Spring Final Review

Range Extending System to Complement Underground Exploration **(RESCUE)**

Customer: Prof. Eric Frew

University Of Colorado Boulder

Project overview

Project Overview: Background

The Subterranean Challenge

"The DARPA Subterranean Challenge seeks novel approaches to rapidly map, navigate, and search underground environments during time-sensitive combat operations or disaster response scenarios." (DARPA)

Multi-agent Autonomy with Radar-Based Localization for Exploration (MARBLE)

Project Overview: Purpose and Objectives

Field of Application

MARBLE's Clearpath Husky UGV being used in DARPA's Subterranean Challenge.

Problem Addressed

Ground based vehicles with onboard sensors have an inherent limitations on field of view and mobility.

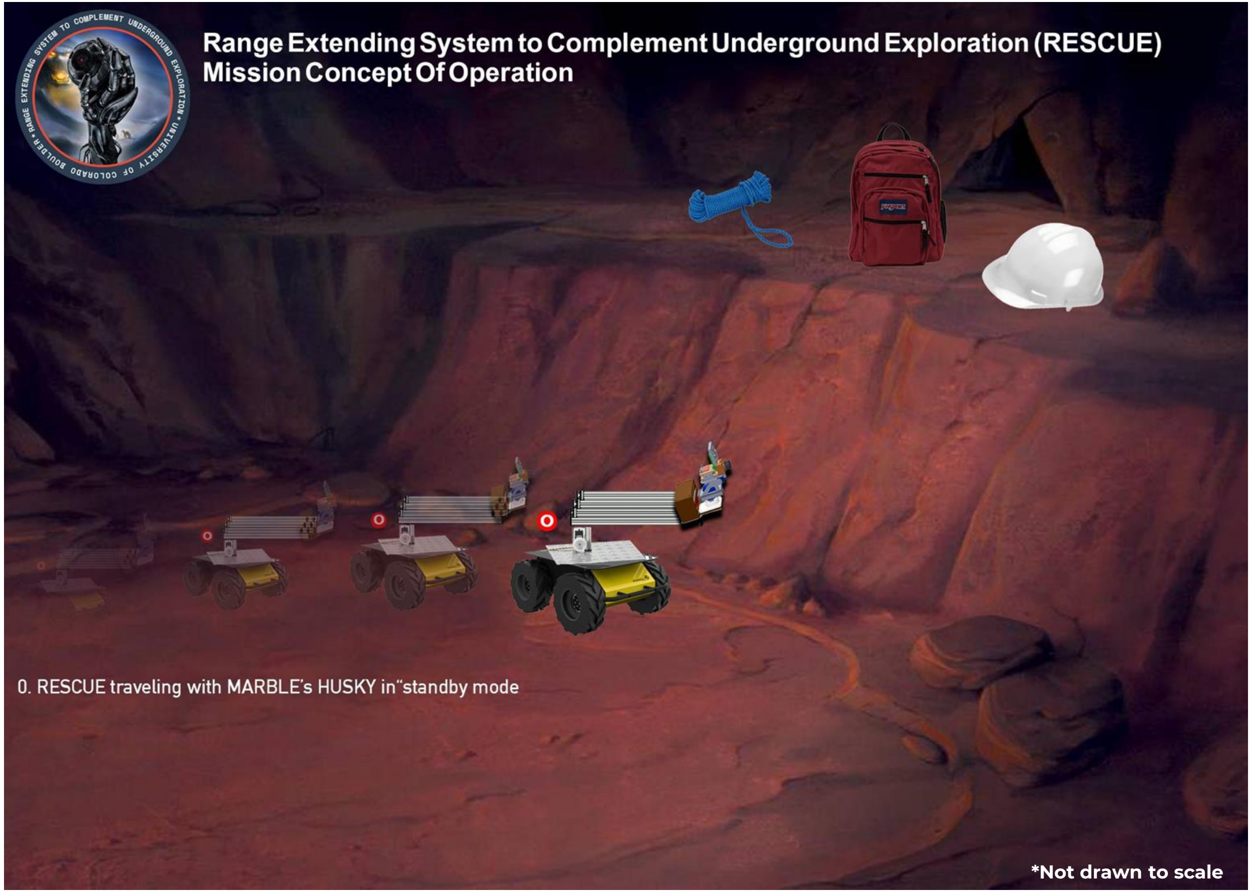
Potential Impact

Enhanced capabilities for UGVs that will provide them an edge over airborne drones in a wide variety of exploration activities.

Acronyms

DARPA: The Defense Advanced Research Projects Agency
MARBLE: Multi-agent Autonomy with Radar-Based Localization for Exploration
UGV: Unmanned Ground Vehicle

CONOPS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Mission Concept Of Operation
0. RESCUE traveling with MARBLE's HUSKY in"standby mode
*Not drawn to scale

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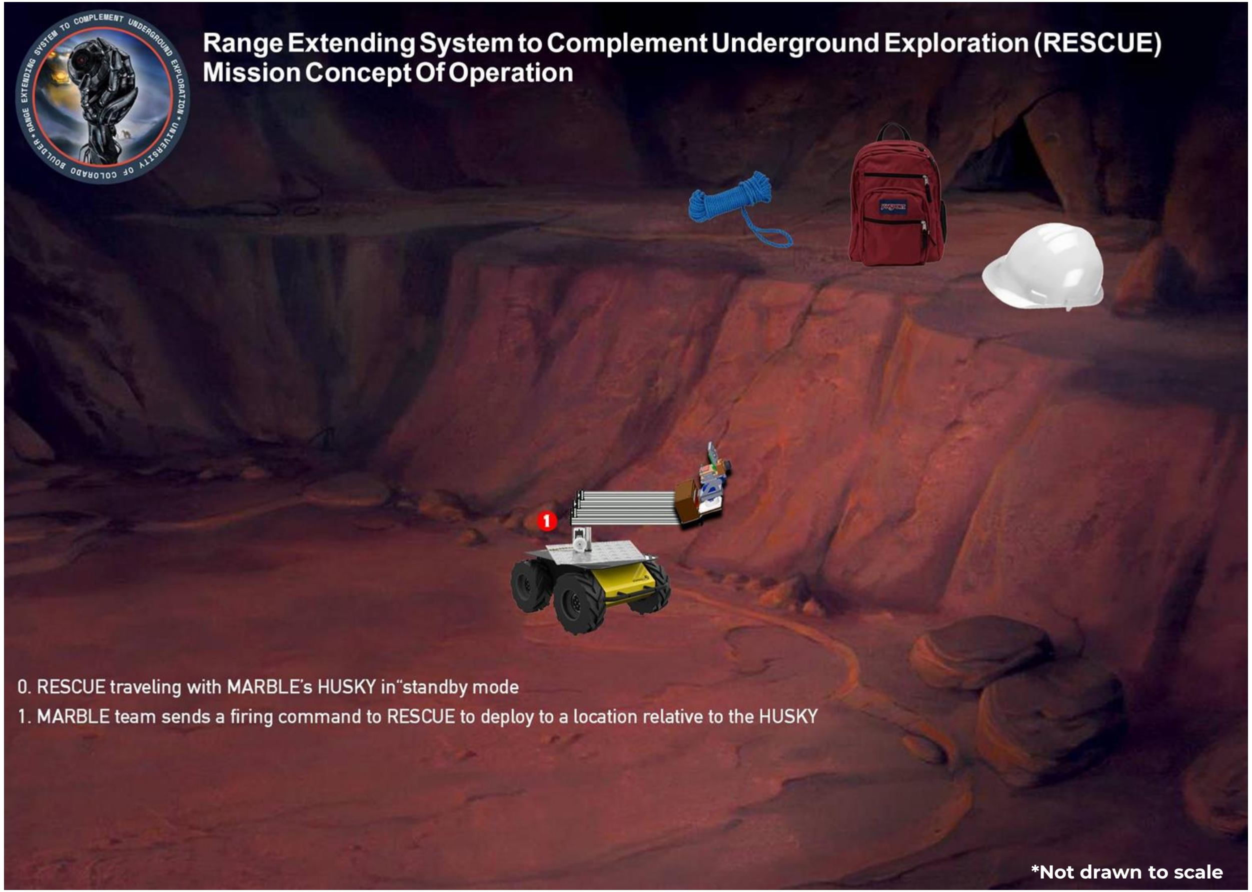
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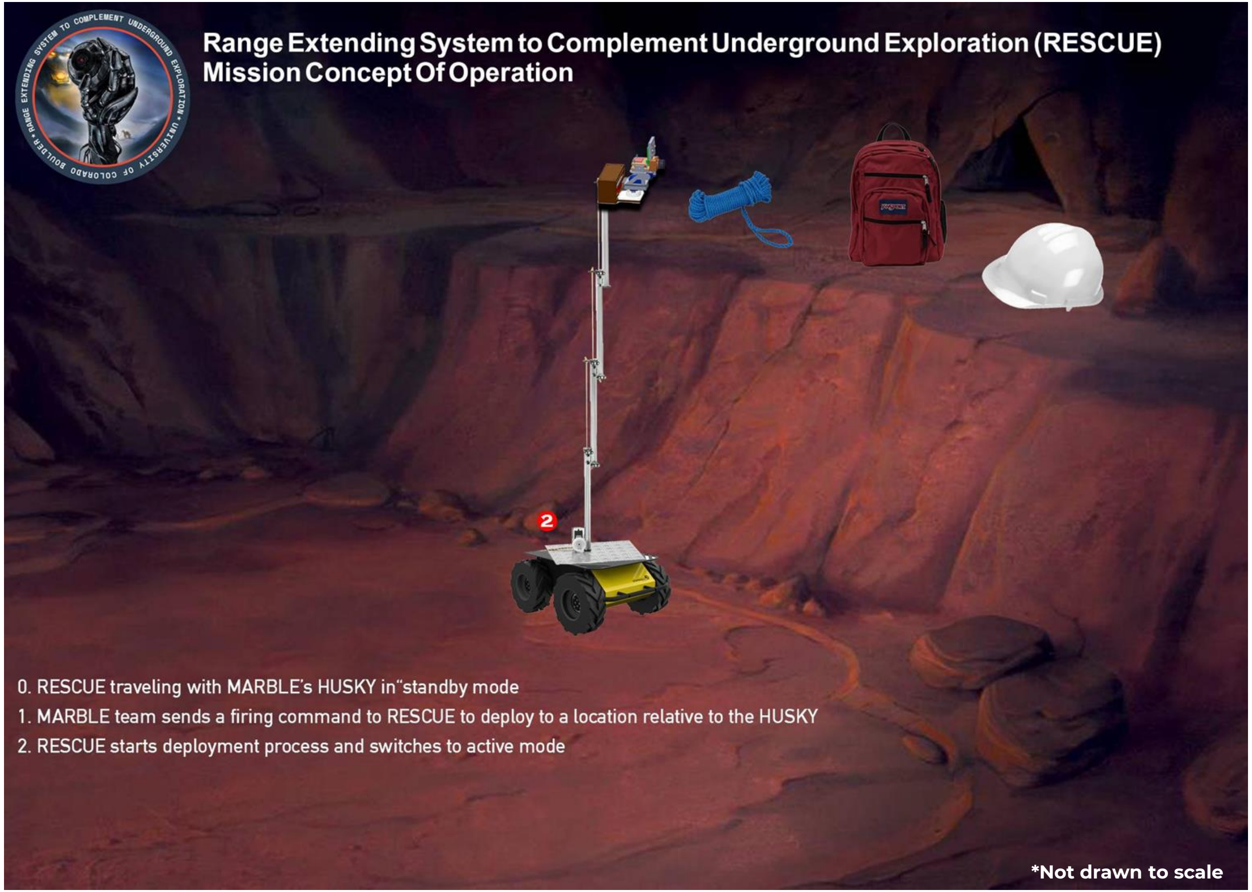
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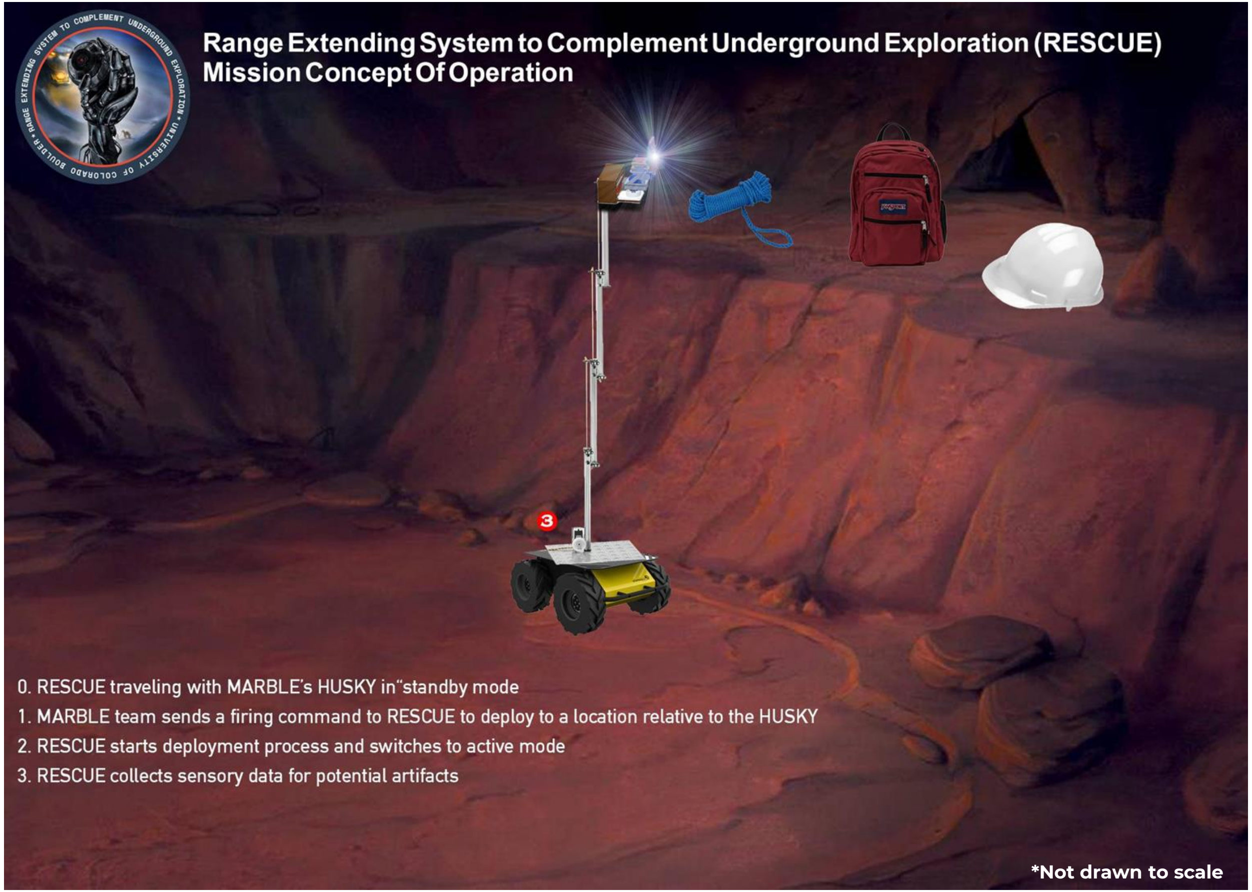
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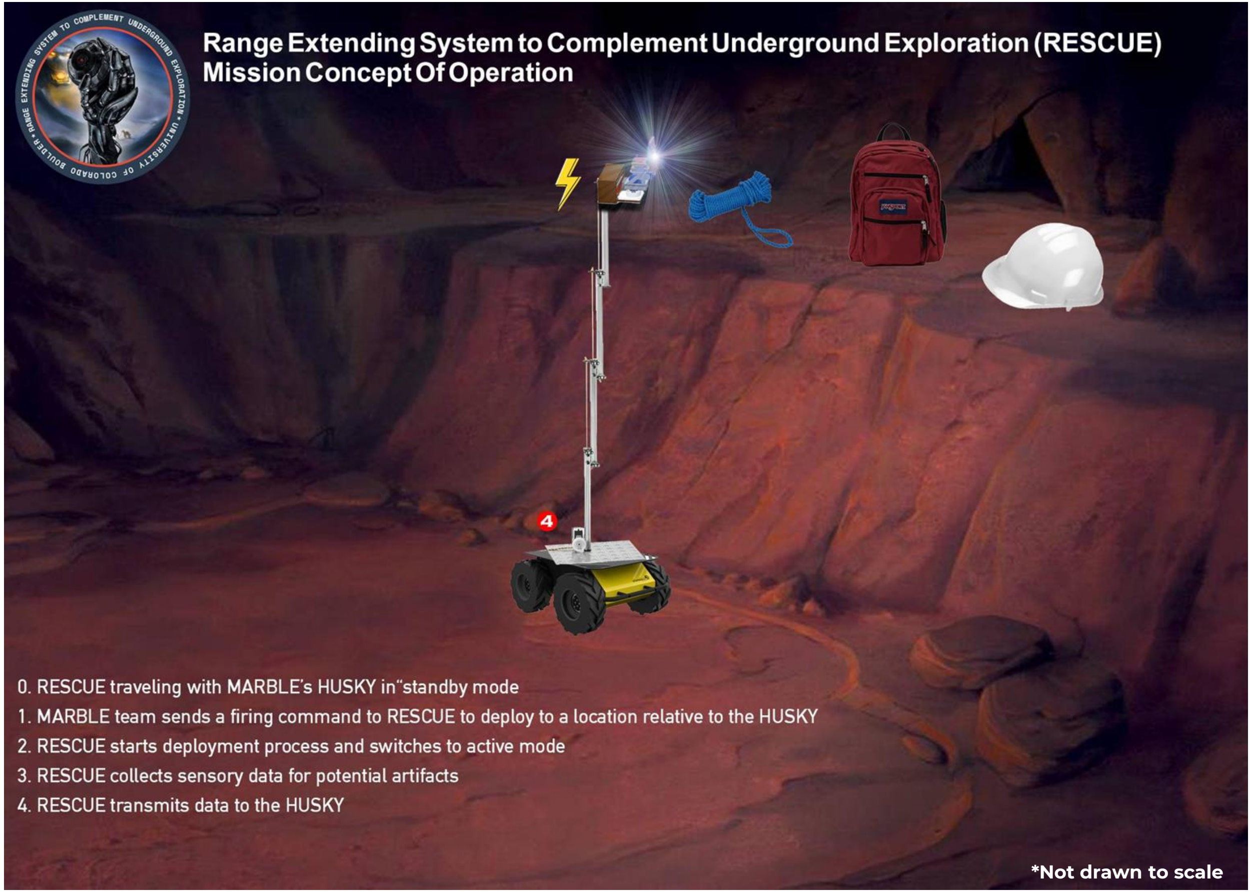
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4. RESCUE transmits data to the HUSKY
*Not drawn to scale

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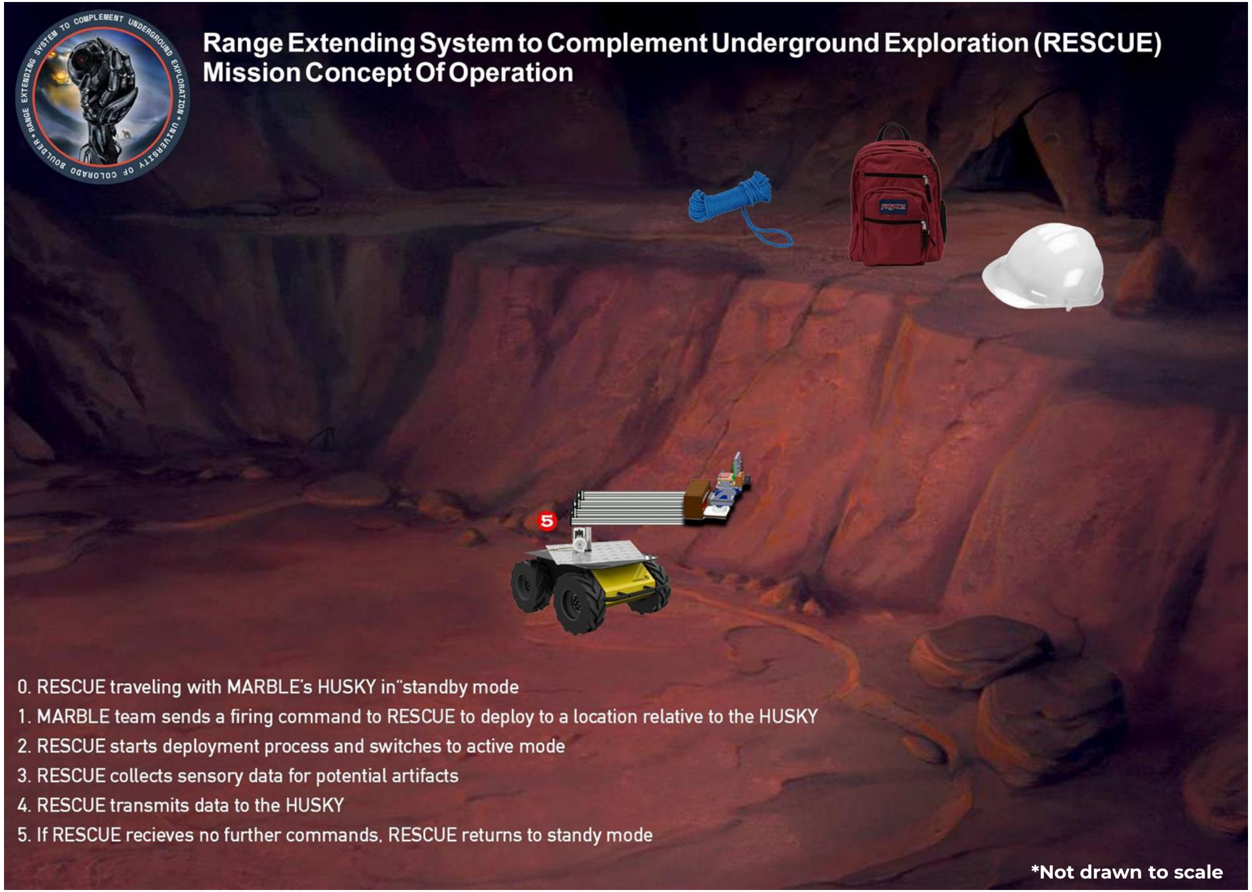
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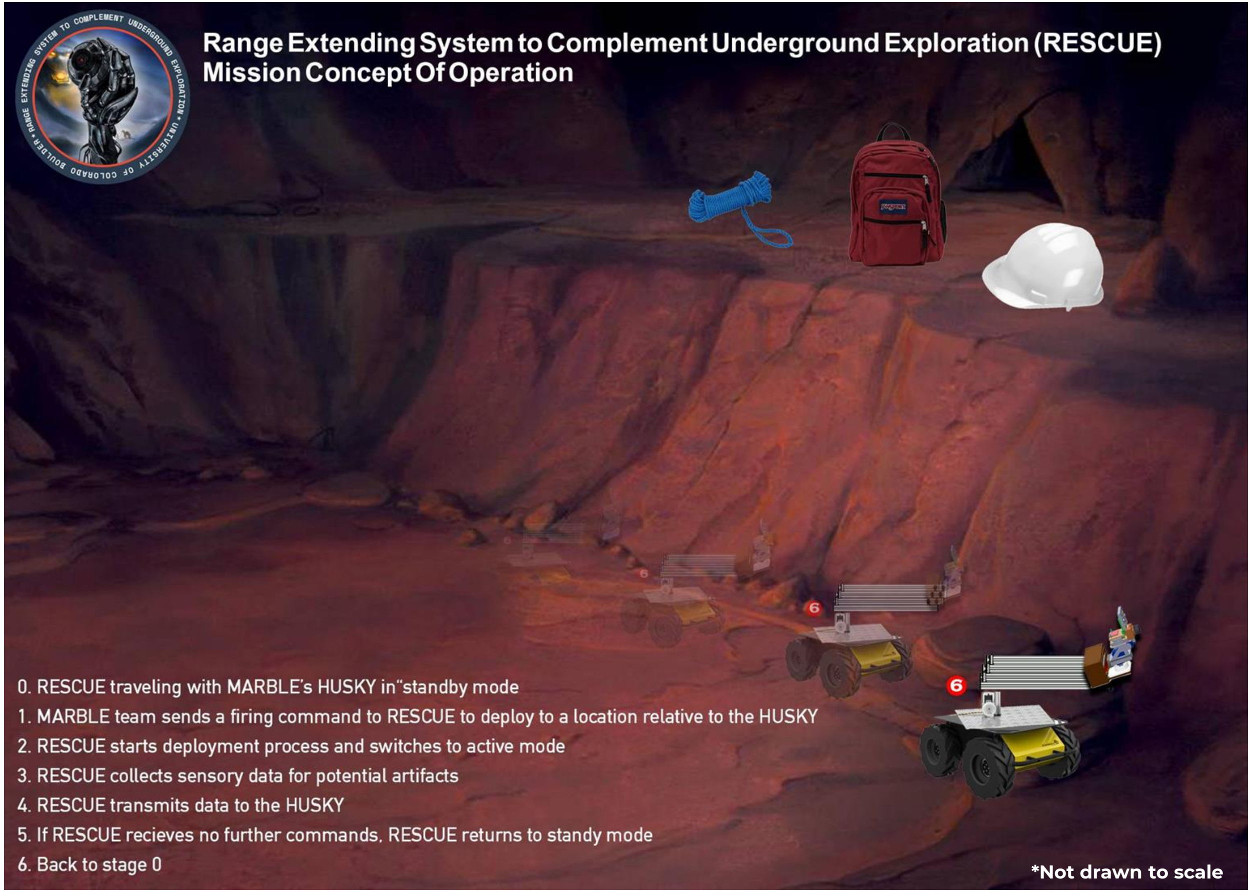
4. RESCUE transmits data to the HUSKY
5. If RESCUE recieves no further commands, RESCUE returns to standy mode
*Not drawn to scale

