system's LED bulbs and the voltage regulation board are not shown:



(a) Components

(b) Dimensions (mm)

Figure 17: End Effector: Main Components and Dimensions

The end effector includes the following components:

Table 6: *End effector components*

1. PLA printed main body	7. Adafruit micro pan/tilt kit	12. PLA support structure
2. Battery holder cap	8. RunCam Split 3 Micro	13. RunCam Tx200U transmitter
3. SCD30 CO_2 Sensor	9. BrightPi lighting system	14. PLA support decks (grey)
4. Servo City X Rail L mount	10. PLA AHRS sensor container	15. RunCam Split 3 Micro PCB
5. USB micro B connector	11. AHRS sensor	16. 7.4V 2200 mAH LiPo battery
6. Rasberry Pi Zero W		

The end effector's total mass, including all wiring, was 435 grams.

3.6.2 End Effector: Mechanical Assembly

The End Effector's mechanical assembly contributes to completing FR2.1 by supporting all of the electronics and sensing components on the end of RESCUE's arm. The functions of the electrical and sensing components are described later in this section. In order to accomplish

TDR 2.1.3, the Adafruit micro servo pan-tilt enables rotating the AHRS, camera, and lighting assembly by approximately 180° in pan and 150° in tilt.

3.6.3 End Effector: Sensor Package

3.6.3.1 Camera and Lighting

Technical design requirement 2.1.1 dictates that RESCUE shall be able to visually sense the brightly colored DARPA artifacts to include: human survivor, backpack, fire extinguisher, and rope. As RESCUE'S sensing capabilities directly correlate to MARBLE's ability to detect artifacts and score points, this is a critical project element.

When the camera was being selected in trade studies the critical aspects under consideration were the FOV, mass, and power draw. The RunCam Split 3 Micro had the best combined performance with a diagonal FOV of 165 degrees, a mass of 14 grams, and a power draw of 3.25 Watts. With the camera selected the team needed to ensure that the lighting solution would provide adequate lighting in a cave environment to allow for accurate sensing of artifacts (as dictated by TDR 2.1.4). To accomplish this the team referred to the U.S. Department of Energy lighting design requirements for an underground parking garage [6]. This source dictates the lighting requirement should be 15.4 lumens per square foot from one foot away from the lighting source. The team decided to illuminate a one and a half square meter area as this, when combined with the pan and tilt capabilities of the end effector, would allow for adequate artifact sensing. Ultimately, this requires a lighting solution that can provide over 311 lumens which led us to the BrightPi lighting board. Both the camera and lighting solution can be seen in Figure 57.

3.6.3.2 Carbon Dioxide Sensor

Technical design requirement 2.1.2 says that RESCUE shall be able to sense and detect carbon dioxide at 2000 parts per million (ppm). As discussed in the CO_2 trade study conducted below, RESCUE decided to use the SCD30 CO_2 sensor, shown in Figure 54. This sensor was integrated into the end effector electronics via I2C connections using the manufactured I2C circuit and the Raspberry Pi. These communications were controlled using a python package that managed the clock stretching, command confirmations, and data retrieval from the sensor. Ultimately, this python package was used in a script that was integrated into RESCUE's ROS environment.

3.6.4 End Effector Design: Electronics

To operate the sensors at the end effector and ensure the fulfillment of FR 2.1, the RESCUE team needed to develop a sensing electronics package. As this package is necessary for the successful sensing of DARPA artifacts, this is a critical project element. A schematic of the sensing electronics package can be seen below in Figure 18 and shall be referenced throughout the following discussion.

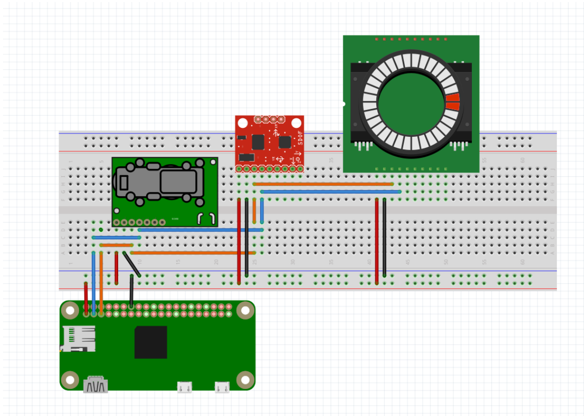


Figure 18: Diagram of the end effector electronics package that supports the sensing system.

The above diagram shows each of the sensors wired in parallel with the final connections being made to the Raspberry Pi Zero W I2C, power, and ground GPIO pins. This design decision was made because the RasPi Zero is capable of sustaining multiple devices on the same I2C bus. This is because each sensor (including the BrightPi) has a unique I2C address that the RasPi Zero can use to distinguish the data.

The power to the end effector electronics is supplied by a 7.4V 2200 mAh LiPo battery pack. The voltage is then regulated down to 5V through the use of an LM317 adjustable voltage regulator. A battery was chosen to power the end effector both to avoid running a cable up the length of the arm and to provide the sensors with a more stable power source in order to reduce noise in the data. The voltage regulation circuit also acts to protect the sensors from the battery and further reduce noise in the data. From the battery and voltage regulator, 5V is supplied to the Raspberry Pi Zero W, the camera transmitter and to both the servos. The Raspberry Pi powers the C02 sensor, the AHRS and the lights while the camera transmitter powers the camera.

3.6.4.1 End Effector Pan and Tilt Electronics

Technical design requirement 2.1.3 dictates that the RESCUE sensor package shall be able to rotate by at least 90 degrees about one or more axis. This FR in combination with FR 3.1, which demands the ability for RESCUE to determine and report its location and orientation, necessitates the use of electronics to accurately command the end effector pan and tilt servos. As the specific servos are discussed in a separate section, this portion of the paper will focus on the electronics and controls driving them.

As the Raspberry Pi Zero W has two pulse width modulation command outputs, the team decided to command the end effector pan and tilt servos via Raspberry Pi Zero W. However, the servos will be powered externally with 5 Volts so as to avoid feedback that could interfere with other sensors. Although the team initially intended to use ROS MoveIt to control the pan and tilt servos this was not implemented due to time constraints. Instead, a pan and tilt routine was implemented to ensure the same functionality with the trade off of having less control. The routine was that the pan servo would move left 90 degrees, back to center, and right 90 degrees following this the tilt servo would move down 90 degrees and the pan servo would repeat the previously detailed process.

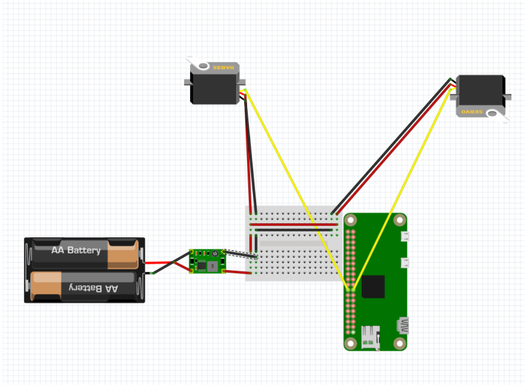


Figure 19: Diagram of the end effector electronics package that supports the pan and tilt servos.

Given that the Raspberry Pi Zero W allows for the accurate pointing and control of servos and further integrates with our software architecture, this design choice facilitates the fulfillment of requirements FR 2.1 and FR 3.1.

3.6.4.2 End Effector Communication

Functional requirement 6.1 dictates the RESCUE shall communicate all of its sensed data with MARBLE without causing interference and FR 4.2 dictates that RESCUE's deployment operations shall be rapid enough to incur a minimal time cost to MARBLE's total mission time. To satisfy these requirements the team implemented two types of communication at the end effector: I2C and wireless.

The team had the unique challenge of determining a design that would satisfy the communication requirements and integrate with the chosen sensing package. With the knowledge that cabling would cause unneeded structural complexity, the team decided to focus on wireless solutions for communication between the end effector and base. First, candidate wireless transmitters for the RunCam Split 3 micro camera were investigated. An obvious choice was the wireless transmitter built by the same company (RunCam) seen in Figure 59. Not only would this ensure that the transmitter could integrate with the camera, but it is also a cost effective solution at $14.99. To ensure that this transmitter would work with the chosen receiver(detailed in the base communication section), the team developed the link budget seen in Appendix E, Figure 62.

This link budget predicts a received signal strength of -41.27 dBm, which lies between IEEE 802.11 categories of "excellent" at -30 dBm and "very good" at -67 dBm [7]. From here the team calculated the signal to noise ratio (SNR) using the expected 720x480 NTSC video data, which demands a 10.37 Mbit/sec data rate. The signal to noise ratio was calculated to be 39.284 dB, which is very close to the IEEE 802.11 "excellent" SNR at 41 dB. This wireless transmitter also allows for a myriad of frequencies to be used to avoid interference with MARBLE's communications. The frequencies available can be seen in Appendix F, Table 48.

To wirelessly transmit the sensor data, the team needed to determine a design solution that would be able integrate with the sensors as well as the base Raspberry Pi. This led the team to the Raspberry Pi Zero W, which has an embedded wireless transmitter as seen in Figure 60. The Raspberry Pi Zero W has the capability to interface with the SCD30 CO_2, sensor, BrightPi lighting board, and control the end effector servos via its GPIO pins. Furthermore, the Raspberry Pi Zero W is able to directly connect the Raspberry Pi 4 at the base using Message Queuing Telemetry Transport (MQTT). MQTT acts as broker between the two Raspberry Pis and allows them to transmit data back and forth via a TCP/IP connection.

As the previously discussed design decisions satisfy requirements related to the efficient communication of data between the end effector and base the team still had to tackle the issue of communicating data between sensors and the Raspberry Pi Zero W. To accomplish this the team implemented I2C communication protocol. Each sensor has serial clock, serial data, power, and ground connections that were wired in parallel with to the Raspberry Pi Zero W. As previously discussed, this parallel connection would allow the Raspberry Pi Zero W to detect each of the sensors unique addresses and thus communicate with them.

Given that the FPV transmitter is able to directly interface with the camera and operate on a myriad of frequencies, it fulfills FR 6.1. When this FPV transmitter is combined with the communications and sensor interface capabilities of the Raspberry Pi Zero W, the RESCUE team is able to satisfy FR 6.1.

3.7 Base Electronics

Author(s): Johnathan Tucker, Riley Swift

To ensure the fulfillment of our requirements, RESCUE needed to develop a myriad of electronics packages. The team decided to split the electronics packages into base and end effector sub-packages. The following sub-sections detail the requirements and subsequent electronics needed to fulfill them for the base of the robot.

At the foundational level, the base electronics will be driven by a Raspberry Pi 4 computer. It will be used to control the rotation and pivot servos, the extension DC motor, as well as to communicate with the end effector and MARBLE.

3.7.1 Base Rotation

Functional requirement 1.1 dictates that RESCUE shall be able to variably extend in an upper-half hemisphere. This FR in combination with FR 3.1, which demands the ability for RESCUE to determine and report its location and orientation, necessitates the use of electronics to accurately control base pitch and yaw servos. As the specific servos are discussed in a different section, this portion of the paper will focus on the electronics and controls driving them.

The team will be using the Adafruit 16-Channel 12-bit pulse-width modulation (PWM) based servo driver board to integrate with the base rotation servo. This design decision was driven by the boards capability of driving multiple servos at once as well as the easy integration with the Raspberry Pi 4 via I2C. The Adafruit 16-Channel 12-bit PWM servo driver board can be seen in Figure 61 below. Although this servo driver board does not have an immediate integration with ROS, it does have a code base that was developed by Adafruit for easy implementation of PWM based servo commands. Furthermore, given the teams decision to use ROS-python these Adafruit developed python scripts can be easily wrapped in ROS for final integration. The AHRS will be used to check the orientation of the base rotation servo after which the error, or difference between the two orientations, will be minimized.

Given that the Adafruit 16-Channel 12-bit PWM servo driver board allows for the accurate pointing of servos and further integrates with our software architecture, this design choice facilitates the fulfillment of requirements FR 1.1, FR 3.1.

3.7.2 Base Communication

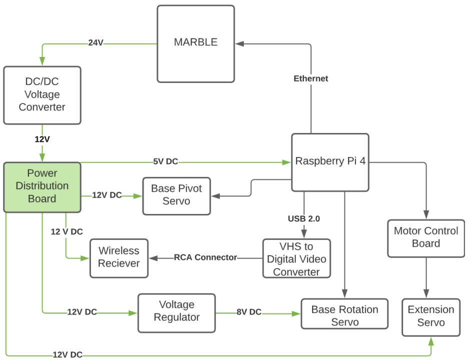
Functional requirement 6.1 dictates the RESCUE shall communicate all of it's sensed data with MARBLE without causing interference. Under this FR lies technical design requirements 6.1.1, 6.1.2, 6.1.3, and 6.1.4 which dictate that RESCUE will be able to receive firing commands via ROS and communicate data with MARBLE via a wired connection within 60 seconds of post-deployment. As the communication infrastructure is imperative to the success of MARBLE's mission this is a critical project element that had correspondingly critical design decisions.

With the knowledge that the RunCam FPV wireless transmitter would be used to communicate the video data, the team needed to find a compatible receiver. Furthermore, the wireless receiver must be able to interface with the VHS to digital video converter. This led the team to choosing the Wolfwhoop WR832 5.8GHz 40CH Wireless FPV Receiver as it is compatible with the RunCam FPV transmitters channels as well as the video converter (seen in Figure 58). To ensure this receiver is capable of sustaining the needed communications and data rate, a link budget was calculated as seen Figure 62. In addition, the signal to noise ratio was calculated to be 39.284 dB, which is very close to the IEEE 802.11 "excellent" SNR at 41 dB. As previously discussed, the sensor data will be communicated using the embedded transmitter in the Raspberry Pi Zero W and the Raspberry Pi 4 at the base via MQTT. These connections ensure that technical design requirement 6.1.2 is fulfilled.

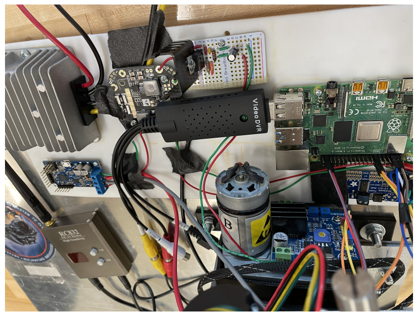
To communicate the sensor data to MARBLE from one of the Raspberry Pi 4's at base, a Gigabit Ethernet connection will be used. The data will be encoded into a ROS message that will be published as soon as it is received by the base Raspberry Pi. In addition to the sensor data, the Ethernet connection will also facilitate the firing commands and status reports that will also be sent via ROS messages. This ensures technical design requirements 6.1.1, 6.1.2, 6.1.3, and 6.1.4 are all fulfilled.

3.7.3 Voltage Regulation

Since RESCUE draws power for the base electronics directly from MARBLE, FR 5.2 requires RESCUE to use less than or equal to 24 volts at 25 amps, or 600 watts. The power provided from MARBLE is controlled by a series of voltage regulators. The 24V input from MARBLE is reduced to 12V with a DC/DC step down converter with a 20A max. Next, the Matek X Class 12S Power Distribution Board (PDB) is used to output both 12V and 5V to multiple outputs at a max 15A. From this PDB the base pivot servo, wireless receiver and extension servo receive 12V and the Raspberry Pi is supplied with 5V. Another 12V from the PDB is reduced to 8.2V using an LM1084 voltage regulator. Overall, all the voltage regulators output the required voltages and can handle the max currents required by the base electronics. All base electronics connections can be seen in Figure 20a and the actual setup is shown in Figure 20b.



(a) Base Electronics Connection Diagram



(b) Actual Base Electronics Setup

Figure 20

3.8 Power System Design - Power Budget

Author(s): Riley Swift

FR 3.3 and TDR 3.3.1 state that RESCUE shall have enough electrical power to maintain standby, active, and operational states fitting the MARBLE team's mission performance expectations and that RESCUE shall have enough electrical power to maintain a standby state for at least 135 minutes. FR 5.2 and TDR 5.1.3 state that when in standby configuration, RESCUE shall be compatible with the MARBLE team's Clearpath Husky and that if RESCUE is directly connected to the Husky, power drawn from the Husky robot shall be less than or equal to 24 Volts at 25 Amps.

The base electronics will all be powered by MARBLE and the end effector electronics will be powered by a 7.4V 2200 mAh battery. Given an available power of 600W from MARBLE, a power budget was designed. This is shown in Figure **??**. Every component of the design that requires power was listed along with their respective required operational voltages and currents. The total power required was calculated by summing the power of each component, which will likely be an over estimate. The total power was then multiplied to include a 50% margin. This is a very large margin for a power budget but was done to emphasize there is no power usage concern. The total power usage including the margin is 265.3 watts. This is just under half the available power.

To satisfy FR3.3, the watt-hours RESCUE's base electronics require were also calculated. A 30 minute minimum of active use at 265.3 watts is 132.7 watt-hours. The required 135 minutes of standby time is guaranteed to use less power than 135 minutes of full active power which would be 596.9 watt-hours. The battery is rated at 2200 mAh and the end effector electronics draw about 1.9A. This means in active state the battery should last for approximately 68 minutes. This exceeds the 35 minute active state requirement. Overall the power RESCUE requires is compatible with the available power from MARBLE. A more detailed power budget breakdown can be found in Appendix F, Figure 63.

3.9 Software Architecture

Author(s): Ryan Hughes

To satisfy functional requirements 2.1, 3.1, 4.2, and 6.1, the RESCUE software system needed to be robust and responsive. Though Python was slower than its C-based counterparts in terms of programming language, it made up for this in robustness of integration between ROS architectures and other necessary libraries. Furthermore, software processing time did not prove to be a critical issue in the scope of the Python-based final RESCUE system.

Thw primary node in the ROS package is being run on the base Raspberry Pi and is called `rescue_main`. This node communicates with two other nodes: `rescue_ee` and `marble_dummy`. The former handles end effector operations - camera activation, actuation, and lighting, as well as sensor operation and data transmission. `marble_dummy` is the MARBLE simulator node, from which a user inputs command-line commands and receives data and status updates. These firing commands are further described in Section 5.5.

4 Manufacturing

4.1 Mechanical Manufacturing

4.1.1 Mechanical Manufacturing: Extension System

Author(s): Evan Welch

The extension system is a modulated version of ServoCity's Cascading X-Rail Slide Kit. It consists of a series of t-slot aluminum arm sections and pulley wheels that are slotted together and allowed to slide along each other via rollers. ServoCity also provided the suggested motor and wench assembly that is required to spool and unspool the tension pulley system, allowing the arm to extend and retract. The extension pulley system and rollers are shown in Figure 7, and the extension motor assembly is shown in Figure 8b.

Considering that all of these parts were sold in a kit, assembly was relatively straightforward. ServoCity provided an instructional video on how to manufacture the wheel assemblies and pulley assemblies, and then join them with the t-slot aluminum arm sections. There was a slight modification necessary in order to build a six-section arm instead of the standard four-section arm, but each section is just a repeating pattern of the one before it, so this was not difficult to do. The only challenge faced during the manufacturing of the arm was that everything had to be assembled in a very specific order, which was not clearly outlined in the instructional video. Due to the nature of the design, with parts slotting into each other and then being locked along each rail section, the assembler often had to think far ahead in the assembly process to ensure that something being done would not need to be undone in the future.

4.1.2 Mechanical Manufacturing: Rotation System

Author(s): Michael Martinson, Jack Zeidlik

A diagram of the complete rotation system and its components appears in fig. 10. Of the total components, the 6mm shaft oil bearing, flange mount shaft collar, and tapered-roller thrust bearing were all purchased from McMaster Carr and did not require custom machining. All required fasteners were also purchased from McMaster Carr The ASMC 04B was purchased from Amazon.

The aluminum L brackets, PLA printed servo mount, square aluminum tube, 6mm 1566 carbon steel rotary shaft, PLA printed bearing support, aluminum disk shaft connector, base plate, and both the driver bevel gear and driven pinion gear all required custom machining.

The three aluminum L brackets used to support the square tube tower were 44.45x44.45x50.8mm, 3mm thick brackets purchased from McMaster Carr. The 7.93mm holes required to be drilled were completed using a teammate's drill press with titanium bits. The fourth aluminum bracket was 75x50x50mm, 3mm thick, and was used to mount the rotation motor to the base plate. The two motor holes were drilled using 3.97mm titanium bits while the base hole was

7.93mm. Then 25mm was cut off of the 50x50mm face to accommodate the fit with the tower support bracket. The challenge was ensuring a very high tolerance fit with just a basic drill press.

The servo mount was 3D printed using 3mm PLA on a teammate's 3D printer. The component yielded slight difficulties due to expansion during the print; moderate sanding with a Dremel was required to fit the servo into the support. The two holes in the support for anchoring it to the base plate with 6.35mm diameter bolts were drilled using a teammate's hand drill.

The rotation system tower was machined from a 63.5x63.5x152.4mm, 6.35mm thick square aluminum tube purchased from McMaster Carr. This was cut down to 78.03mm in height and a 25.4mm diameter hole was cut into one side, at the machine shop, to allow the servo shaft to connect to the gears. There were three 7.93mm holes drilled to connect the aluminum L brackets to the tower using the teammate's drill press. This component posed no major manufacturing issues.

The rotation shaft was cut to length from a 200mm long, 6mm diameter 1566 carbon steel shaft purchased from McMaster Carr. Both this cut and the cutout for the 20mm, 2mm deep set screw slot for the pinion gear were commissioned on aerospace shop machinery due to the required level of precision. Both elements of the shaft were satisfactory and did not contribute to the gear alignment problems discussed later in this section.

The bearing support cup was 3D printed using 3mm PLA on a teammate's 3D printer. This component proved to be the second most challenging manufacturing element of the rotation system due to the part expanding during its longer print time. This meant that it had to be sanded with a Dremel extensively to fit the tapered roller thrust bearing, and Dremel sanding and hammering was required to fit the base over a square aluminum tube. The advantage of this tight fit was better retention of the bearing under the elevated torque loading with the arm fully extended.

The connector disk was cut to length from a 50.8mm OD, 152.4mm long piece of solid aluminum stock. This cut, the 6 3mm diameter holes for the screws connecting it to the pivot base plate, and the 5mm hole for the rotation shaft were all machined at the machine shop due to the high accuracy required to have a perfect fit for all six bolts. The only issue with this component was that the 6mm shaft become permanently stuck in the 5mm alignment hole; this actually improved the part's ability to maintain the shaft alignment under torque.

The set of carbon steel beveled gears used to create the rotation gear system, as discussed in section 3.4, required having their M4x0.7mm set screw holes tapped. This task was commissioned from the aerospace machine shop due to its complexity and required precision.

