Test Readiness Review

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

Customer: Prof. Eric Frew

University Of Colorado Boulder

Project overview

Project Overview: Purpose and Specific Objective

Figure 1: Clearpath Husky

Main Objective

Improve subterranean unmanned ground vehicles' ability to sense locations that the vehicle cannot travel to or are obstructed from the onboard sensors' field of view.

Proposed Solution

A robotic arm, mounted to the top of the UGV, that extends an RGB camera, CO_2 Sensor, and AHRS up to 1.89 meters from its base.

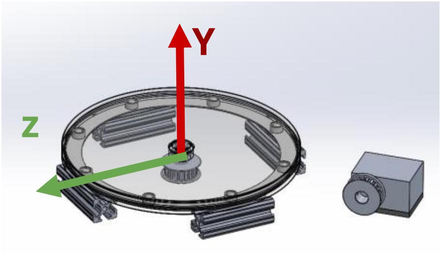
Specific Application

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

Acronyms

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

New Extension Method: Offramp



	MSR	TRR
Base	• 360° rotation about the y-axis • 90° rotation about the z-axis	• 360° rotation about the y-axis • 90° rotation about the z-axis
Extension method	• Inflatable robotic arm • Controlled by air pressure • Range ≈ 4m (3x the original range)	• Sliding robotic arm • Extended by a pulley system • Range ≈ 1.85m tentatively (within requirements)
End Effector	• RGB camera • CO_2 sensor • AHRS • Servos to control sensor orientation	• RGB camera • CO_2 sensor • AHRS • Servos to control sensor orientation

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).

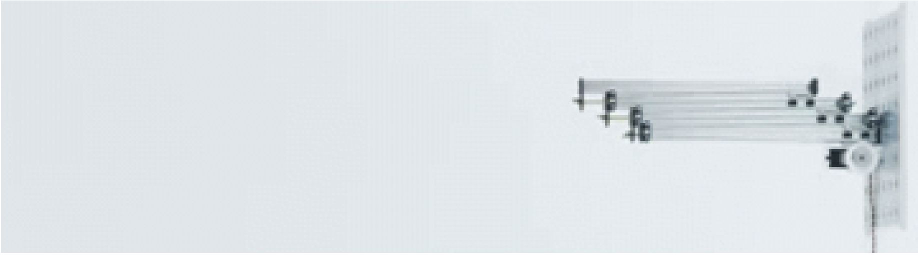


Figure 2: GIF of the X-rail kit being extended

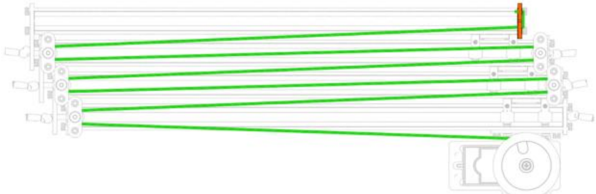


Figure 1: X-rail kit and tension system

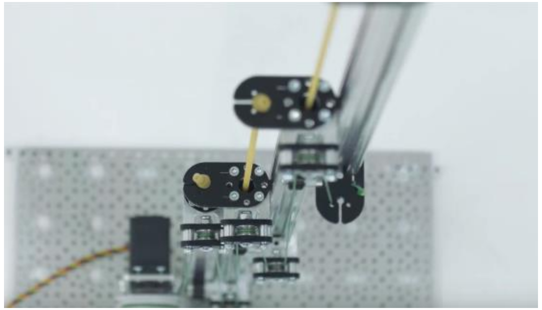


Figure 3: elastic restorative bands

Project Design

- **Basic components (figure 2):**
  - Extension System: X-Rail Slide Kit paired with 5202 series yellow jacket planetary gear motor
  - Pointing System: base capable of pointing the extension system
  - End Effector: housing sensors (camera, CO_2 sensor, and AHRS)
- **Key characteristics:**
  - **Total Mass:** 6 kg (MSR: 8 kg, requirement 10 kg)
  - **Total Power Consumption:** 411.5 W (MSR: 303.5 W, max allowable: 600 W)
  - **Extension distance:** 1.89 m (MSR: 4m, requirement 1-5m)
  - **Number of Deployments:** 14 >= (MSR: 14, requirement 5).
  - **Communication:** wireless communication between RESCUE's subsystem and wired connection to the mother rover: MARBLE.
  - **Mounting space:** 15" x 18" x 12"
- **Changes since MSR:**
  - Extension Mechanism has switched to an X-Rail Slide Kit.