CONOPS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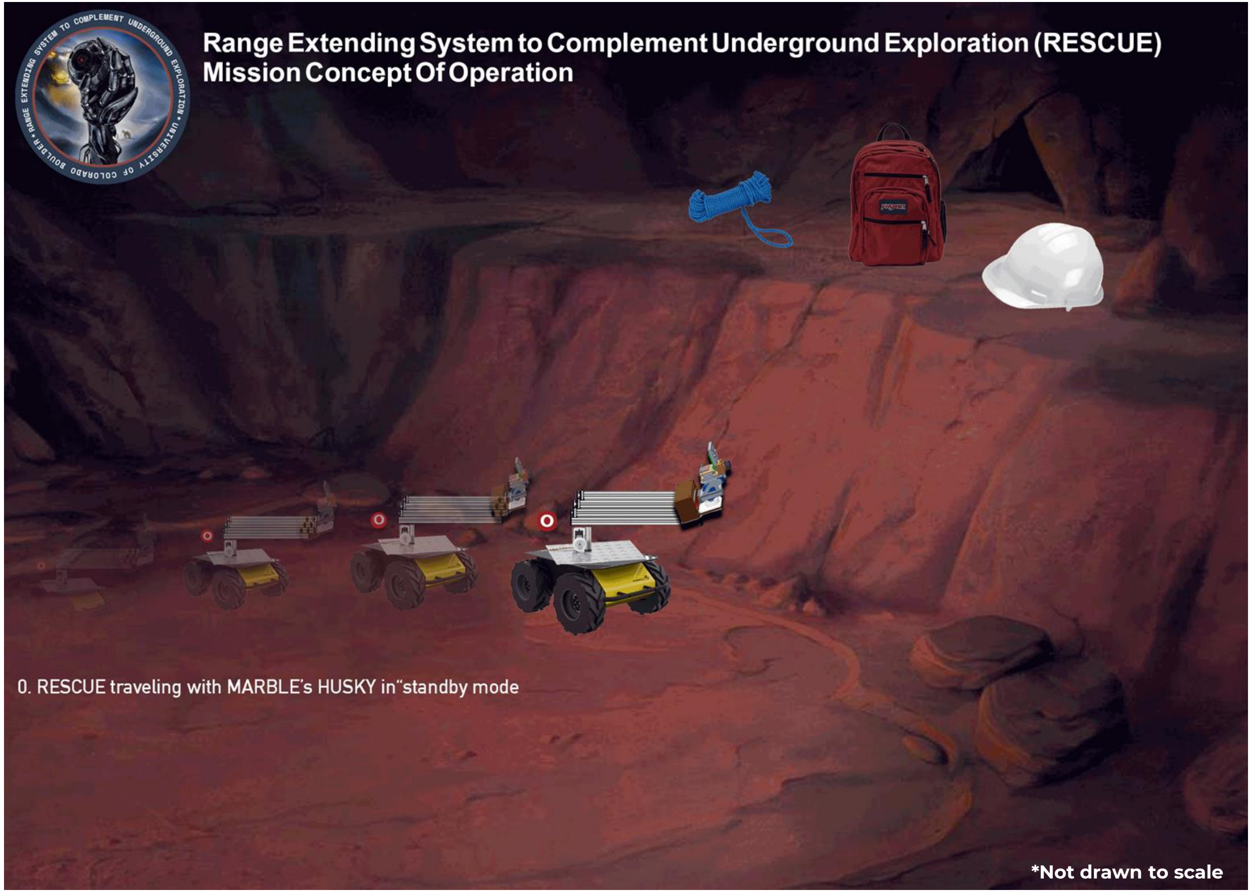
4. RESCUE transmits data to the HUSKY
5. If RESCUE recieves no further commands, RESCUE returns to standy mode
6. Back to stage 0
*Not drawn to scale

CONOPS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Project Overview: Levels of Success

	Level 1	Level 2	Level 3
Artifact Sensing	Able to visually sense the following brightly colored artifacts: human survivor, backpack, fire extinguisher, and rope.	Able to sense and detect carbon dioxide (CO_2) at 2000 parts per million concentration.	
Extension Range	Sensor apparatus has the ability to physically reach a location that is along an unobstructed radial path ≥ 1 m from mounting location	Sensor apparatus has the ability to physically reach a location that is along an unobstructed radial path ≥ 2.5 m from mounting location	Sensor apparatus has the ability to physically reach a location that is along an unobstructed radial path ≥ 5 m from mounting location
Deployment Time	The total time to go from standby state to active state shall be ≤ 30 s.	The time of responding to firing commands shall be instantaneous ≤ 1 s	The time between receiving deactivation commands and returning to standby state shall be ≤ 120 s
Number of Deployments	The sensor apparatus can be deployed and utilized ≥ 5 times.	The sensor apparatus can be deployed and utilized ≥ 10 times.	The sensor apparatus can be deployed and utilized ≥ 15 times.

Design Description

Design Description

Extension Distance	1.89 m (Requirement: 1-5m)
Stowed Volume	38.1 x 45.5 x 30.40 cm (Requirement: 38.1 x 45.72 x 30.48)
Reusability	Up to 50 deployments (Requirement: 15)
Communication	Wireless end effector to base, wired base connections to MARBLE
Total Mass	6.6 kg (Requirement: 10 kg)
Total Power Consumption	265.3 W (Max allowable 600 W)

<u>Main Subsystems</u>: FR4.1 and all lower levels requirements are met, RESCUE is within the size, mass, and power requirements.

Extension System: X-Rail slide kit

Orientation System: Rotating and tilting base

Base Electronics: Wireless communications to End Effector and servo control

End Effector: Sensors housed on pan/tilt mount

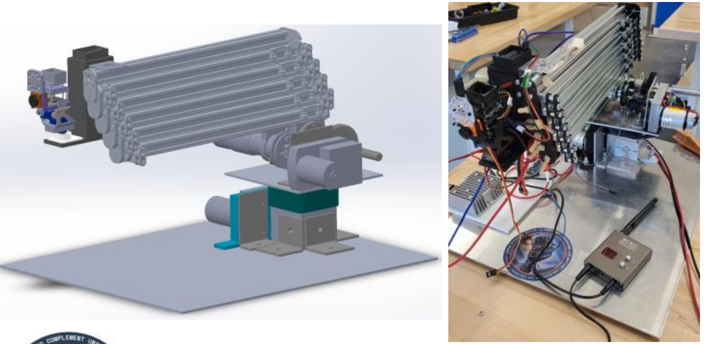


Figure 1. Complete System, Iso. Views

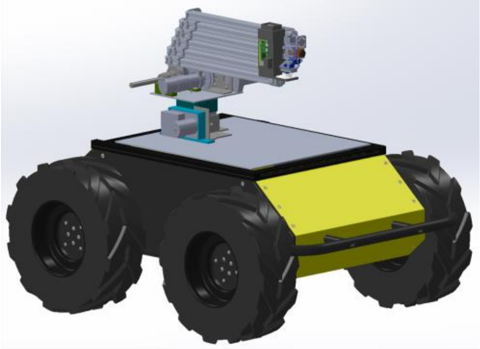


Figure 2. Complete System on UGV

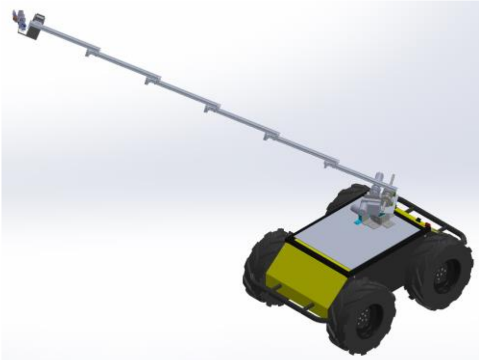


Figure 3. X Rail Arm Extended From UGV

Extension System

Design Requirements:

- Extend sensor package along unobstructed linear path between 1m and 5m
- 30 s deployment (orient + extend)
- Reusable at least 5 times
- Does not pose a tipping risk

Design Solution:

- Modular X-Rail kit from ServoCity, “cascade lift”
- Planetary geared motor connected to winch and pulley system
- Internal surgical tubing for retraction

Extension Length	1.89 meters
Extension Time	≈12s
Communication	Wired connection to MARBLE
Motor RPM	117 RPM
Motor Torque	68.4 kg*cm
Motor Voltage	12 VDC

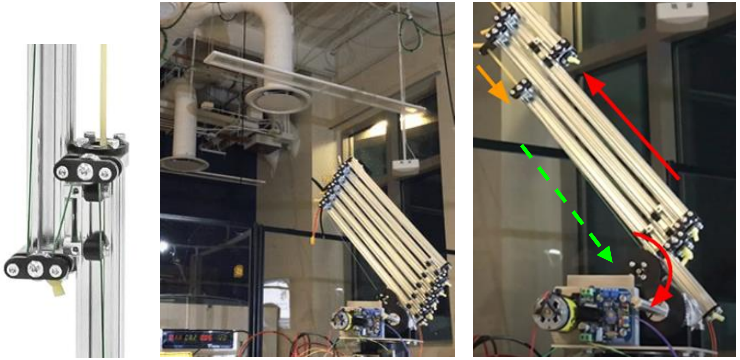


Figure 1. Extension System Operation

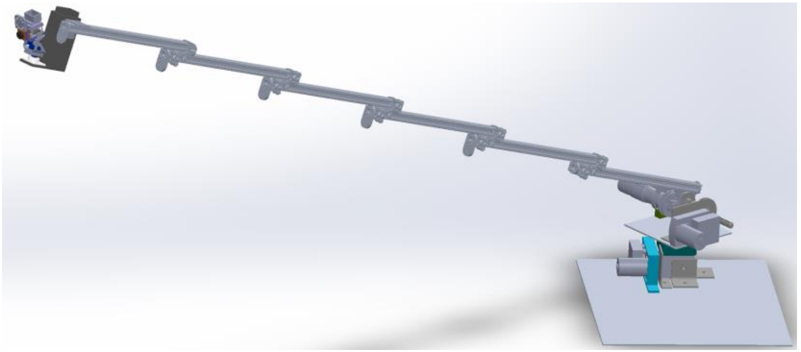


Figure 2. Fully Extended X-Rail

Orientation System

Design Requirements:

- Capable of physically reaching any location in an unobstructed hemisphere located above the UGV
- 30 s deployment (orient + extend)
- Reusable at least 5 times

Design Solution:

- 2 ASMC-04B Servos, 90 kg cm, 60/s at 12V
- Pivot: 1:2.5 gear ratio; 225 kg cm at 12V
- Rotation: 2:1 bevel gear ratio; 180 kg cm at 12V
  Tapered Roller Thrust Bearing

Rotation Range	360°
Pivot Range	90°
Speed	≈ 5 s
Communication	Both motors wired to base electronics
Servo Voltages	8V Rotation, 12V Pivot
Expected Torques	115 kg cm Rotation, 185 kg cm Pivot

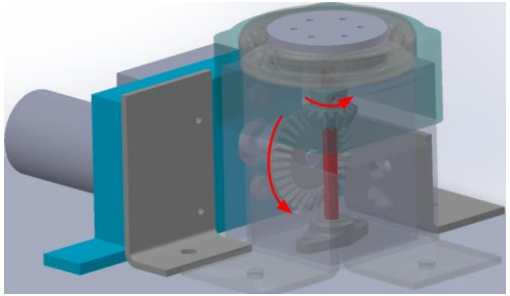


Figure 1. Rotation System Mechanism

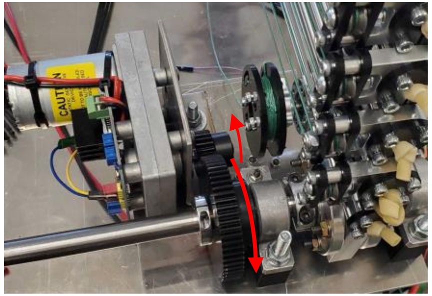


Figure 2. Pivot System

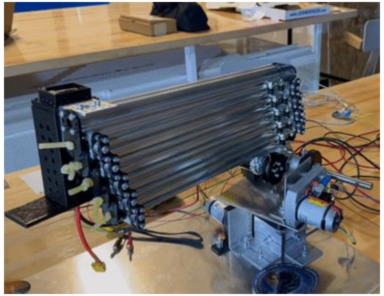


Figure 3. Rotation/Pivot Testing

Base Electronics

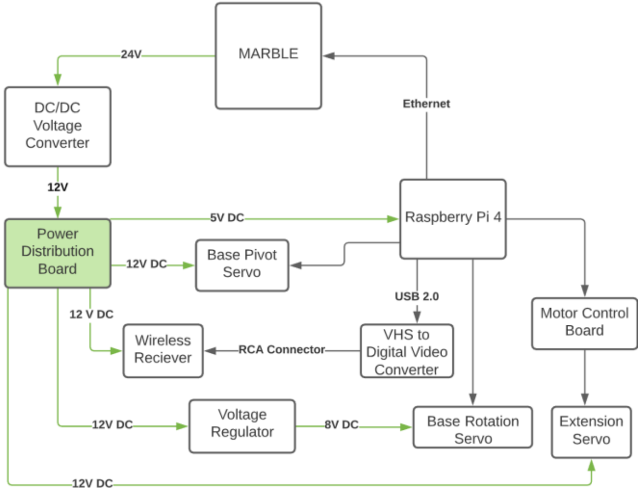
Communication	Wired connection to MARBLE, wireless connection to EE
Max Power Allowable	600 W
Input Voltage	24V
Required Voltages	12V, 8V, 5V

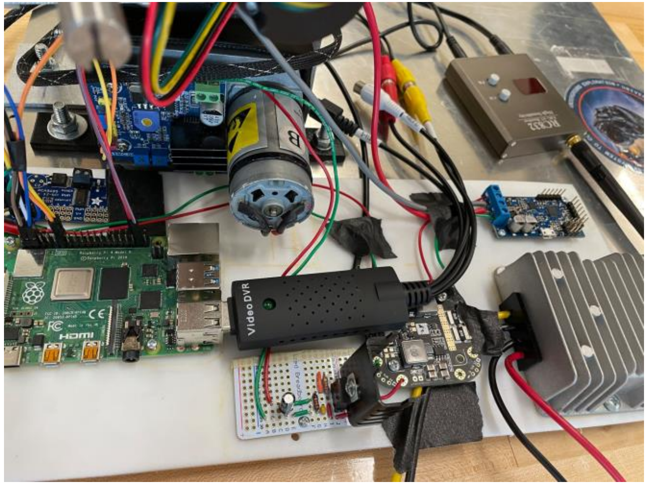
Design Requirements:

- Power drawn from MARBLE must be less than 24V at 20A
- RESCUE has enough electrical power to maintain standby for 135 min and operational state for 30 min
- Can communicate data to MARBLE within 60 seconds via wired connection

Design Solution:

- Raspberry Pi 4 Model B
- Servo Control Boards
- Wireless Receiver
- Voltage Regulation
  - Supplies 12V, 8V and 5V
- Ethernet connection to MARBLE





End Effector System

FOV	104° vertical 119.5° horizontal
Light Output	61.98 cd
Communication	Wireless connection to RESCUE base
Total Mass	435 g
Total Power Consumption	10 W

Design Requirements:

- Able to sense DARPA competition artifacts
  - Visual Artifacts (lighting)
  - CO_2
- Visual artifact signature sensor capable of rotating at least 90° or more about at least one axis.
- Determine and report sensor's location and orientation relative to UGV
- Communicate sensed data to MARBLE within 60 seconds

Design Solution:

- Sensors: Camera, transmitter, Raspberry Pi Zero W, AHRS, C02 Sensor, LED lights
- Pan and tilt servos
  - Capable of ~180° Pan and ~150° Tilt ±3 deg
- 3D printed sensor housing
- 7.4V 2200mAh LiPo Battery
- Wireless communication
  - 5.8 GHz wireless Camera data transmission
  - 2.4 GHz wireless Raspberry Pi Zero data transmission

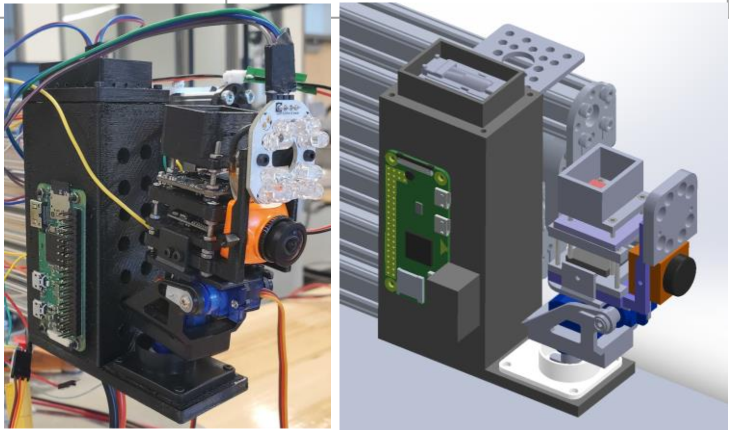
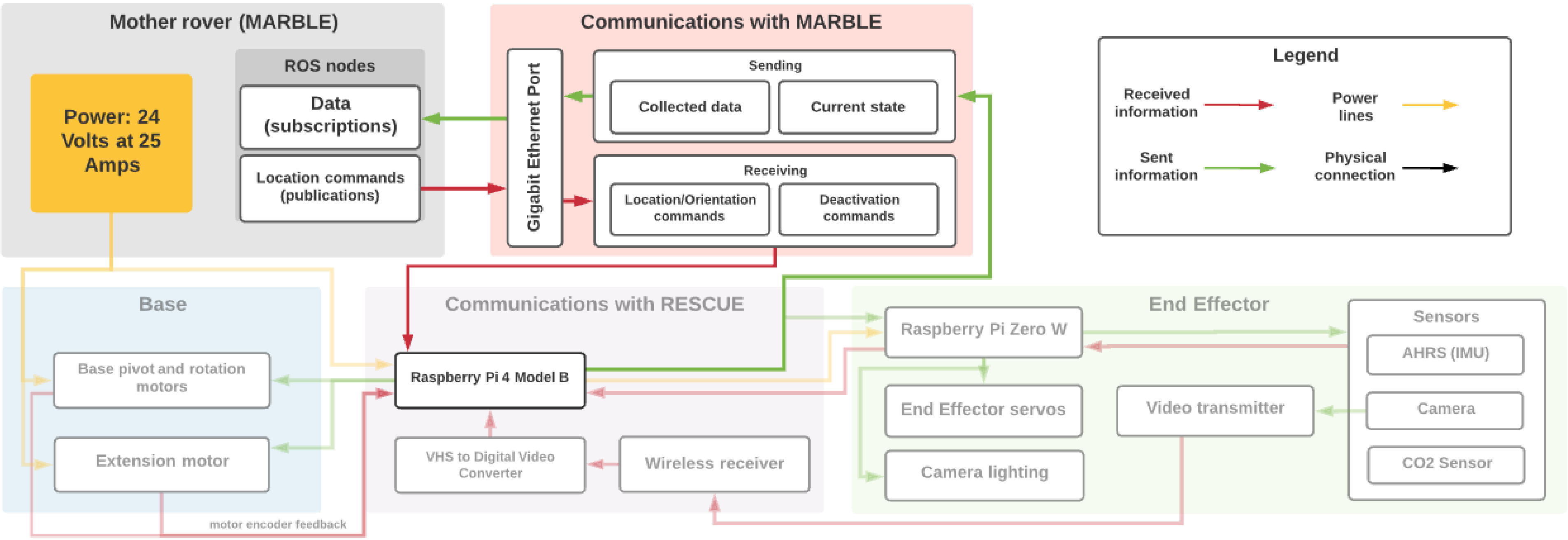


Figure 1. End Effector Subsystem

FBD



Mother rover (MARBLE)
Power: 24 Volts at 25 Amps
ROS nodes
Data (subscriptions)
Location commands (publications)
Communications with MARBLE
Gigabit Ethernet Port
Sending
Collected data
Current state
Receiving
Location/Orientation commands
Deactivation commands
Legend
Received information
Power lines
Sent information
Physical connection
Base
Base pivot and rotation motors
Extension motor
motor encoder feedback
Communications with RESCUE
Raspberry Pi 4 Model B
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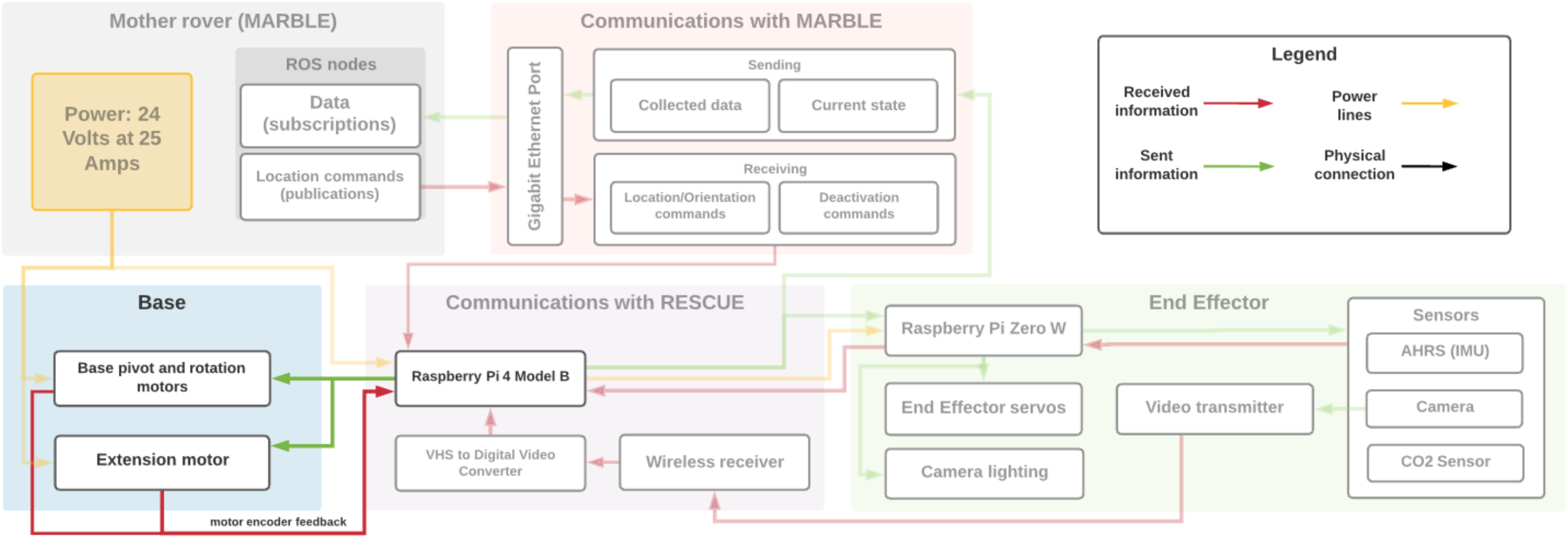
Wireless receiver
End Effector
Raspberry Pi Zero W
End Effector servos
Camera lighting
Video transmitter
Sensors
AHRS (IMU)
Camera
CO2 Sensor