All of these components were integrated onto an aluminum plate to represent MARBLE's Clearpath Husky. First, the pivot system, as discussed in the next section, was assembled, then the center shaft system comprised of the connector disk, flange mount, 6mm shaft, and pinion gear were connected together and attached through the six holes in the pivot base plate, as seen in fig.10. Next, the oil bearing was connected to the system base plate followed by the tower, aluminum L brackets and the servo and servo mount. These were all tightened down with 6.35mm bolts and washers. Finally, the large beveled gear was connected to the servo shaft and the bearing and bearing support were added to the top of the tower. Then the pivot system with the center shaft was dropped into the tower and aligned with the oil bearing at the bottom. Due to many slight imperfections in machined components and the limited working space inside of the tower, issues were encountered with creating a strong mesh between the beveled gears. This mesh was improved through adjusting the position of the pinion gear along its axle and realigning the tower multiple times. Additionally, the voltage of the servo was decreased to 8V reduce the skipping caused by fast rotation interacting with the gear mesh.

4.1.3 Mechanical Manufacturing: Pivot System

Author(s): Michael Martinson

All of the pivot system's components are identified in Fig. 14. Of the total components, the 1045 carbon steel rotary shaft, the pair of 12mm clamping shaft collars, the pair of 12mm shaft aluminum flange mount collars, the 1045 Carbon steel machine keys, the pair of 12mm dry running mounted sleeve bearings, both the driver and driven gears, and all required fasteners were purchased from McMaster Carr. The ASMC 04B servo was ordered from Amazon. The X Rail surface adaptor and X rail screw plate were purchased from Servo City as proprietary components for the X Rail system.

The custom aluminum connector in the pivot block, the machined steel L bracket, the aluminium pivot base plate, and the PLA printed bearing risers were all manufactured.

The custom aluminum connector in the pivot block (fig. 16) was machined from a 12.7x50.8mm, 152.4mm long piece of 6061 aluminum stock. Initially the block was cut to length with a miter saw and then the holes were drilled using titanium bits on a drill press in a team member's garage. However, the team found that while hand machining was possible, the precision fit required for the screws connecting the block to the X Rail components and the flange mount shaft collars was difficult to achieve and required extensive sanding beforehand. Disassembling the pivot block with the hand machined piece was nearly impossible. Therefore, for the final version of the aluminum connector the team had the aerospace machine shop machine the part on a CNC lathe. This solved all fit issues for the component.

The custom steel L bracket was initially machined from a 75x60x75mm, 3mm thick stainless steel L bracket blank from McMaster Carr. The holes in the bracket were drilled using a drill press and titanium bits, while approximately 30mm was cut of one end of the bracket to fit on the base plate using a miter saw. Both tasks were completed in a team member's garage. The key challenge in machining the bracket was the miter saw cut: this required a clamp and multiple attempts to fully cut through the 3mm thickness.

The pivot base plate was cut from a 304.8x152.4mm, 3.175 mm thick 6061 aluminum stock sheet. Given the precise fit required for the rotation system attachment holes, both the cutting and hole drilling was commissioned on the aerospace shop's CNC lathe. This approach yielded a perfect fit with no issues.

The bearing risers were printed with 3mm PLA on a teammate's 3D printer; these posed no major challenges.

The integration of the pivot system and its integration into the complete RESCUE system is shown in fig. 14 and described in section 3.5. All pivot system assembly was possible by hand using wrenches and hex keys.

4.1.4 Mechanical Manufacturing: End Effector

Author(s): Michael Martinson

The complete end effector mechanical assembly, with the exception of fasteners, is shown in fig. 17. Of the total components, all of the electronic and sensing parts were purchased. The pan/tilt kit was purchased as a complete system from Adafruit, while the X Rail mounting bracket and the fasteners used to connect it to the battery housing and the X rail were purchased from ServoCity.

The PLA main body, battery holder cap, AHRS sensor container, PLA support structure, and support decks were 3D printed with 3mm PLA filament on a teammate's 3D printer. The printing itself did not yield major problems for any of these components.

All of the components were integrated, including attaching electrical components to their support plates, into the end effector using M2x0.4mm, 10mm steel socket head screws. The 10mm screws were also used to attach the pan/tilt kit to the main battery housing. The exception to this rule was the system for ataching the PLA AHRS sensor container and the PLA support structure: this was accomplished using M2x0.4mm, 25mm steel flat phillips head screws.

4.2 Electrical Manufacturing:

Author(s): Johnathan Tucker, Riley Swift

4.2.1 Sensor Manufacturing

The RESCUE sensor package is made up of a BrightPi LED board, Sensirion SCD30 CO_2 sensor, and Adafruit BNO055 AHRS. Each of these sensors was purchased and required minimal soldering to attach the necessary header pins. The soldering was performed in the electronics shop under the supervision of a lab assistant (LA). Furthermore, equipment such as a fume extractor was used to ensure the safety of each team member while soldering.

Although the manufacturing process for the electronics sensors was relatively straight forward there was one challenge that needed to be overcome. The first was determining the optimal method for soldering the Yost Labs AHRS onto perfboard. Initially, the header pins were used to keep the AHRS in place while the soldering was performed from the bottom of the perfboard. This led to the header pins being soldered in crooked which prevented it from being placed directly onto a breadboard for testing. Ultimately, under guidance from the electronics shop LAs, the team soldered the header pins onto the perfboard after removing the header pin sleeve. Although this did make the soldering process more difficult, the end result was an easily testable AHRS with header pins.

4.2.2 Circuit Manufacturing

Two circuits were used in the final design for RESCUE's electronics. Both circuits contained 1/4W resistors, ceramic capacitors and adjustable voltage regulators and were soldered using Adafruit solderable breadboards. All soldering was safely performed in the Electronics Shop. Once soldered, the breadboards were carefully cut to reduce excess weight and size using scissors and pliers.

While the actual soldering was straightforward, due to the angle at which one of the breadboards had to be attached to the end effector, some of the wires needed to be constantly adjusted. Specifically, the wires from the battery to the breadboard were strained every time the battery was attached and detached. Because of this, the wires were slowly breaking just above where they were soldered. To fix this and create a more durable design solution, the wires were re-soldered to the board and then the connections reinforced using hot glue at the recommendation of an LA.

4.3 Software Manufacturing

The RESCUE software package was made using a series of ROS resources and Python libraries, all of which were open-source. Python libraries, including some dedicated to ROS, were combined in scripts that acted as nodes in the ROS framework. As all software resources used were open-source, there were no purchases necessary for the software package. Integration of software components mostly involved editing make files and downloading libraries, so there is little to show for the effort in a report of this nature.

The software development process yielded a cohesive ROS package capable of running functions to field location commands, determine and command arm actuation angles and extension distances, activate the camera and sensors, and port the resulting data back to MARBLE.

The most prevalent challenge faced by the software team was the lack of development time. As a result of team miscommunications and other mishaps, the software team was limited to 1-2 consistently developing members through the duration of the project manufacturing process.

5 Verification and Validation

5.1 Extension Model

Author(s): Abdulla Al Ameri, Evan Welch

5.1.1 Motivation

The goal of the first model was to estimate the amount of force it takes to keep the extension mechanism extended at a given extension distance without any retraction. In other words, the goal of this model is to estimate the amount of tension force the pulley cable (shown in figure 8a) must be under at any given extension distance.

Knowing this force means that the extension motor could be sized properly, such that the motor can provide the tension force needed to keep the arm extended. If the arm cannot be extended, this means that all functional requirements related to physical reach will not be met. Moreover, given that the extension will deliver the sensors to the desired location, with no extension this cannot happen. Thus it comes as no surprise that trying to estimate this amount of force plays is of significant importance.

5.1.2 Model development

To develop the model, some simplifying assumptions were made:

- Ignore friction
- Model the elastic surgical tubing as springs
- Assume each spring elongates the same amount
- Ignore rollers and joints
- Model the spring attachment points as simply supported ends

What this means is that now the actual physical xrail system could be converted to something that is idealized and subject to first principles analysis. Figure 21 highlights the real system, converted into an idealized free body diagram, with the coordinate system shown.

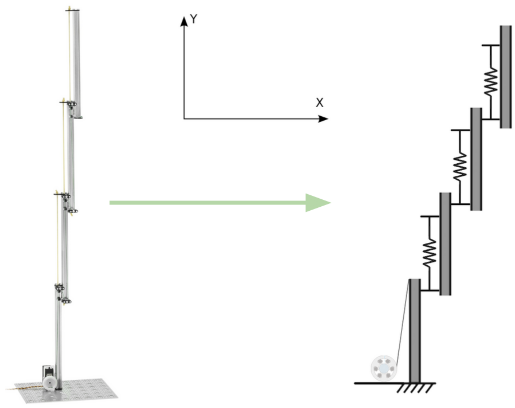


Figure 21: Going from the xrail kit to an idealized FBD

From here, the free-body diagram can be subjected to the principle of static equilibrium for the two worst case scenarios: vertical extension, and horizontal extension.

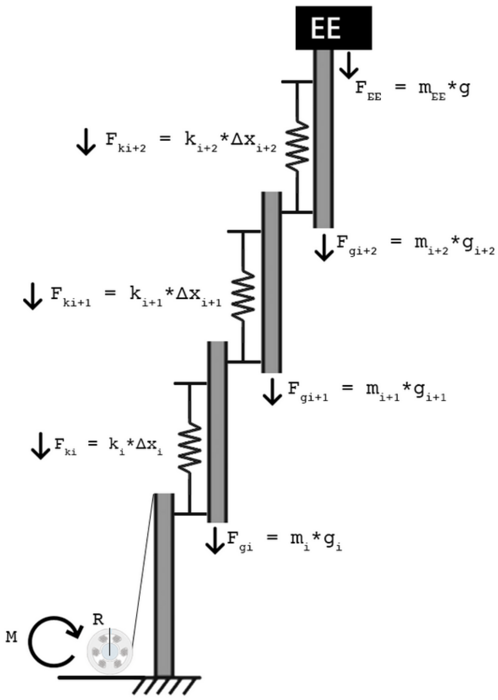


Figure 22: FBD for vertical extension case

In figure 22, the free-body-diagram can be seen with all of the forces acting on the xrail system which are $F_{k,i}$: spring force from spring i, $F_{g,i}$: gravity force from the weight of member i, and F_{EE} the weight of the end effector. If the arm is extended, the motor must counteract all of the other forces, which means mathematically:

$$\sum F_y = \frac{M}{R} - \sum_{i=1}^{N-1} m_i g_i - \sum_{i=1}^{N-1} k_i \Delta_{x,i} - m_{EE} g = 0 \tag{4}$$

Which is generalized for N number of xrail members. This equation could be further simplified to the following:

$$\sum F_y = \frac{M}{R} - A\rho g \sum_{i=1}^{N-1} L_i - k \sum_{i=1}^{N-1} \Delta_{x,i} - m_{EE} g = 0 \tag{5}$$

With rearrangement of the terms, we can get the following:

$$M_{vertical} = R \left[A\rho g \sum_{i=1}^{N-1} L_i + k \sum_{i=1}^{N-1} \Delta_{x,i} + m_{EE} g \right]$$

$$\mathrm{F}_{vertical} = \left[A\rho g \sum_{i=1}^{N-1} L_i + k \sum_{i=1}^{N-1} \Delta_{x,i} + m_{EE} g \right] (6)$$

Where $F_{vertical}$ is the force the motor needs to provide to keep the arm extended vertically a distance $= \Delta x \times (N-1)$.

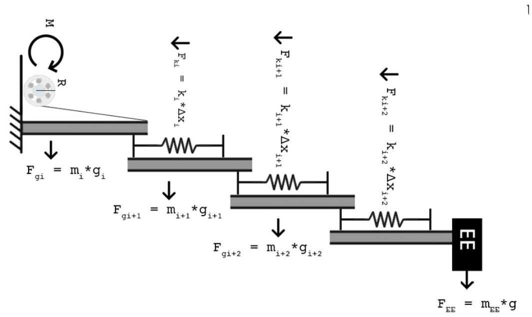


Figure 23: FBD for horizontal extension case

Moreover, the same process could be repeated for the horizontally case extension, which is simpler because the motor does not have to counteract gravity. Shown in figure 23 is the free-body-diagram. Following a similar procedure, the following expressions could be developed:

$$\mathrm{F}_x = \frac{M}{R} - \sum_{i=1}^{N-1} k_i \Delta_{x,i} = 0$$
$$\mathrm{F}_x = \frac{M}{R} - k \sum_{i=1}^{N-1} \Delta_{x,i} = 0$$
$$\mathrm{M}_{horizontal} = R \left[k \sum_{i=1}^{N-1} \Delta_{x,i} \right]$$
$$\mathrm{F}_{horizontal} = \left[k \sum_{i=1}^{N-1} \Delta_{x,i} \right] \tag{7}$$

Where $F_{horizontal}$ is the force the motor needs to provide to keep the arm extended horizontally to a distance $= \Delta x \times (N-1)$.

5.1.3 Test Setup & Procedure

In order to determine how much force is required to extend the elastic tubing and the X-Rail as a whole, the test utilized a simple setup consisting of the RESCUE system clamped to a table and a force gauge and tape measure. By pulling on the end of the arm with the force gauge and measuring the extension distance with a tape measure, the team can gather experimental data relating the extension distance to the force required. Figure 24 below shows how this test was performed, with the same test being performed on the elastic tubing by itself.

Figure 24: Testing the force required to extend the arm

5.1.4 Test Results

In order to complete the model, the spring constant of the elastic tubing needed to be measured experimentally. As stated above, this was done by extending the elastic tubing with a force gauge and measuring the extension distance at several different points. Plotted below is this experimental data, along with a line of best fit to determine the spring constant.

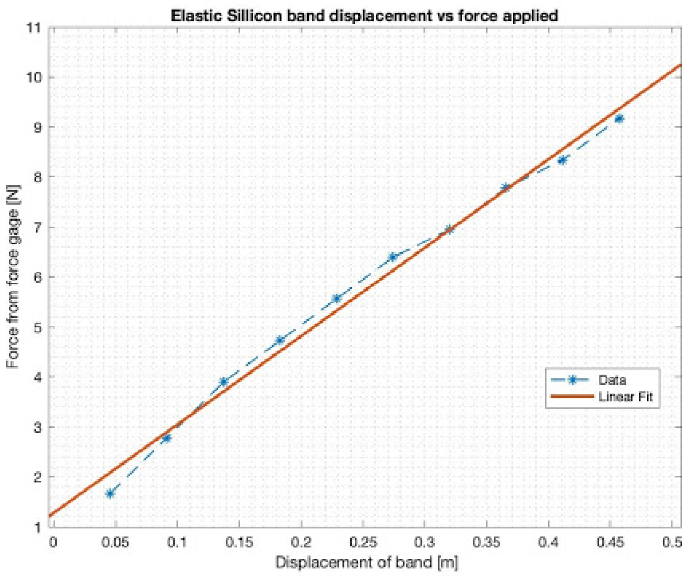


Figure 25: Elastic tubing: Extension vs Force required

From Figure 25, the spring constant of the elastic tubing was determined to be 17.7 N/m. This can now be plugged into the equations for modeling the full arm's extension force. This also allows the team to select a motor that will apply the required torque to the arm's pulley system. One elastic tube had a maximum required force of 9 Newtons, which when multiplied by five for the five elastic tubes on the six-section arm, gives a total force of 45 Newtons. With a spool radius of 0.025m, the motor at the base needs to supply a torque of 1.125 N*m to overcome the restorative force from the elastics. Adding in a large factor of safety to also account for the arm sections and end effector, the team landed on a Yellow Jacket Planetary Gear Motor capable of outputting 6.7 N*m of torque. This torque is outputted at 117 RPM, which on a spool of radius 0.025m, allows the 1.9-meter arm to fully extend in around 6 seconds.

As previously stated, the force gauge test was then conducted for the full arm in both horizontal and vertical orientations. Due to inconsistencies and imperfections in the rollers, the tests were conducted several times in each orientation and the results were averaged. The rollers had a lot of friction which did not allow the arm to extend in a consistently smooth fashion, so averaging the results over many trials gave the team the most accurate experimental data. Shown below in Figures 26 and 27 are plots comparing the model to the experimental data for both horizontal and vertical orientations.

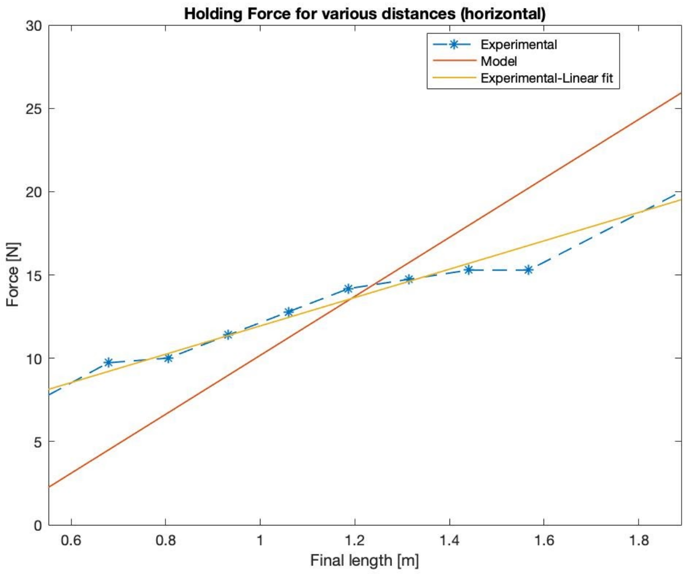


Figure 26: Full Arm in horizontal orientation: Extension distance vs force required

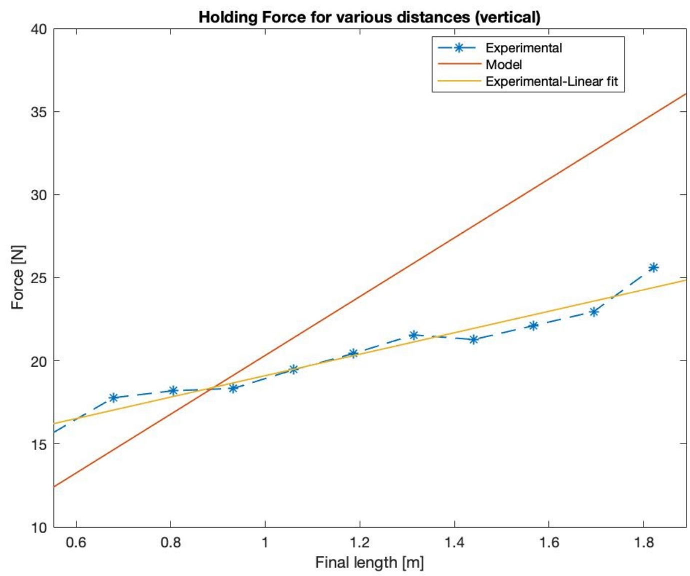


Figure 27: Full arm in vertical orientation: Extension distance vs force required

As seen in Figures 26 and 27, the experimental data has a higher slope than the model for both orientations. This is likely a result of the rollers on the X-Rail, which are rather inconsistent as mentioned before. They do not always roll smoothly, so when this testing was performed, the team noticed that they would often lock up slightly and function to keep the arm at its extended length, thus lowering the holding torque. As touched on before, the extension tests were all performed five times with the results being averaged, but it was difficult to get a smooth and consistent pull on the force gauge due to the friction in the rollers.

Overall, the goal with this model and test was to verify that our required variable extension distance could be achieved consistently (FR2.1 and FR3.1), which ultimately relies on the extension system and motor. By modeling the system and measuring the tension force in the elastic bands, the team was able to select a motor that could supply enough torque to the pulley system to extend the arm. Through testing, the team was able to compare the actual force needed to extend the arm with the predicted force, and given that the predicted model and experimental data were close enough, the selected motor was able to extend and hold the arm at variable distances up to 1.89 meters.

5.2 Deflection/FOV Verification and Validation

Author(s):Evan Welch

5.2.1 Motivation

In order to verify FR1.1 from a structural perspective, the arm must be capable of sensing DARPA artifacts despite deflection and a limited camera FOV. This model will attempt to answer the following question: If an artifact is centered in the camera's FOV while the arm is stowed, will the artifact still be in the camera's FOV when the arm is extended, despite the arm's deflection?

5.2.2 Model Development

Due to the nature of the arm having several rollers, joints, and press-fittings, the deflection cannot be accurately modeled within the scope of this project. However, since the deflection is a necessary piece of modeling the camera's shift in FOV while extended, the team will have to measure the arm's deflection. This will be done in the worst-case scenario when the arm is fully extended in the horizontal orientation. This is achieved by mounting a laser pointer to the arm such that the laser is in the center of the camera's unextended FOV. Below in Figure 28 is a diagram of how the arm's deflection was measured. As the arm is extended, the laser pointer moves down the wall that it is pointed at. This vertical distance can be measured, and the team can use similar triangles and other known lengths to estimate the arm's vertical deflection.

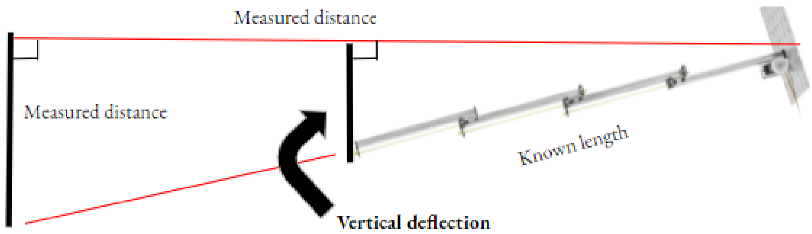


Figure 28: Diagram of how the deflection is measured

The arm's vertical deflection was measured to be 0.3 meters. With this value, a model predicting how the camera's FOV shifts as a result of deflection can be created.

Knowing that the camera's vertical FOV is 104 degrees, a similar figure can be developed below, where the red lines represent the laser pointer and the green lines represent the camera's FOV. The blue horizontal line is the important one, which represents the object's horizontal distance away from the camera. Again, what the team wants to determine here is how far can the artifact be away from the camera before the arm's deflection moves the artifact outside of the camera's FOV?