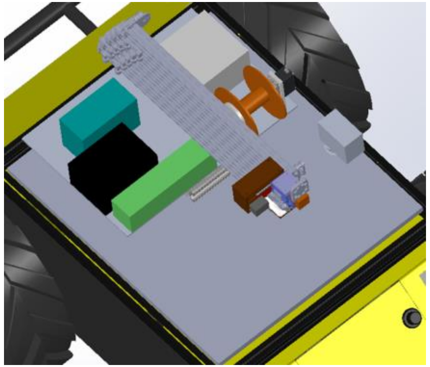


Figure 1. Complete System, Top View

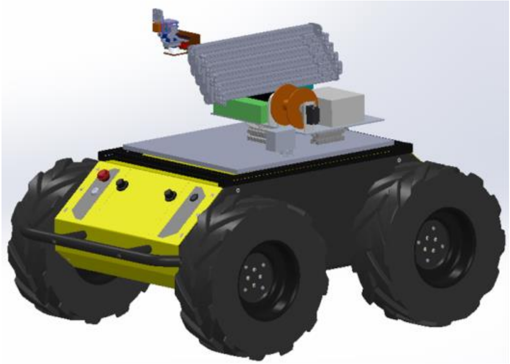


Figure 2. Complete System on UGV

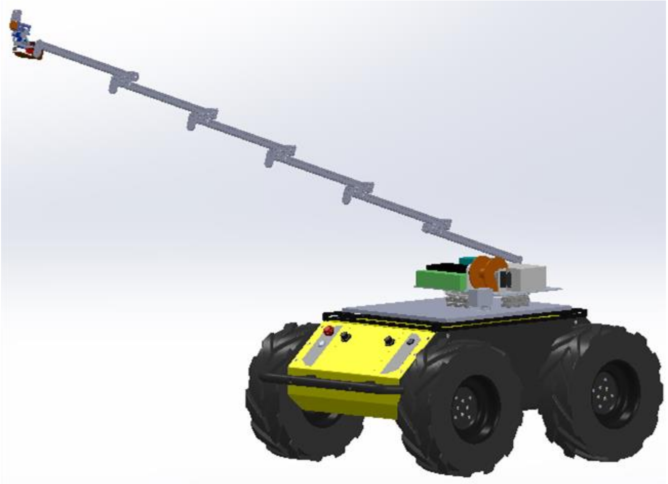
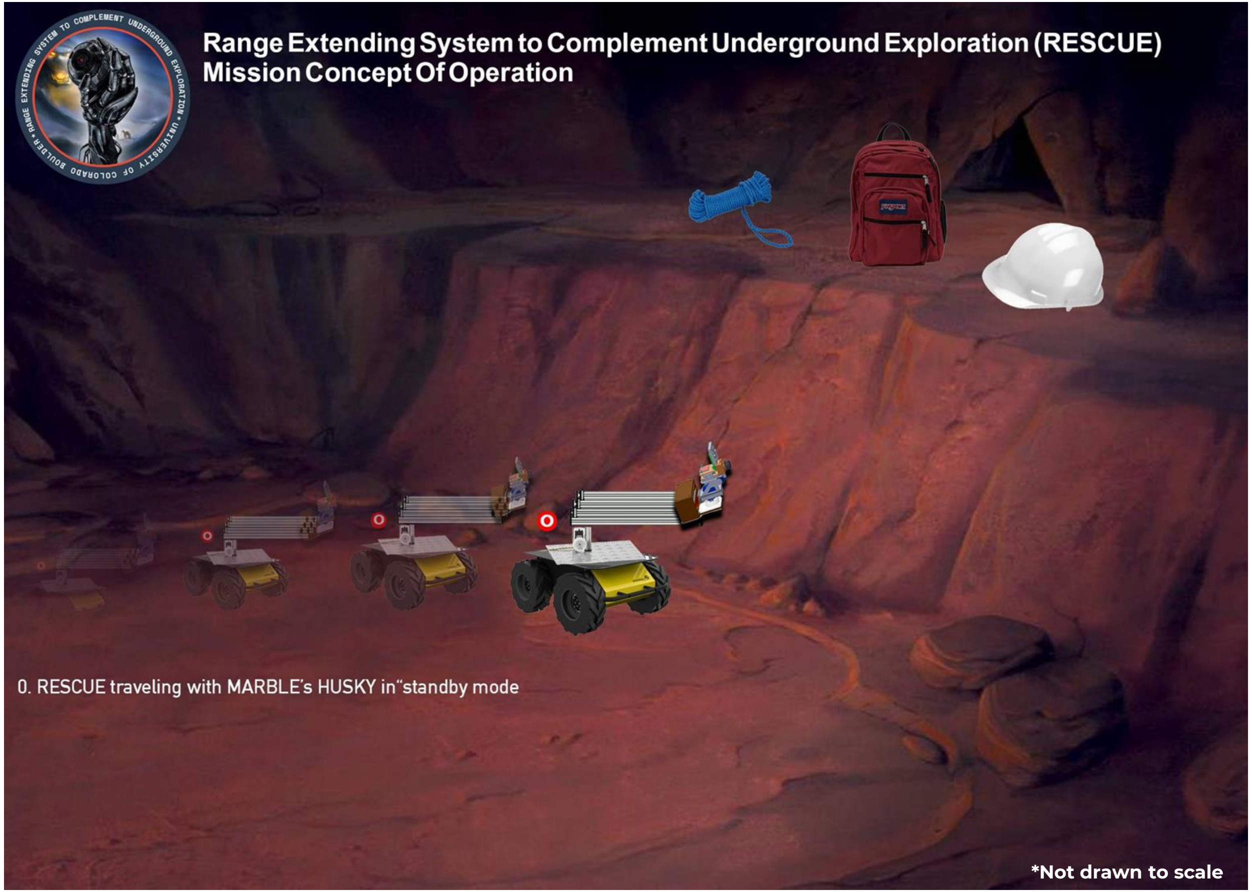
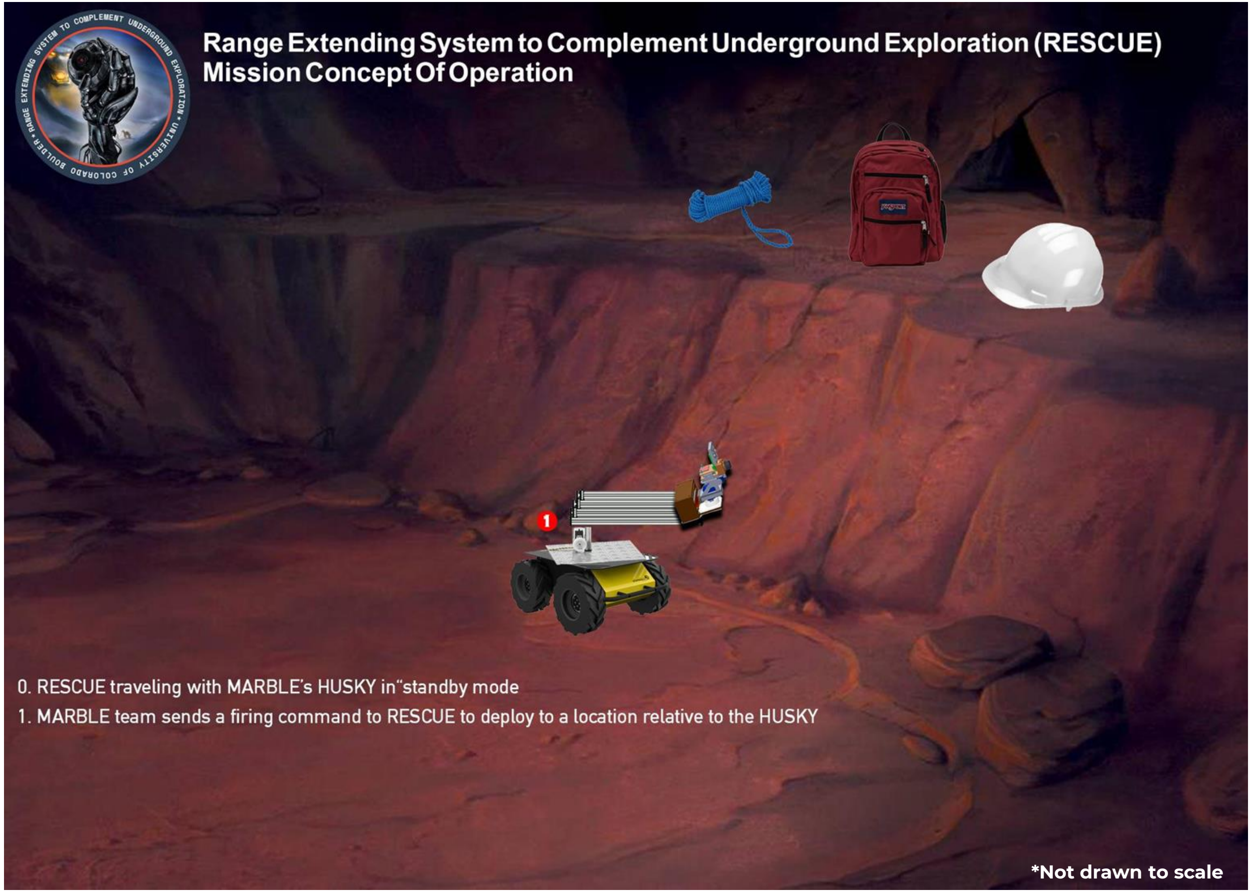