FBD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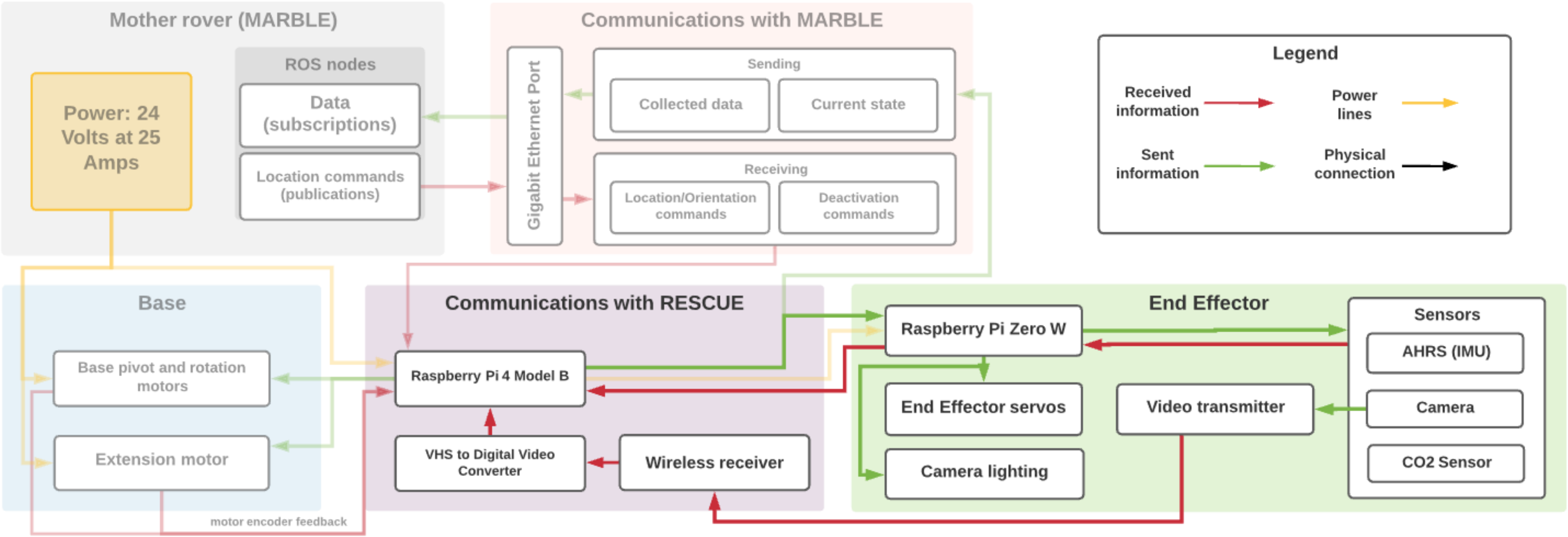
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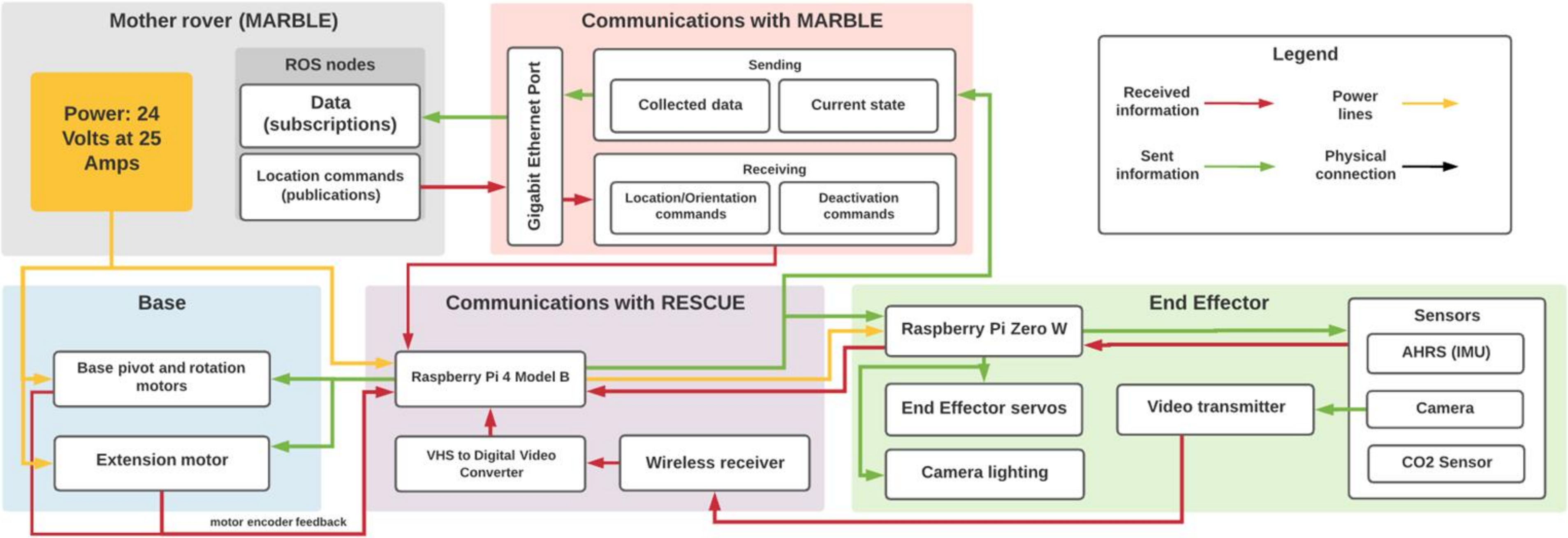

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Changes Since TRR

- Orientation system: concrete design
  - Composed of two identical servos and different gear ratios to control pivot and rotation
  - Tapered Thrust Bearing used to counter torque on rotation bearing
  - Oil bearing to stabilize rotation shaft
- Wireless End Effector
- End Effector Modifications

Figure 1. TRR End Effector

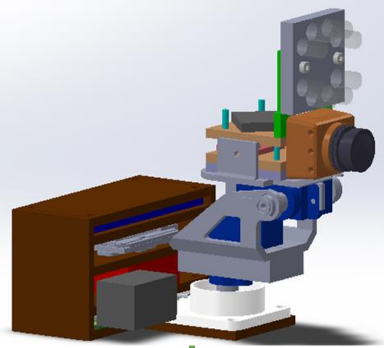
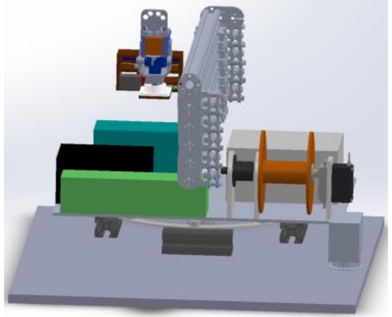


Figure 2. TRR Complete System



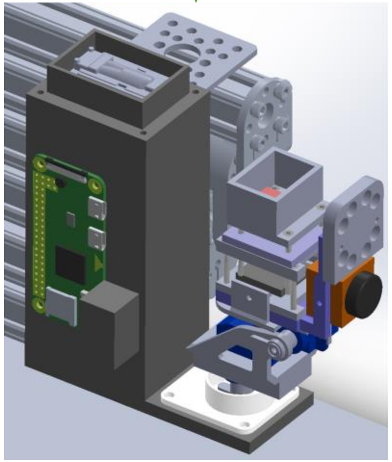


Figure 3. Final End Effector

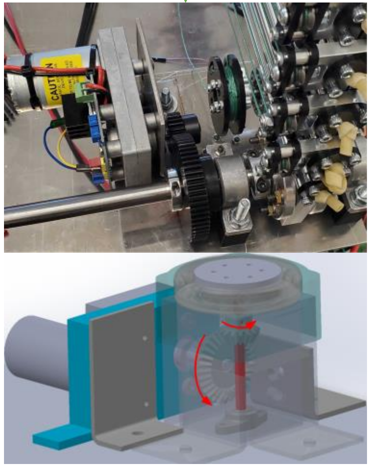


Figure 4. Pointing System

Critical Project Elements

Critical Project Elements	Physical reach	Data collection	Communication	Deployments
The success of RESCUE	RESCUE shall be able to reach a position in an upper hemisphere within 1-5 m of its mounting position.	RESCUE shall be able to collect sensory data and communicate the collected data back to MARBLE.	RESCUE shall be able to receive predetermined commands from MARBLE and perform in accordance with the commands given.	RESCUE shall be able to deploy repeatedly for a predetermined portion of the competition time. (at least 5 deployments).

Test Overview and Results

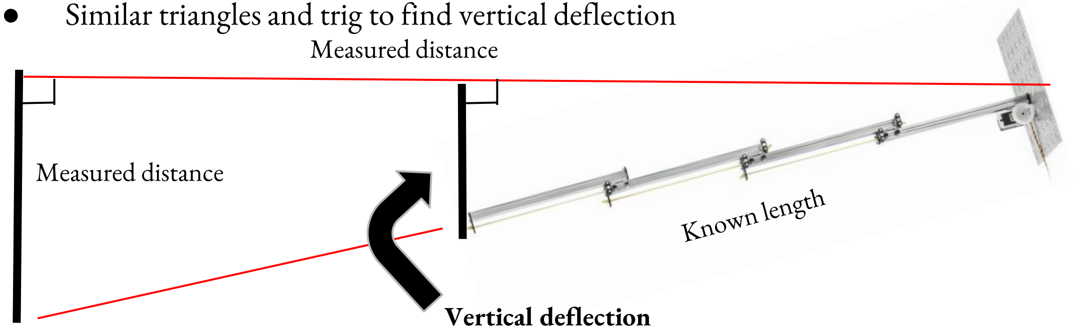
Artifact Sensing: Deflection/FOV Model

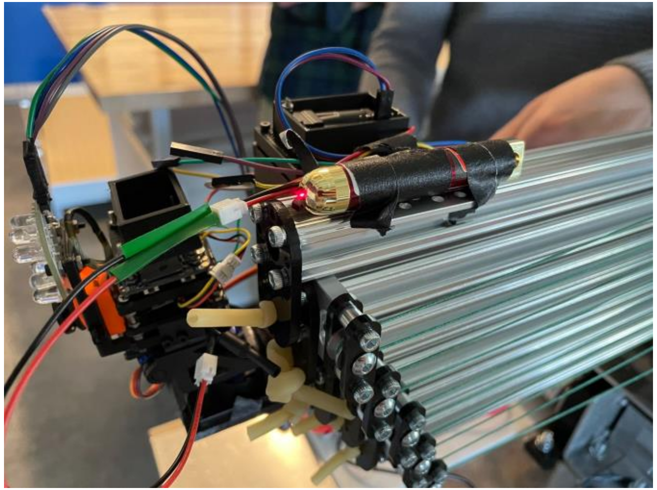
FR 2.1: The sensing system shall be able to sense DARPA subterranean challenge competition artifacts.

Question: If an object is in the center of the camera's FOV while the arm is stowed, will the arm's deflection at full horizontal extension be enough such that the object is no longer in the FOV?

Test Setup

- Laser pointed at wall from horizontal stowed position
- Arm extended, laser moves down wall
- Similar triangles and trig to find vertical deflection





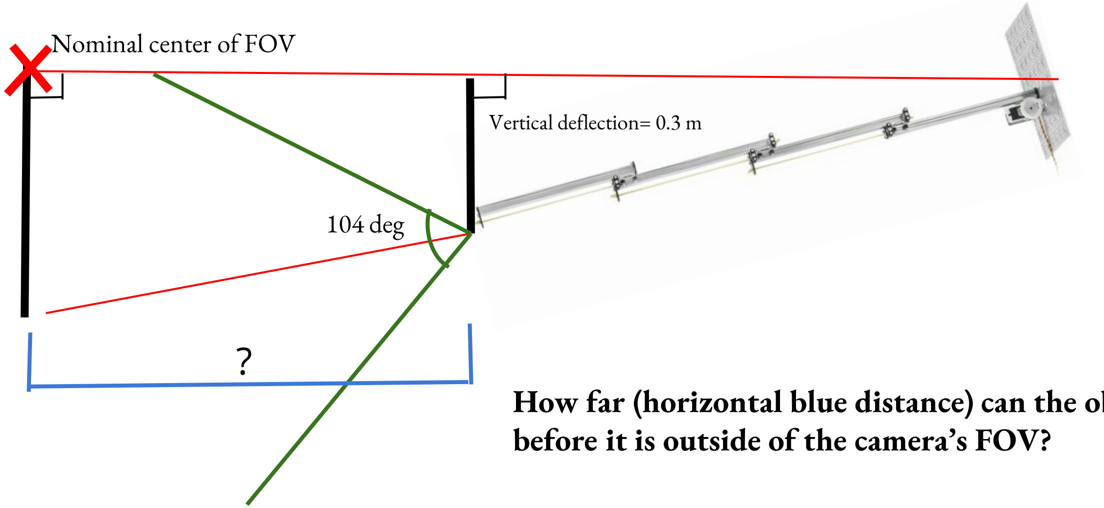
X-rail with mounted laser pointer

Vertical deflection at full extension: 0.3 meters

Artifact Sensing: Deflection/FOV Model

Vertical FOV of camera = 104 degrees

Question: If an object is in the center of the camera's FOV while the arm is stowed, will the arm's deflection at full horizontal extension be enough such that the object is no longer in the FOV?

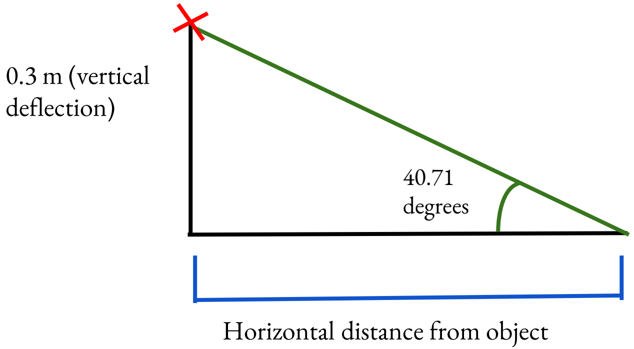


Purpose: Quantify deflection in terms of competition objectives

How far (horizontal blue distance) can the object be away from the camera before it is outside of the camera's FOV?

Artifact Sensing: Deflection/FOV Model

Through geometry and trig, we can simplify the model down to the following triangle relating the horizontal distance from the camera to the top of the camera's FOV



From this, we can model the relationship between the object's distance from the camera and whether or not the object is still in the camera's FOV while the arm is deflected.

Artifact Sensing: Deflection/FOV Model

FR 2.1: The sensing system shall be able to sense DARPA subterranean challenge competition artifacts.

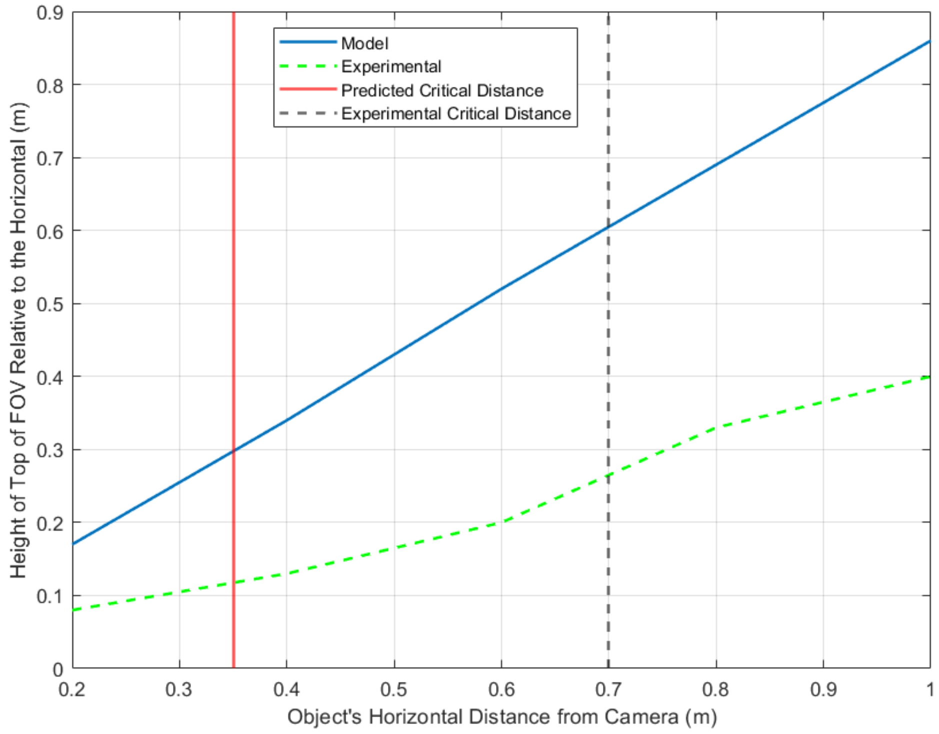
Critical distance = artifacts distance away from camera such that it's centered in the non-extended FOV, but outside of the extended FOV

Predicted critical distance = 0.35 m
Measured critical distance = 0.7 m

What this means: the artifact must be >0.7 meters away from the camera (fully extended, horizontal) for no tilt compensation to be necessary

Reasons for discrepancy:

- Actual camera FOV could be smaller than what the manufacturer quoted
- The arm does not remain straight during deflection
    - In reality, the camera is pointed further down than a straight-line estimate



Artifact Sensing: Vibrations

Although cannot be modeled due to complex nature, can be tested for extensively.

- The camera can be turned on through the whole process of extension and retraction
    - On average, it takes about approximately 7 s for the sensors to damp itself to a minimal levels of vibrations
    - In all cases, we never hit a level of vibrations such that RESCUE cannot sense an object.
    - Thus, RESCUE's critical CPE: the ability to sense an object is met.

System Position and Orientation Testing: Extension

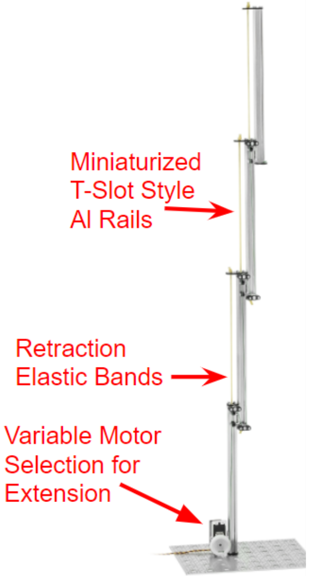
FR1.1: RESCUE shall have the ability to physically reach a location along an <u>unobstructed path</u> that is between 1 meter but not more than 5 meters away from RESCUE's stowing position on the MARBLE Clearpath Husky.

Test Purpose: Can we extend to our required physical reach (1-5 meters) reliably in any orientation and stay there for as long as it takes to sense the environment?

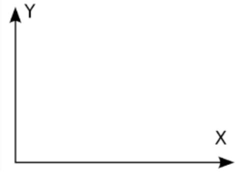
- Directly related to one of the project critical elements: Physical reach.

This is governed by the **extension motor,** which spools and unspools the arm's pulley system

- **How much torque** will the extension motor need to supply?
- Can we create a model to predict this?
- Can we find a motor that supplies this much torque?
- Can we **validate** the required torque?

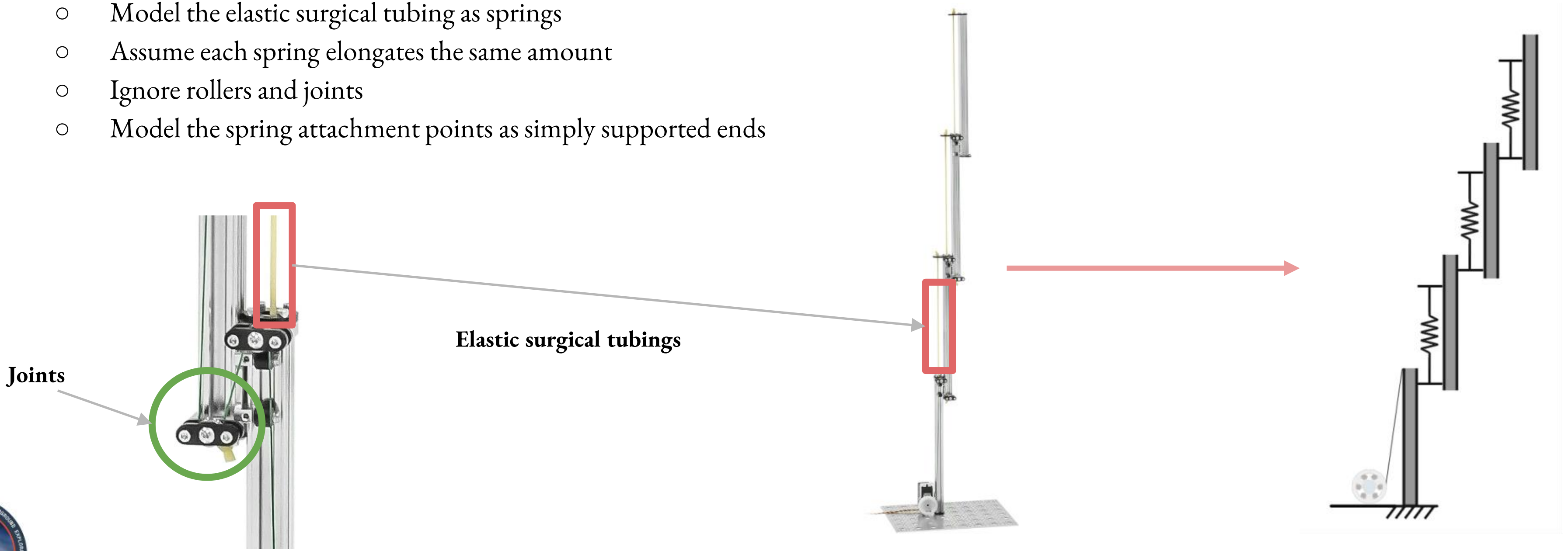


System Position and Orientation Testing: Extension



Step 1: Create a model predicting how much torque (force) is needed to keep the arm extended at a given length

- Assumptions
  - 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



System Position and Orientation Testing: FBD for vertical extension

- The goal is to have the net forces acting on this body = 0
  - **N = number of tubes**
  - **M = moment the motor is applying**
  - **R = Radius of the spool**
  - **k= spring coefficient**
- Adding all the forces, we get: $\sum F_y = \frac{M}{R} - \sum_{i=1}^{N-1} m_i g_i - \sum_{i=1}^{N-1} k_i \Delta_{x,i} - m_{EE} g = 0$

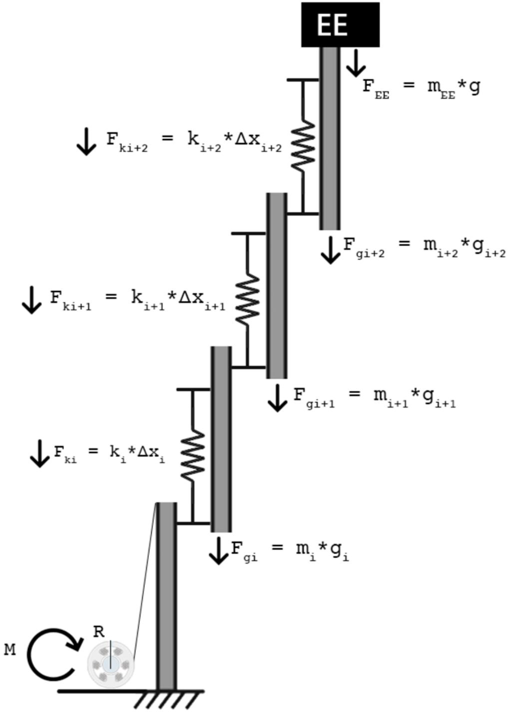
We can simplify this problem further by assuming a constant density and cross sectional area, which means the mass could be estimated as: $m_i = V_i \rho_i = A_i L_i \rho = A L_i \rho$