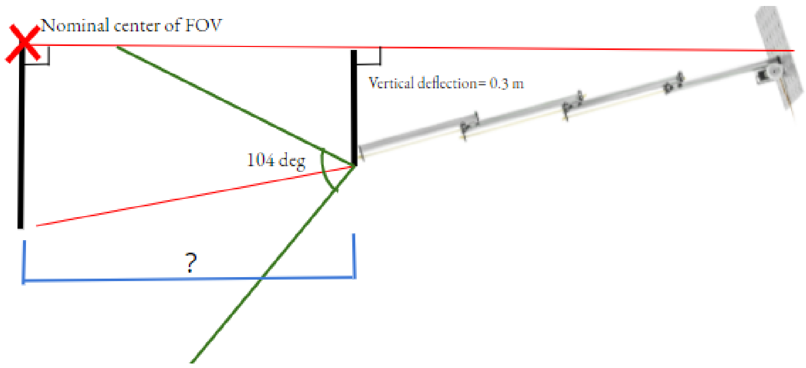


Figure 29: Camera's FOV model with shift due to deflection

Simplifying figure 29 using trigonometry allows the team to get a relationship between the artifact's horizontal distance away from the camera (the blue line) and whether or not the artifact is still in the camera's FOV when the arm is extended and deflected. As one might be able to imagine, having the artifact closer to the camera is equivalent to zooming in with a camera, in which case the camera's FOV is very sensitive to movement. What the team expects to see with this model is that far away artifacts can still be seen in the deflected FOV, while close-up objects will be outside of the deflected FOV and will require tilt compensation from either the base or end effector in order to sense the artifact.

5.2.3 Test Setup & Procedure

The test setup is the same as the test that was done for measuring the arm's deflection. Necessary materials for this test include a laser pointer, the RESCUE system, a large box to mark measurements on, the live camera feed from RESCUE's end effector, and clamps to hold the base of RESCUE in place. A laser pointer was mounted to the arm such that it points in the center of the arm's stowed FOV. This was then pointed at a large box and marked, giving the team the nominal center of the camera's FOV.

The arm is then extended, and as expected due to deflection, the laser representing the center of the camera's FOV shifts downwards on the box. The artifact's horizontal distance away from the camera will be tested throughout a range of 0-1 meters, so the box is initially placed 1 meter away from the camera. Using the live camera feed, the team can mark the top of FOV, shift the box closer to the camera, and repeat. This creates the "zoom in" effect, and since the arm is extended and deflected downwards, eventually the camera will be "zoomed in" to a part of the box such that the nominal FOV center is outside of the new FOV.

5.2.4 Test Results

Shown below in Figure 30 is a plot comparing the model to the experimental data. One thing to note is how the axes are defined. The x-axis is the object's horizontal distance away from the camera, which corresponds to the blue line in figure 29, and the y axis represents how high the camera can see above the horizontal line from the camera to the box.

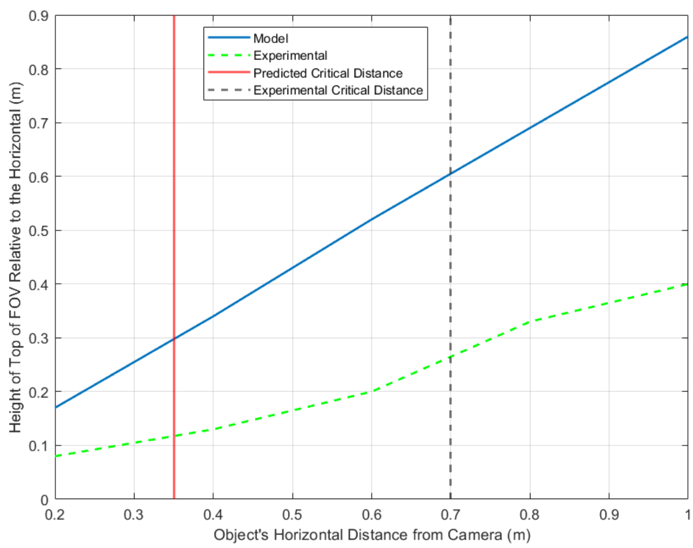


Figure 30: Shift in camera's FOV at various distances due to deflection

One thing to note in this plot is the critical distance, which is defined as the artifact's distance away from the camera such that it was centered in the stowed FOV, but is now just outside of the deflected FOV. Essentially, this is the artifact's horizontal distance away from the camera such that tilt compensation from either the base or the end effector will be needed to see the artifact. This distance was predicted to be 0.35 meters, but was measured to be

0.7 meters. The reasons for this discrepancy are that the camera's FOV is slightly smaller than what the manufacturer quoted, but more importantly, the arm does not remain straight during deflection. The arm is not a diagonal line that points slightly downwards; the arm actually bends, which means that the camera on the tip of the arm is pointed further down than the straight-line estimate that was used for the model.

Most importantly, as far as validating the FR1.1 goes, the team now has a distance at which either the camera's tilt motor or the base tilt system will need to be used. The camera can tilt back 75 degrees, which when combined with its vertical FOV, allow the camera to see directly overhead. In total from this model, we have quantified the arm's vertical deflection as 0.3 meters, which is a slight overestimate due to the arm's bending talked about in the previous paragraph, and given a value for when the camera's tilt mechanism will need to be used. When the artifact is equal to or less than 0.7 meters away from the extended camera, the camera will have to tilt up slightly in order to still see the artifact, which the system is capable of doing. This proves that the arm's deflection does not impede RESCUE's ability to sense artifacts, thus the requirement of the system being able to sense competition artifacts is validated.

5.3 Vibration Verification and Validation

Author(s):Johnathan Tucker

5.3.1 Motivation

Another important aspect of verifying the functionality of our sensing system and validating that functional requirement 2.1 was met, team RESCUE also needed to ensure vibrations would not impede the camera's ability to sense artifacts.

5.3.2 Model Development

Due to the complex nature of our extension mechanism, an accurate and worthwhile vibration model could not be constructed. Instead, the team decided to verify that the vibrations would not impede sensing capabilities by an iterative test and inspection process.

5.3.3 Test Setup & Procedure

As previously mentioned, the testing procedure for this verification and validation plan was to iteratively test the system and inspect the results. The procedure for the test was to extend the X-rail mechanism at different pitch angles while capturing video data. For each test, the camera data was captured in VLC media player to ensure that the impact of vibrations could be inspected and measured. The measurement process was to watch the video back and record the amount of time it took for the vibrations to completely damp out. This test and inspect process was repeated for extension lengths of 0.5, 1, 1.5, and 1.89 meters at orientations of 30, 40, and 50 degrees.

5.3.4 Test Results

The results of these tests that would verify the functionality of the FPV camera hardware and validate that functional requirement 2.1 is met would be an average dam out time at all orientations and extensions that is less than our communication time of sixty seconds dictated by TDR 6.1.2. If the vibrations take less than sixty seconds to damp out then we can ensure

MARBLE will be able to accurately detect an artifact during RESCUE's operating time. Ultimately it was measured that the average vibration damp-out time was seven seconds.

5.4 Communication Verification and Validation

Author(s):Johnathan Tucker

5.4.1 Motivation

TDR 6.1.2 dictates that after deployment and retraction, RESCUE shall communicate sensing data with the MARBLE robot before its next deployment, or within approximately 60 seconds. In order to ensure that this requirement was met, RESCUE developed a verification and validation plan for the critical wireless communication between the FPV camera and the base receiver. The wireless transmission of the camera data was the focus of this verification and validation plan because the communications are not insured by an IEEE wireless protocol whereas the wireless communication between the Raspberry Pi Zero W and Raspberry Pi 4 is.

5.4.2 Model Development

Initially, the team based their development of this verification and validation plan on the link budget model that can be seen in Figure 62 below. After receiving guidance from Professors Akos and Schwartz the team decided that the link budget model is inconsequential given we're communicating wirelessly across a distance of 1.89m. However, this doesn't change the fact that these systems must be verified and validated to ensure the requirements are met. Therefore, team RESCUE decided to verify the capabilities of the commercial off the shelf (COTS) hardware by testing in an environment that is more extreme than the operating environment.

5.4.3 Test Setup & Procedure

Two tests were conducted to verify the functionality of the COTS hardware. The first was to separate the receiver and transmitter by a distance of about 7 meters. The second was to separate the receiver and transmitter by a distance of about 10 meters and place the transmitter in a separate room. Both tests were conducted in the electronics shop in the Smead Aerospace building which is an environment rich with ambient radio-frequency interference. An example diagram of the first and second test setups can be seen in Figures 31 and 32 respectively. The procedure for each of these tests was to provide power to the wireless receiver and transmitter and ensure a laptop was capturing the camera data through VLC media player.

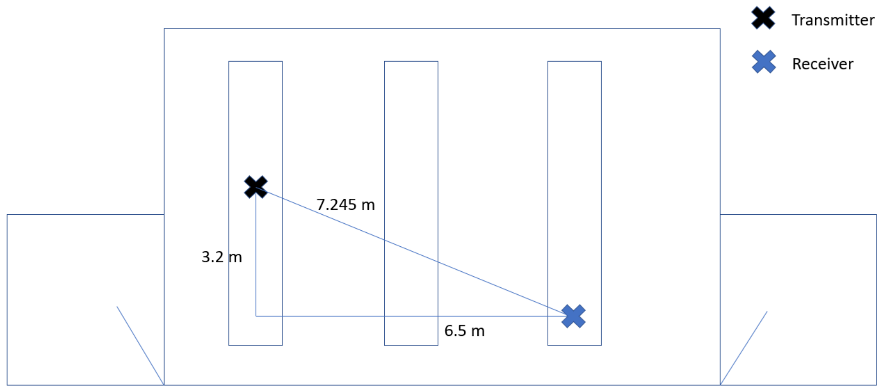


Figure 31: The test setup in the electronics shop for the first communications test.

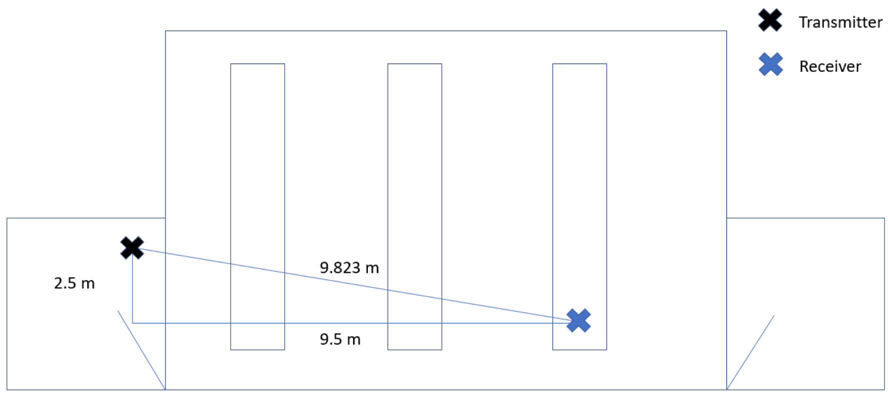


Figure 32: The test setup in the electronics shop for the second communications test.

5.4.4 Test Results

The results that would verify our COTS wireless transmitter and receiver are successful camera data transmission in each of the environments. After conducting the tests the successful transmission of camera data was confirmed and can be seen in Figures 33 and 34. Not only do these results verify the functionality of the COTS transmitter and receiver, but they also validate that the FPV wireless communications satisfy technical design requirement 6.1.2. In order to ensure that this requirement was validated the time of transmission for new data was measured. Here, new data was taken to be any change in the scenery that the camera was capturing. On average this transmission took about four seconds which is well within the sixty second time limit dictated by TDR 6.1.2.

Figure 33: The results from the first communications test.

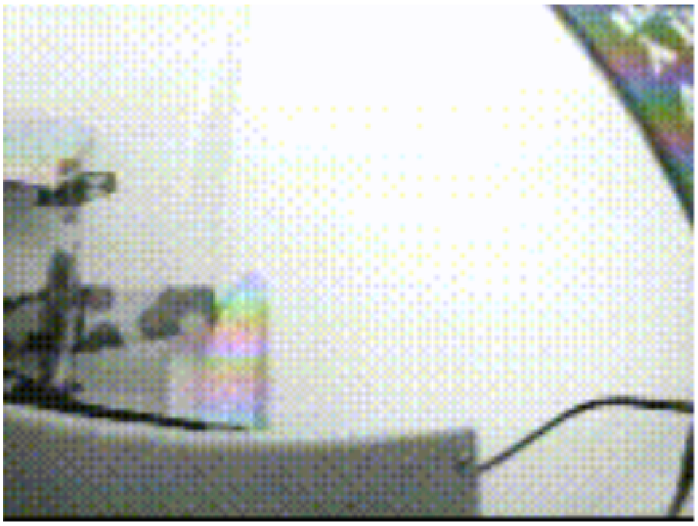


Figure 34: The results from the seconds communications test.

5.5 Day-In-The-Life Verification and Validation

5.5.1 Motivation

The Day-in-the-Life test is a comprehensive test that assesses RESCUE's functionality from "beginning-to-end," or a "Day in the Life" in the competition environment. The goal of the day-in-the-life test is to mimic the actual environment and scenarios RESCUE's system will be subjected to. Thus, this test was repeated multiple times at different scenarios (dark room, room with light, etc.) and for various extension distances and orientations (horizontal, vertical, somewhere in between, etc.)

All project requirements are in some way assessed by the Day-in-the-Life test. This is done to ensure that compliance within the subsystems level is carried over to the system level. By ensuring that all requirements are met, RESCUE can be considered a successful design.

Moreover, the day-in-the-life test serves to ensure that all integration was done properly and will identify any integration mistakes and streamline the user experience (the customer) with the system.

5.5.2 Model Development

In the case of the day-in-the-life verification and validation process, rather than validating specific models team RESCUE was validating the functionality of the entire system in a standard operating environment. Furthermore, another goal of the verification and validation process was to determine if any of the software and communications-based requirements that could not be directly tested were not being satisfied.

5.5.3 Test Setup & Procedure

RESCUE's mission begins when MARBLE's team determines a remote or obstructed location of interest. This location could contain artifacts the UGV cannot sense. To mimic the process, the team carefully created a test environment in which certain artifacts are scattered in a room, shown in Figure 35. From RESCUE's point of view, there exists a linear path from the stowed position (0,0,0) to the area of interest at a given (x, y, z) despite obstacles obstructing the artifacts themselves. In the competition setting, MARBLE will ensure that the path to the target end effector location is unobstructed. This test required the use of an enclosed room with assorted furniture and capability to go dark, as well as mock artifacts for the RESCUE system to view with the FPV camera. Key measurements were taken using a stopwatch and the `ping` command line tool.

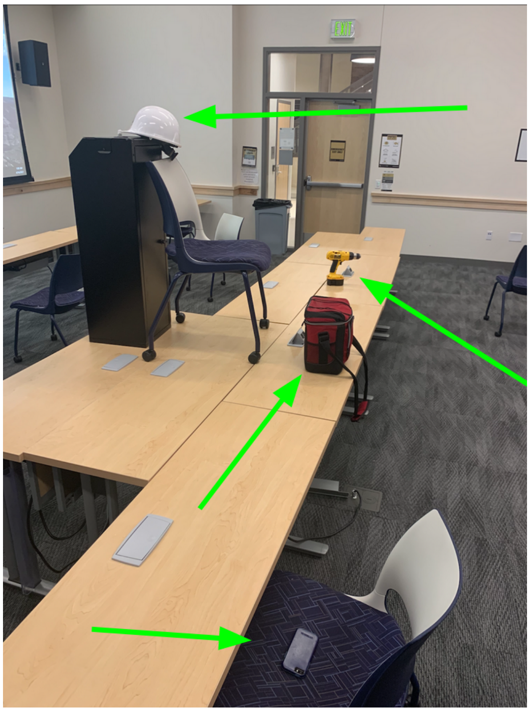


Figure 35: The artificial environment created by RESCUE's team members to mimic the cave environment from an artifact placement point of view

A Day-in-the-Life test for RESCUE follows this procedure:

1. **Commanding RESCUE:**

   A team member sends a firing command on the command line to activate RESCUE's deployment process. The firing command will contain three coordinates and a type flag that denotes whether the coordinates are in the relative inertial frame or target angles and extension distance. These firing commands look something like this (slightly simplified for readability):

```
roslaunch rescue_pkg rescue.launch type_flag:=a coord1:=65 coord2:=45 coord3:=56
roslaunch rescue_pkg rescue.launch type_flag:=c coord1:=34 coord2:=29 coord3:=44
```

2. **Interpreting Commands:**

   The RESCUE software package then uses algorithms to convert inertial coordinates to target angles and extension distances (if necessary), which are then converted to pulsewidth commands for servos and PWM commands for motors.

3. **Executing Base Commands:**

   When the Rasbperry Pi at the base of the RESCUE system receives a firing command, its first course of action is to convert locations to pulsewidth and PWM commands. Subsequently, these commands are sent to the base pivot and rotation servos, as well as the extension motor, to orient and extend the arm to the target location. The extension command is defined by active extension time, so a timer is used to determine when RESCUE has finished extending (pivoting and rotation are executed before extension to ensure accuracy in this regard). The base Pi also sends an activation command to the end effector with active sensing time as a parameter.

4. **Executing End Effector Commands:**

   When the Raspberry Pi Zero W at the end effector receives the sensing command, it activates its entire sensor suite and actuation kit at once. The camera turns on and the pan/tilt kit performs a 'sweep' of the surrounding area (pan from one side to the next at various tilt angles). At the same time, the CO_2 sensor and AHRS begin collecting data, which is read by the end effector Pi via GPIO and I2C.

5. **Data Collection and Transmission:**

   Video data is relayed using an integrated transmitter attached to the FPV camera to a receiver plugged into the base Raspberry Pi, which then transmits the data to MARBLE. The rest of the sensory data is transmitted via ROS messages straight to the MARBLE ROS node.

6. **Retraction:** After sensory data is collected, the arm will retract to a standby state on the MARBLE UGV.

5.5.4 Test Results

The following table in figure 36 indicates the key measurements from the day-in-the-life tests performed.

Component	Results	CPE and requirements validated
Total “day in the life” tests performed	30	FR 5.3: RESCUE shall withstand repeated deployments (min of 5 deployments)
Average deployment time	14 [s]	FR 4.2, TDR4.2.1, 4.2.2 : RESCUE’s deployment operations shall be rapid enough [30 seconds or less] to incur a minimal time cost to MARBLE’s total mission time.
Max data transmission time	50 [ms]	TDR 6.1.2 After deployment and retraction, RESCUE shall communicate sensing data with the MARBLE robot before its next deployment, or within approximately 60 seconds.

Figure 36: Results from day-in-the-life test

It is worth noting that, though all requirements were validated during the day in the life, only the performance parameters that change between deployments are measured. For example, with each deployment the deployment time and data transmission time could vary slightly. However, other requirements that are constant with deployments and time such as total mass, total volume, power draw, etc, are not recorded for each day-in-the-life test, but rather recorded once and validated only once because they are regarded as constant values (barring design changes). For a list of all requirements, review section three Figure 3.

6 Risk Assessment and Mitigation

Author(s): Seth Krein The risk analysis for this project was conducted by first compiling a list of all subsystems and components which were susceptible to failure as well as the types of potential failures they may experience. Once this list was established, the risk analysis matrix shown in figure 37 was used to rank the risks in order of severity and probability.

		Probability			
		Very Unlikely	Unlikely	Likely	Very Likely
Severity	Intolerable	Medium 5	High 7	Extreme 9	Extreme 10
	Undesirable	Medium 3	Medium 6	High 8	Extreme 9
	Tolerable	Low 2	Medium 4	Medium 6	High 7
	Acceptable	Low 1	Low 2	Medium 3	Medium 5

Figure 37: Risk Analysis Matrix.

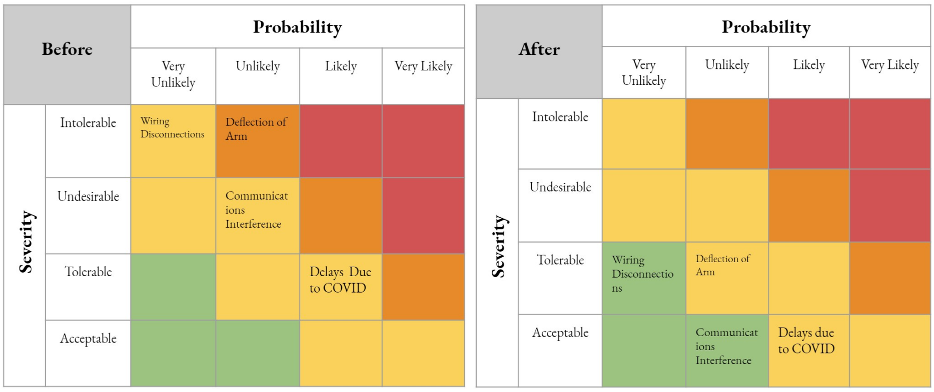


Figure 38: Risk Analysis:Before and After Mitigation Strategies

The locations of major risks in the risk matrix prior to mitigation can be seen in Figure 38. Although this is not an exhaustive list of all risks, these are what were found to pose the most significant threats to the success of the project. Brief descriptions of each risk, the rationale for their ranking, and mitigation strategies will be discussed in the following subsections. Upon implementation of the mitigation strategies, all major project risks shift into the more favorable regions of the matrix as shown in Figure 38

6.1 Deflection of the Arm When Extended

Author(s): Seth Krein

Assessment In order for the RESCUE system to be successful, the extension mechanism needed to rigid enough to ensure the arm would not deflect downward due to play in the connections between sections and/or bending of the beams. If the deflection of the arm prohibited the systems ability to extend to a specified location, the ability of RESCUE to collect useful image and video data would be jeopardized. Thus, arm rigidity in the extended configuration was vital to the success of this project. The main design aspects that influence the probability of deflection when extended are the end effector mass, tolerances in the connections between segments of the arm, and flexural strength of the arm segments.

Mitigation and Tracking

To minimize the probability of deflection when extended, an end effector mass limit of 450 grams was implemented based on pivot motor torque and thorough structural analysis and testing of the X-rail slide kit. With this measure in place, this risk becomes unlikely and tolerable if it were to occur. It is tolerable due to the fact that the deflection would be small enough that artifacts will still be within the field of view of the camera. The

6.2 Communications Interference

Author(s): Seth Krein, Johnathan Tucker

Assessment In a cave environment, wireless communication between the end effector and the base can be interfered with from two main sources: RFI and multipath. Radio-frequency interference occurs when multiple wireless devices are communicating on the same frequency which can cause noise, or a disturbance, to occur on the frequency spectrum. Multipath interference occurs when multiple signals from the transmitter are received by the receiver due to the reflection of the radio-waves off the walls of the cave. Ultimately the probability of these occurring is high given the operating environment, but the probability of them impacting communication functionality is low because modern wireless transmitters and receivers include on board filters to mitigate their impact.

Mitigation and Tracking To ensure data is successfully transmitted and received by the end effector and base, a wireless receiver and transmitter combo were chosen that can operate on a wide variety of channels and at a much greater separation distance than they would be at when the arm is extended. Another mitigation tactic the team employed was to test the wireless transmitter and receiver in an environment with ambient RFI to ensure the functionality of the COTS hardware.