Figure 3. X Rail Arm Extended

CONOPS


Range Extending System to Complement Underground Exploration (RESCUE)
Mission Concept Of Operation
0. RESCUE traveling with MARBLE's HUSKY in"standby mode
*Not drawn to scale

CONOPS



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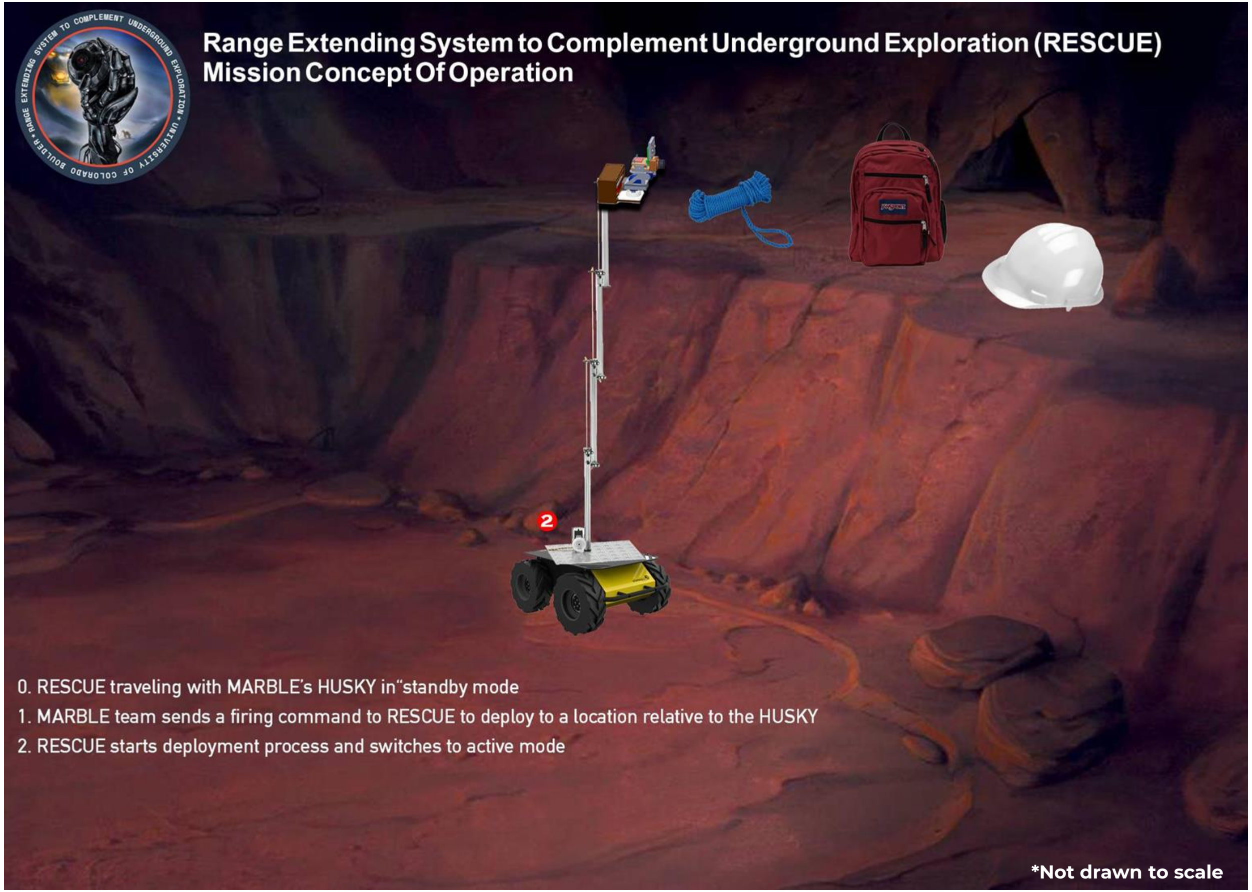