This means that we can rearrange the formula : $\sum F_y = \frac{M}{R} - A\rho g \sum_{i=1}^{N-1} L_i - k \sum_{i=1}^{N-1} \Delta_{x,i} - m_{EE} g = 0$

And from that we can figure the moment (or the force) that our motor needs to apply to keep the arm extended:

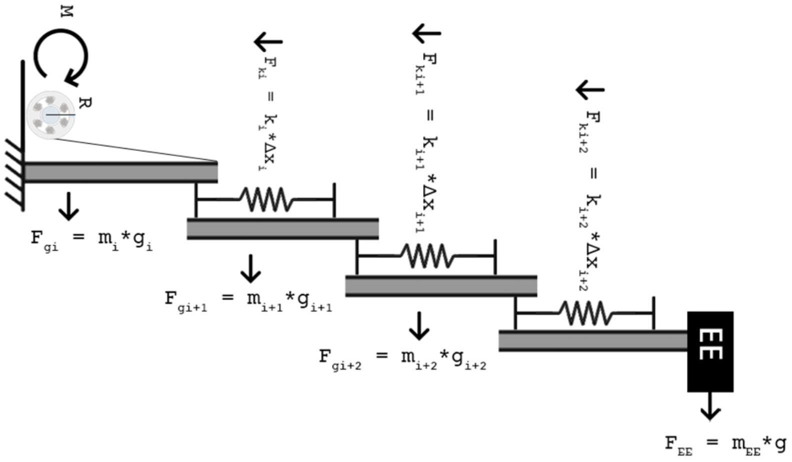
$$M_{vertical} = R \left[A\rho g \sum_{i=1}^{N-1} L_i + k \sum_{i=1}^{N-1} \Delta_{x,i} + m_{EE} g \right]$$

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



System Position and Orientation Testing: FBD for horizontal extension

- We can repeat the same process for horizontal extension, and the FBD will look like:



Unlike the vertical case, the motor does not have to counteract gravity!

$$\sum F_x = \frac{M}{R} - \sum_{i=1}^{N-1} k_i \Delta_{x,i} = 0$$

$$\sum F_x = \frac{M}{R} - k \sum_{i=1}^{N-1} \Delta_{x,i} = 0$$

$$M_{horizontal} = R \left[k \sum_{i=1}^{N-1} \Delta_{x,i} \right]$$

$$F_{horizontal} = \left[k \sum_{i=1}^{N-1} \Delta_{x,i} \right]$$

System Position and Orientation Testing: Extension

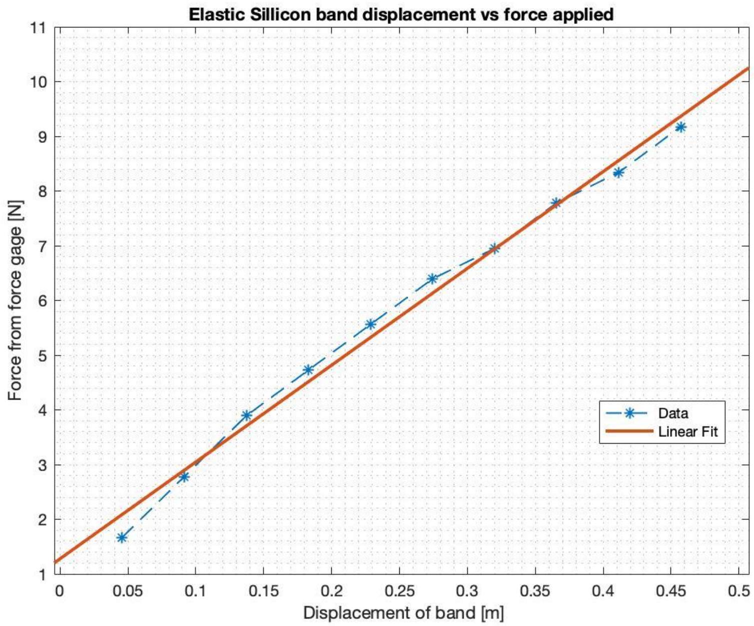
All of the following parameters are known except k, the spring coefficient:

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

$$F_{spring} = -k\Delta_x \rightarrow k = \left|\frac{F_{spring}}{\Delta_x}\right|$$

Now, using the elastic bands, a tape measure, and a force gauge, we can measure the force vs extension distance

The test was conducted for a distance of 2.5m (5 elastic bands, each elongated 0.5m), which is higher than the expected distance of 1.89m (each band will elongate by 0.378m)



Plotting the data and giving it a linear fit allows us to see that:

- The slope = “spring constant” = k = 17.6887 N/m
  - SSE: 0.4806
  - R-square: 0.9912
  - Adjusted R-square: 0.9901
  - RMSE: 0.2451

Test setup

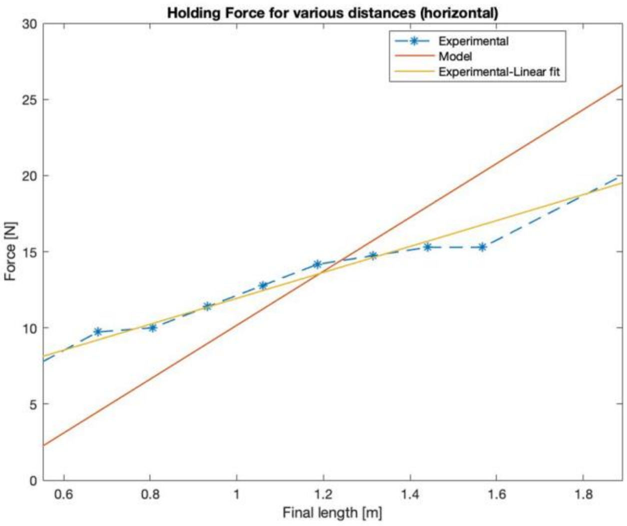
- Using a force gage, and the RESCUE system attached to the base to provide support and the real environment, the arm tip was pulled to various extension distances
- The team worked carefully to minimize the errors stemming from human factors such as errors related to pointing the force gage and applying external force by the test conductor.
- The test was repeated several times and the average of the measurements was taken for results

Figure 1: the horizontal test conducted by RESCUE team. Similar procedure was done for vertical

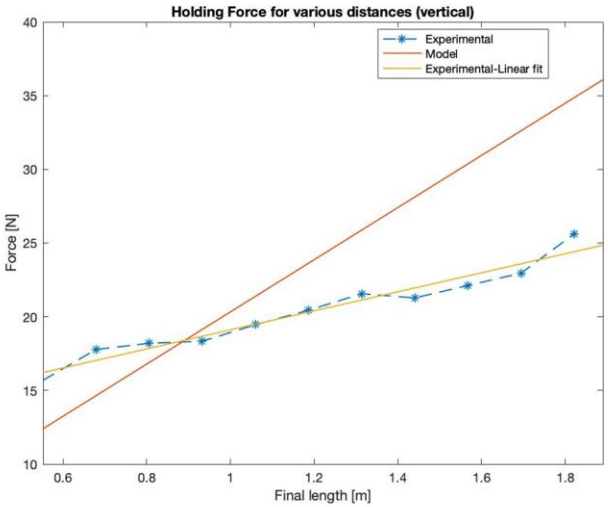
Test Results

$$F_{horizontal} = \left[k \sum_{i=1}^{N-1} \Delta_{x,i} \right]$$

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



SSE: 4.076
R-square: 0.9675
Adjusted R-square: 0.9635
RMSE: 0.7138



SSE: 4.01
R-square: 0.9485
Adjusted R-square: 0.9428
RMSE: 0.6675

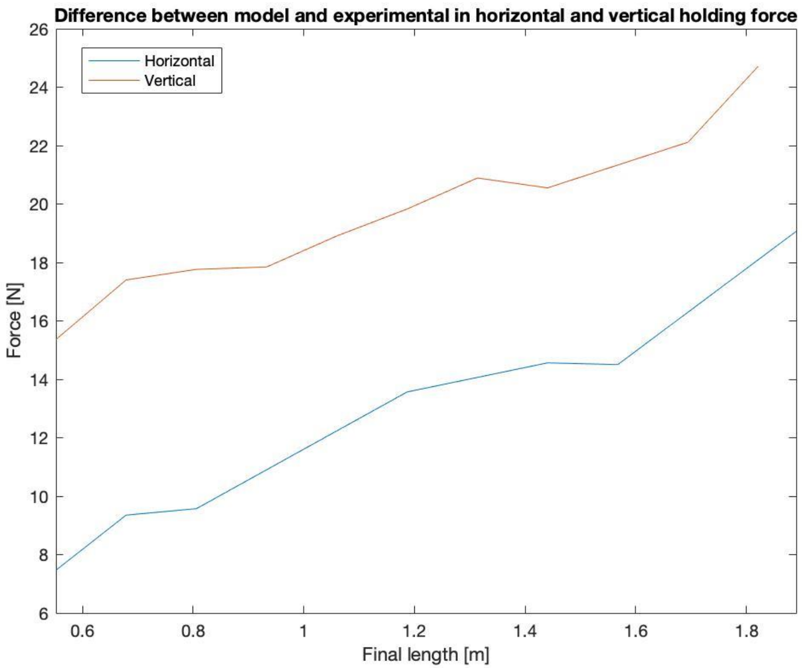
- The model predicts the linear nature of the the force needed as a function of the arm physical reach
- In both cases, similar orders of magnitude were predicted
- Some of the hypothesis for these differences discussed in backup slides.

Test Results: Quantifying the Differences

- The error in the vertical data is almost an exact shift up from the error in the horizontal
- Linear increase due to elastics getting stretched out

- Simplifying assumptions could be a source of errors:
    - No friction: as the arm extends, friction increases
    - All elastic bands are not exactly the same length, some had to be tighter in order to provide a larger restorative force
    - Disregarded the joints: some of the joints come with aluminum connectors and their weight adds up

- Due to limited time, only the friction assumption was adjusted and tested for by lubricating the joints, could be discussed in backups.
- In all cases, the motor can provide enough force to keep the arm extended through more than 20 testing cases the team conducted. Thus, **FR1.1 is satisfied.**



Electronics Testing: Communications

TDR 6.1.1: RESCUE shall be capable of receiving firing commands from the ROS nodes in the existing MARBLE architecture.

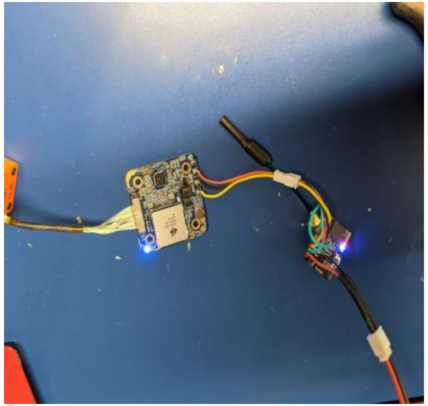
TDR 6.1.2: After deployment and retraction, RESCUE shall communicate sensing data with the MARBLE robot before its next deployment, or within approximately 60 seconds.

- **Test Purpose:** Verify that the FPV wireless communications work successfully and transmits all camera data within the required time limit.
- **Risk Mitigation**: Build confidence in wireless communications in the presence of a cave environment and interference.
- **Model Verification:** This test was initially designed to verify the link budget and data budget models. However, these models are inconsequential at the distances RESCUE will be operating at

Electronics Testing: Communications

Test Setup

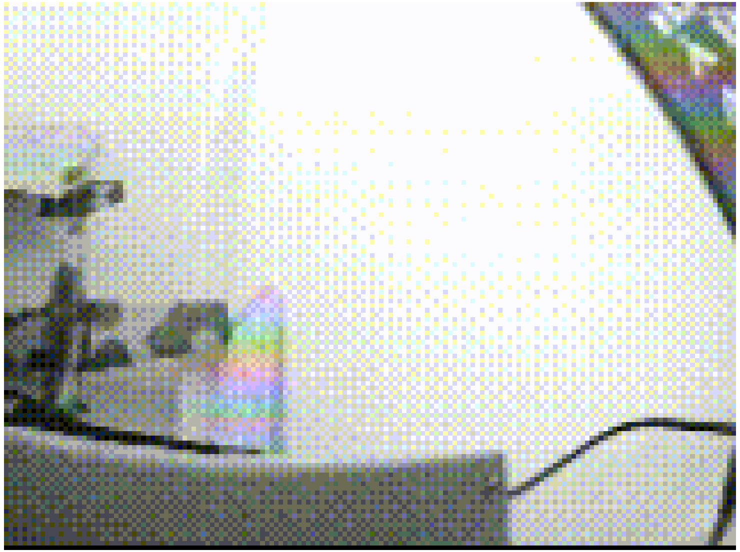
- RESCUE operated the FPV camera in environments that were more severe than the standard operating conditions to prove that we satisfied requirements.
- The first environment was transmitting FPV data across an **8 meter** distance (4x larger than operating conditions) in an environment with ambient RFI.
- The second environment was transmitting FPV data across an **10 meter** distance (5x larger than operating conditions) in an environment with ambient RFI while **the receiver was in another room.**



Completed Tests: Communications

TX and RX separated by 8m:

TX and RX separated by 10m and in separate rooms:



Day in the Life of RESCUE

Day in the Life: The Environment

- RESCUE's mission begins when MARBLE's team determines a remote or obstructed location of interest.
- To mimic the process, the team carefully created a test environment in which certain artifacts are scattered in a room.
- 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). MARBLE will ensure that the path given to RESCUE is unobstructed.

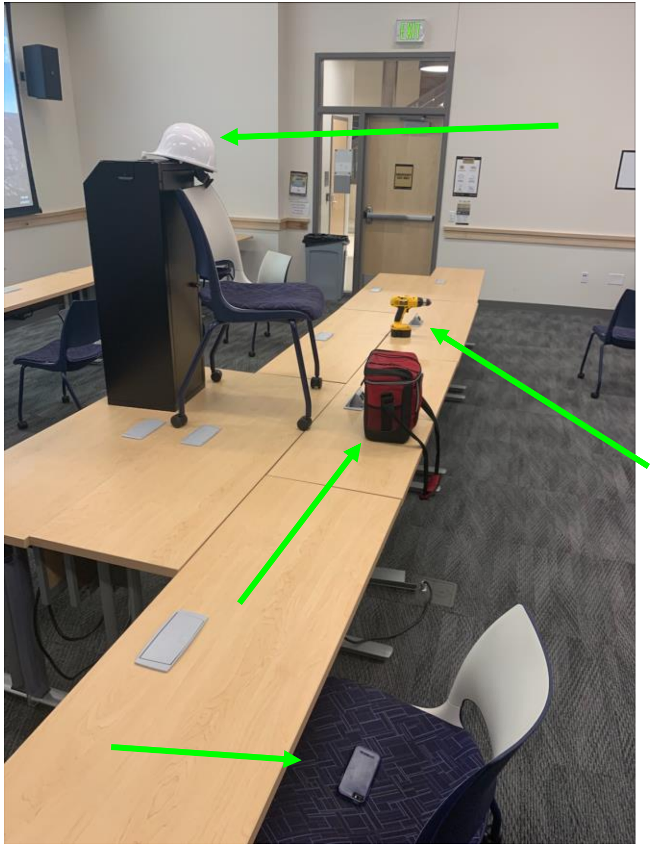


Figure: Test environment with artifacts of interest to MARBLE. These artifacts were moved to various obstructed positions during testing. RESCUE (not shown) is to the left of the frame.

Day in the Life: Commanding RESCUE

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.

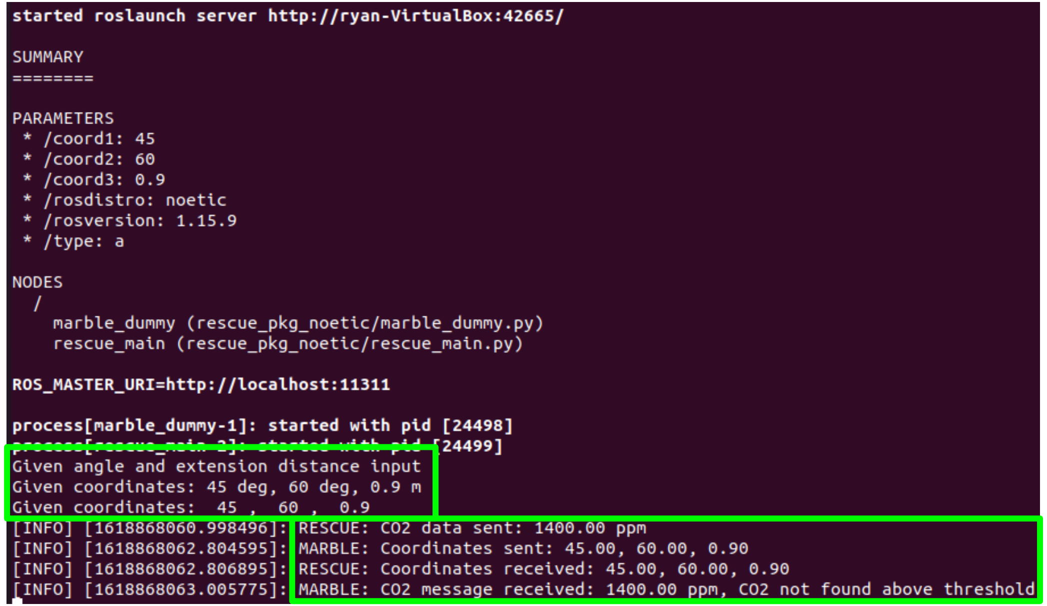
- RESCUE was granted complete authority over the commands architecture
- MARBLE will be connected to RESCUE via a Gigabit Ethernet cable, enabling MARBLE to send commands via command-line arguments
- The commands are structured as follows (figure 1):
  - Argument 0: Executable script name, rescue_run
  - Argument 1: Angle or coordinates flag, -a or -c
  - Argument 2: Pivot angle or x-coordinate
  - Argument 3: Rotate angle or y-coordinate
  - Argument 4: Extension distance or z-coordinate

```
ryan@ryan-VirtualBox:~/RESCUE_ws_python/rescue_ws$ roslaunch rescue_pkg_noetic rescue.launch type_flag:=a coord1:=45 coord2:=60 coord3:=0.9
```

Figure: User command sent to RESCUE with angles and extension distance as arguments

Day in the Life: Interpreting Commands

- Each actuator is connected to the base Raspberry Pi via GPIO to motor control board or USB serial connection.
- RESCUE runs a series of algorithms to convert the specified desired position and orientation to PWM signals in the form of pulse-width values for the motors.
  - Pulse-width input range of 1000-2000 µs

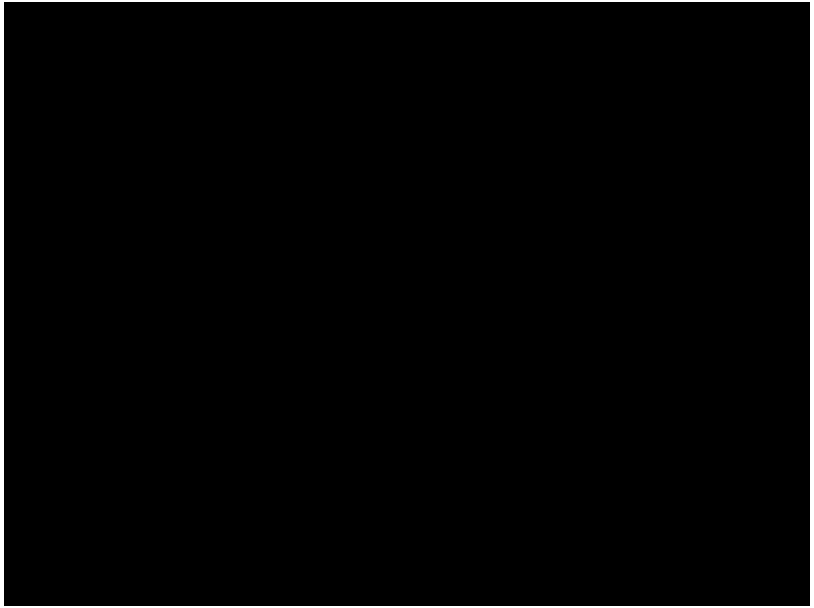

```
started roslaunch server http://ryan-VirtualBox:42665/

SUMMARY
========

PARAMETERS
 * /coord1: 45
 * /coord2: 60
 * /coord3: 0.9
 * /rosdistro: noetic
 * /rosversion: 1.15.9
 * /type: a

NODES
  /
    marble_dummy (rescue_pkg_noetic/marble_dummy.py)
    rescue_main (rescue_pkg_noetic/rescue_main.py)

ROS_MASTER_URI=http://localhost:11311

process[marble_dummy-1]: started with pid [24498]
process[rescue_main-2]: started with pid [24499]
Given angle and extension distance input
Given coordinates: 45 deg, 60 deg, 0.9 m
Given coordinates:  45 ,  60 ,  0.9
[INFO] [1618868060.998496]: RESCUE: CO2 data sent: 1400.00 ppm
[INFO] [1618868062.804595]: MARBLE: Coordinates sent: 45.00, 60.00, 0.90
[INFO] [1618868062.806895]: RESCUE: Coordinates received: 45.00, 60.00, 0.90
[INFO] [1618868063.005775]: MARBLE: CO2 message received: 1400.00 ppm, CO2 not found above threshold
```
Figure: RESCUE sample command-line output. Key output statements are shown in green boxes

- The PWM signals are then sent to the motors and the motors start running.
  - Ensuring that actual angles/distances matches the commanded angles/distances can be discussed in backup slides.

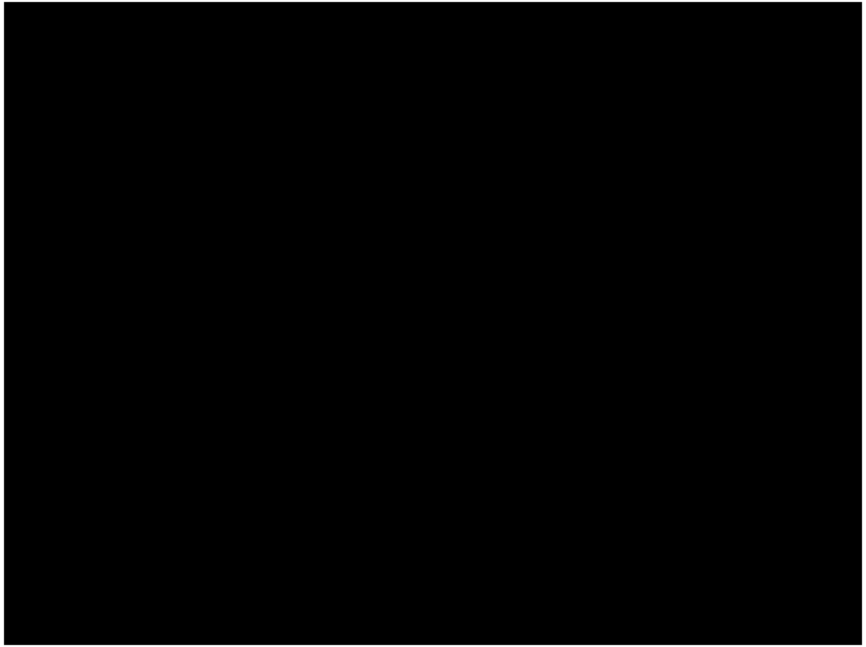
Day in the Life: Executing Commands

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.