6.3 Wiring Disconnections

Author(s): Seth Krein

Assessment The risk of wiring disconnections is intolerable for obvious reasons. If components become disconnected this can be detrimental to the success of the system and can also threaten MARBLE's performance in the Subterranean challenge if RESCUE were to become fixed in place in an undesirable orientation.

Mitigation and Tracking The mitigation of this risk was performed by reinforcing soldered connections using hot glue so that they cannot be broken off. For tracking this risk we routinely examined connections after each subsystem and full system test and found the hot glue to be a sufficient solution to this risk.

6.4 Delays Due to COVID-19

Author(s): Seth Krein

Assessment Due to the limited capacities of manufacturing facilities during the COVID-19 pandemic, lead times were a significant risk to all aspects of this project which relied on COTS hardware. The pandemic also created difficulty in terms of assembling RESCUE in that there was limited capacity in all of the on campus work spaces.

Mitigation and Tracking The impact of the pandemic on this project was minimized by increasing the shipping budget to allow for expedited shipping. As the project progressed this proved to be an effective strategy to mitigate the effect of lead times. In response to the limited capacity of on campus work spaces the team chose essential personnel to gain access to campus while the remainder of assembly was conducted off campus. These strategies enabled the project to remain on schedule and overcome the complications created by the pandemic while still complying with CDC guidelines.

7 Project Planning

Author(s): Seth Krein

7.1 Organizational Chart

Due to the broad spectrum of engineering disciplines involved in the development of the RESCUE system, this project relies on each team member specializing in certain aspects of the project while still being able to collaborate on other components and integrate subsystems efficiently. With this in mind, each team member was assigned a leadership role based on their individual skills, experience, and interests. Teams were created to assist each lead and every team member is a part of at least three of these teams. This method of organization will enable team members to interact with each other to ensure there is no oversight in subsystem development that creates integration issues. The organizational chart shown below in figure 39 shows the breakdown of the engineering disciplines and what subsystems each team member is involved with. The two main teams are hardware and software with each broken down into sub-teams to further specify each person's responsibilities.

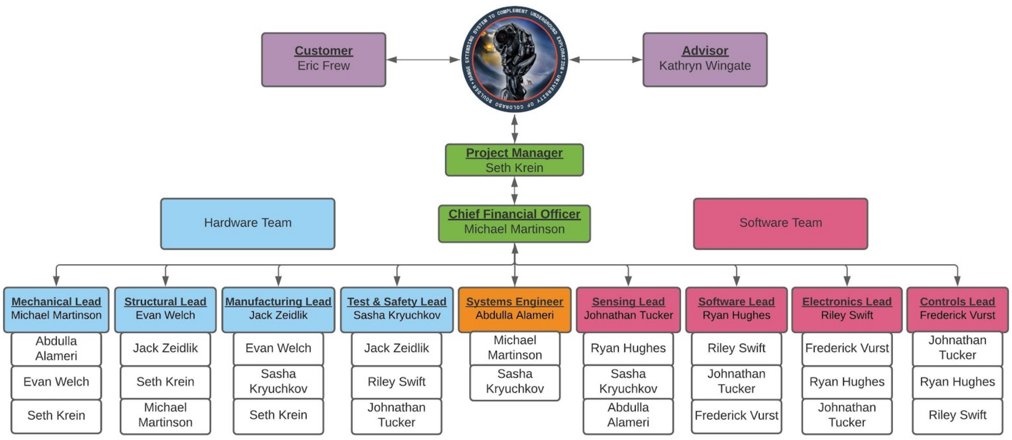


Figure 39: Organizational chart.

7.2 Work Breakdown Structure

The work breakdown is comprised of the major project deliverables, tasks, and milestones. All of the completed work is highlighted in green. The work that still needs to be done, shown in white, mainly consists of parts ordering and manufacturing, assembly and integration of subsystems, and validation/verification testing. These major work products were determined by ensuring that once every item on this chart is completed, all requirements for both the RESCUE project and the senior design course are met. The chart encompasses all work that needs to be done throughout this course to produce a functional product which meets the customer and PAB's expectations.

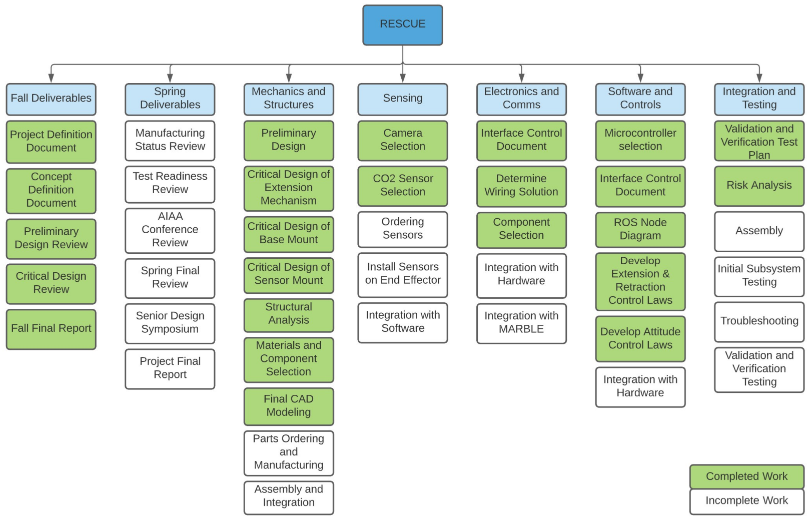


Figure 40: Work Breakdown Structure.

7.3 Work Plan

Figure 41 shows a high level overview of the Gantt Chart for this project with the critical path highlighted in red. As noted in our Critical Design Review, there are limited parallel efforts and this is due to the fact that we anticipate operating with limited personnel having access to lab resources and limited available lab time. With 18 senior projects teams, consisting of approximately 10 members each, along with the severe COVID-19 restrictions in place in the city of Boulder, the probability of having enough personnel with access to labs to enable parallel manufacturing and testing is unlikely. With these considerations in mind, if we are able to have a team of 4-5 with access to lab resources as expected, certain manufacturing and assembly processes can take place simultaneously. We are planning on a majority of subsystem testing and integration taking place after manufacturing and assembly to allow adequate time for troubleshooting during this phase. Wide margins are in place on both the construction and testing timelines to account for potential delays due to COVID-19 and unexpected issues with the novel technology we are utilizing.

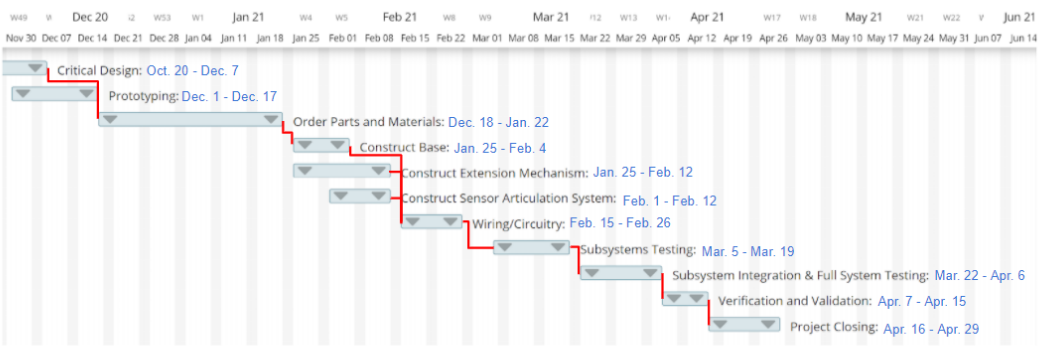


Figure 41: Work Plan Overview

Construction is broken down into three main components: the base, extension mechanism, and sensor articulation system. Due to the design of our system construction will start at the base and progress upwards towards the sensor package. We have allocated two days of margin on manufacturing and 3D printing of each part to account for potential failures, errors, or lack of available machines. Assembly of each major component will start as soon as the parts are completed/acquired.

Upon completion of the construction phase we will move into the testing phase which we have dedicated approximately five weeks to in order to allow adequate time for troubleshooting. Due to the novel technology we are utilizing, there are certain failures that we may encounter during the testing phase. To mitigate those risks, we are making efforts to identify potential issues early in the prototyping phase that takes place over winter break. We have also prepared a set of design off ramps in the event that a major problem arises. .

7.4 Cost Plan

Author(s): Michael Martinson

Figure 42 shows RESCUE's final financial results in comparison to the planned budget at CDR:

CDR vs. Final Budgets:

Budget	CDR	Final
Hardware	$1,328	$1,679
Electronics	$1,920	$807
Sensors	$300	$270
Software	$42	$42
Shipping	$300	$547
Total	**$3,890**	**$3,343**
Margin	**$1,110**	**$1,657**
Pre-Design Change Costs	**$435**	

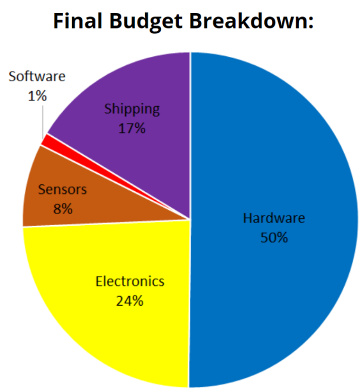


Figure 42: CDR vs. Final Budget, Final Budget Breakdown

Despite the project's significant redesign between FFR and SFR, the final cost was just 14.06% under CDR's initial prediction. Ultimately, only $435 was sunk into non reusable or refundable expenses testing the soft robotic design. Primarily due to the increased number of higher cost mechanical components for the cascade arm design, hardware costs were marginally above CDR's prediction. The cost of electronics was more than halved due to the elimination of costly pressure control components and the team discovering lower cost servo alternatives. The cost of sensors proved to be correct; the team did need to use margin to buy replacement sensor components. Shipping costs increased significantly as a result of expediting shipping on several components to complete a late redesign on a tight schedule.

7.5 Test Plan

Author(s): Seth Krein Figure 43 shows the testing flow for the RESCUE project.

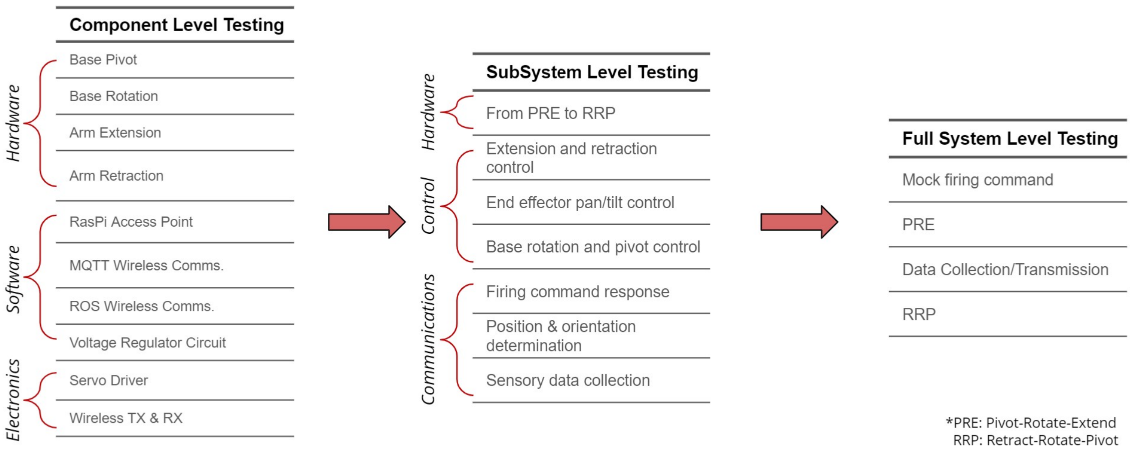


Figure 43: Testing Plan

The component level testing took place concurrently with the schedule in figure 41 as each component was acquired and assembled. Upon completion of assembly subsystems were tested to identify issues early, minimize variables, and prevent integration issues. Full system "Day in the Life" testing was conducted repeatedly to ensure reliability of the system. In hindsight this testing procedure was essential to the success of this project as many failures were identified throughout the component and subsystem level testing which were able to be resolved early on to avoid larger complications and delays.

8 Lessons Learned

Author(s): Sasha Kryuchkov, Abdulla AlAmeri, Riley Swift

8.1 General Team

The general challenges that the team faced were with scheduling, testing scheduling, and wants vs needs of the customer.

The most prominent issues was scheduling as it seemed there was never enough time for anything in the project. Fall semester, the team had to do a redesign since the initial design did not meet the customer's expectations, even though it met all of the requirements. Therefore, a large amount of workforce was put into looking for a new design solution for the project. This has made it challenging to focus on the tasks of CDR and making sure that the theoretical design worked. Unfortunately, this had significant effects on the spring semester. The team has found an important flaw in the fall-semester design. Fortunately, the team has considered multiple off-ramps, one of which was the ServoCity X-rail. Off-ramps were an important part of the project and are recommended for future teams to consider.

Testing was another challenge for the team that involved scheduling. Since the team was unable to purchase parts most of the fall semester, it was impossible to make predictions about part specifications that were not listed by the manufacturer. Specifically, when RESCUE was looking into an inflatable tube, LDPE tubes on the market did not have maximum pressure values, which meant we had to rely on our tests in January to see what material worked best. Having p-card available for usage as soon as possible would simplify scheduling and not delay it.

Finally, knowing the difference between the needs and wants of the customer were crucial to the team. The team did not communicate enough with Professor Frew when the requirements were set, which led to the team and the customer having different views on how the final product should have looked. While meeting all of the requirements, the team did not consider which of them were more important to the customer. For example, the team did not realize that having a longer reaching distance could have taken priority over the maximum mass requirement. This misunderstanding led to the delay in the project and subsequent issues mentioned above. What future project teams must pay attention to is what their customer favors the most in the design and make it the crucial goal of the project.

8.2 Mech Team

One of the main lessons learned by the mech team is the importance of prototyping. During the design phase in the first semester, the team tried to make sure that requirements for the project were possible to meet. The desire to reach the upper limit of reach (5 meters) was the driving design requirement for the team and for the customer. With such ambitious goals and lack of prototyping, the team fell into a trap of relying too much on testing. It was easy to postpone decisions until the following semester until there was no more time to waste. The piece of advice for future seniors is to not rely on having lots of time and not relying on testing things later. Completing tasks early can greatly help teams in the future.

Talking the PAB members and professors at the department is an incredible tool to keep the PAB members up to date on the project and get incredibly useful knowledge on what challenges the project may face in the future. RESCUE has not been seeking for help at the beginning of the year when selecting the design, but talking to the PAB proved itself to be crucial to avoid future mistakes and time wastes.

Additionally the mech team learned the lesson that many designs will work well in CAD but can be extremely difficult to manufacture and assemble. There will be issues with the Assembly of small systems so extra time needs to be considered to ensure a project can still be completed on schedule.

8.3 Electronics Team

One of the main lessons learned by the electronics team is that getting help and advice from professors is invaluable. With the aerospace curriculum only requiring one software and one electronics course, there are always going to be necessary elements that weren't taught. By utilizing resources like professors and LAs, the electronics team was able to ask questions, determine what they didn't know how to do and learn how to do it.

In addition to asking for help, googling was a crucial part of this project. Learning how to efficiently search for electronics online and filter out useful information was key. Being able to read and understand sensor specification sheets was also very important. During the trade studies the team based all their trades on the data provided in the spec sheets. Despite choosing and ordering the best option, some of the parts were not as good as their spec sheets would have us believe. We learned that the quality of cheap parts, even with sufficient specs, may not be worth the low price. In multiple cases, the team had to reorder sensors because they arrived broken. Whether this was due to the low cost of the sensor or just due to the shipping process of delicate sensors, the team learned that ordering backup parts is important. Testing new electronics as early as possible to determine if they are working properly is crucial but it does not hurt to have a backup ordered, especially if it is within the budget.

Lastly, the electronics team learned that it is important to be flexible and ready for design changes. Electronics design changes occurred not only because of the team's overall design change but also during testing. For example, as the team tested the optimal way to operate the design, it was determined that one of the servos needed to be run at a lower voltage. Because of this a last minute voltage regulator needed to be added to the base electronics. Also, small changes often needed to be implemented such as adding heat sinks, accounting for a higher current, or switching to battery power at a professors recommendation.

8.4 Software Team

The primary challenge faced in the software development cycle was the lack of development time. On the one hand, the technical challenges faced during the manufacturing phase of the project had pushed back development time as subsystems could not be properly tested with RESCUE's software package without being fully derived and assembled. On the other, utilizing open-source ROS resources and Python libraries proved more challenging than originally thought as not all libraries are catered towards this project's specific goals, resulting in time costed due to having to work around compatibility issues. Furthermore, the lack in development time led to miscommunications and other mishaps, which limited the software team to 1-2 consistently developing members through the duration of the project manufacturing process.

One of the main takeaways from this is that ample time is needed to effectively test all of a system's components as configuring the software subsystem to work as intended is heavily dependent on the manufacturing state of the mechanical and electrical subsystems. With that, it is essential that the software team keeps track of the project's timeline and to tailor their development strategy to meet any changes that would affect their work. Another thing to note is that when using open-source resources and libraries, it is important to not only become well acquainted with those that intend to be utilized, but also to have plenty of alternatives. This would have possibly enabled the software team to be prepared for selecting more specific libraries and packages that are better suited for this project, allowing for more efficient software development time.

8.5 Systems

One of the most important aspects of the design cycle is scoping the project. If scoping the project is not done properly, and the stakeholder values are not well evaluated before starting the design, it is almost a certainty that some of the stakeholders expectations will not be met. Thus, the initial phase of any project starting with the PDD document is one of the most important phases and must be given sufficient time.

This goes hand in hand with defining the requirements. Senior design was the first experience where the requirements had to be derived from customers wishes and envisions to how the system should work. Therefore, it could be sometimes the case that some requirements are inherently contradictory or makes the project impossible to implement within the school year. An inexperienced undergraduate students could easily fall into that trap given that it is the first time they experience such things. It is thus important to have a lot of conversations with the customer.

Another key lesson learned is that all of the design process from theoretical design to implementation is a fluid process. Design changes will happen through all of the design cycle as situations change and new challenges arise, and thus it must not be approached with frustration but with open mindedness towards the whole process.

Moreover, margins are really important because in actual design and build projects it is almost a certainty that something will not follow the schedule, and it is of extreme importance to leave ample margins on everything and try to respect the margins.

In addition, exploring design space is a very challenging process. Sometimes, the team could get tunnel visioned by past experiences and/or being under the impression that some things are required to be done when in fact they are not, which ties in with the first lesson learned about the importance of keeping the channels of communications open with the customer.

9 Individual Report Contributions

9.1 Abdulla Al Ameri

Abdulla was the systems engineer for the project. His responsibilities ranged from contributing to design and implementation to making sure all subsystems are compatible and the project requirements are met and verified and the final product satisfies all stakeholders expectations. Thus, he was involved heavily with all aspects of design, testing, and manufacturing.

work on this report:

- Section 3: Conceptual Design
- Section 5: Detailed Design
- Section 6: Verification and Validation
- Appendix B: All Technical Design Requirements
- Appendix C: Conceptual Design: Design Alternatives

9.2 Evan Welch

- Section 3: Final Design
- Section 4: Manufacturing
- Section 5: Verification and Validation
- Appendices C, D, F, H, and I

9.3 Fredrick Vurst

For the PFR assignment, Frederick discussed some of the challenges and lessons learned by the Software Team in Section 8. Frederick contributed to the software development team in the form of development-related research and testing of RESCUE's ROS package. Additionally, Frederick made an effort to create a basic user-interface for RESCUE's software to enable positioning and flag commands to be sent via command-line arguments.

9.4 Jack Zeidlik

Jack contributed to the mechanical design efforts and PFR writing for the following sections: 3.3, 4.2, Appendix sections C.3, C.5, C.7, D,2. Conducted significant amounts of research into arm design alternatives and developed the entire mechanical base system.

Jack was responsible of for majority of the work on the rotation system, with partial design of aspects of the pivot and extension systems. Jack lead the early testing work for the inflatable designs and the majority of the final design manufacturing including prototyping parts outside of the shop and submitting to the shop when high accuracy was required. Jack acted as one of the mechanical team liaisons during system testing. Additionally Jack worked on many aspects of the base system CAD and assisted Micheal with many calculation and part ordering checks and design considerations through the redesign processes.

Jack wrote in full onm contributerd to writing the following sections:

- 3.3
- 4.1.2
- 8.2

9.5 Johnathan Tucker

Johnathan contributed to the sensing, electronics, controls, and software teams. This was accomplished through the selection of hardware, manufacturing of circuits, creation of control laws, and writing of scripts.

- Section 3: Final Design
- Section 4: Manufacturing
- Section 5: Verification and Validation
- Section 6: Risk

9.6 Michael Martinson

Michael was responsible for the complete design work on the mechanical aspects of the pivot system and partial design work on the mechanical aspects of the extension/retraction, rotation, and end effector systems. Michael contributed to all aspects of the project's mechanical system manufacturing and assembly, and acting as one of the mechanical team liaisons during system testing. Michael was also responsible for all finance tracking and documenting for the project, as well as creating all of the CAD based diagrams and dimensional drawings for PFR.

Michael wrote in full or contributed to writing the following sections:

- 3.1 - 3.5
- 3.6.1-2
- 4.1.2 - 4
- 7.4

9.7 Riley Swift

Riley contributed to the electronics and sensing teams, mainly through selection of hardware, manufacturing of circuits and design and implementation of the power systems and voltage regulation.

- Section 3.6: Final Design - End Effector System
- Section 3.7: Final Design - Base Electronics
- Section 3.8: Final Design - Power System Design Power Budget
- Section 4.2: Manufacturing - Electrical Manufacturing
- Section 8.3: Lessons Learned - Electronics Team

9.8 Ryan Hughes

- Section 2: Project Objectives and Functional Requirements

- Section 3: Final Design
- Section 4: Manufacturing
- Section 5: Verification and Validation

Ryan was responsible for the development and integration of all software on the RESCUE project. He designed and compiled the entire ROS package and was responsible for software components and adjustments during testing.

9.9 Sasha Kryuchkov

Sasha was responsible for the inflatable material testing and FOV testing. He did the models for the number and length of sections used and the original deflection model, which was then replaced.

- Section 3: Final Design
- Section 5: VnV
- Section 8: Lessons Learned
- Appendices C and D

9.10 Seth Krein

As the project manager, Seth contributed to the project by scheduling and coordinating team members efforts as well as making critical decisions. He also contributed to the physical design of the system by producing the CAD models of the end effector and iterating that design to house all of the necessary electronics and meet the volume and mass requirements.

- Section 1: Project Purpose
- Section 6: Risk Assessment and Mitigation
- Section 7: Project Planning, Test Plan

A Appendix: Artifacts

All artifact descriptions were pulled from the DARPA competition rules [8].

A.1 Survivor

The survivor artifact will be represented by an anatomical, thermal manikin to represent both human shape and body temperature. The manikin will be fitted in a high-visibility jacket, grey work pants, and standard yellow steel-toed work boots. It is anticipated that survivor manikins will be placed in a sitting position in the competition course.

A.2 Cell Phone

The cell phone artifact will be represented by a standard smartphone (Samsung Galaxy J J19M/DS). It will be placed in the competition course with the screen on and playing a full-screen video with audio. The phone will also have 2.4GHz WiFi operating as an access point with a visible SSID, as well as a Bluetooth radio operating in discovery mode. The latter two features will reflect the artifacts unique name, which will have the form 'PhoneArtifactXX,' where XX will be a random, but static, combination of any 2 letters or numbers.

A.3 Backpack

The backpack artifact will be a JanSport backpack whose front and back portions are all-red and all-black, respectively. All of the zippers will be closed. The artifact may be found on the ground, hanging on a wall, or resting on a work surface in the competition course. The backpack will be placed with its red front portion facing outward or upward.

A.4 Drill

The hand drill artifact will be represented by a Black Decker GC960 Cordless Drill with an orange body, black battery, and black chuck collar. It will not be in operation during the competition run, and may be found on the ground or on work surfaces. The drill's resting orientation is unspecified.

A.5 Fire Extinguisher

The fire extinguisher artifact will be a typical red hand-held, metal cylinder fire extinguisher commonly found in everyday environments. This artifact will not be in operation during the competition run, and its hose will be attached in the stored configuration. It may be found on the ground, hanging from a wall, or resting on a work surface in the competition course.

A.6 Gas

The gas artifact will be represented by CO_2 emitted in a confined area to maintain a concentration of approximately 2000 parts per million. This confined area will be a room with a clearly defined ingress/egress point (doorway). This artifact will have no visual identifier.

A.7 Vent

The vent artifact will be a Grainger 4MJV3 three-cone square ceiling diffuser that is fabricated from sheet metal and painted white. This artifact will be actively heated to produce a distinct thermal signature that is at least 30°C above ambient temperature. The air vent may be found on a wall or ceiling at any height, protruding no more than 300 mm.

A.8 Helmet

The helmet artifact will be a typical white caving helmet and headlamp, with the latter operating in the 'low spot' setting. This artifact may be found on the ground, on a wall, or on a ledge. The localization point at the crown of the helmet will be visible, but the front of the helmet may be pointing in any direction in the competition course.

A.9 Rope

The rope artifact will be represented by a coiled 35m length of blue climbing rope, held together by a black strap located approximately in the middle. This artifact may be found on the ground, suspended from a wall, or on a ledge. The coiled rope may be accompanied by additional uncoiled sections of the rope and/or other climbing equipment nearby.

B Appendix: All Technical Design Requirements

B.0.1 FR1.1 - Artifact Sensing Requirements

FR1.1: The sensing system shall be able to sense DARPA subterranean challenge competition artifacts.

TDR1.1.1: The sensing apparatus shall have the capability to visually sense the following: brightly colored artifacts: human survivor, backpack, fire extinguisher, and rope. The visual sensing of these artifacts shall occur within the visual sensor's operational field of view

Motivation: Most of the artifacts can be sensed by a visual sensor, the more artifacts the sensing apparatus can visually sense, the more useful it is to MARBLE and the better it satisfies FR1.1.

Relationship to parent requirement: Directly enables the team to sense the majority of the artifacts.

TDR1.1.2: The sensing apparatus shall be able to **sense** and **detect** carbon dioxide (CO_2) at 2000 parts per million concentration.

Motivation: Being able to sense CO_2 makes the sensing apparatus more valuable to MARBLE by enabling RESCUE to potentially sense an additional artifact.

Relationship to parent requirement: Allows the team to sense the last non-visual artifact.

TDR1.1.3: RESCUE shall have enough lighting to perform all of its sensing operations in a possibly aphotic environment..

Motivation: It is expected that the RESCUE system will encounter areas without ambient light. In this event, the camera must still be capable of taking image data in order to sense artifacts. This would be enabled by adequate lighting on the sensor suite.

Relationship to parent requirement: Enhances the quality of the visual data.

TDR1.1.4: Once RESCUE is re-positioned, the mechanical mount for the visual artifact signature sensor shall be capable of rotating at least 90° or more about at least one axis.

Motivation: If RESCUE's visual capabilities were limited to a radial direction from the MARBLE system, the ability to see over and around obstacles would be significantly hindered.

Relationship to parent requirement: Allows for a change in the field of view of the visual sensor without necessarily having to move from one location to another.

B.0.2 FR2.1 - Physical Reach Requirements

FR2.1: RESCUE shall have the ability to physically reach a location along an unobstructed linear path that is at least 1 meter but not more than 5 meters from RESCUE's stowing position on the MARBLE Clearpath Husky in an upper-half hemisphere.

Motivation: This FR has no TDRs because it is either you are within the 1-5m range or you are not. In other words, there are no TDRs that must be fulfilled to satisfy FR 2.1.

Relationship to parent requirement: N/A

B.0.3 FR3.1- Reusability Requirements

FR3.1: RESCUE shall withstand repeated deployments.

TDR3.1.1 The MARBLE team shall be able to deploy RESCUE at least 5 times during a competition run.

Motivation: If RESCUE could not deploy at least several times over the course of a competition run, the MARBLE team deems that it would not be worth mounting to the MARBLE Husky for weight and other mission considerations.

Relationship to parent requirement: Satisfying TDR 3.1.1 means that RESCUE is cost-effective from MARBLE's point of view, and thus the project is of use and value.

TDR3.1.2 Upon receiving an firing command from the MARBLE team when in standby configuration, RESCUE shall reach an active state in 40 seconds or less.

Motivation: Rapid command processing & deployment is crucial for feasibility of multiple uses over a single competition run, especially since the competition is timed.

Relationship to parent requirement: Satisfying TDR 3.1.2 means that RESCUE is helpful to MARBLE because it can quickly deploy and collect data without delaying MARBLE over the course of the competition.

B.0.4 FR3.2- Endurance: Environmental Hazard Requirements

FR3.2: RESCUE shall withstand the environment of the DARPA subterranean challenge which is to be restricted to possible dust/mist and restricted temperatures.

Relationship to parent requirement: The functionality of RESCUE is only useful if it can operate in the environment MARBLE is operating in.

TDR3.2.1 RESCUE's mechanical and electrical components shall be able to function in a musty and/or dusty environment.

Motivation: DARPA specifies that the competition environment can to be typical to cave environments, which we restrict to potential dust and light mist [1]. The customer requests resistance from these kinds of hazards. Although water resistance could be a concern, exposure to waterfalls type of environmental hazards will cause both MARBLE and RESCUE to fail. Thus, the mitigation of such a hazard is on MARBLE.

Relationship to parent requirement: Designing the mission with the environmental hazards in mind increases the probability of effectiveness and success.

TDR3.2.2 The system shall accomplish all other design requirements in an nominal thermal environment of 50-65° F.

Motivation: Temperatures underground below 10 meters stay approximately constant throughout the year. Since the tests will likely be conducted in Colorado, the average underground temperatures being used are those from Colorado. [9]

Relationship to parent requirement: Same as TDR 3.2.1.

B.0.5 FR3.3 - Endurance: Time Requirements

FR3.3: RESCUE shall have enough electrical power to maintain standby, active, and operational states fitting the MARBLE team's mission performance expectations.

TDR:3.3.1 The system shall have enough electrical power to maintain a standby state for at least 135 minutes.

Motivation: Customer requirement. A SubT Challenge final competition run can last as long as 120 minutes, and our customer requests a 15 minute buffer time for when the Husky is preparing to start its competition run [1].

Relationship to parent requirement: Without enough power all of RESCUE's operations are impossible to happen, thus, this requirement is essential to the project overall objective .

TDR:3.3.2 The system shall have enough electrical power to maintain an operational state for at least 30 minutes.

Motivation: Customer requirement. The customer requires the sensor to be capable of actively conducting sensing operations for at least 25% of a 120 minute maximum duration SubT challenge final course run [1].

Relationship to parent requirement: This is the minimum time as specified by the customer means that RESCUE when meeting TDR 3.3.2 is cost-effective to MARBLE.

B.0.6 FR4.1 - System Position and Orientation Requirements

FR4.1: RESCUE shall determine and report its location and orientation relative to the ground robot.

TDR4.1.1: RESCUE shall be able to determine its position relative to the ClearPath Husky within 1 meter accuracy of its ground truth location at all times.

Motivation: Recognizing the sensor location would better allow the MARBLE robot to move within 5m of artifacts sensed outside of this range. Achieving this proximity would enable the MARBLE team to report the Husky's ground truth location for successful scoring.

Relationship to parent requirement: Enables the position to be determined, satisfies half of the FR 4.1.

TDR4.1.2: RESCUE shall be able to determine its orientation relative to the ClearPath Husky within 5° accuracy of its ground truth orientation at all times.

Motivation: This design requirement augments the previously listed design requirement in that it assists the MARBLE team in determining the ground truth location of the artifact.

Relationship to parent requirement: Enables the orientation to be determined, satisfies the other half of the FR 4.1.

B.0.7 FR5.1 - Deployment: Constraints Requirements

FR5.1: When in its standby configuration, RESCUE shall be compatible with the MARBLE team's Clearpath Husky.

TDR5.1.1 When in its standby configuration, RESCUE shall not exceed a volume of 38 centimeters wide by 45 centimeters long by 30 centimeters tall.

Motivation: Fixed limit from customer on how much space the RESCUE system can occupy when mounted to the Husky in its standby state.

Relationship to parent requirement: Puts requirements related to the volume compatibility.

TDR5.1.2 RESCUE shall not exceed a total mass of 10 kilograms.

Motivation: Fixed mass restriction from customer.

Relationship to parent requirement: Puts requirements related to the mass compatibility.

TDR5.1.3 If RESCUE is directly connected to the Husky, power drawn from the Husky robot shall be less than or equal to 24-30 Volts at 25 Amps.

Motivation: Fixed power restrictions from customer.

Relationship to parent requirement: Puts requirements related to the power compatibility.

TDR5.1.4 When RESCUE is deploying, in its active state, or in its operational state, the sensing apparatus shall not apply a force or moment that can unintentionally alter the position and/or orientation of or damage the MARBLE Clearpath Husky.

Motivation: Altering the position or orientation of the MARBLE Husky would be catastrophic to mission success, especially if the disturbance were to cause the Husky to lose balance or put it in harm's way of an environmental hazard.

Relationship to parent requirement: Puts requirements related to the mechanical and operational compatibility.

B.0.8 FR5.2 - Deployment: Time Requirements

FR5.2: RESCUE's deployment operations shall be rapid enough to incur a minimal time cost to MARBLE's total mission time.

TDR:5.2.1 Upon receiving a firing command from the MARBLE team when in its active configuration, RESCUE shall respond in an operational state as soon as the command is received (within 2 seconds).

Motivation: Customer mandated. Once the 30 seconds or less activation time is complete, RESCUE must not expend any additional time preparing to deploy.

Relationship to parent requirement: Bounds the concept of rapidity by ensuring instantaneous response to commands.

TDR:5.2.2 Upon receiving an deactivation command from the MARBLE team, RESCUE shall return from its operational/active configuration to its standby configuration within 120 seconds.

Motivation: Customer mandated. This allotted time is greater than the time for RESCUE to respond to an activation command to account for retraction time of the physical system.

Relationship to parent requirement: Bounds the concept of rapidity by ensuring timely return to standby mode.

B.0.9 FR6.1 - Communication Requirements

FR6.1: RESCUE shall communicate its sensed data with MARBLE and this process shall not interfere with MARBLE's communication systems. The sensor system shall be able to receive firing commands, nested firing commands, and deactivation commands from MARBLE's team.

TDR6.1.1: RESCUE shall be capable of receiving firing commands from the ROS nodes in the existing MARBLE architecture.

Motivation: The ability to receive firing commands enables the RESCUE system to deploy at appropriate times as designated by the MARBLE team.

Relationship to parent requirement: Describes the communication method.

TDR6.1.2: After deployment and retraction, RESCUE shall communicate sensing data with the MARBLE robot before its next deployment, or within approximately 60 seconds.

Motivation: The customer suggests that at minimum, RESCUE should report its sensing data prior to the next deployment. This provides for each use of the sensing apparatus to be analyzed separately by the MARBLE team.

Relationship to parent requirement: Puts restrictions on communication rates.

TDR6.1.3: RESCUE shall transmit data to the MARBLE robot through a wired connection that will remain securely attached and functional throughout the duration of competition use.

Motivation: Data transmission via a direct, wired connection will be more stable and reliable than wireless communication. This measure will allow the team to focus on achieving communication at a higher data rate.

Relationship to parent requirement: Specifies the method of communication.

TDR6.1.4: RESCUE shall deliver frequent status reports to the MARBLE robot regarding deployment status and data collection.

Motivation: Knowing the current status of the sensor apparatus will enable the MARBLE team to avoid sending premature firing commands to RESCUE. It will also simplify identification of unsuccessful deployments (e.g. the apparatus getting stuck on an obstruction).

Relationship to parent requirement: Keeps MARBLE in the loop more often by providing status update. This is helpful because MARBLE can make different decisions based on RESCUE's status.

C Appendix: Conceptual Design: Design Alternatives

C.1 Introduction

Over the course of the project, the team assessed the following design concepts for mechanically deploying a sensor package to meet functional requirements FR2.1, FR3.1, FR3.2, and FR3.3 and their included TDRs:

- Drones
- Sensor projectile launchers
- Folding robotic arm
- Telescoping robotic arm
- Sliding robotic arm
- Pneumatic/Hydraulic robotic arm
- Soft robotic arm

The following set of sensing, control, and electronics conceptual design alternatives were considered in order to meet functional requirements FR 1.1, FR3.1, and FR 6.1 and their included TDRs:

- RGB-D Camera
- VR Camera
- CO_2 Sensors
- System Position and Orientation
- Communication and Data Transmission

C.2 Drone

C.2.1 Functionality (how it works)

Drones are becoming very common for sensing and gathering data in missions similar to this, and they should definitely be considered as a design solution. The high-level concept will be a drone carrying the required sensors on board. This high level concept could come with multiple different solutions for power and sensors orientation as well as collision avoidance mechanism.

The drone would need a method to deal with potential collisions inside the cave. This could either be an active collision avoidance system, or some sort of protective padding on the drone. (either a spherical cage that surrounds the drone, or bumpers that protect protruding surfaces and the rotors). Active collision avoidance would require dedicated sensors on the drone, and a good bit of software to process the data of the drones surroundings and react accordingly. Even with collision avoidance software, it would be unwise to assume that the software is perfect and the drone will never contact anything, so some sort of protection would still be needed. A collision avoidance system is a great solution to operate in an environment with random obstacles, however it has requires a dedicated sensors and software that will likely require a significant amount work.

Figure 44: Protective Cage Around Drone, Camera's Perspective [10]

The other option for drone protection is some sort of protective padding, either a spherical cage-like structure or bumpers around the rotors and protruding surfaces. Both of these would likely be custom made out of a rubber type of material, something with the right amount of give. The maximum speed for the drone would be known, so the right material with the right properties to absorb the impact could be determined (not too stiff so the drone is not basically still hitting a wall, but stiff enough to stop the impact from occurring). The material also would ideally not exert a large restorative force on the drone, which could cause instability in it is flight and a possible crash. The cage would need to be tight enough so that pointy surfaces on the walls of the cave could not penetrate through and get to the drone. The sphere could be able to freely rotate along a couple different axes, which would help a lot with collisions so any moments are not just translated straight to the drone. Flyability partnered with a team from Zermatt Mountain Rescue to build a great example of this structure [10]. Their drone is used to explore the crevasses of the Zermatt Glacier and help with search and rescue missions. The drone is able to successfully navigate the glacier with excellent stability while bumping into walls constantly. There is likely some sort of gimbal system that allows the cage to spin and absorb moments without making the drone's flight unstable. Pictured below is a capture from video footage on the drone, where you can see the protective cage and the type of environment that the drone can explore.

C.2.2 Diagram

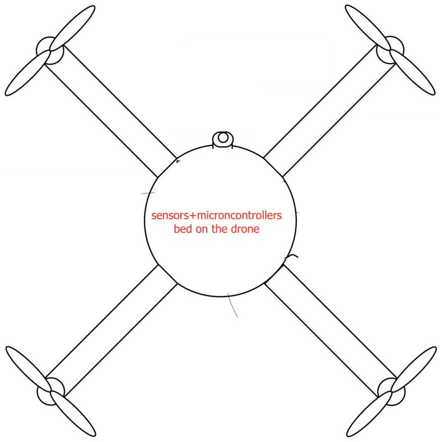


Figure 45: Top view of drone design solution.

Figure 45 represents a typical drone design for the mission. On the top of the drone, the sensors and microcontrollers could be placed. To change the field of view of the visual sensor one can either title the visual sensor with servos or tilt the whole drone. This schematic shown in figure 45 does not include the possible design for collision avoidance.

C.2.3 Pros and cons

In general, relative to the functional requirements, the drone has the pros and cons shown in table 7.

Table 7: *Drone Pros and Cons*

Drone	
Pros	**Cons**
Easy physical reach. 5 meter reach as well as positioning and changes in direction are easily achievable.	Mounting on the Husky may be a dimensional issue if its protective system takes up a lot of space. It would have to be a relatively small drone which could mean smaller instruments and less sensing capabilities.
The drone will not be tipping the Husky over and will have minimal to no interference with the husky.	Possible impacts with the environment could damage the drone if not protected.
The drone turns on and can lift off of the Husky with electric motors instantly.	Operational time could require batteries which increases weight. Tethered solution represent a complexity when it comes to retraction in safe way and manage the connections smoothly.

Moreover, the team conducted pros and cons studies on specific aspects such as powering mechanisms and protection methods. For the powering and communication mechanisms, the two available options are tethered drone and wireless drones. The pros and cons are shown in tables 8 and 9.

Table 8: *Wired (Tethered) Drone Pros and Cons*

Wired (Tethered) Drone	
Pros	**Cons**
Wired communication is much easier and more robust.	There is a potential for the tether to get tangled or caught up on the Husky or cave walls.
Power could be sent directly to the drone at all times.	

Table 9: *Wireless Drone Pros and Cons*

Wireless Drone	
Pros	**Cons**
More maneuverability and freedom.	Battery life becomes an issue. The drone would either need to carry extra batteries (more weight), or the docking and charging process becomes very complicated.
	Harder to transmit data and communicate with the Husky.

A tether could supply power to the drone, as well as serve as a communications line between the sensors and the Husky. It would eliminate the need to carry batteries on the drone, as well as the need to wirelessly transmit the data wirelessly communicate with the drone and send/receive positioning commands. Two of the main problems with drones of any kind are battery power and signal loss, so having it tethered would eliminate these two issues. Wireless would let you go farther from the ground robot, but that is not really needed for this application since there is maximum physical reach. The tether could just be made as long as we need. There is a concern of possible tangling of the tether, whether getting tangled on itself or getting caught on a cave wall. As for wireless, there would not be any concern of getting tangled, but sending data and communicating with the Husky would be much harder. Also, battery life becomes a big issue with being wireless. Charging while docked on the Husky could be a possibility, but it would have to be a very accurate landing system, probably impossibly accurate. All of these points are listed below in a pros vs cons list for wireless and wired approaches.

Moreover, the team considered mainly two passive protection mechanisms for the collision avoidance, a set of bumpers or a protective spherical cage. The pros and cons for each are shown in tables10 and 11.

Table 10: *Spherical Cage Pros and Cons*

Spherical Cage	
Pros	**Cons**
Protective coverage against collisions in all 3 dimensions.	Takes up a lot of space, so mounting on the Husky could be difficult.
	Keeps the drone from fitting in tighter spaces.

Table 11: *Bumpers Pros and Cons*

Bumpers	
Pros	**Cons**
Likely uses less material than the spherical cage, meaning it is lighter.	Incomplete protective coverage.
Does not take up very much space so a larger drone could be used.	

C.3 Sensor Projectile Launchers

C.3.1 Functionality (how it works)

A projectile launching system mounted to the MARBLE Clearpath Husky used to launch a sensor cluster to a desired location requiring three primary elements, diagrammed below in Figure 46. The sensor system being used will be in the form of a sphere. This is due to the sphere being a simple shape to integrate into the launch system and it is able to be adjusted to fit the sensors required in any orientation desired. The sensors in use shall be determined by the sensor team and the deployable vehicle will be designed to accommodate there needs.

C.3.2 Diagram

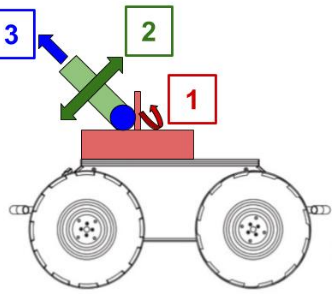


Figure 46: Projectile Launch Basic Element Breakdown

Figure 46 shows the projectile launcher designed integrated to MARBLE's Clearpath Husky. The numbers in figure 46 represent the following:

1. **Base Plate:** Indicated as 1 in the diagram above, the base plate would provide two critical functions. First, the plate must keep the launcher attached to the Husky and stable during firing (TDR 4.2.1). This includes supporting the cannon in both it is standby state and its deployed state, and acting as the base link for power and data connections to the Husky (FR4.1). Second, the base will rotate and incline the launch system to achieve TDRs 1.1.1 and 1.1.2.

2. **Launch Mechanism:** Indicated as 2 in the diagram above. The launch mechanism includes the system to launch the sensor cluster to the target to achieve TDR 1.1.1. as well as reset the mechanism to be ready for another deployment to satisfy FR5.3.

3. **Rearm Mechanism, Reusable vs. Single use:** Indicated as 3 in the diagram above. This includes either a retrievable and reusable sensor on a tether or a storage space housing discard-able sensor cluster to be used. This reload system will reset the deployable sensor cluster to be ready for another deployment to satisfy FR5.3.