Deployment from a third person point of view



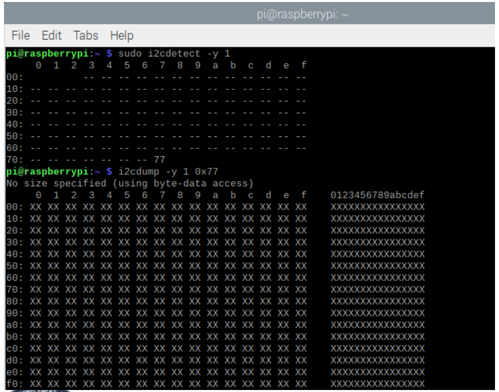
Deployment from camera's point of view

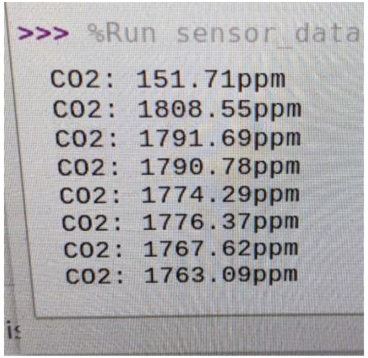


Day in the Life: Data Collection

CO_2 and AHRS data

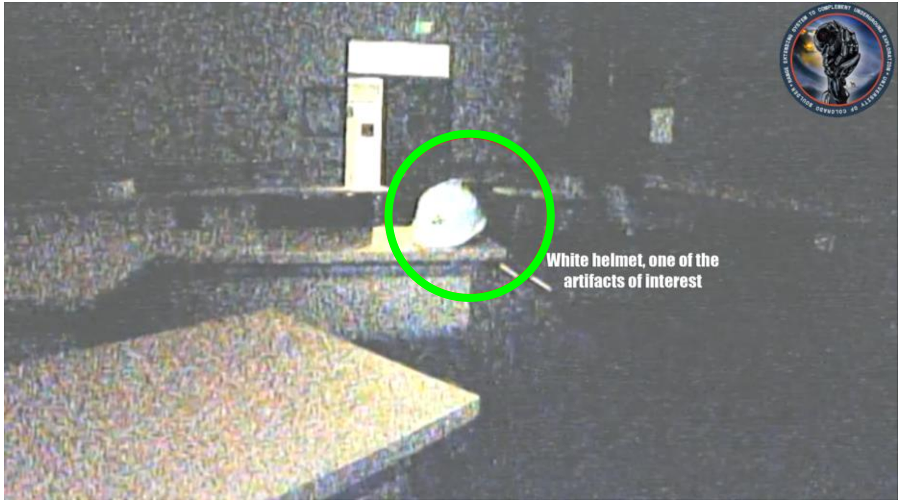
Data size: 12-byte resolution
Format: I2C, SPI (respectively)





Camera data

Data size: 2 MP image resolution
Format: NTSC Video



Day in the Life: Data transmission

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.

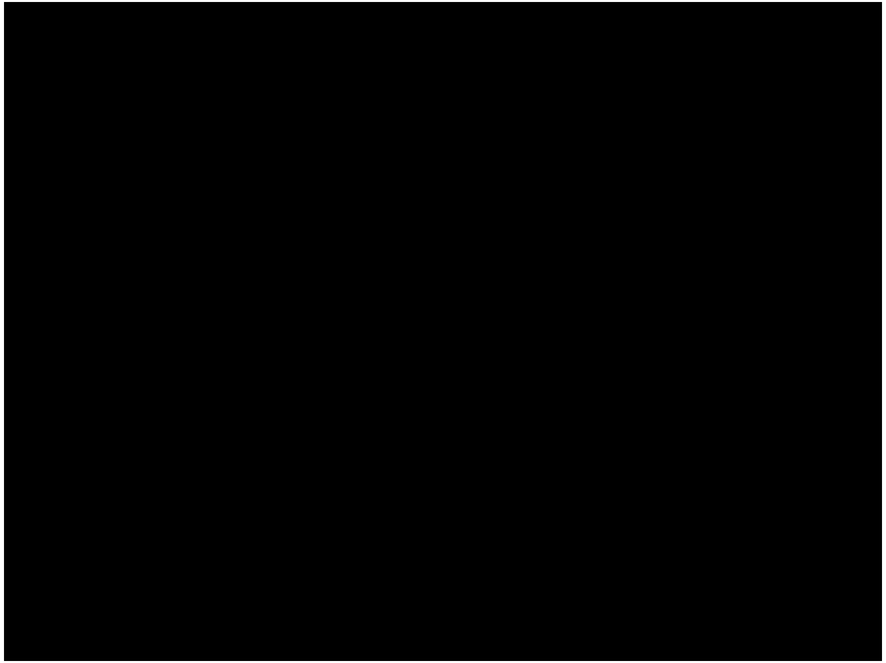
Primary Means of Data Transmission:

- FPV video data transmitted via 5.8 GHz wireless.
  - Transmission rate: 2-4 seconds

- Sensor data transmitted via 2.4 GHz wireless using the MQTT protocol.
  - Transmission rate: 1-2 seconds

- ROS messages transmitted via gigabit ethernet to and from MARBLE using TCP/IP protocol.
  - Transmission rate: 10-50 milliseconds

Day in the Life: Retraction and extreme cases



Retraction

Day in the Life: Results

Component	Results	CPE and requirements validated
Total "day in the life" tests performed	15 times, including the extreme case of horizontal and vertical extensions.	FR 5.3: RESCUE shall withstand repeated deployments
Average deployment time		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.
Average data size		CPE: Communications
Average data transmission time		TDR 6.1.2

Day in the life results confirm that 86% of the Functional/Technical requirements and CPE such as: physical reach, deployments, data collection, an communications, **are satisfied**.

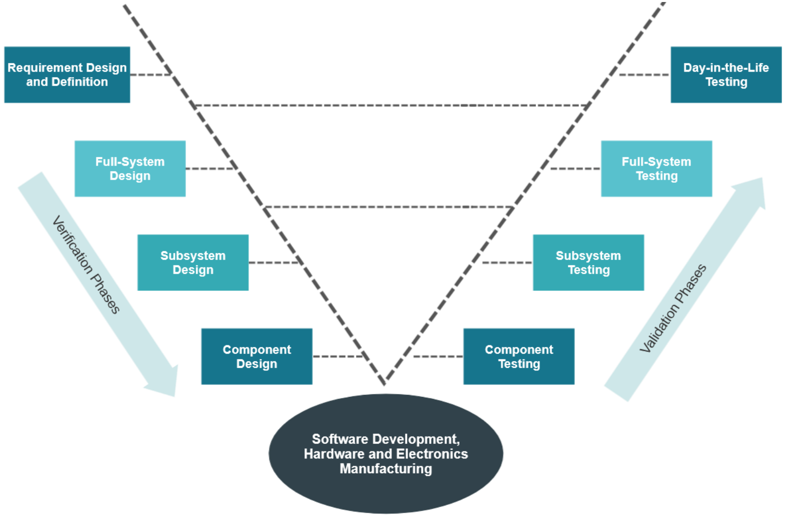
- There remains 1 functional requirements related to the mechanical interface with MARBLE that cannot be until integration if it was to happen
- There remains 2 functional requirements related to the accuracy, which is to be included in the final report and can be discussed in backup slides.

Systems Engineering

Systems engineering: Trade Studies and Requirements

Guided by the **systems engineering "V",** the first step was to scope the project:

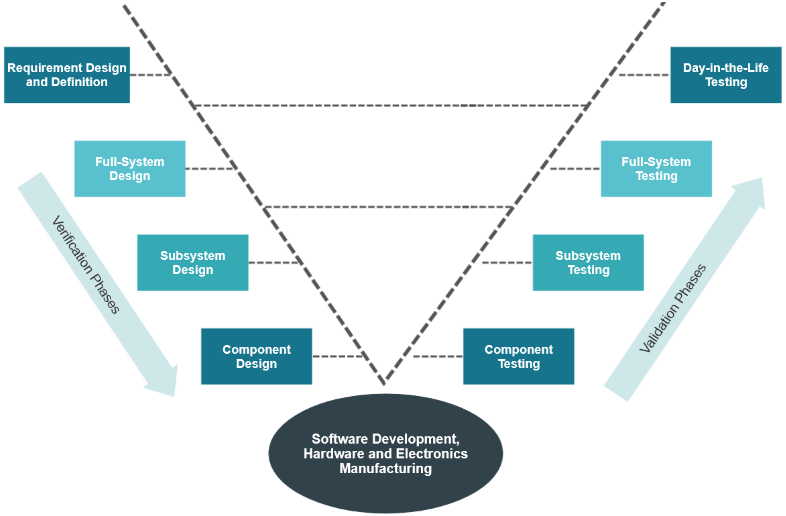
- Meetings with the customer to define verifiable coherent requirements, levels of success, critical project elements, and initial CONOPS.
- Chief high level functional requirement (from PDD document) : **"The sensor setup shall be able to "sense" artifacts up to 5m away from the stowing location in any given accessible direction (i.e. the sensor system shall NOT force its way through anything, but rather maneuver to reach the designated accessible destination)."**
    - By CDD and PDR, lower level requirements were derived from all top level requirements



Trades	Options	Winner
Deployment mechanisms	Drones, robotic arms, Projectile Launchers,	Folding robotic arm (1.3 m reach) with pointing base.
Communication method	Wired vs wireless.	Wired ethernet communications
Sensors	Visual sensors (cameras, thermal cameras, LIDAR), CO_2 sensors, orientation sensors.	RGB-D camera, and a specific brand CO_2 sensors and AHRS.

Systems engineering: Design change between PDR and CDR

- **"The sensor setup shall be able to "sense" artifacts up to 5m away from the stowing location in any given accessible direction (i.e. the sensor system shall NOT force its way through anything, but rather maneuver to reach the designated accessible destination)."**
    - The customer valued the physical reach "up to 5m" far more than the mobility of the arm and the ability to maneuver around obstacles.
    - A new operational condition was invoked: RESCUE now will not worry about overcoming obstacles, the path is guaranteed to be obstacles free.
- Due to complexity during the subsystems testing, RESCUE switched to **the backup option that existed since CDR: Xrail sliding kit.**



Trades	Options	Winner
Deployment mechanisms	Inflatable robotic arm, gears based robotic arm, telescoping robotic arms, hydraulic actuated arms.	Inflatable robotic arm **(4m reach)** as main choice and Xrail kit **(1.89m reach)** as backup plan.
Sensors	Cameras	Drone FPV camera (to reduce sensors suite mass)

Systems engineering: Interfaces

Software

Interface	Design choice
Commands architecture (Interfacing with MARBLE)	Command line arguments that includes position and orientation.
Data flow	ROS topics published by different nodes

Electrical

Interface	Design choice
Power reception and regulation (Interfacing with MARBLE)	Power in to DC/DC Voltage converter
Power distribution to motors and sensors	Power regulated using DC/DC converter, power regulation board and LM317 adjustable regulator

Mechanical

Interface	Design choice
Mounting on MARBLE's husky.	TBD if customer decides to integrate. Currently represented by an aluminum base plate.
Pivot/Rotation/Extension interfaces	Brackets, screws, gears, and 3D printed parts.
End Effector interface	3D printed housing, mounted via screws and brackets.

Systems engineering: Risks

Risk	CDR Mitigation Strategy	Encountered (Yes/No)	Effect on the Project
Inflatable am Buckling	Anti-buckling motors in end effector that assist in even retraction of tubing.	No	If it was to happen, it would have been detrimental to the overall inflatable design scussess.
Inflatable Arm Rigidity	Factors of safety for end effector mass and tube pressure. Extensive testing.	Yes	Facilitated the choice to resort to the backup option: Xrail sliding kit.
Communications Interference	Choose a wireless receiver and transmitter combo that has a variety of channels to avoid interference.	No	If it was to happen, RESCUE would not be able to control sensors and control data flow.
Delays Due to COVID: shipping and manufacturing	Establish a manufacturing team that is able to go on campus to use campus based resources. Wide margins on manufacturing schedule. Order things with fast shipping when possible if items are critical.	Yes	Caused major delays in construction times and accuracy of manufactured components sometimes.

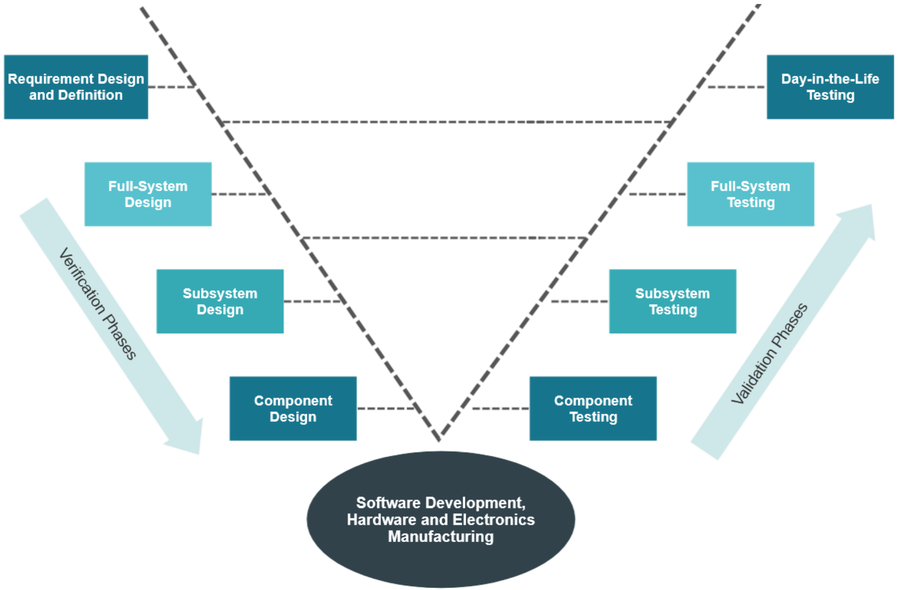
Systems engineering: Lessons learned

- **Customer values and project scoping are very important:**
  - More and more conversations with the customer, it is better to talk more than you need to than to talk less than you need to.

- **The design V:**
  - Redesigns happen in the industry, and it is typical to go back and forth sometimes to adjust some of the design aspects.
  - The project is not necessarily in one phase at a time Be flexible with requirements changing and propagate that properly across all subsystem.
  - Be able to navigate multiple solutions rapidly and asses initial feasibility: is this even doable? Can this actually be built? (A lot of designs look really good, on paper!)

- **Everyone should be involved:**
  - All subsystems bring concerns from their system's point of view, and it is important that everyone is involved so everyone is aware of the interdependencies between each other.

- **Necessary requirements only!**
  - Broaden the design choices and avoid tunnel vision.
  - Have backup plans



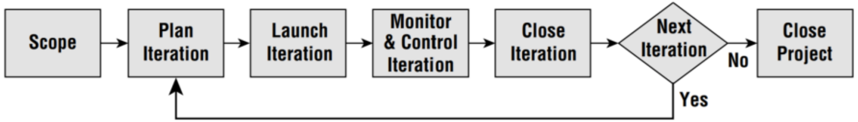
Project Management

Project Management

Approach:

Followed principles of Agile Project Management:

- Solving a critical problem without a known solution
- Iterative Project Management Life Cycle:



Key Management Successes:

- Cohesion and flexibility among sub-teams
- Team members were specialized and could present the PM the necessary information to make educated decisions
- Overcame many major design changes and still completed the project

Difficulties Encountered:

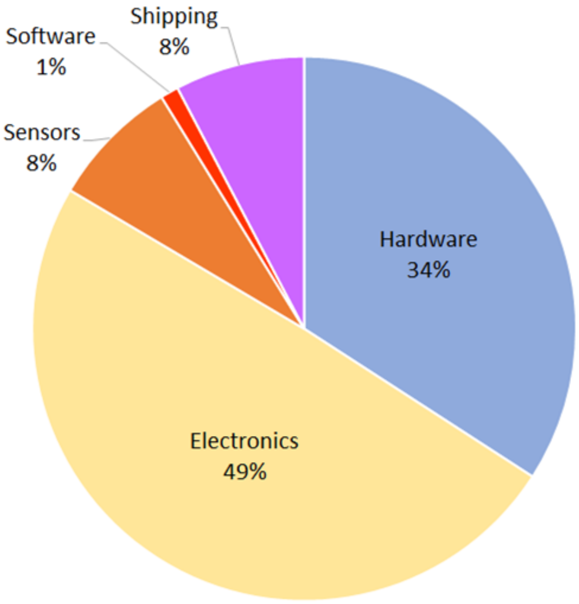
- Delayed decisions due to uncertainty
- Conflicting opinions
- Lack of ability to prototype early

Lessons Learned:

- PM must stay equally involved with all sub-teams
- Systems Engineering is essential in agile projects
- Make decisions and changes as early as possible

Final Budget

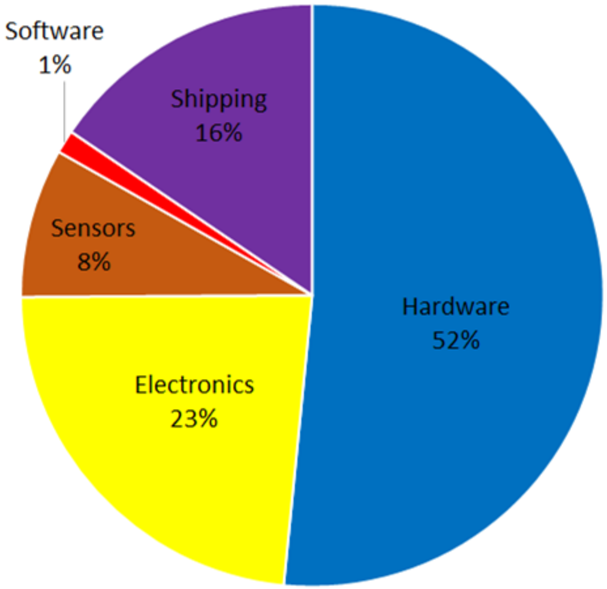
CDR Planned Budget



CDR vs. Final Budgets:

Budget	CDR	Final
Hardware	$1,328	$1,679
Electronics	$1,920	$760
Sensors	$300	$270
Software	$42	$42
Shipping	$300	$505
Total	**$3,890**	**$3,255**
Margin	**$1,110**	**$1,745**

Final Budget



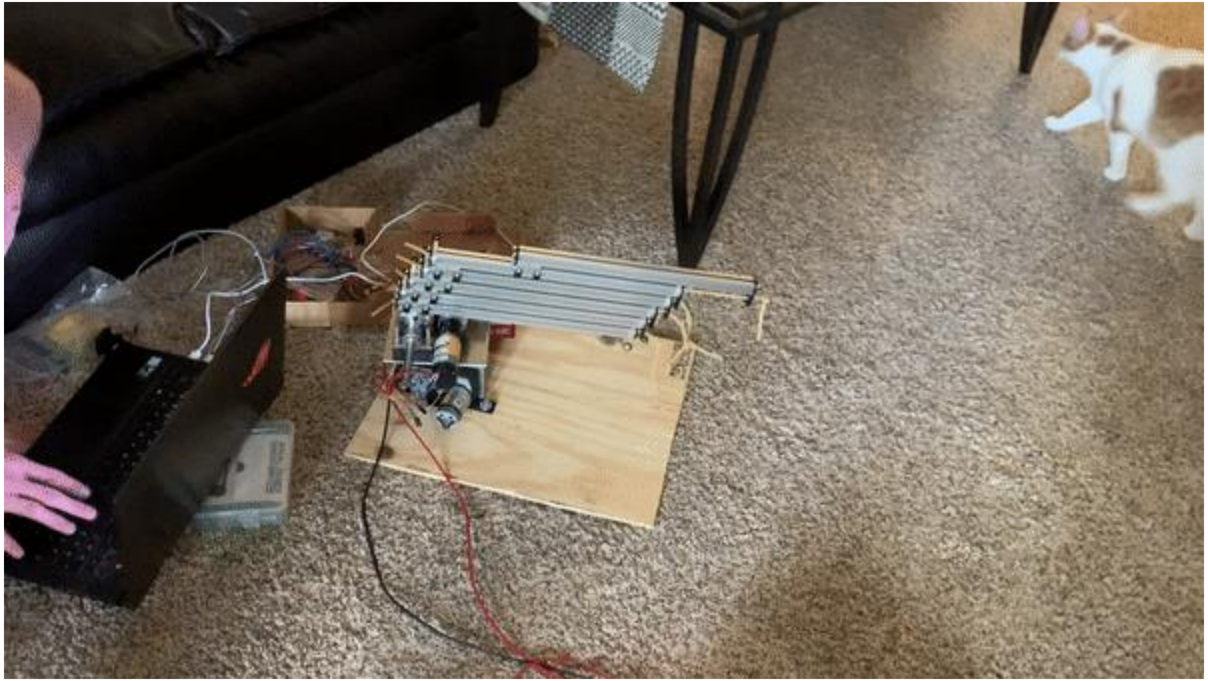
Industry Cost

- Starting from week of 10/25/2020, 20 Weeks
- **3275 Total Hours**
- Assuming $65,000 Salaries = $31.25/hour
- **Labor: $102,344**
- **Materials: $3,255**
- Total Cost: $105,599.00
- Total Cost * 200% Overhead Rate...

- **INDUSTRY COST: $211,198**

Special thanks to the following people, without them it would have been impossible to make it this far:

Professor Kathryn Wingate
Professor Eric Frew
Professor Bobby Hodgkinson
Professor Trudy Schwartz
Professor Matt Rhode
Professor Nicholas Rainville
Professor Josh Mellin
Professor Dennis Akos
Professor John Mah



And Jack (the cat), who did not do any work whatsoever … but kept us a good company

Questions?

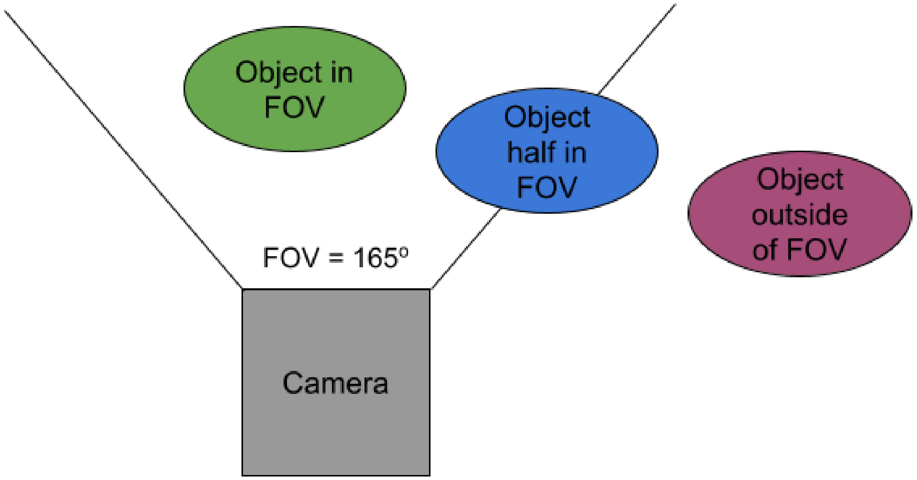
Backup Slides

Artifact Sensing: Deflection Model

- With the pan-tilt, the FOV can extend to 165+150 = 315 degrees. Even if our pivot motor fails, we can still see artifacts above the arm

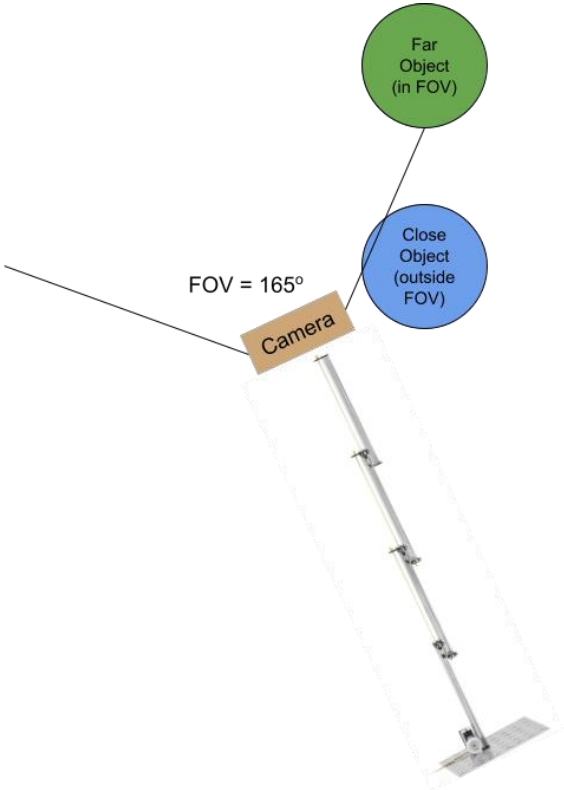
Let's look at the worst case scenario - broken motor (can't lift the arm) and camera pan-tilt:

- Based on the *camera* FOV, determine the maximum *allowed* deflection
- Treat the artifact as a point in space



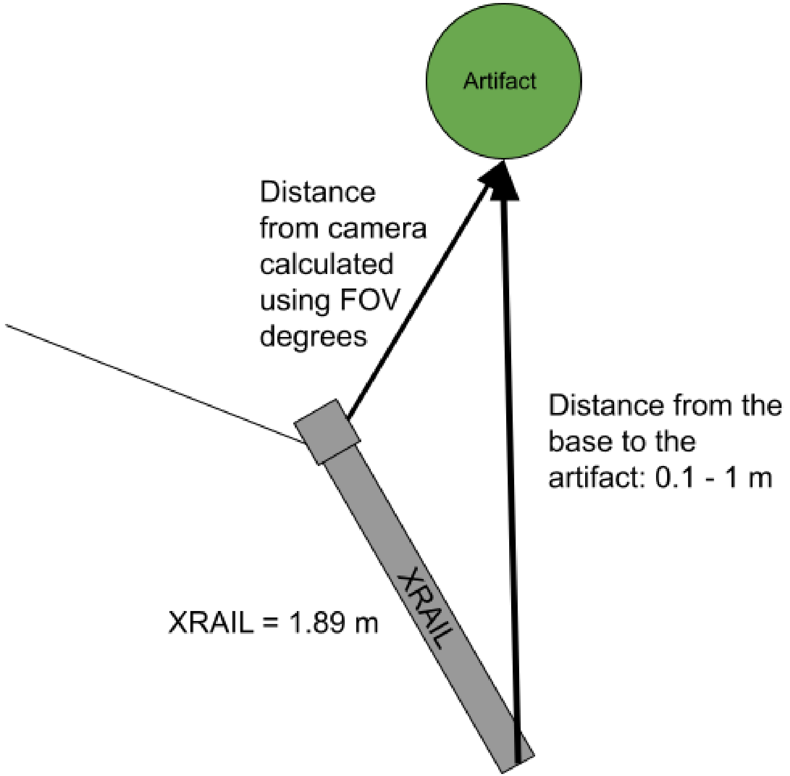
Artifact Sensing: Deflection Model

- Based on the camera FOV, determine the maximum *allowed* deflection
- FOV = 165 degrees
- At least half of the artifact has to be in FOV to be noticed



Artifact Sensing: Deflection Model

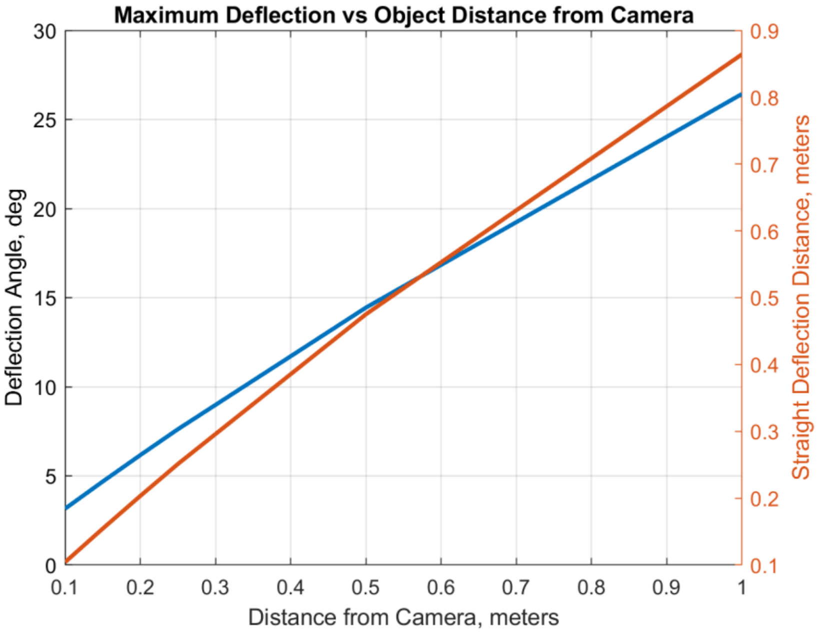
1. The allowed deflection angle depends on the distance between the camera and the artifact
2. Use geometry to figure out the allowed deflection at the base of the Xrail



Artifact Sensing: Deflection Model

Measuring the straight line displacement

Artifact distance from camera	1 m	0.5 m	0.25 m	0.2 m	0.15 m	0.1 m
Maximum Allowed Deflection of the x-rail	26.4 deg	14.4 deg	7.6 deg	6.2 deg	4.7 deg	3.2 deg
Straight line displacement	86 cm	48 cm	25 cm	20 cm	15 cm	10 cm



Backup: CDD/PDR requirements

FR1.1	At minimum, RESCUE shall have the ability to physically reach a location that is at least 1 meter but not more than 5 meters from the apparatus' mounted position on the MARBLE Clearpath Husky.
FR2.1	RESCUE shall be able to sense DARPA subterranean challenge competition artifacts.
FR3.1	RESCUE shall determine and report its location and orientation relative to the ground robot.
FR4.1	When in its standby configuration, RESCUE shall be compatible with the MARBLE team's Clearpath Husky.
FR4.2	When in operation, RESCUE shall not interfere with the MARBLE team's Clearpath Husky's operations.
FR4.3	RESCUE's deployment operations shall be rapid enough to incur a minimal time cost to MARBLE's total mission time.

Back

Backup: CDD/PDR requirements

FR5.1	RESCUE despite the splash exposure to mud, water, and dust expected in the DARPA Subterranean Challenge circuit environment. RESCUE shall withstand the thermal environment of the DARPA subterranean challenge.
FR5.2	RESCUE shall have enough electrical power to maintain standby, active, and operational states fitting the MARBLE team's mission expectations.
FR5.3	RESCUE shall withstand repeated deployments.
FR6.1	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.

Back

Backup: CDD/PDR requirements

FR1.1	TDR1.1.1	RESCUE shall have the ability to physically reach a location that is at least 1 meter but not more than 5 meters along any unobstructed direction from the mounted position of the apparatus of the MARBLE ClearPath Husky.
	TDR1.1.2	RESCUE shall have the ability to make at least one directional change of 45 or more about at least one axis from the starting extended location to physically reach a location that is at least 1 meter but not more than 5 meters and not within a clear line of sight from the mounted position of the apparatus on the MARBLE Clearpath Husky.
	TDR1.1.3	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.
FR2.1	TDR2.1.1	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.

Back

Backup: CDD/PDR requirements

	TDR2.1.2	The sensing apparatus shall be able to sense and detect carbon dioxide (CO_2) at 2000 parts per million concentration.
FR3.1	TDR3.1.1	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.
	TDR3.1.2	RESCUE shall be able to determine its orientation to the ClearPath Husky within 5 accuracy of its ground truth orientation at all times.
FR4.1	TDR4.1.1	When in its standby configuration, RESCUE shall not exceed a volume of 38 centimeters wide by 45 centimeters long by 22-30 centimeters tall.
	TDR4.1.2	RESCUE shall not exceed a total mass of 10 kilograms.
	TDR4.1.3	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.

Back

Backup: CDD/PDR requirements

FR4.2	TDR4.2.1	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 of or damage the MARBLE Clearpath Husky.
FR4.3	TDR4.3.1	Upon receiving an activation command from the MARBLE team when in standby configuration, RESCUE shall reach an active state in 30 seconds or less.
	TDR4.3.2	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.
	TDR4.3.3	Upon receiving an deactivation command from the MARBLE team while, RESCUE shall return from its operational/active configuration to its standby configuration within 120 seconds.

Back

Backup: CDD/PDR requirements

FR5.1	TDR5.1.1	RESCUE's mechanical and electrical components shall meet at least IP43 water exposure tolerances.
	TDR5.1.2	RESCUE's mechanical and electrical components shall meet at least IP43 dust exposure tolerances.
	TDR5.1.3	RESCUE shall accomplish all other design requirements in an nominal thermal environment of 50-65 F.
FR5.2	TDR5.2.1	RESCUE shall have enough electrical power to maintain a standby state for at least 135 minutes.
	TDR5.2.2	RESCUE shall have enough electrical power to maintain an operational state for at least 30 minutes.

Back

Backup: CDD/PDR requirements

FR5.3	TDR5.3.1	
FR6.1	TDR6.1.1	The sensing system shall be capable of receiving firing commands from the ROS nodes in the existing MARBLE architecture.
	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.
	TDR6.1.4	RESCUE shall deliver frequent status reports to the MARBLE robot regarding deployment status and data collection.

Back

Models: requirements validation

FRs	TDRs	Requirement	Functional Category	Validated? (Y/N)
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.	Physical Reach	Y
FR 2.1		The sensing system shall be able to sense DARPA subterranean challenge competition artifacts	Artifacts Sensing	Y
	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	Artifacts Sensing	Y
	TDR2.1.2	The sensing apparatus shall be able to sense and detect carbon dioxide (CO_2) at 2000parts per million concentration.	Artifacts Sensing	Y
	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.	Artifacts Sensing	Y
	TDR2.1.4	RESCUE shall have enough lighting to perform all of its sensing operations in a possibly aphotic environment.	Artifacts Sensing	Y
FR 3.1		RESCUE shall determine and report its location and orientation relative to the ground robot	System Position and Orientation	Y

Models: requirements validation

FRs	TDRs	Requirement	Functional Category	Validated? (Y/N)
FR 4.1		When in its standby configuration, RESCUE shall be compatible with the MARBLEteam's Clearpath Husky.	Deployment: Constraints	Y
	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.	Deployment: Interference constraints	Y
	TDR 4.1.2	RESCUE shall not exceed a total mass of 10 kilograms	Deployment: Interference constraints	Y
	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.	Deployment: Interference constraints	Y
	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	Deployment: Interference constraints	N
FR 4.2		RESCUE's deployment operations shall be rapid enough to incur a minimal time cost toMARBLE's total mission time.	Deployment: Time	Y
	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.	Deployment: Time	Y
	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.	Deployment: Time	Y
FR 5.1		RESCUE shall accomplish all other design requirements in an nominal thermal environment of 50-65°F.	Endurance: Environmental Hazard	Y
FR 5.2		RESCUE shall have enough electrical power to maintain standby, active, and operational states fitting the MARBLE team's mission performance expectations.	Endurance: Power Time	Y
	TDR 5.2.1	RESCUE shall have enough electrical power to maintain a standby state for at least 135 minutes.	Endurance: Power Time	Y
	TDR 5.2.2	RESCUE shall have enough electrical power to maintain an operational state for at least 30 minutes.	Endurance: Power Time	N
FR 5.3		RESCUE shall withstand repeated deployments.	Endurance: Operational Time	Y
	TDR			

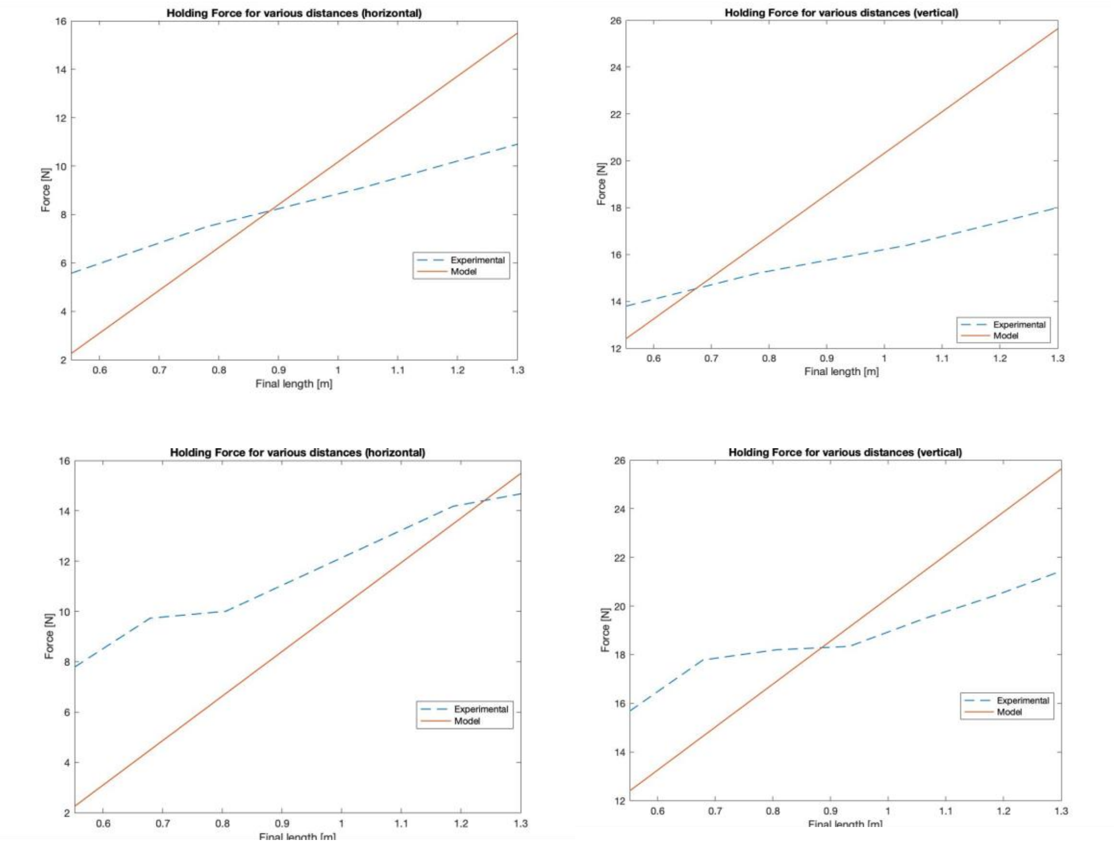
Models: requirements validation

FRs	TDRs	Requirement	Functional Category	Validated? (Y/N)
FR 5.2		RESCUE shall have enough electrical power to maintain standby, active, and operational states fitting the MARBLE team's mission performance expectations.	Endurance: Power Time	Y
	TDR 5.2.1	RESCUE shall have enough electrical power to maintain a standby state for at least 135 minutes.	Endurance: Power Time	Y
	TDR 5.2.2	RESCUE shall have enough electrical power to maintain an operational state for at least 30 minutes.	Endurance: Power Time	N
FR 5.3		RESCUE shall withstand repeated deployments.	Endurance: Operational Time	Y
	TDR 5.3.1	The MARBLE team shall be able to deploy RESCUE at least 5 times during a competition run.	Endurance: Operational Time	Y
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.	Communications	Y
	TDR 6.1.1	RESCUE shall be capable of receiving firing commands from the ROS nodes in the existing MARBLE architecture.	Communications	Y
	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.	Communications	Y
	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.	Communications	Y
	TDR 6.1.4	RESCUE shall deliver frequent status reports to the MARBLE robot regarding deployment status and data collection	Communications	Y

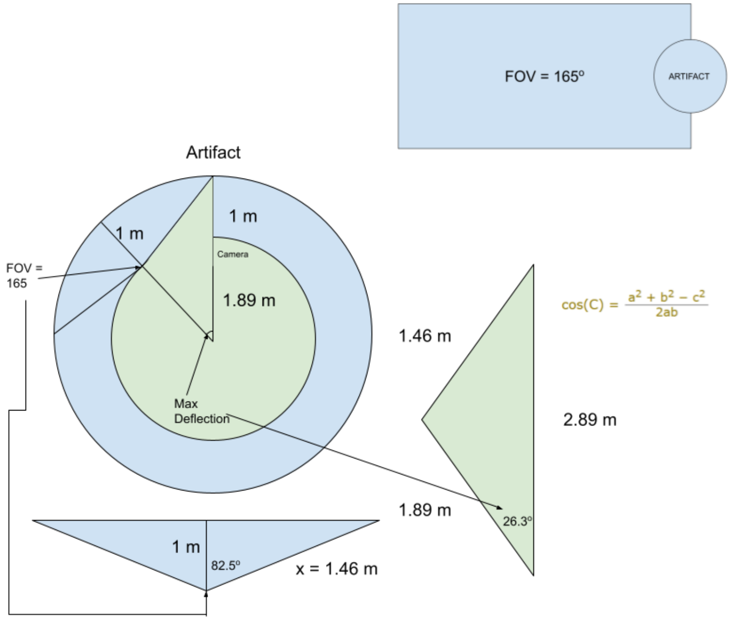
Extension Model: Sources of Error

Original Test: Xrail not attached to pivot and rotation.

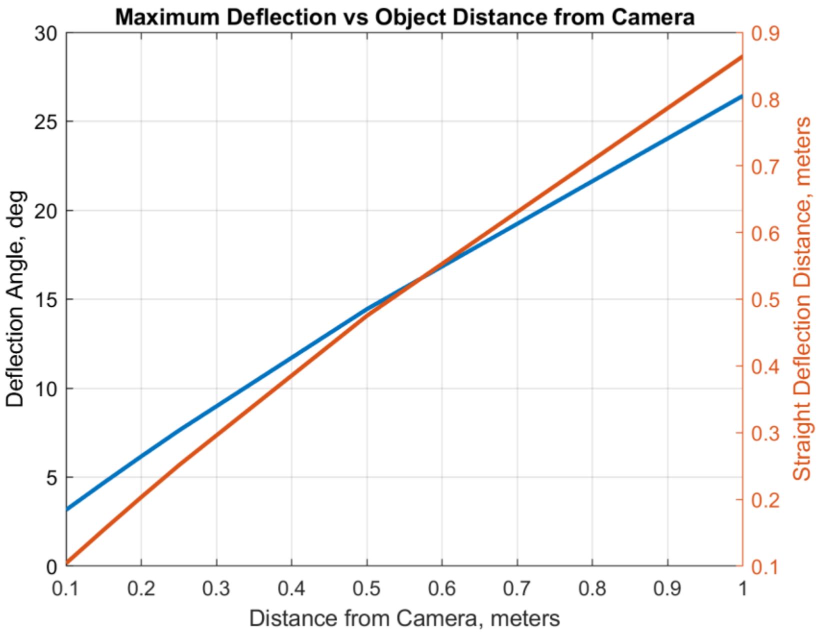
Modified test: Xrail attached to pivot and rotation



Models: Deflection

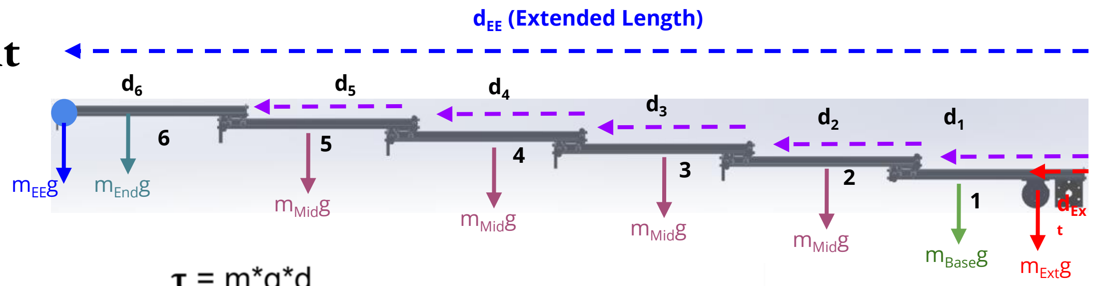


Artifact distance from camera	1 m	0.5 m	0.25 m	0.2 m	0.15 m	0.1 m
Maximum Allowed Deflection of the x-rail	26.4 deg	14.4 deg	7.6 deg	6.2 deg	4.7 deg	3.2 deg
Straight line displacement	86 cm	48 cm	25 cm	20 cm	15 cm	10 cm



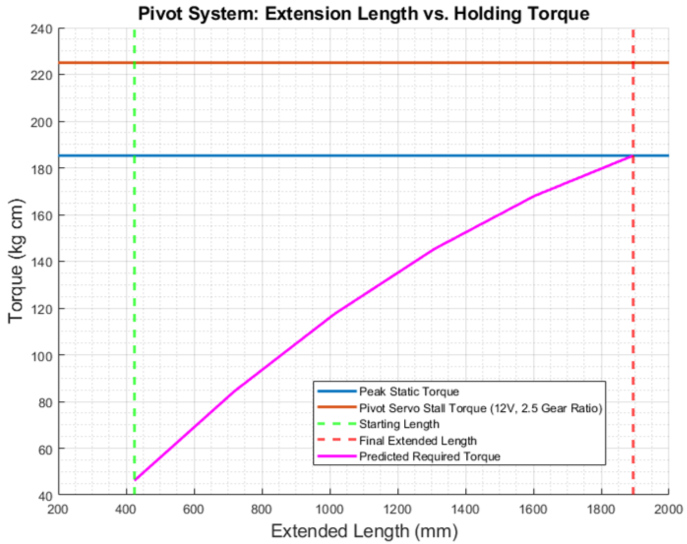
Models: Pivot Torque Design Development

- Worst Case: Horizontal Extension
- Assuming:
    - 450g End Effector, point mass
    - 520g Extension system, 116mm from pivot axis, point mass
    - 1060 Al for all X Rail components; 138g base, 176g middle, 143g end sections
    - Extension from 425mm collapsed to 1895mm extended, rotation about end
    - d_1, d_{Ext} Constant
    - All other d values dynamic
    - Assuming perfect cascade



$$\tau = m*g*d$$

$$\tau_{Total} = (m_{Ext}d_{Ext} + m_{Base}d_1 + m_{Mid}d_2 + m_{Mid}d_3 + m_{Mid}d_4 + m_{Mid}d_5 + m_{End}d_6 + m_{EE}d_{EE})*g$$



New Extension Method: X-rail Sliding Kit

Xrail sliding kit:

- A modularized sliding kit developed by ServoCity.
- Has been purchased and assembled.
- Extension done by reeling in a cable (figure 1), retraction done by reeling out the cable and using restorative force from elastic cables (figure 3)
- Physical reach of 1.89m tentatively.
- Simplifies electronics and software structures respectively
- Mass reduced from ≈ 8.3 kg to ≈ 6 kg (lighter and faster system).

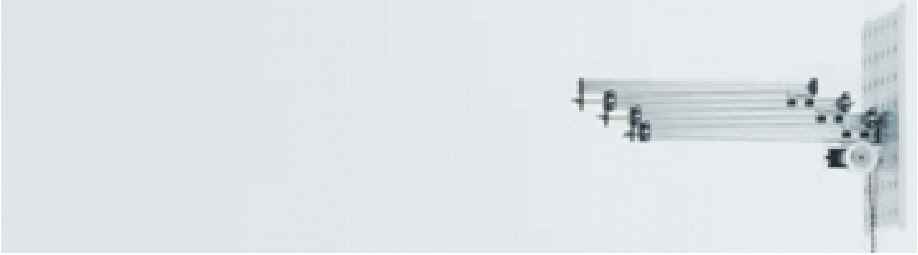


Figure 2: GIF of the X-rail kit being extended

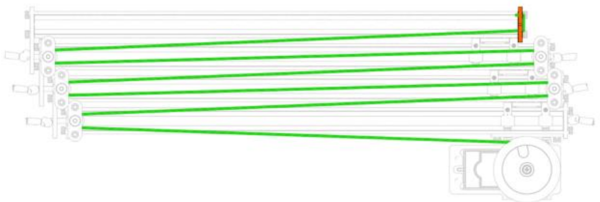


Figure 1: X-rail kit and tension system

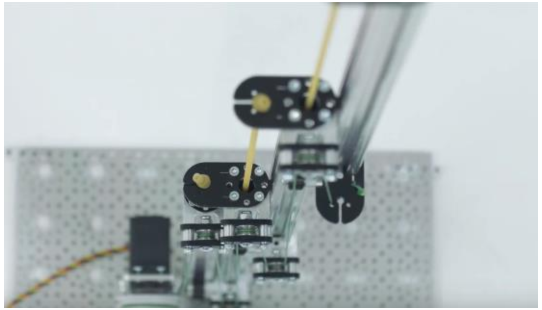


Figure 3: elastic restorative bands

Hardware Test Readiness: X-rail Extension

Goals: Verify load capacity and extension rate of motor

Preliminary Test: Assemble 4 section x-rail and measure the deflection with a 500 gram payload. It is rated to support 907 grams.

Procedure

1. Fully extend arm and position in horizontal, 45 degree, and vertical orientations. Ensure that the motor can keep the arm extended by counteracting the latex tubing and weight of the arm. Measure the deflection in each orientation.
2. Time how long it takes for the arm to fully extend in these orientations. Each needs to be less than 10 seconds.
3. Extend to various commanded lengths to ensure that partial extension is possible and accurate.