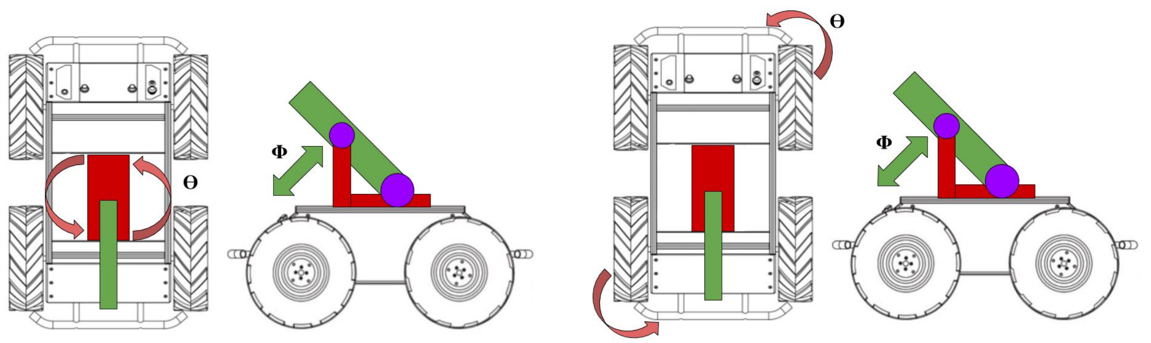
In the next three subsections possible design solutions are considered for each design element:

Projectile Launch Base Plate

1) Rotational Base Plate:

Rotating base mounts are common in projectile launching systems such as navel turrets and air defense systems like anti-aircraft guns. These systems have motors that rotate they base as well as change the inclination of the barrel to achieve the desired firing arc. This project would use a similar system on a smaller scale.

The mechanical approach to rotating the base is similar to the process the robotic arm from before utilizes. The system is attached to a motorized base plate and is rotated on command using a motor connected to a series of gears that swivel the plate to the desired direction. The inclination, at a basic level, is handled by placing an axis through some point along the barrel and applying a rotation to that axis to set the inclination. This and be done by many methods such as sets of gears and motors, or servos directly places onto the axis. Below in Figure 47a the axes are labeled as θ and ϕ for base rotation and inclination respectively. The system would be encased in a cover to avoid any obstructions to the moving components to meet FR 5.1 while mounted to the MARBLE Husky rover.



(a) Projectile Launch Rotational Axis

(b) Projectile Launch Rotational Axis, Static Mount

Figure 47: Projectile Launcher Rotational Methods

Designs, such as this, have a high mechanical complexity owing to the need to develop a rotation and inclination system using gears and motors able to function under the mass of the system and achieve a high degree of accuracy to ensure that the projectile is launched to the desired location.

2) Static Base Plate:

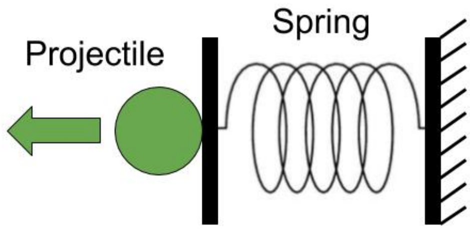
Static base mounts are similar to statically mounted arms on robots. The inclination would still be controlled in a similar way as the rotational base mount while the rotation would be controlled by rotating the rover to the desired orientation. This is very similar to a fixed robotic arm system such as the University of Sydney's Continuum Rover from before. In Figure 47b an example is shown of the rotational axis for this case.

Having a static base required more communication with the MARBLE rover to deploy in the correct direction. However, this simplification reduces the mechanical complexity of the system reducing the locations where error or failure could occur.

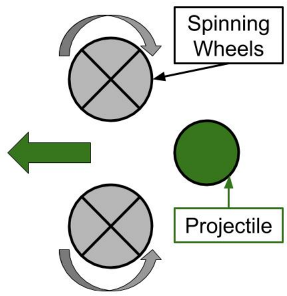
Launch Mechanism

1) **Spring Loaded:** A simple system that is used in many other applications to launch projectiles, like nerf guns. A spring is compress behind the projectile, when released the projectile is pushed forward. Systems like this are able to produce consistent forces that can be easily modeled for projectile motion using the spring force equation below Equation 8, where F is force, k is the spring constant, and x is the distance compressed. Also the force can be easily adjusted by adjusting the compression distance allowing for variations in the trajectory.

$$F = -k * x \tag{8}$$



(a) General Spring Loaded System



(b) General Spinning Wheels System

Figure 48: Launch Mechanisms

Figure 48a is an example of the general configuration of a spring loaded projectile system. The complexity is increased by the need to be able to re-compress the spring to different distances depending on the desired trajectory. Once the spring is compressed the system can fire right away resulting in faster results. The spring will be re-compressed when the next target is determined.

2) **Spinning Wheel:** The spinning wheel system is similar to how tennis ball launching machines operate. Using two wheels that are spinning at the same rate projectiles that pass in between and contact the wheels are ejected along a trajectory. The trajectory is able to be adjusted by changing the spin rate of the wheels. Additionally the trajectory is able to be simulated using the kinetic energy transferred during contact. In Figure 48b, is an example of the general system to fire projectiles. Once launched the system will return to a standby state where the wheels are stationary.

This system reduces mechanical complexity by not requiring a rearm system, however there is increase complexity in keeping both wheels rotating at the same rate. Unbalanced rotation can lead to spin being imparted to the projectile and/or a misaligned trajectory resulting in missing the target.

Rearm Mechanism, Reusable vs. Single use

1) **Reusable Sensor:** The reusable sensor cluster shall be attached to the system using a cable tether that will also handle power and communications with MARBLE. The tether shall be on a spool, similar to a fishing reel, and retracted using a electric motor once the sensor scan is complete.

2) **Single Use Sensor:** The single use sensor cluster shall be deployed and not retrieved. This requires the cluster to have its own power and communications system to return data to the rover. A storage system shall be arranged connected to the launcher. When reset to standby configuration the storage system shall place another sensor cluster into the launcher using either gravity or mechanical movement.

C.3.3 Pros and cons

The first list of pros and cons compare the rotational base with the static base. The rotational base pros and cons are shwon in table 12 and the static base pros and cons are shwon in table 13

Table 12: *Rotational Base Plate Pros and Cons*

Rotational Base Plate	
Pros	**Cons**
Allows for orientations that would be unachievable by the Husky when operating in restrictive environments	Increased mechanical complexity to develop, manufacture, and test
High accuracy to orient at target location	Increased attitude determination and controls system to be developed and tested
Regularly used mechanism with large amounts of examples research from	

Table 13: *Static Base Plate Pros and Cons*

Static Base Plate	
Pros	**Cons**
Static mount required less complex mechanical development	Requires additional communication with the rover to be able to point in desired direction
Know single source of forces that could result in destabilizing the MARBLE rover in relation to FR4.2	Decrease in ability to target a location dependent on the ability of MARBLE to position itself
Removes potential components that could be impeded by dust and water in relation to FR5.1	

The second list of pros and cons discusses the spring loaded and the spinning wheel mechanisms mentioned previously. The spring loaded mechanism pros and cons are shown in table 14 and the spinning wheel mechanism is shown in table 15

Table 14: *Spring Loaded Mechanism Pros and Cons*

Spring Loaded Mechanism	
Pros	**Cons**
Springs produce a repeatable and model-able force for ballistic trajectories	Required a system to re-compress the spring for each reuse
Adjustable depending on the desired trajectory to achieve accurate results	Spring is easily able to be obstructed

Table 15: *Spinning Wheel Mechanism Pros and Cons*

Spinning Wheel Mechanism	
Pros	**Cons**
Trajectory is easily simulated and adjusted	Induce unknown spin on the sensor ball
No complex mechanism to reset the system	Required additional time to spin wheels up to desired configuration

Lastly, the pros and cons comparing the disposable vs reusable sensors are shown in tables 17 and 16 respectively.

Table 16: *Reusable Sensor Cluster Pros and Cons*

Reusable Sensor Cluster	
Pros	**Cons**
Increase budget allowing for increased quality of sensors	Retrieval can be blocked by many obstacles
Reduced number of systems required to be contained by deployable	Hazardous objects could sever the tether

Table 17: *Disposable Sensor Cluster Pros and Cons*

Disposable Sensor Cluster	
Pros	**Cons**
No need to retrieve deployed ball saving mission time	Extra storage space required to house at least five total deployables for FR5.3.
Lower cost per deployable	Increased systems, power and communications, required inside of the deployed ball

Lastly, a table that summarizes the pros and cons of the projectile launcher design in general is shown in table 18.

Table 18: *Projectile Launcher Pros and Cons*

Projectile Launcher	
Pros	**Cons**
Long physical reach satisfying FR1.1	Increased mechanical complexity can create issues satisfying FR5.1
Low chance of disturbing rover satisfying FR4.2	Increased software complexity to satisfy FR3.1
Highly controllable trajectories satisfying FR1.1	Requires projectile simulations to satisfy FR3.1
Rapid deployability satisfying FR4.3	Increase complexity and chance for failure to satisfy FR5.3
Low power draw in active and standby states satisfying FR5.2 and TDR4.1.3	Difficult to satisfy mass and volume for TDR's 4.1.1 and 4.1.2

C.4 Folding robotic arm

C.4.1 Functionality (how it works)

The folding robotic arm works similarly to most robotic arms that one would generally imagine. The team's robotic arm design for PDR consisted of 3 sections, jointed together and stacked vertically, that achieved a physical reach of 1.3 meters. During the redesign phase after PDR, the team was able to add a fourth section to the folding arm, giving it a physical reach of 1.8 meters. Each joint contained a servo that allowed the member to rotate, and these servos were picked to account for deployment speed and moment acting on each specific joint.

C.4.2 Diagram

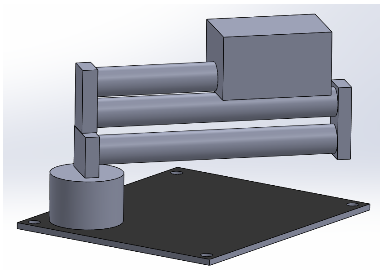


Figure 49: Folding Arm in Stowed Configuration

Figure 49 shows the 3 member folding arm in its stowed configuration. Again, the team was able to add a fourth member and account for the added mass and moments, but this still only gave a physical reach of 1.8 meters. After PDR, the physical reach became the driving requirement for the system, so the team switched to an inflatable arm that reaches closer to the 5 meter mark.

C.4.3 Pros and cons

Table 19: *Folding Robotic Arm Pros and Cons*

Folding Robotic Arm	
Pros	**Cons**
Folding mechanism allows long full extension length relative to required standby configuration storage space (TDR1.1.1, TRD4.1.1)	Multiple motorized joints require additional motors, which increases project cost and arm mass (TDR4.1.2)
Jointed arm segments can be controlled to meet TDR 1.1.2 extremely well	Fully extended arm could create a torque risk for mounting on the Husky without additional support (TDR 4.2.1)
Folding mechanical arms are common in similar applications, and design inspiration is plentiful	Folding mechanism is mechanically complicated, and would require extensive design research
Wired connections between the sensor package on the end of the arm and the Husky are possible, which improve power and communications performance	A longer folding arm would require lightweight components, which would increase cost
FR 5.1 - 5.3 appear highly achievable based on design space review	

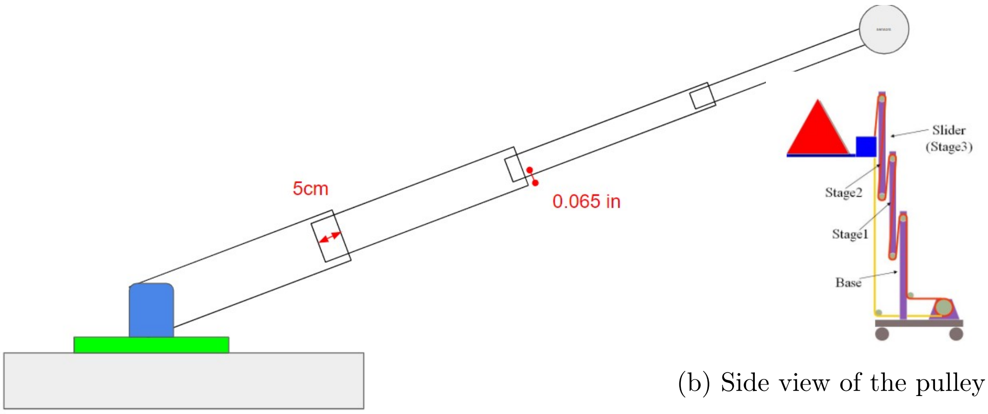
C.5 Telescoping robotic arm

Author(s): Jack Zeidlik

C.5.1 Functionality (how it works)

The telescoping are works similarly to extendable poles. By having nested tubes or decreasing radius it is possible to create a longer arm while using the same or less volume. The system is extended and retracted by a set of internal pulleys connected by a single cable. The teams design consisted of nine nested circular tubes of aluminum of decreasing radii from 2.5in to 0.5in in quarter inch increments. The tube thickness was 0.065in to allow for a tight packing of tubes. Each section was 11.811in long with a 1.9685in overlap to ensure structural rigidity. The team was able to reach a physical distance of 2.3m, a 1m increase over the original three section folding arm design. Attached to the end of the smallest tube is the end effector system to house and rotate the sensors.

C.5.2 Diagram



(b) Side view of the pulley concept

(a) Diagram of a three tube case

Figure 50

Figure50(a) shows a three section telescoping arm at full extension. The design consists of nine tubes with a deflection at full extension of 2mm which is negligible compared to the 2.3m extension length. Figure50(b) shows a side view of the general layout the pulley and cable system used to extend and retract. With physical reach becoming the driving design parameter post PDR this was one of the eary designs to increase the reach.

C.5.3 Pros and cons

Table 20: *Telescoping Arm Pros and Cons*

Folding Robotic Arm	
Pros	**Cons**
Longer reach enables the system to easily extend to 2.3 meters	Small space for wires and guides creating manufacturing and assembly concerns
Reduced storage volume due to tube nesting	High dependency on the connective wires/strings not failing
Small amount of power required to extend and retract	Complex internal pulleys creating infeasible manufacturing ans assembly criteria
Low deflection of arm of 2mm at full 2.3 meter extension	Significantly increased weight due to large amount of metal tubing

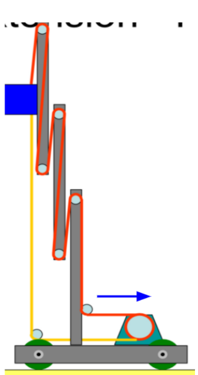
C.6 Sliding Robotic Arm

Author(s): Michael Martinson

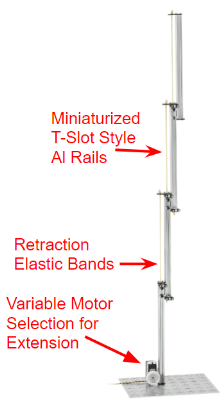
C.6.1 Functionality (how it works)

A sliding robotic arm extension system, also known as a cascade extension system, uses a series of interlocked rectangular rails connected to a pulley system that extends each rail in series when the pulley system's rope is wound around a winch. Fig. 51a shows a functional diagram of how this kind of pulley configuration operates; note that this example is shown lifting a payload (represented as a blue rectangle) vertically. As with the other arm designs, the cascade/sliding system would have to be mounted on a rotating and panning turret system in order to meet the project's FR2.1 requirement. This type of extension system can be retracted several ways; two possible methods are either using a second pulley rope to apply a retraction force (shown with the yellow line in Fig. 51b) or elastic tubing attached to each segment placed under tension that will pull the sections back into a stored configuration if the pulley rope is spooled back out.

C.6.2 Diagram



(a) Sliding/Cascade Arm Mechanism: Functional Diagram, Vertical Orientation



(b) Sliding/Cascade Arm Mechanism: Commercial Example, Vertical Orientation

Figure 51: Sliding Robotic Arm: Function Diagram [11] and Commercial Example

C.6.3 Pros and cons

Table 21: *Sliding/Cascading Arm Pros and Cons*

Folding Robotic Arm	
Pros	**Cons**
Rapid Extension is possible depending on pulley system winch RPM	Base motors have to be custom selected
Commercial options with minimal assembly are available	FR2.1 - Initial estimates from commercial designs indicate roughly a 2m max reach for a design meeting RESCUE's volume constraints
Reduced volume consumption; sections can be stored vertically or horizontally	Aluminum rails add mass at extended length, which increases the UGV's tipping risk
Strong Heritage of design application in FIRST robotics competitions	Panning/Tilting applications are less common than vertical deployments

C.7 Pneumatic/hydraulic telescopic cylinders

Author(s): Jack Zeidlik

C.7.1 Functionality (how it works)

This design is similar to the telescoping cylinders design from before, however instead of pulleys and a cable the cylinders are nested with expanded bases to create an air tight seal allowing either a fluid or gas to be pushed into the cylinders to extend and a cable attached to the end of the smallest cylinder to retract the entire system. This alternative was considered as another less mechanically intricate solution to telescoping. However the team quickly found that any benefit to simplify created new problems to solve and the design did not result in any significant increase to physical reach

C.7.2 Diagram

Below in Figure 52 shows an example of the pneumatic telescoping system on the left and a simplified cut view of the internal layout of the telescoping system.

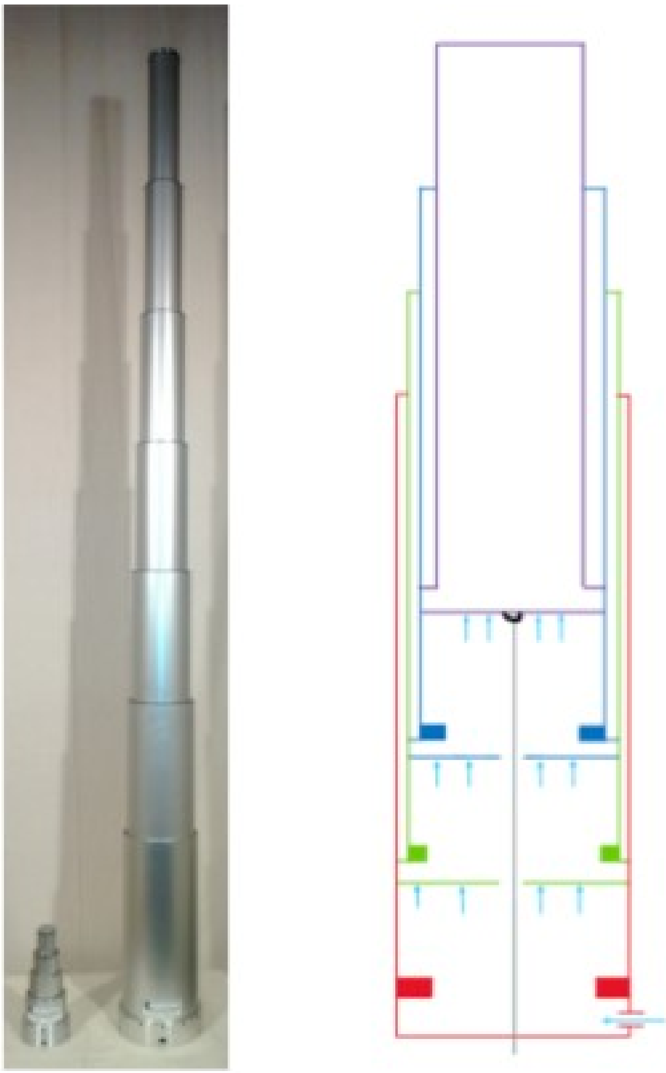


Figure 52: Pneumatic/Hydraulic Telescoping Cylinder

C.7.3 Pros and cons

Table 22: *Pneumatic Telescoping Arm Pros and Cons*

Folding Robotic Arm	
Pros	**Cons**
Small amount of power required to extend and retract	Cylinders require complex machining with increased weight and careful assembly
Reduced storage volume due to tube nesting	High dependency on seals not failing
	Sliding loads at various angles create a path for working fluid to leak
	Increased mass and volume to store working fluid system
	System will not fit inside of mounting volume and be able to extend beyond 2m

C.8 Soft robotic arm

Author(s): Michael Martinson

C.8.1 Functionality (how it works)

Soft robotic extension arms operate by pressurizing a tube, typically made of a thin polyethylene, that extends in a fashion similar to a balloon inflating or using an eversion process (discussed in detail in the main body of this report) where material is spooled out and inflated as needed for the system to extend. Sensor packages on the ends of such arms are supported typically using tension cables back to the arm's base, magnets, or mechanical clamps on the material at the end of the arm. The diagram below shows an example of an underwater, eversion style soft robotic arm that uses spooled material and a water pump (a design operating on land would use air as the pressurization fluid) to extend the arm. A camera end effector is attached using a magnetic clamp.

C.8.2 Diagram

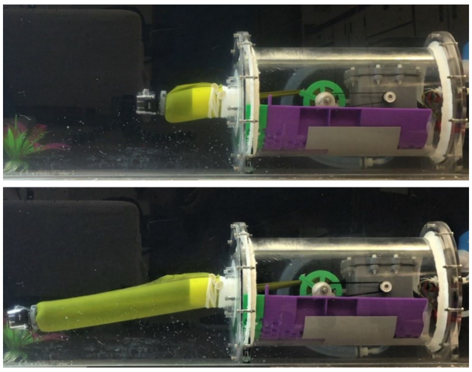


Figure 53: Soft Robotic Arm Concept [12]

C.8.3 Pros and cons

Table 23: *Soft Robotic Arm Pros and Cons*

Folding Robotic Arm	
Pros	**Cons**
FR2.1 - Eversion design offers significant deployment length at reduced mass	Pressurization system adds significant mass and volume
Rapid extension is possible with appropriate pressurization system	Manufacturing complexity is significant compared to other designs
Heritage of well documented research project examples	Attaching larger/heavier end effector packages complicated to model and usually developed experimentally

C.9 RGB-D Camera

C.9.1 Functionality (how it works)

An RGB camera is a digital camera that produces color images. They mostly see in the visible light spectrum and therefore require a sufficient light source to produce a quality image. RGB-D cameras have the same capabilities as RGB cameras but augment the image with depth information. This allows for a more 3-dimensional perception of the environment. These cameras will be most useful for **visually sensing** the brightly colored artifacts.

C.9.2 Pros and cons

Table 24: *RGB-D Camera Pros and Cons*

RGB-D Camera	
Pros	**Cons**
Color Image	Needs Lighting
Depth Sensing	Limited FOV
Dedicated ROS library	Quantity of Images

C.10 VR Camera

C.10.1 Functionality (how it works)

A VR or virtual reality camera is used to create single images encompassing a larger view, up to 360 degrees. These omnidirectional, panoramic style photos are useful when large visual fields need to be covered. VR images use multiple shots merged together to create a singular complete image which increases FOV but also takes longer to capture.

C.10.2 Pros and cons

Table 25: *VR Camera Pros and Cons*

VR Camera	
Pros	**Cons**
Color Image	Needs Lighting
Depth Sensing	High Time per Image
Wide FOV	
Fewer images needed	

C.11 CO_2 Sensors

C.11.1 Functionality (how it works)

CO_2 sensors range in quality, price and size. Most sensors are fairly small and as they increase in price, the speed in which the sensor delivers results and sensing capabilities improve. There are not a lot of design options for CO_2 sensors besides brand. The only direct requirement for the sensor is that it needs to be able to **sense** and **detect** Carbon Dioxide at about 2000 PPM so smaller, lighter and cheaper sensors with this capability are more ideal. The two carbon dioxide sensors being considered are the SCD30 from Sensirion and the CCS811 Air Quality Breakout from SparkFun. Because these two sensors are very similar in terms of performance, it was determined that it would be more effective to do pros and cons of each rather than do a full trade study.