Electronics Test Readiness: Voltage Regulation

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 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.

- **Test Purpose:** Verify that the voltage regulation circuits output the expected voltages and properly power the required electronics for the max possible duration of use.
- **Risk Mitigation**: Build confidence in consistency of input power system for all electronics.
- **Test Status**: Incomplete but on schedule - needs to be performed by March 12th.
- **Expected Results (success criteria)**: An output of 12V and 5V with the ability to power the Raspberry Pi 4, wireless receiver, rotation servo, pivot servo, and extension servo for a consecutive 135 minutes (TDR 5.2.1) while using less than 600 watts (TDR4.1.3). Active minutes will be tested in system integrated tests.
- **Model Validation**: Test will validate the expected output.

Electronics Test Readiness: Voltage Regulation

Facility:

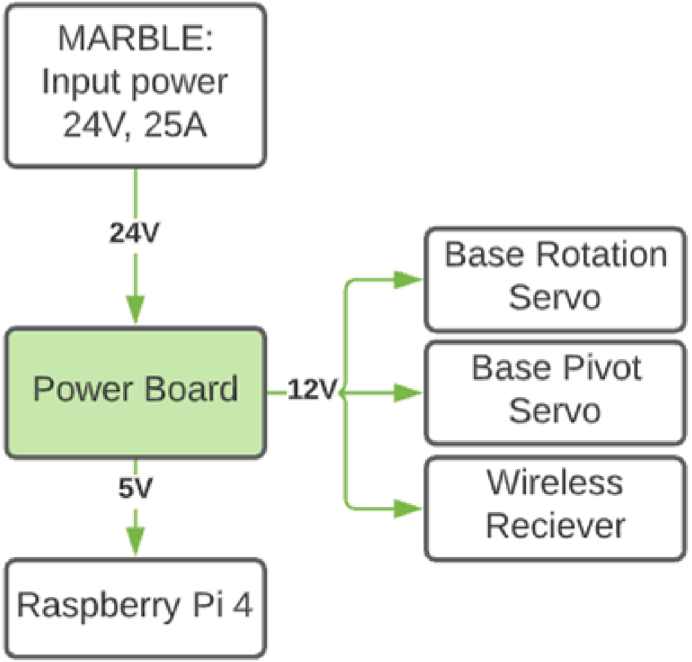
- Electronics Shop

Equipment:

- Digital Multimeter
- Power Supply
- Bread Board

Procedure Overview:

1) Set power supply to 24V
2) Plug all electronics into their power sources
3) Turn on power supply and monitor each device. Ensure the power lights are on for the Raspberry Pi, wireless receiver and servos.
4) Maintain for 135 minutes. Also monitor current being drawn through power supply.



Electronics Test Readiness: End Effector Voltage Regulation Overview

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 5.2.1: RESCUE shall have enough electrical power to maintain a standby state for at least 135 minutes.

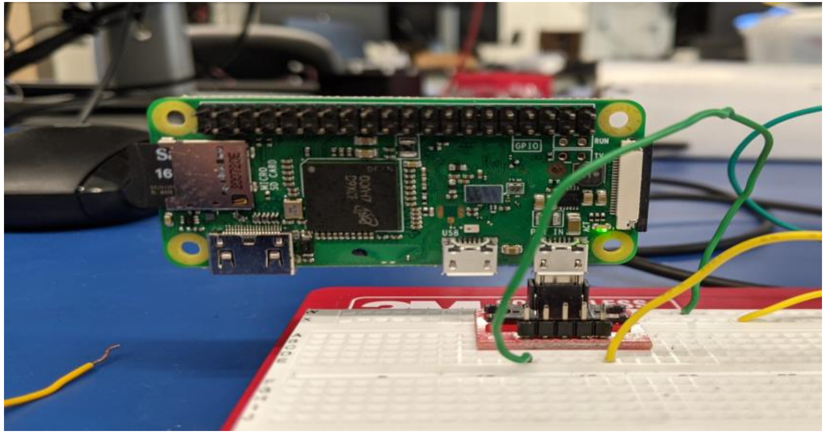
TDR 5.2.2: RESCUE shall have enough electrical power to maintain an operational state for at least 30 minutes.

- **Test Purpose:** Verify that the battery, voltage regulator and micro-USB breakout are able to successfully power the Raspberry Pi Zero W.
- **Risk Mitigation**: Build confidence in consistency of input power system for all electronics.
- **Test Status**: Preliminary test complete (February 26th) - further testing required by March 14th.
- **Expected Results (success criteria)**: An output of 5V with the ability to power the Raspberry Pi Zero W for a consecutive 135 minutes (TDR 5.2.1) while using less than 600 watts (TDR4.1.3). Active minutes will be tested in system integrated tests.
- **Model Validation**: Test will validate the expected output.

Electronics Test Readiness: End Effector Voltage Regulation

Facility:
- Electronics Shop

Equipment:
- Digital Multimeter
- Power Supply
- Bread Board



Procedure Overview:
1) Plug in 7.4V, 2200 mAh battery
2) Wire the voltage regulator and micro-USB breakout together in the breadboard.
3) Connect the micro-USB breakout to the Raspberry Pi Zero W.
4) Turn on power supply and monitor each device. Ensure Raspberry Pies' power lights are on. Maintain for 135 minutes. Also monitor current being drawn through power supply.

Project overview: motivation and background

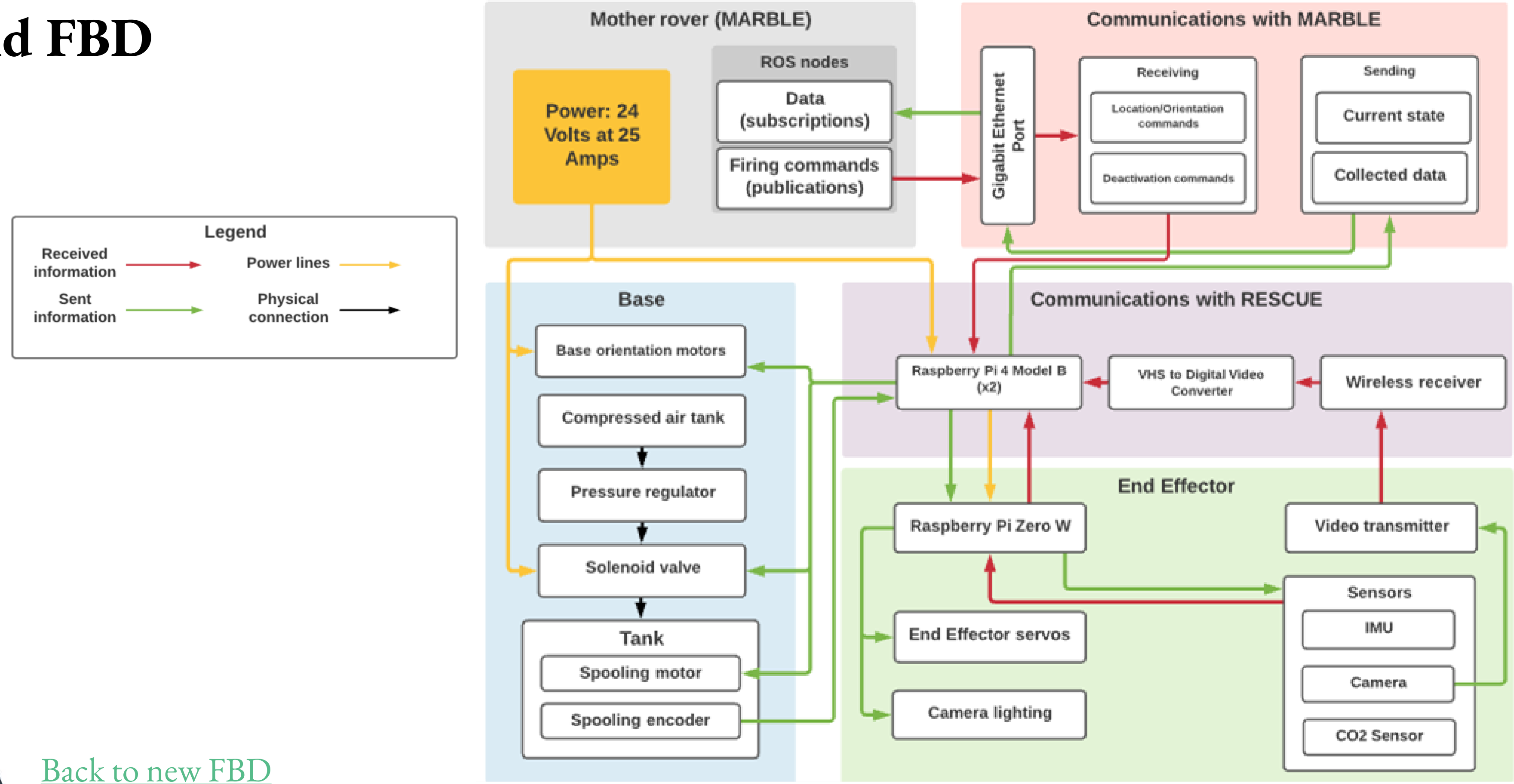
Background

- “The DARPA Subterranean Challenge seeks novel approaches to rapidly map, navigate, and search underground environments during time-sensitive combat operations or disaster response scenarios.” (DARPA)
- MARBLE is CU Boulder’s DARPA funded team competing in the systems portion of the Subterranean Challenge in which autonomous robots are tasked with the responsibility of locating various “artifacts”.

Motivation

- MARBLE’s UGV has **limited sensing** capabilities in comparison to other competitors in DARPA’s Subterranean Challenge.
- UGVs offer greater endurance than UAVs, however, **field of view and mobility are limited**.
- Certain obstacles are currently **impassible** and/or out of the FOV of the UGV.

Old FBD



Back to new FBD

Test Readiness: Subsystems Integration Overview

Component Testing: In Progress

- Test instruments and parts individually
- Ensure that each instrument/part is functional as expected
  - Outputs correct data and/or performs as expected
  - Units could include: Sensors, motors, pressure regulators, microcontrollers, arm material, etc.
  - So far, all units subjected to the unit testing have passed with the *exception* of the LDPE material

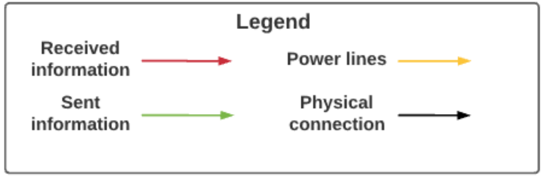
Subsystems Testing: Planned

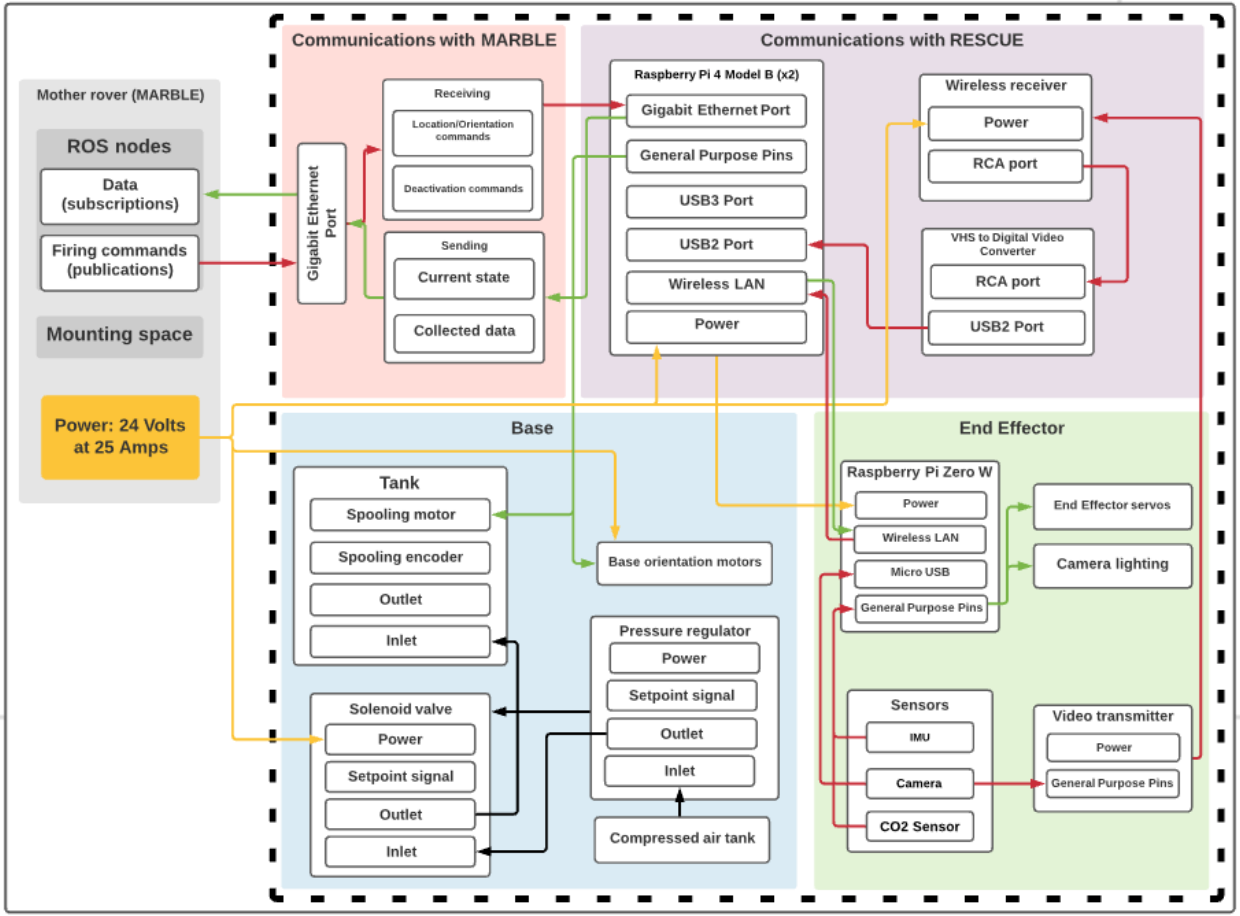
- Ensure that subsystems operate as planned
- Test subsystems separately:
  - Test the base mobility, material spooling and retraction (including pressurization and venting), sensors data collection and transmission, system response to commands and status report

Full System Integration Testing: Planned

- Test all subsystems together
  - Go through full proces, start to finish
    - Based on mock firing command
    - Attach RESCUE to a base on the ground and run the test.

Detailed FBD





Back to FBD

Xrail Extension Motor

Necessary Torque

- Needs to resist the restoring force from the elastic tubing and the weight of the arm
- Elastic tubing roughly doubles in size
- From testing: around 2 pounds of force to extend 1 elastic
    - 10 pounds total for 5 elastic tubes
  - ~ 18 pounds total, lever arm of one inch

Necessary Torque ~ 288 oz*in

Necessary RPM

- Needs to extend 6 rail sections in 10 seconds
- Servocity (manufacturer) achieved 4 rail section extension in 8 seconds at 60 RPM
- From this, 6 section in 10 seconds equates to 72 RPM

Solution: 5202 Series Yellow Jacket Interplanetary Motor
950 oz in, 117 RPM, encoder included, 12VDC input, 0.25A

Figure 1: 5202 Series Yellow Jacket Interplanetary Motor

Backup Slides: Hardware Manufacturing

Backup Slide: Off Ramp Option: X-Rail

- COTS option, **all components commercially available**
- Adding 2 x 12.45in. extension lengths would provide max ≈ 74in. **≈ 1.88m**
  - Required rails, extension line, cabling = 0.45kg
- 49.8in. kit supports ≈ 0.64 kg. In **horizontal** orientation.
  - Performance indication from ServoCity, **verification required.**
- **Base actuation, end effector, instrument design elements experience minimal change**
  - PDR/Redesign work is highly applicable
  - Removes need for any pressurized components
  - Would require additional servo analysis/selection
- **Decision Point: NLT 2/7**
  - Depends on inflation/weight support testing results

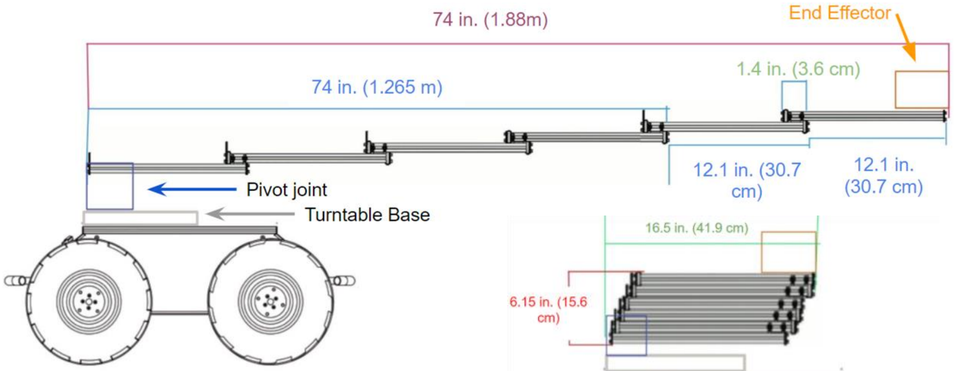


Figure 1. X Rail Arm on UGV

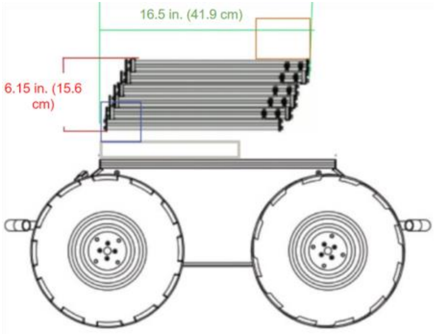


Figure 2. Collapsed X Rail on UGV

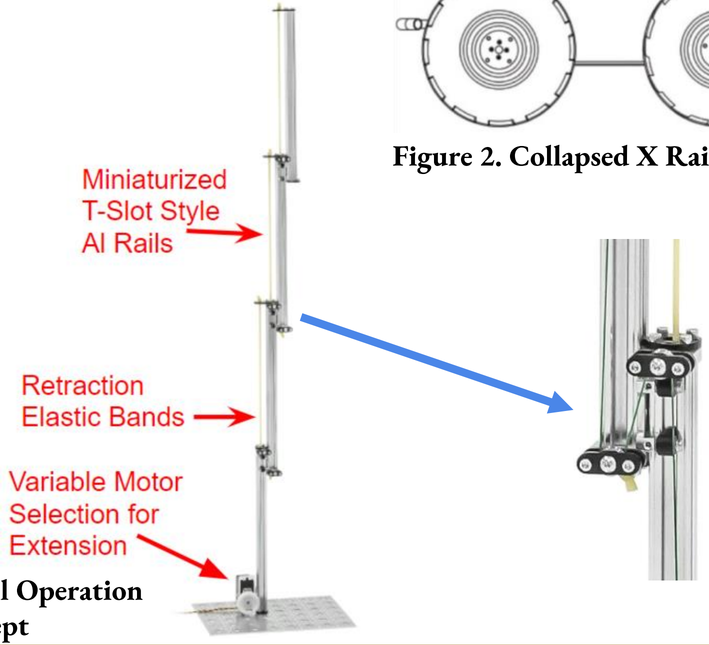
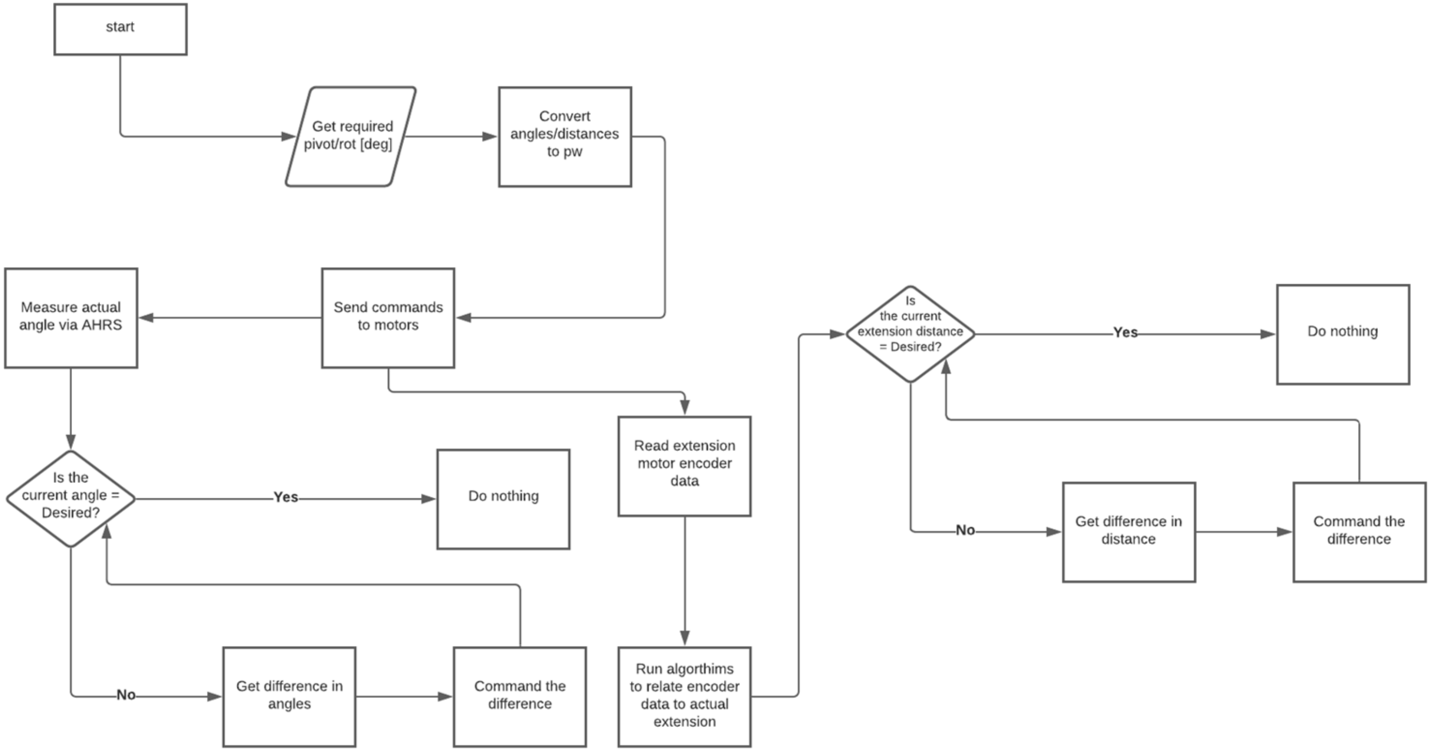