C.11.2 Pros and cons

- *PPM Sensing Capability:* Both sensors have the ability to sense 400 ppm and greater which satisfies the 2000 ppm requirement. The difference is the accuracy of the measurements. The Sensirion SCD30 has an accuracy of $\pm(30ppm + 3\%)$ where the Sparkfun CCS811 does not have a determined accuracy.

- *Size:* The Sensirion SCD30 has dimensions of 35 mm x 23 mm x 7 mm. The Sparkfun CCS811 has dimensions of 4mm x 2.5 mm x 1mm. The smaller the sensor the better, as these decreases likelihood the sensors will limit mechanical design choices. This means that the Sparkfun CCS811 is better in this category.
- *Power Draw:* Both sensors require a very minimal amount of power which is advantageous. Because both their power draws are so small, this is no longer a good criteria to determine which is better. The Sensirion SCD30 uses about 400 mW and the Sparkfun CCS811 requires about 60 mW.
- *Cost:* The Sensirion SCD30 costs about $60.00 while the Sparkfun CCS811 costs about $20.00. The cheaper cost of the Sparkfun CCS811 makes it preferable.
- *Other Considerations:* While both sensors have a calibration period that ranges from hours to days, this can be performed prior to attaching the sensor to the final design. The Sparkfun CCS811 requires an additional 20 minute warm up when started in order to output valid data. This is a major con for the Sparkfun CCS811 because the sensor system is being designed to be used during a DARPA competition and to be complimentary to the MARBLE robot while constraining and affecting it minimally. If MARBLE is turned on right before the competition, the Sparkfun CCS811 would be useless for the first 20 minutes of the 60-90 minute long competition. This means the sensor could be useless for up to 33.3% of the competition.

Due to the additional 20 minute warm up requirement for the Sparkfun CCS811 and lack of determined accuracy in parts per million measurements, the perception team has decided to eliminate the Sparkfun CCS811. Therefore, the only remaining CO_2 sensor is the Sensirion SCD30 which will be used as a component of the sensor suite.

Figure 54: CO_2 sensor to be used in the sensing package.

C.12 System Position and Orientation

Determining system position and orientation is a key element in a project of this nature. Accurate position and orientation of the sensing system helps the MARBLE team to approximate the ground truth location of a sensed artifact. The sensing system will do all of its tasks based on relative location provided by firing commands so accurate position and orientation readings are vital.

C.12.1 Functionality (how it works)

Determining attitude and position is a task typically performed by sensors. Different sensors use different methods to extract information regarding change in position and orientation. Most available attitude determination sensors rely on readings from gyroscopes, magnetometers, and accelerometers. The main differences stem from how the readings from these sensors are combined together to produce meaningful results, such as position and orientation, and how error is handled.

In general, there are two solutions to FR4.1: employing independent sensors to satisfy TDR4.1.1 and TDR4.1.2 separately, or use one sensor to achieve both tasks. Typically, since sensor technologies can often be applied to determine changes in either position or orientation, a combined configuration is more frequently used. Such a shift towards dual-purpose sensor configurations has been enabled by sensor technologies decreasing in price and increasing in precision over time, especially in recent years. Separate-sensor arrangements are less common; they are rarely used unless a sensing task requires position and orientation measurements to be taken independently. These configurations offer more abstraction than combined sensors; if one sensor loses functionality, the system will still be able to report data from the other sensor. However, if a combined sensor fails, neither position nor orientation can be reported.

C.12.2 Position Determination Design Options

There are three typical sensors that are used to determine positions. The first, and most widely known, option is the Global Positioning System (GPS)/Global Navigation Satellite System (GNSS). Such systems relay heavily on satellite communications to determine position and are used for a wide variety of applications, from cell phones to autonomous cars. One of the main challenges that comes with GPS/GNSS systems is reception. If a device using GPS/GNSS technology is in an environment where the signals could be blocked, GPS/GNSS systems tend to perform poorly. GPS/GNSS systems' pros and cons in the context of this project are compared in Table 26.

Table 26: *Pros and cons for using GPS to determine position*

GPS/GNSS	
Pros	**Cons**
Easy to use	Low-accuracy relative to the requirements
Direct measurements	Limited coverage in cave environment

Another option is Inertial Measurement Units (IMUs). IMUs are very popular in the robotics field, and have been used for various distinguished missions, including NASA's Apollo program. IMU sensors are unique because they use a combination of different sensors in conjunction. The readings of the sensors could be used to determine position and orientation too, however, orientation has to be done by post-processing sensor data. IMUs are notorious for accumulating errors due to Gyroscope drift and other issues. These small deviations can propagate and accumulate to make significantly erroneous readings. To determine position, usually acceleration data is integrated twice to estimate position so small deviations in acceleration cause large errors. Typically filters and error-correcting mechanisms are used to account for these errors. The pros and cons of IMUs are listed in Table 27.

Table 27: *Pros and cons for using IMU to determine position*

IMU	
Pros	**Cons**
Relatively cheap	Needs external processing to determine position
Could satisfy both TDR3.1 and TDR3.2	Accumulated errors
Wide range of accuracies	Sensitive to thermal gradients
	Errors could be corrected using other methods at the cost of additional complexity

The final sensor considered was the Attitude and Heading Reference System (AHRS). AHRS sensors give very accurate readings for both position and orientation and have been used more often in recent years because they have been developed in smaller sizes and more affordable options. AHRS sensors are far more accurate than IMUs because they contain filtering systems and complicated algorithms that use a technique called "sensor fusion" to eliminate errors from sensors and present accurate measurements by using multiple readings. These systems have on-board processing units so the readings of the sensors are converted into orientation readings on board. Position could be obtained from acceleration data which is filtered and calibrated by the AHRS. AHRS pros and cons are shown in Table 28.

Table 28: *Pros and cons for using AHRS to determine position*

AHRS	
Pros	**Cons**
Accurate	More expensive relative to IMU and GPS/GNSS
Could satisfy both TDR3.1 and TDR3.2	Complex integration
Internal processing to determine position and orientation	
Error correcting mechanisms	
Various outputs options	
Sensor fusion	

C.12.3 Orientation Determination Design Options

Though information from the same sensors (gyroscopes, magnetometers, and accelerators) is typically used to determine both position and orientation, it is processed differently for each of the two measurements. Both IMUs and AHRS sensors are used to determine orientation, and both are discussed thoroughly in the Position Determination Design Options section above.

Another option, the Vertical Reference Unit (VRU), measures roll, pitch, and yaw and therefore deals primarily with orientation. This is done by using a gyroscope, accelerometer, and inclinometer. Table 29 discusses the pros and cons of the VRU.

Table 29: *Pros and cons for using VRU to satisfy orientation determination requirements*

VRU	
Pros	**Cons**
Relatively cheap	Gets only orientation and not position
Accurate	

C.12.4 Design choice

Based on the discussion in this section, a trade study on position and orientation is not an necessary and the most technical solution seems obvious from the pros and cons tables. Either an AHRS or IMU is the the best solution to determine orientation and position. Since both sensors can be purchased off the shelf, any with sufficient accuracy will satisfy FR4.1. The final choice will depend on weight and size of the particular sensor. Both AHRS and IMUs come in small lightweight packages but since the end effector has very specific weight and size restrictions, whichever happens to best fit will be chosen. The exact sensor chosen is discussed in the Detailed Design section.

Figure 55: Inertial measurement unit to be used for sensor package attitude determination.

C.13 Communications and Data Transmission

The RESCUE system will transmit data from the end effector to its base microcontrollers using wireless transmission via a 0.3 MBit/s Raspberry Pi Zero W and a 10.37 MBit/s video transmitter fixed to the FPV camera. The former will handle CO_2 and attitude data, while receiving and handling commands from the base station. The latter will be easily integrated with the camera, as it was made by the same manufacturer as the camera for this specific purpose.

Two Raspberry Pi 4 Model B microcontrollers will be positioned at the RESCUE base to interface with the end effector, base orientation and pressure controls, and the MARBLE Husky. The base system will be connected by a Gigabit Ethernet cable from a Raspberry Pi to a respective port on the MARBLE Husky. This connection is estimated to have approximately 400 MBit/s of bandwidth available for communications. The base system will also connect to the various servos (base orientation, tension, material extension) and the solenoid valve via GPIO connections [13], [14].

All of these interactions will be handled to some degree by ROS, with nodes at each respective device and topics according to transmitted data formats. The specific architecture of ROS nodes and topics is discussed in a later section.

D Appendix: Conceptual Design: Trade Studies

D.1 Introduction

Author(s): Abdulla Al Ameri

To conduct the trade studies for this document, NASA's System Engineering handbook guideline were followed [15]. In addition, NASA's Trade Studies Module for Space Systems Engineering approach was also taken [16] to develop the trade studies. In particular, the trade studies were designed such that they started from the high level requirements in order to accomplish "pruning unattractive early alternatives" in what is sometimes known as doing "killer trades." [15]. This allows for secondary trades to dive deeper into the most promising solutions.

Secondly, as a practice to make the trade studies more rigorous, uncertainty estimation was included in some the trade study matrices to favor solutions the team was more confident of being able to design. This practice highly recommended by NASA's Handbook [15]. Furthermore, to support the decision making process and ensure that the most acceptable technical solution emerges, the trade studies criteria was chosen to cover both Measures Of Performance (MOP) and Measures Of Effectiveness (MOE). A MOE is "A measure of how well mission objectives are achieved.", while a MOP is "a quantitative measure that, when met by the design solution, will help ensure that an MOE for a product or system will be satisfied." [16]. Hence, every criteria chosen for any trade study in this document will be either a MOP or MOE, and it would be obvious from the criteria itself whether it is a MOP or MOE.

D.2 Physical Reach and Deployment Options

Author(s): Abdulla Al Ameri, Michael Martinson, Evan Welch, Jack Zeidlik

For deployment and mobility solutions going into CDD (prior to the major shift in requirement prioritization post PDR) the team started with a trade between the three general categories of mobility solutions. Conducting a trade between the robotic arm, a drone, and a sensor launcher prevented needing to perform unnecessary trades within solution spaces that were not going to be chosen for the final design. Note that at the time of this initial trade, the robotic arm was assessed as a general category and the team was primarily aware of the folding arm attributes discussed in section **??**.

Design effects for this initial trade study were directly based on the FRs and TDRs that a sensor system mobility system would have to accomplish. These effects were selected as follows, note the the FR and TDRs referenced correspond to their definitions at the time of CDD:

1. **Maneuverability and Reach** FR1.1, including all three of its TDRs, was selected to encompass all of the design effects important to how the system could actually move a sensor package around in the competition environment. The group determined that not all solutions considered had the same chances of achieving unobstructed reach, directional changes, and being able to rotate the sensors attached to them; therefore this effect was included into the trade as a quick way of ruling out solution spaces without a balance of all three factors.

2. **Communications and Sensing Interface** The point of a sensor deployment system is to physically re-position a sensor. Therefore, "communications and sensing interface"

was selected as an important design effect where the team could evaluate how well a mobility system could support large and/or heavy sensor options, as well as if the mobility system could support wired and/or wireless sensor systems. The group noted that 80g, 56250mm^3 was a rough mass and size benchmark for the smallest sensor combination considered.

3. **Weight/Size** FR4.1's weight and size limitations for the overall system were chosen as a broad design effect to assess how well mobility solutions could fit the volume and mass limits set by the customer. These effects were chosen given that the team expects the vast majority of the project's allocated mass and volume to be taken up by the mobility system.

4. **TDR4.2.1** TDR4.2.1 was selected as a design effect because all mobility solution spaces involved moving parts attached to the UGV. Therefore, the risk the selected mobility solution created for tipping or otherwise damaging the UGV needed to be evaluated.

5. **FR4.3** As with FR1.1 and FR4.1, FR4.3 was evaluated a design effect category including all of its TDRs. Any mobility solution worth selecting would need to perform within the rigorous time constraints the customer requested.

6. **FR5.1** FR5.1 was evaluated as a design effect important to mobility solutions because water and dust damage could result in a inadequately protected mobility solution being rendered inoperable and therefore a liability to the MARBLE mission. FR5.1's temperature TDR, although clearly achievable for all solution spaces, was included in the trade for completion.

7. **FR5.2** FR5.2 was evaluated as a mobility design effect given that not all solution considered had the same operational speed, and faster deployment and return to standby make the project more useful the MARBLE's mission.

8. **Design Complexity** The team noted that the mobility solutions had noticeable variations in how likely the team could design and construct them effectively within the time-span of the senior projects course. Therefore, design complexity was marked as an important effect: a mobility system prohibitively difficult to produce on time would fail by default.

9. **TDR5.3.1** Any mobility solution selected would have to meet the repeat deployment requirement of TDR5.3.1; a solution more preferable to MARBLE would need to exceed the minimum five deployments according the the customer's comments.

The criteria were then assigned percent weights as follows:

Table 30: *Rationale for criteria of deployment system category trade study.*

Criteria	**Weight**	**Rationale**
Maneuverability and Reach	20%	Sensor system mobility was given the heaviest criteria weight given that the primary objective of the project is to expand the MARBLE team's sensing range: all other requirements enable this objective.

Comms. and Sensing Interface	15%	The ability to support the specific sensors selected for the system, both in terms of size/weight and connections, was heavily weighted. If the mobility solution cannot support the selected sensors, it is pointless.
Weight/Size	10%	While important to mission success, the TDRs under FR4.1 were given only a 10% weight because the team's research indicated that all considered mobility solutions could be designed to meet all three TDRs.
TDR4.2.1	5%	The team decided to give this criteria a low weight of 5% since it has a high chance of being met by all 3 solution options. It is unlikely that any of the solution options would tip over the Husky or cause damage to it during the competition, so it does not make sense to give this criteria a large weight and have it be the deciding factor.
FR4.3	10%	The team decided to give this criteria an average weight of 10%. The deployment times are important and should be considered when trading solution options, but they are not a very limiting factor. The mission goal could still be accomplished given slightly longer deployment times. This is also a criteria where all three solution options will likely meet the requirements.
FR5.1	10%	The environmental hazard requirements were given an average weight of 10%. If the system gets damage due to environmental elements and cannot function properly, the mission is a failure. However, the team feels confident that the system can endure any environmental hazards that will realistically be present in the cave.
FR5.2	10%	The longer the system is able to remain in a standby state increases the usability over the course of the mission. The longer the system can remain in the active state increase the amount of potential artifact locations that could be scanned. For these reasons this category was given a weight of 10%.
Design Complexity	10%	This was given a weight of 10%. If the system is too complex or not feasibly to manufacture then there is no reason to pursue it.
TDR5.3.1	10%	This criteria was implemented to ensure customer requirements are met. For this reason the category was given a weight of 10%.

Value assignment for this trade was arranged on a 1-5 scale, note again that this trade was weighted based on understood priorities at the time of CDD:

Table 31: *Deployment and Mobility Solutions: Solution Categories Trade Study Values Scale*

Criteria	**1**	**2**	**3**	**4**	**5**
Maneuverability and Reach	The reach apparatus has $<$ three degrees of freedom and $<$ 0.5 meters of reach.	[...] at most four degrees of freedom and at least 1 meter of reach.	[...] at most five degrees of freedom and at least 1.5 meters of reach.	[...] at most six degrees of freedom and at least 2 meters of reach.	[...] more than six degrees of freedom and definitely more than 2 meters of reach.
Sensing and Comms. Interface	Does not meet included FRs/TDRs	Supports only wireless or only wired sensors; supports less than the 80g, 56250mm^3 sensor package minimum set by sensing subteam	[...] wired and wireless sensors; up to 80g, 56250mm^3	[...] wired and wireless sensors; sensor package in excess of of 80g 56250mm^3	[...] wired and wireless sensors; minimal concern over sensor package mass/size
Weight/Size	Research suggests the reach apparatus has a footprint larger than 110% of the 51300cm^3 max volume and/or weighs more than 15kg in standby state	[...] larger than 105 percent of the 51300cm^3 max. vol. or weighs more than 15kg in standby state	[...] 51300cm^3 max. vol. and weighs 10kg max. in standby state	[...] 95 percent of 51300cm^3 max. vol. in standby state and weighs 10kg max.	[...] 90 percent of the 51300cm^3 maximum volume in standby state and weighs 10kg max. in standby state
TDR4.2.1	Certain that system will damage or alter the position of the Husky	Highly likely [...]	Likely [...]	Unlikely [...]	Nearly impossible [...]
FR4.3	Meets none of the FR4.3 requirements	Reaches active state in over 30s, returns from operating to standby configuration in longer than 120s. Firing commands require greater than 10s response.	Reaches active state in 30s, respond to a firing command as soon as received, returns from operating to standby configuration in longer 120s	Reaches active state in 30s, respond to a firing command as soon as received, returns from operating to standby configuration in 120s	Reaches active state in under 30s, responds to firing command as soon as received, returns from operating to standby configuration in under 120s
FR5.1	Meets none of the FR5.1 requirements	System can operate in 50-60 deg. F ambient temperature, neither mechanical nor electrical components meet IP43 standards.	System can operate in 50-60 deg. F ambient temperature, either mechanical or electrical components meet IP43 standards.	System can operate in 50-60 deg. F ambient temperature, mechanical and electrical components meet IP43 standards.	System can operate in 50-60 deg. F ambient temperature, mechanical and electrical components exceed IP43 standards.
FR5.2	Standby time of less that 60 min., active time of less than 15 min.	75 min. standby, 15 min. active	105 min. standby, 23 min. active	135 min. standby, 30 min. active	Standby $>$ 135 min. and/or active time $>$ 30 min.
Design Complexity	Solution is unachievably difficult based on consideration of mechanical, software, and manufacturing development efforts required relative to project timeline and team skills	Solution is extremely difficult [...]	Solution is difficult [...]	Solution is achievable [...]	Solution is highly achievable [...]
TDR5.3.1	The system cannot be deployed	The system can be deployed 1-2 times	[...] 3-4 times	[...] 5 times	[...] $>$ 5 times

This resulted in a trade study where the group concluded that the robotic arm was the best mobility option to pursue:

Table 32: *Deployment and Mobility Solutions: Solution Categories Trade Study*

Criteria	1	2	3	4	5	6	7	8	9	Weighted Score		
Criteria Description	Maneuver-ability and Reach	Comms. & Sensor Interface	Weight & Size	TDR 4.2.1	FR 4.3	FR 5.1	FR 5.2	Design Com-plexity	TDR 5.3.1			
Weight	20%	15%	10%	5%	10%	10%	10%	10%	10%	100%		
OPTIONS										Certainty	Numerical Score	Percent-age Score
Robotic Arm	3	4	3	4	4	4	4	3	5	1.00	3.70	74%
Drone	4	3	5	5	3	3	3	2	3	1.00	3.40	68%
Sensor Projectile Launcher	2	2	3	4	4	3	5	3	3	1.00	3.10	62%

Moving past the requested requirement changes and reprioritizations after PDR resulting in the FRs and TDRs found in this report, the team conducted another trade on the various extension arm system options. Specifically, the group assessed the Folding, Telescoping, Sliding, Pneumatic/Hydraulic, and Soft Robotic arm options.

The following design effects were considered when developing the trade:

1. **Extension Length:** Extension range, identified as FR2.1, was a critical effect to consider based on the customer's key comment after PDR being that adding reach length to the design would directly improve its usefulness to MARBLE.

2. **Extension and Retraction Speed:** The system's extension and retraction speeds, addressed in FR5.2, were another key point to consider in the arm design trade based on the customer's PDR comments. He indicated that having a rapidly deployable system, ideally faster than the set time requirements, would improve MARBLE's competition performance.

3. **Manufacturing Complexity:** This design effect was considered given that the arm options researched varied in their level of complication. While the primary purpose of the post PDR redesign was to meet the customer's range and speed executions, the group concluded that completely discounting manufacturing difficulty, especially with Spring 2021's anticipated job-shop manufacturing model and likely lead-time issues, would be ill-advised.

4. **Maneuverability:** Maneuverability, referring to design's ability to perform more complicated deployments than simply extend in a straight line, was identified as an important design effect because the customer still wanted a design capable of deploying to as many radial positions in a hemisphere about the UGV as possible (as indicated in FR2.1).

5. **Availability of Research:**The group considered access to design inspiration and analytical models of arm design and performance, especially in industry and academic projects with similar goals, an effect worth considering. All arm solutions appeared likely to require significant amounts of new design work from the team rather than simply combining off the shelf components.

There criteria were then weighted based on the following considerations:

Table 33: *Rationale for criteria of sensor type trade study.*

Criteria	**Weight**	**Rationale**
Extension Length	50%	Extension length was given the largest weight based on the customer's clear concerns after PDR that deployment distance, even deployment distance in a straight line, was a priority. The customer noted that PDR level 1.3m reach was within initial specifications, but not preferred compared to an option that could reach 2m or more.
Extension and Retraction Speed	20%	Extension and retraction speed was given the second largest weight based on the customer's concerns over the PDR design being overly slow to operate.
Manufacturing Complexity	10%	Manufacturing complexity, while important, was given a lower weight because the group did not want to allow better performing but more difficult arm concepts from being eliminated simply because they might require more manufacturing efforts to function properly.
Maneuverability	10%	Maneuverability's weight in comparison the first trade was significantly reduced based on customer comments after PDR indicating that the ability to have the sensor system "bend" around obstructions via joint mechanisms was beneficial, but unimportant compared to reaching longer straight line distances from the UGV.
Availability of Research	10%	The ability to find successful applications of an arm design in similar projects and models for the arm's performance was given a lower weight. Being able to find high quality design assistance was considered important, but not more important than advancing design performance.

Value assignment for this trade was arranged on a 1-4 scale:

Criteria	1	2	3	4
Extension Length	1m - 2m Extension Length	2m - 3m Extension Length	3m - 4m Extension Length	4m - 5m Extension Length
Extension and Retraction Speed	30s Extension time, 120s retraction time	30s Extension time, 90s retraction time	30s Extension time, 60s retraction time	Under 30s Extension time, Under 30s retraction time
Manufacturing Complexity	Borderline infeasible to manufacture and assemble	Significant manufacturing and assembly complexity expected	Moderate amount of premade components with moderate amount of assembly time required	Significant amount for premade components requiring minimal amounts of assembly
Maneuverability	Straight-shot extension with no base rotation or tilting	Straight-shot extension with either a rotating or a tilting base	Straight-shot extension with a rotating and tilting base	Jointed extension with a rotating and tilting base
Availability of Research	Minimal heritage and minimal available technical modeling in similar applications	Minimal heritage and moderate amount of available technical modeling in similar applications	Moderate heritage and significant amount of technical modeling in similar applications	Extensive heritage and available technical modeling in similar applications

Table 34: *Arm Extension Options Trade Study*

This resulted in a trade study where the group concluded that the soft robotic arm was the best option to pursue moving into CDR. The sliding or cascading robotic arm was the second ranked choice, and ultimately became the team's final selection after the initial soft robotic prototyping issues discussed at TRR.

CRITERIA DESCRIPTION	Extension Length	Extension and Retraction Speed	Manufacturing Complexity	Maneuverability	Availability of Research	Min Score	0
						Max Score	4
WEIGHT	50%	20%	10%	10%	10%		
OPTIONS						Numerical score	Percentage score
Folding Arm	1	4	2	4	4	2.30	58%
Telescoping Arm	2	4	1	3	3	2.50	63%
Sliding Arm	2	4	3	3	3	2.70	68%
Pneumatic/Hydraulic Arm	1	2	2	1	1	1.30	33%
Soft Robotic Arm	4	2	2	3	2	3.10	78%

Table 35: *Arm Extension Options Trade Study Results*

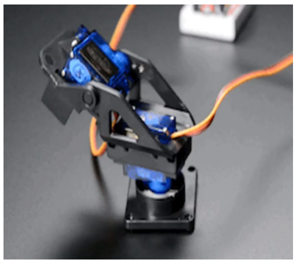
 

Figure 56: Adafruit Mini Pan-Tilt Kit

D.3 Sensing

Author(s): Johnathan Tucker

D.3.0.1 Visual Sensor Type Trade Study The sensor apparatus is an extremely critical component to the overall system design. The visual sensor component specifically provides the system with the capability to sense the DARPA artifacts. It can act as an avenue for the apparatus to localize itself within the global map that MARBLE builds. Therefore, it is important to conduct a trade study to first determine which category of visual sensor we should use. From there, we will be able to conduct another trade on specific sensors within these visual sensing categories.

Table 36: *Rationale for criteria of sensor type trade study.*

Criteria	Weight	Rationale
Different Artifact Capabilities	30%	This criteria describes how well the visual sensor is able to sense different artifacts. A visual sensor that is able to sense more artifacts has the ability to earn team MARBLE more points according to the DARPA rules. Therefore, this criteria was assigned the majority of the weighting as it essentially measures how useful our sensor suite is to the customer.
Weight and Size	18%	The visual sensor will be placed on the carrying apparatus and must be not interfere with it is operation or place an unnecessary burden on the structure. Although most visual sensors intended for robotics applications are small we decided that the size could severely limit our carrying apparatus design choices and thus should be assigned a weight of 18%.
Compatibility with MARBLE's Sensing & Comms	16%	This criteria was created to ensure the chosen visual sensor data was usable by team MARBLE. More specifically, the sensor data must be able to be processed by the object detection algorithm YOLOv3. However, we recognized that we can train a YOLOv3 model on the chosen visual sensors data, giving it a weight of 16%.

Cost	21%	The total budget is \$5000 and visual sensors for robotics can range from \$100 to \$1000 dollars. Given that we are constructing the carrying apparatus ourselves we need to ensure that there is financial leeway. Therefore, we decided to weight cost at 21% to ensure the visual sensor does not place an unnecessary financial burden on the project.
Versatility of Application	15%	This criteria was designed to capture the additional benefits that a visual sensor could provide. These added benefits are the ability for some visual sensors to provide the pose of the apparatus which eliminates the need for an added attitude sensor. However, because this is not the primary goal of the visual sensor it was assigned a weight of 15 %.

Table 37: *Table showing the criteria and their respective numeric breakdown.*

Criteria	**1**	**2**	**3**	**4**	**5**
Different Artifact Sensing Capability	The sensor type is not capable of sensing any of the brightly colored artifacts.	The sensor type is able to sense one of the brightly colored artifacts.	The sensor type is able to sense two of the brightly colored artifacts.	The sensor type is able to sense three of the brightly colored artifacts.	The sensor type is able to sense all four brightly colored artifacts.
Weight & Size	<1kg	0.75 - 1 kg	0.5 - 0.75 kg	0.1 - 0.5 kg	< 0.1 kg
Compatibility with MARBLE Sensing & Comms	YOLOv3 has not been applied to the visual sensor type's data.	N/A	N/A	N/A	YOLOv3 has been applied to the visual sensor type's data.
Cost	>\$1000	\$500 - \$1000	\$100 - \$500	\$50 - \$100	<\$50
Versatility (i.e. Controls)	No onboard capability for detection of position and orientation.	N/A	N/A	N/A	Onboard capability for detection of position and orientation.

To score each visual sensor type our perception team developed a 1-5 scale for each criteria. The different artifact sensing capability criteria was graded on the visual sensor types ability to sense different numbers of brightly colored objects, as seen in Table 40. Scaling based on the capability for the visual sensors to detect the brightly colored artifacts ensures that any sensor type that is capable of fulfilling FDR2.1 will get selected for a more in depth trade. The weight and size category was developed after extensive research on industry standard visual sensors. The heaviest visual sensor found was 1.6 kilograms, which lead to the lowest numeric score being any visual sensor that was heavier than 1 kilogram. For the compatibility with MARBLE sensing criteria we created a binary scale to quantify if MARBLE would be able to apply their object detection algorithm to the output data from each visual sensor. This essentially quantifies if the visual sensors data is usable by team MARBLE for artifact detection or not. The cost criteria was divided into the numeric categories based on fractions of the $5,000 budget. The perception team decided that the visual sensor should not cost more than 20% of the final budget, which was used to establish the lowest category. For the final criteria, versatility, we decided to establish another binary categorization system that quantifies whether or not the visual sensor type has on board capability for position and orientation determination.

Table 38: *Trade matrix for the visual sensor type.*

Criteria	1	2	3	4	5	**Weighted Score**		
Criteria Description	Artifact Sensing Capability	Weight Size	Compatibility with MARBLE Sensing & Comms	Cost	Versatility (i.e. Controls)			
Weight	30%	18%	16%	21%	15%	100%		
OPTIONS						**Certainty**	**Numerical Score**	**Percent-age Score**
Camera	5	5	5	3	5	1.00	4.58	92%
Thermal	2	3	5	1	1	1.00	2.30	46%
LIDAR	5	2	5	1	5	1.00	3.62	72%

D.3.0.2 Camera Trade Study

Table 39: *Rationale for criteria of camera trade study.*

Criteria	Weight	Rationale
Field of View	18%	The larger the field of view the camera has the more coverage it will have. This translates into the ability for the camera to identify artifacts or even multiple artifacts at once. Therefore, this criteria was given a weighting of 18%.
Weight and Size	25%	The camera will be placed on the carrying apparatus and must be not interfere with its operation or place an unnecessary burden on the structure. Although most cameras intended for robotics applications are small we decided that the size could severely limit our carrying apparatus design choices and thus should be assigned a weight of 25%.
Perception Capability	21%	This criteria was designed to capture the cameras ability to work cohesively with the object detection algorithm that team MARBLE uses, YOLOv3. It is imperative that the camera data is usable by team MARBLE for the intended purpose of detecting artifacts. Due to these considerations we assigned a weight of 21%.
Cost	21%	The total budget is $5000 and cameras for robotics can range from $100 to $1000 dollars. Given that we are constructing the carrying apparatus ourselves we need to ensure that there is financial leeway. Therefore, we decided to weight cost at 21% to ensure the visual sensor does not place an unnecessary financial burden on the project.
Resolution	15%	Following the same line of reasoning as field of view, a higher resolution will allow us to take images with a higher coverage area. Furthermore, a camera with a wider range of possible resolutions reduces the burden of image processing prior to passing the data to MARBLE because the images will be in a resolution they expect. Because most robotics cameras will be capable of a wide array of resolutions we gave resolution the lowest weight at 15%.

Table 40: *Table showing the criteria and their respective numeric breakdown.*

Criteria	**1**	**2**	**3**	**4**	**5**
FOV	Horizontal 40 degrees. Vertical 40 degrees. Diagonal 40 degrees.	Horizontal between 40 and 70 degrees. Vertical between 40 and 70 degrees. Diagonal between 40 and 70 degrees.	Horizontal between 70 and 100 degrees. Vertical between 70 and 100 degrees. Diagonal between 70 and 100 degrees.	Horizontal between 100 and 150 degrees. Vertical between 100 and 150 degrees. Diagonal between 100 and 150 degrees.	Horizontal 150 degrees. Vertical 150 degrees. Diagonal 150 degrees.
Weight/-Size	>1kg	0.75 - 1 kg	0.5 - 0.75 kg	0.1 - 0.5 kg	<0.1 kg
Perception Capability	YOLOv3 has not been applied to the cameras data.	N/A	N/A	N/A	YOLOv3 has been applied to the cameras data.
Cost	>$1000	$500 - $1000	$200 - $500	$100 - $200	<$100
Resolution	**424 x 240** is the highest resolution capable.	**480 x 270** is the highest resolution capable.	**640 x 360** is the highest resolution capable.	**848 x 480** is the highest resolution capable.	**1280 x 720** or higher resolution is capable.

To score each camera our perception team developed a 1-5 scale for each criteria.The scaling for the field of view criteria was developed based on the angular view of the cameras. The numeric conditions for each scale were determined based on research on computer vision industry standard cameras. Through this research the perception team did not find a camera with an angular view lower than a 40 degree horizontal, vertical, and diagonal angle of view. Therefore, we decided to set this as the lowest scaling of the field of view category and the largest angle of view we discovered as the largest scaling. The weight and size category was developed after extensive research on industry standard robotics cameras. The heaviest camera found was an ultrasonic camera that weighed 1.6 kilograms, which lead to the lowest numeric score being any visual sensor that was heavier than 1 kilogram. For the perception capability criteria we created a binary scale to quantify if MARBLE would be able to apply their object detection algorithm to the output data from each camera. This essentially quantifies if the cameras data is usable by team MARBLE for artifact detection or not. The cost criteria was divided into the numeric categories based on fractions of the $5,000 budget. The perception team decided that the visual sensor should not cost more than 20% of the final budget, which was used to establish the lowest category. The numeric scaling for the final category, resolution, was determined based on research into industry standard robotics cameras. The largest and smallest scaling categories were based on the largest and smallest resolutions we encountered through research.

Table 41: *Camera type trade study.*

Criteria	1	2	3	4	5	Weighted Score		
Criteria Description	FOV	Weight Size	Perception Capability	Cost	Resolution			
Weight	30%	18%	16%	21%	15%	100%		
OPTIONS						Certainty	Numerical Score	Percentage Score
Intel RealSense Depth Camera D435i (RGBD)	3	5	5	4	5	1.00	4.43	89%
ZED Mini (Depth)	3	3	5	3	5	1.00	3.72	74%
FLIR FireFly DL (IR)	3	5	5	3	5	0.90	3.80	76%
Imperium AcoustoCam i700 (Ultrasonic)	5	1	1	1	1	0.80	1.38	28%
RunCam Split3 Micro	4	5	5	5	5	1.0	4.82	96%

Figure 57: Camera and light to be used in the sensing package.

D.4 Communication & Data Transmission

The communications and data transmission from the sensor suite to MARBLE is a crucial part of meeting the set requirements for success. Communications need to occur not only between the sensor suite when deployed and its base, but also from the base to MARBLE. It is important to do trade studies to determine the most effective yet efficient way to transmit useful data. There will be one trade study for the method of communication between the sensor suite and its base and another trade study for communication with MARBLE.

Table 42: *Rationale for trade study criteria of communication and data transmission from sensor suite to its base.*

Criteria	Weight	Rationale
Reliability	32%	This criteria is ranked highest because it determines the likelihood a signal can be transmitted. If a signal cannot transmit then it does not matter at what rate it would have transmitted.

Transmission Rate/Resolution	26%	This criteria is designed to ensure the chosen method for communication and data transfer is capable of transmitting usable data that MARBLE can utilize. The data transmitted needs to be sent quickly enough and with enough resolution that MARBLE is able to process it.
Power Consumption	22%	The power consumption that is needed contributes to the overall power draw of the sensor suite. While this can be a limiting factor for a design, the power budget set is not too restricting.
Cost	20%	Cost is a limiting factor for the entire project but relative to the other criteria listed being weighed, it is not the most limiting criteria. Being able to transmit any gathered data is crucial to the success of the project and therefore the cost should not be the determining design factor.

Table 43: *Communications and Data Transfer Criteria for Trade Study*

Criteria	1	2	3	4	5
Reliability	Signal can easily be blocked by obstruction	Signal could possibly be blocked by an obstruction	Signal can be lost due to mechanical failure but not blocked	Signal is not likely to be lost or blocked	Signal is almost never obstructed or lost
Transmission Rate & Resolution	<5 GB/s	5 GB/s	11 GB/s	100 GB/s	$\geq$ 330 GB/s
Power Consumption	>2.5 W	2.49W - 2W	1.99W - 1.5W	1.49W - 1W	<1W
Cost	>$200.00	$141.00 - $200.00	$81.00 - $140.00	$21.00 - $80.00	<$20.00

Each criteria for the communication and data transfer trade study was divided into levels from 1 to 5. Reliability was not set on a numerical scale but rather based on the ability of the communication method to physically transfer data. Because of this, the wireless transmitter was ranked as the lowest given of it is potential to drop its connection when physically blocked. The wired options were all more reliable with the continuous-flex-and-twist cable being the most reliable due to its ability to withstand the most physical motion. To set the ranges for transmission rates and resolutions, the team researched the various options to understand what ranges were typical and which were optimal. The continuous-flex and continuous flex-and-twist cables had the fastest data transfer capabilities at the highest resolution. The power consumption was hard to definitively rank because the maximum for the wired connections was higher than would ever be needed for the amount of data transfer this project will require. Because of this, we ranked both the continuous-flex and continuous flex-and-twist cables at a 5 for power consumption. Lastly the cost of all the options was considered and the continuous flex-cable was the cheapest option at $1-$5 per foot, depending on wire gage and number of wires within the cable. Considering the weights of each criteria as shown in Table 42 and the numerical scores given in Table 44, the best option was the continuous flex-and-twist cable.

Table 44: *Communications and Data Transfer Trade Study*

Criteria	1	2	3	4	**Weighted Score**		
Criteria Description	Reliability	Transmission Rate & Resolution	Power Consumption	Cost			
Weight	32%	26%	22%	20%	100%		
OPTIONS					**Certainty**	**Numerical Score**	**Percentage Score**
Wireless transmitter	1	4	2	3	1.00	2.40	48%
Continuous-flex cable	4	5	4	4	1.00	4.26	85%
Continuous-flex-and-twist cable	5	5	4	3	1.00	4.38	88%
Data transfer while docked (Wired)	3	2	2	3	1.00	2.52	50%

Figure 58: Wolfwhoop WR832 5.8GHz 40CH Wireless FPV Receiver.

Figure 59: FPV transmitter built by RunCam to integrate with the chosen camera.

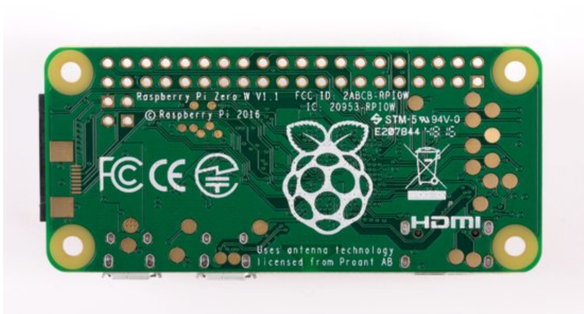


Figure 60: Embedded transmitter on the Raspberry Pi Zero W.

D.5 Microcontroller

A trade study was performed to determine which microcontroller to use as an interface with MARBLE as well as for communications, data transfer and sensor interface. The criteria used to evaluate the microcontrollers is outlined in Table 46. Because the microcontroller is tied to so many subsystems of the project, it is critical to choose a quality brand that can handle all the requirements but also stay within the various budgets set.

Table 45: *Microcontroller Trade Study Criteria*

Criteria	**Weight**	**Rationale**
Software Integration	15%	Being able to complete the project in a timely manner is important given the short duration of the course. A microcontroller that uses a language that is already known by the team will cut out time spent learning the language and leaves more time to ensure the system is working properly and to improve the design.

Hardware Integration	15%	This criteria was considered because it is crucial to ensure the microcontroller will be able to physically interface with MARBLE.
Power Consumption	25%	Power consumption is important given the power budget and the fact that communications, data transfer, the microcontroller and the sensors will all be using power.
Processing Speed	25%	This criteria is important because the microcontroller needs to be capable of handling data transfer, commands from MARBLE, and controls.
Cost	20%	Given the budget, cost is important to consider but is not the most important criteria for this trade because microcontrollers tend to not be prohibitively expensive.

Table 46: *Microcontroller Criteria for Trade Study*

Criteria	**1**	**2**	**3**	**4**	**5**
Software Integration	Unique, unknown language	Familiar to one or two teammates, easy to learn	Familiar to some teammates, easy to learn	Familiar to most teammates	Widely familiar, easily interpreted language
Hardware Integration	No port compatibility	Limited port compatibility	Some port compatibility	Good port compatibility	Very compatable
Power Consumpti	> 15 W	11 - 15 W	6 - 10 W	1 - 5 W	< 1 W
Processing Speed	<10 MHz	10 - 50 MHz	51 - 200 MHz	201 MHz - 1 GHz	> 1 GHz
Cost	>$200.00	$151.00 - $200.00	$101.00 - $150.00	$51.00 - $100.00	<$50.00

The criteria for the microcontroller trade study, explained in Table 46, were divided into five levels to help determine the best microcontroller option. The software integration levels were based on how familiar the team is with the language required to operate each microcontroller. Because of this both the Raspberry Pi and the BeagleBone options were ranked the highest. Hardware Integration was ranked based on the microcontrollers ability to interface with MARBLE. The Raspberry Pi was the most compatible, while the Arduino has no compatibility which all but eliminated it from contention. The power consumption of the microcontroller options ranged from 12 watts to less than 1 watt making the Silicon Labs Pearl Gecko the highest ranked. The processing speeds of the were all fairly high except for the Arduino which makes sense because the Arduino is also the cheapest option. With the criteria weights and the rankings considered, the Raspberry Pi 4 Model B was the best option for this project's microcontroller.

Table 47: *Microcontroller Trade Study*

Criteria	1	2	3	4	5	Weighted Score		
Criteria Description	Software Integration	Hardware Integration	Power Consumption	Processing Speed	Cost			
Weight	15%	15%	25%	25%	20%	100%		
OPTIONS						Certainty	Numerical Score	Percentage Score
Raspberry Pi 4 Model B	5	5	2	5	5	1.00	3.00	60%
Arduino Mega 2560 Rev 3	3	1	4	2	5	1.00	2.60	52%
BeagleBone Black - Rev C	5	3	3	5	4	0.98	2.70	54%
Silicon Labs Pearl Gecko EFM32	4	2	5	4	3	0.95	2.61	52%

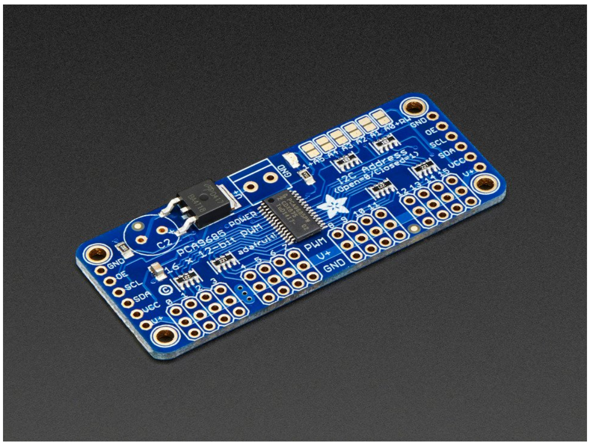


Figure 61: Adafruit 16-Channel 12-bit PWM servo driver board that will be used to command the base pivot and rotation servos.

E Appendix: Link Budget

$$P_{RX} = P_{TX} + G_{TX} - L_{TX} - L_{FS} - L_M + G_{RX} - L_{RX}$$

$$P_{TX} = 23.01029995$$

$$G_{TX} = 2.2$$

$$L_{TX} = 0.5$$

$$L_{FS} = 57.48795996$$

$$L_M = 10$$

$$G_{RX} = 2$$

$$L_{RX} = 0.5$$

$$P_{RX} = -41.27766$$

Figure 62: Link budget to quantify the feasibility of the chosen FPV transmitter and receiver.

F Appendix: Supplementary Tables

F.1 Frequency Options

Table 48: *Frequency options available to the chosen FPV transmitter*

Channel	CH1	CH2	CH3	CH4	CH5	CH6	CH7	CH8
1 Band A	5865	5845	5825	5805	5785	5765	5746	5725
2 Band B	5733	5752	5771	5890	5809	5828	5847	5866
3 Band E	5705	5685	5665	5646	5885	5905	5925	5945
4 Airwave	5740	5760	5780	5800	5820	5840	5860	5880
5 Race Band	5658	5695	5732	5769	5806	5843	5880	5917
6 Low Race	5362	5399	5436	5473	5510	5547	5584	5621
							200 mW Lock	

F.2 Power Budget

	Part Name	Devices per Board	Supply Current per Device (A)	Supply Current per Board (A)	Supply Voltage	Power Subtotal (W)
End Effector (BATTERY POWERED)						
CO2	Sensirion SCD30	1	0.019	0.019	3.3	0.0627
AHRS	3-Space™ Embedded LX	1	0.022	0.022	3.3	0.0726
Camera	RunCam Split 3	1	0.65	0.65	5	3.25
Camera Transmitter	RunCam TX200U	1	0.4	0.4	3.3	1.32
Raspi zero	Raspberry Pi Zero WH	1	0.12	0.12	5	0.6
Lights	Bright Pi- Lights	1	0.016	0.016	3.3	0.0528
Pan/Tilt kit	DigiKey 1967	2	0.36	0.72	4.8	3.456
Base (MARBLE POWERED)						
Microcontroller	Raspberri Pi 4 Model B	1	3	3	5	15
Wireless Reciever	Wolfwhoop WR832 RC832	1	0.22	0.22	12	2.64
Rotation Servo	ASMC-04B Robot Servo	1	3.2	3.2	12	38.4
Pivot Servo	ASMC-04B Robot Servo	1	3.2	3.2	12	38.4
Extention Servo	5202 Series Yellow Jacket	1	9.2	9.2	8	73.6
					Power Total (W)	176.8541
					Margin (%)	0.5
					Input Power Needed (W)	265.28115

Figure 63: Power Budget Breakdown

G Appendix: References

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