Figure 3. X Rail Operation Concept

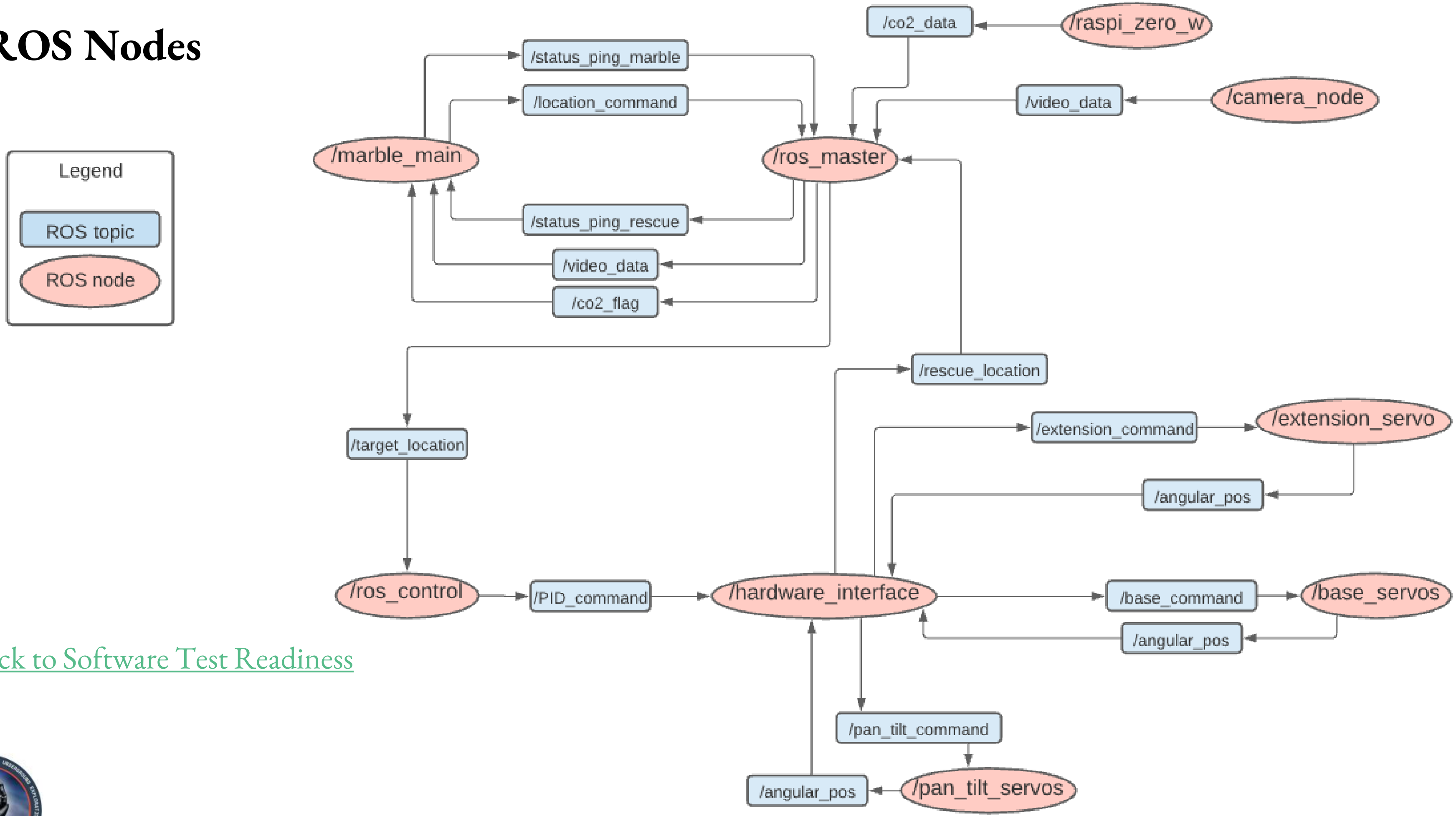
Day in the Life: Interpreting Commands, Controls



Day in the life: commanding RESCUE, user mistakes? (BACKUP)

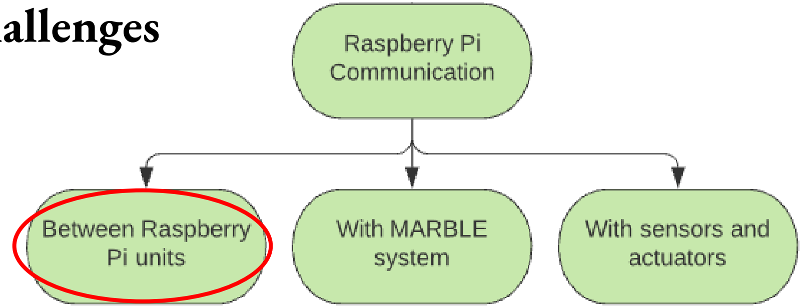
- Get commands from user:
    - If there is an **argument missing** throw an error message
    - For each argument, define specific data type and range, if there is a **mismatch or out-of-range value** throw an error message

ROS Nodes



Back to Software Test Readiness

Software Overview - Challenges



Wireless transmissions between Raspberry Pi units

- Limited resources on establishing communication without network connection
  - Operating under presumption that any MARBLE network is off-limits
- Switching to wired connection is not compatible with overall design

Back to Software Overview

Establishing communications with MARBLE's system and RESCUE's peripherals

- Ensuring RESCUE's software is compatible with and does not interfere with MARBLE
  - Procuring a means of testing with MARBLE's system or imitation of such
- Testing of communications and accuracy of instruments and actuators
  - Timing largely dependent on mechanical subsystem manufacturing completion

Detailed Software Status

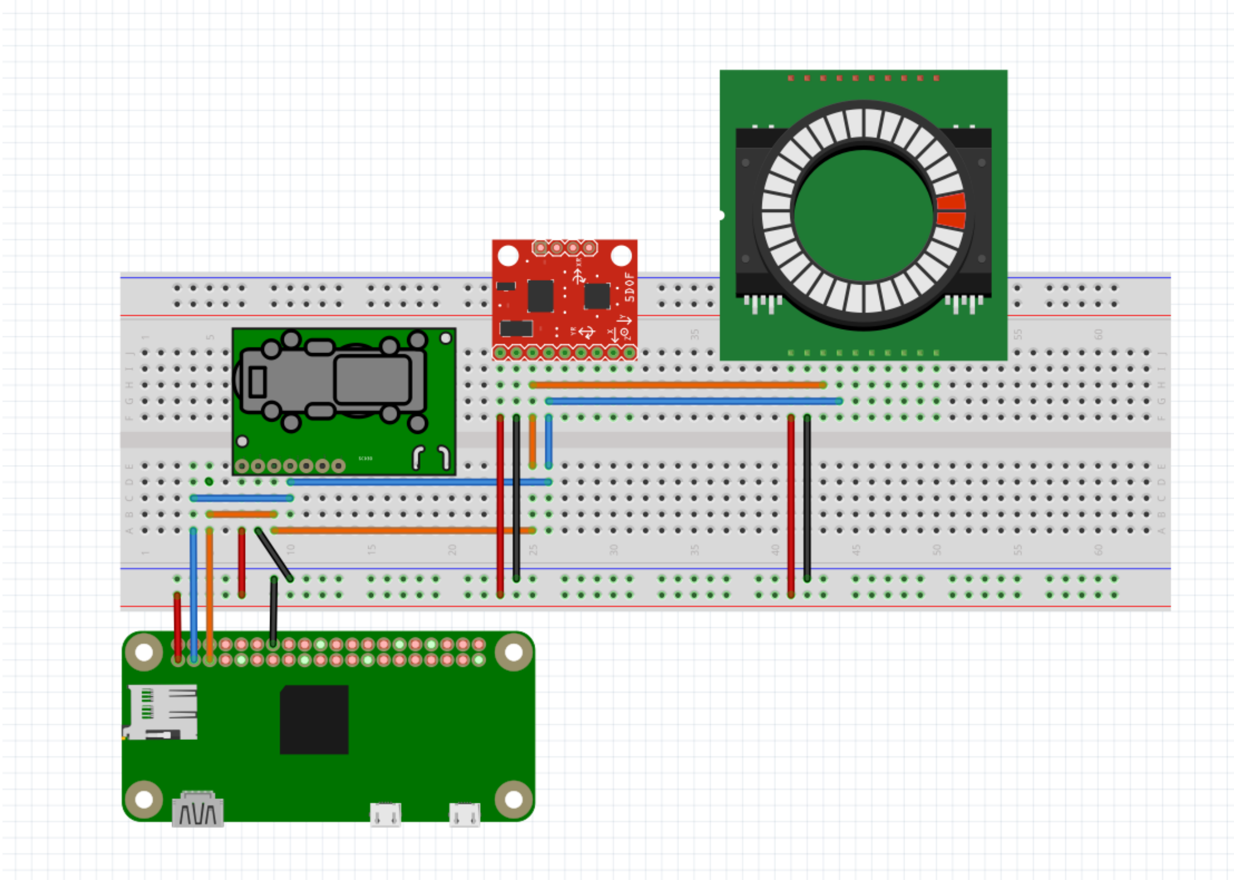
Software Component	Expected Challenges	# of Team Members Assigned	Resources Available	Projected Completion Date
Inter-RasPi Communication	ROS-based communication without wireless internet connection	4	Raspberry Pi tutorials, ROS documentation	2/8
ROS Package	Possibility of separate packages for RasPi and RasPi Zero	3	ROS wiki tutorials, ROS libraries	2/15
Sensor/actuator Interfacing	Remote involvement from software team	4	Instrument datasheets, ROS libraries, ROS wiki tutorials	2/22
RESCUE-MARBLE Communication	Availability of MARBLE team & hardware	2	ROS wiki tutorials, MARBLE team (via Dr. Frew)	3/22

Back to Software Status

Electronics Manufacturing: Sensors Connection to RasPi Zero

	CO2 Sensor	IMU	LED Board
Functionality (purpose):	The purpose of this sensor is to provide readings of the CO2 content of the local air.	The purpose of this sensor is to provide readings of the orientation relative to the base.	The purpose of this sensor is to provide a lighting source to improve video quality.
Manufacturing process	Purchase the sensor and assemble the I2C circuit.	Purchase the sensor and assemble the I2C circuit.	Purchase the sensor and assemble the I2C circuit.
Points of integration (connects to what?)	Connects to the Raspberry Pi Zero via I2C connection(SCL and SDA).	Connects to the Raspberry Pi Zero via I2C connection(SCL and SDA).	Connects to the Raspberry Pi Zero via I2C connection(SCL and SDA).
Used tools/machines	N/A	N/A	N/A
Expected challenges	Securing the wires for repeated deployment.	Securing the wires for repeated deployment.	Securing the wires for repeated deployment.
Manufacturing status	The CO2 sensor is purchased and received.	The IMU is purchased and received.	The LED board is purchased and received.

End Effector Electronics: Sensor Diagram

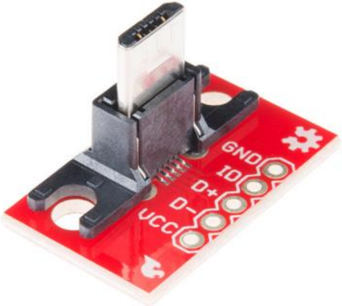


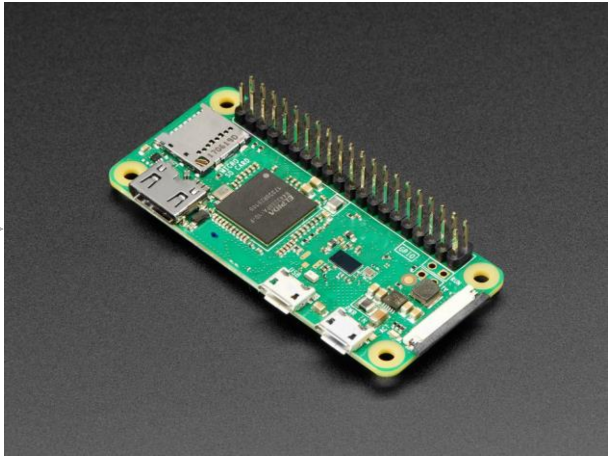
Electronics Manufacturing: Voltage Regulation Circuit to RasPi Zero

	Power Source and Ground Wires to the Voltage Regulator	Voltage Regulator to Micro-USB Converter
Functionality (purpose):	Down step the power from 12V to 5V for the Raspberry Pi Zero W.	Pipe the power into a micro-USB connector that is usable by the Raspberry Pi Zero W.
Manufacturing process	Purchase the voltage regulator.	Connect GND and VIN ports from the output of the voltage regulator.
Points of integration (connects to what?)	Integrates with the micro-USB converter.	Integrates with the PWR micro-USB port on the Raspberry Pi Zero W.
Used tools/machines	N/A	N/A
Expected challenges	Ensuring a connection from the power spool that is robust to the tension from the lines.	Ensuring a connection that is robust to repeated deployment.
Manufacturing status	The voltage regulator has been purchased and received.	The micro-USB converter has been purchased and received.

End Effector Electronics: From Base Power to RasPi

Base power passes through a voltage regulator to obtain the necessary 5.1V





Using a USB MicroB breakout the power will be transferred to the RasPi Zero W

Electronics Manufacturing: Video Transmission Link Budget

Link Budget [dBm]:

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

$$P_{TX} = 23.01029995$$

$$G_{TX} = 2.2$$

$$L_{TX} = 0.5$$

$$L_{FS} = 57.48795996$$

$$L_M = 10$$

$$G_{RX} = 2$$

$$L_{RX} = 0.5$$

$$P_{RX} = -41.27766$$

Signal to noise ratio [dB]:

$$SNR = \frac{P_{RX}}{kT_s Z}$$

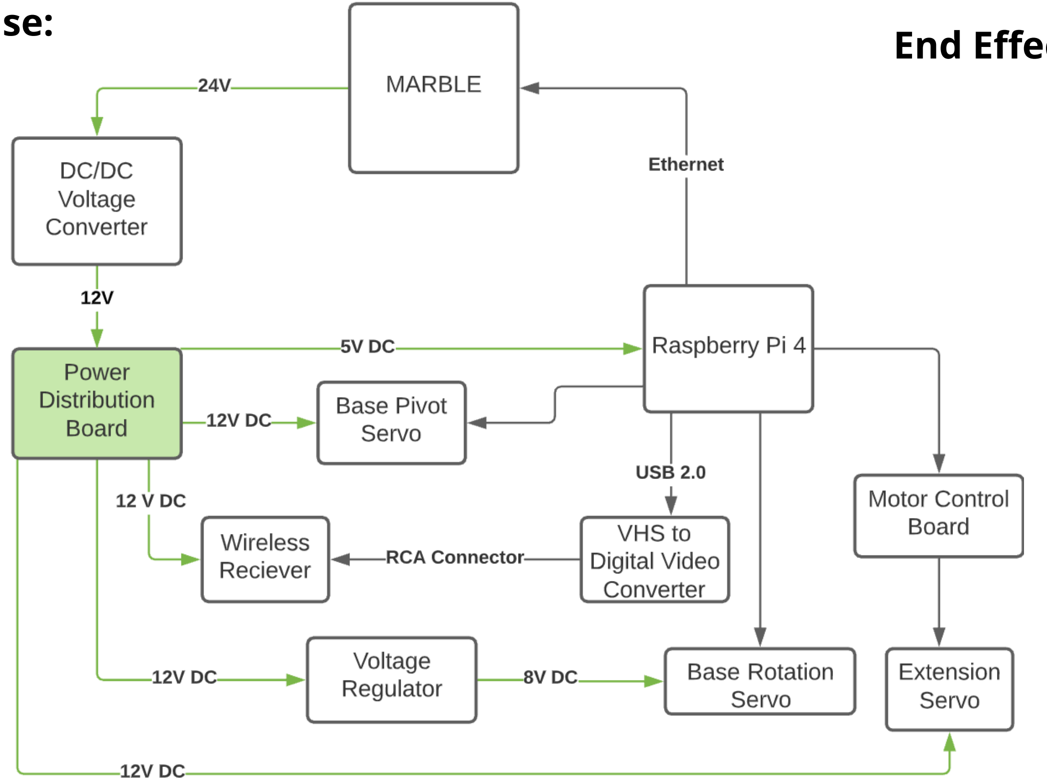
$$SNR = 39.2841$$

Electronics Manufacturing: USB, PWM, GPIO & Ethernet Connections to RasPi

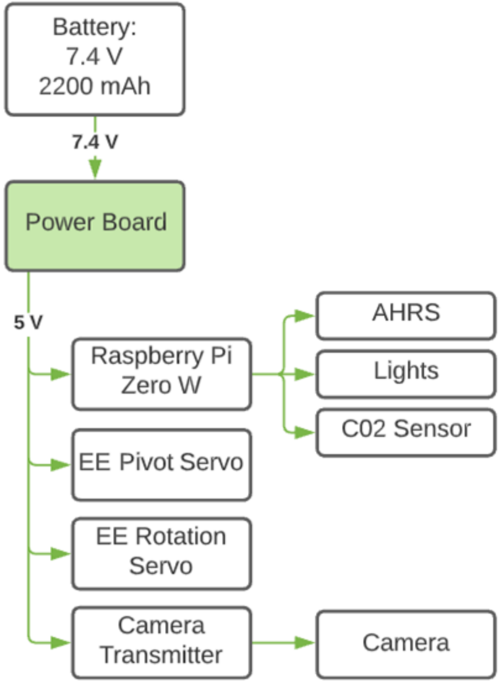
	USB Connection to Dynamixel Servos	Ethernet Connection to MARBLE	PWM Connections to Spooling Servos
Functionality (purpose):	The purpose of these servos is to rotate and pivot the base which will be controlled through the RasPi	To enable MARBLE to send and receive communications with RESCUE	These four servos that will spool both the arm material, tension cables and the power cable will be controlled through the RasPi
Manufacturing process	Purchase the servos	Purchase an ethernet cable	Purchasing the servos and RasPi servo control hat.
Points of integration (connects to what?)	There is a USB connection between each servo and	The RasPi will be connected to MARBLE through the gigabit ethernet cable	The servo control hat will directly connect to the RasPi and the servos will connect to the hat
Used tools/machines	N/A	N/A	N/A
Expected challenges	Securing the wires for repeated deployment	Securing the wires for repeated deployment	Securing the wires for repeated deployment
Manufacturing status	The CO_2 sensor is purchased and received	The ethernet cable has not been ordered yet	The material spool servos has been ordered but the other servos have not

Wiring Diagram

Base:



End Effector:



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
						8.626
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)	185.4801
					Margin (%)	0.5
					Input Power Needed (W)	278.22015

Levels of success: detailed

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.	

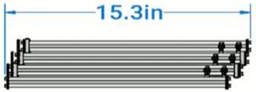
	Level 1	Level 2	Level 3
Response to commands	The total time to go from standby state to active state shall be $\leq 30[s]$.	The time of responding to firing commands should be instantaneous $\leq 1[s]$	The time between receiving deactivation commands returning to standby state shall be $\leq 120[s]$
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)

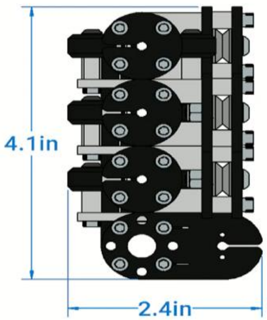
Extension Method Off Ramp 2: X Rail System

- Off the shelf option, all components commercially available
- Adding 2 x 12.45in. extension lengths would provide max ≈ 74in. **≈ 1.88m**
    - Required rails, extension line, cabling = 0.45kg
- 49.8in. k it supports ≈ 0.64 kg. In **horizontal** orientation.
    - Performance indication from ServoCity, **verification required.**
- **Base actuation, end effector, instrument design elements experience minimal change**
    - PDR/Redesign work is highly applicable

Retraction via elastic tubing (customizable)

Customizable extension winch motor





Xrail Tipping Analysis

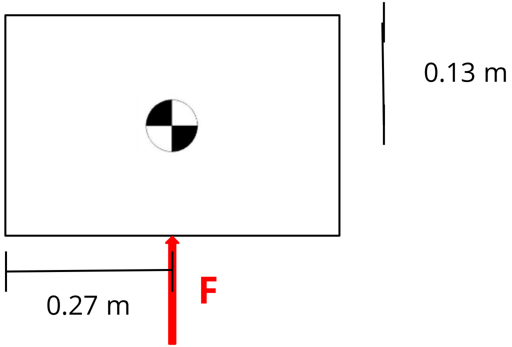
Counterclockwise Moment = Clockwise Moment

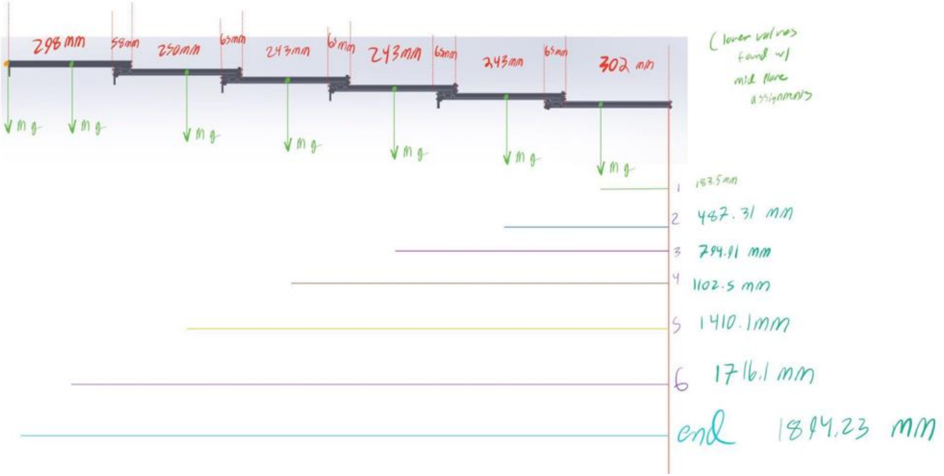
$$F*d_{ccw} = F*d_{cw}$$

$$M_{torque\ arm} = 17.57\ Nm$$

$$M_{min\ torque\ to\ tip} = 50kg * 9.81\ m/s^2 * 0.13m = 63.765Nm$$

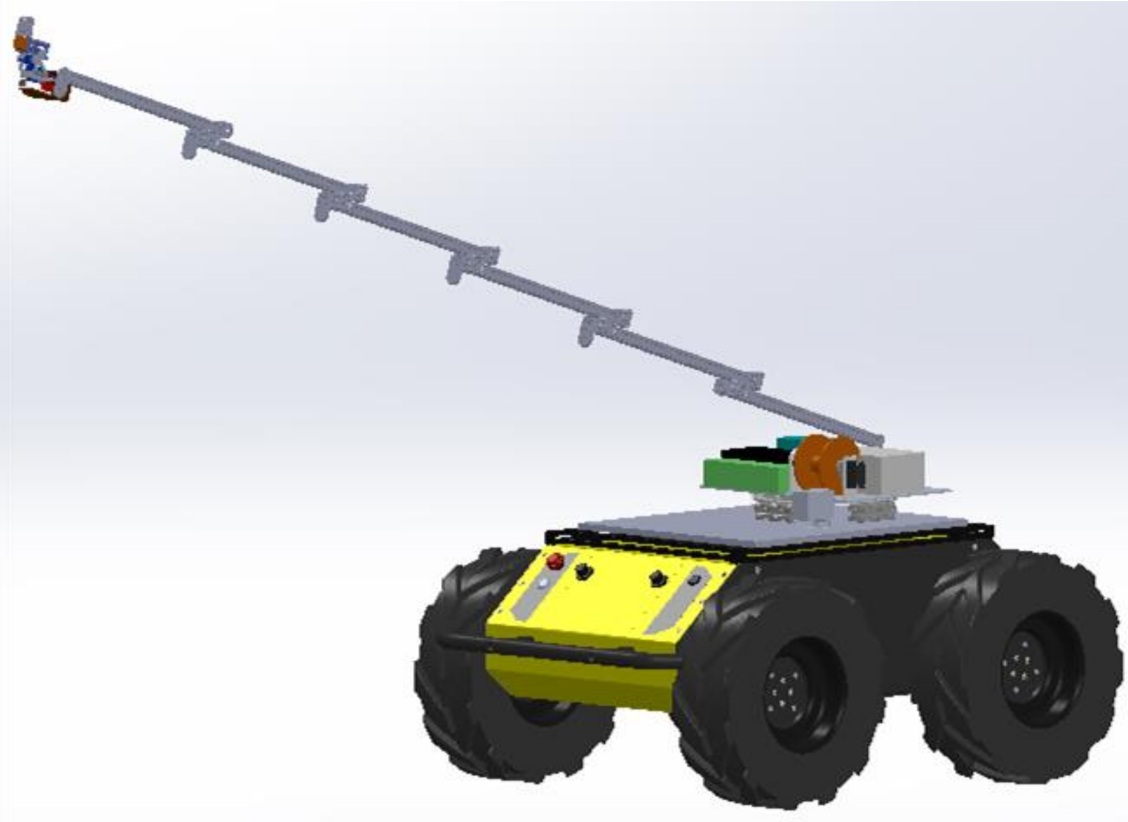
FOS = 3.63





Backup Slide: Base Pivot Motor Selection

- ≈ 160 kg cm max. required pivot torque
- Tested at 90 kg cm, 12 V
- Anticipated 2:1 gear ratio for torque
- 300° max range of motion
- 60°/1s at 12V
- 530g
- COTS mounting options available



RANGE EXTENDING SYSTEM TO COMPLEMENT UNDERGROUND EXPLORATION • UNIVERSITY OF COLORADO BOULDER •

Completed Tests: System Interference and Time Constraints