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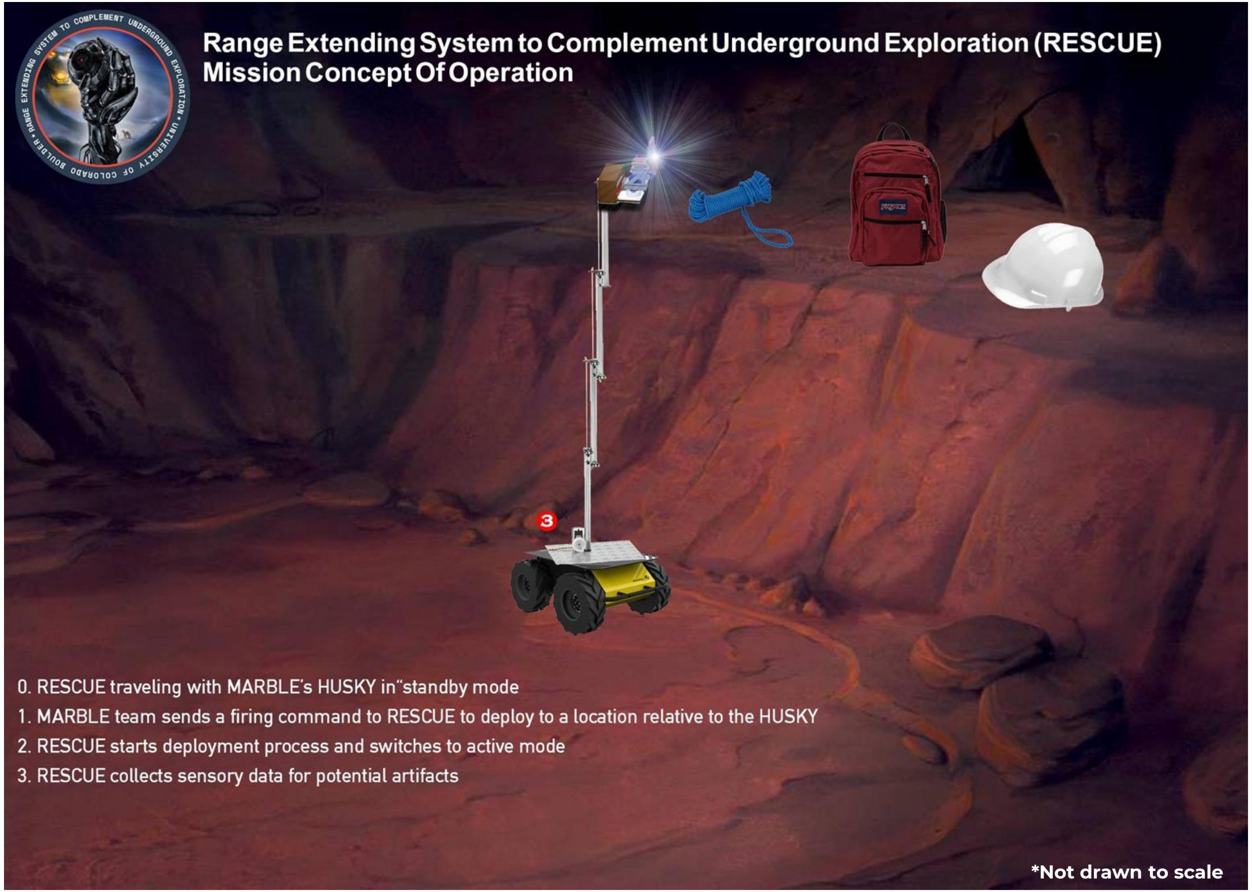
2. RESCUE starts deployment process and switches to active mode
*Not drawn to scale

CONOPS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3. RESCUE collects sensory data for potential artifacts
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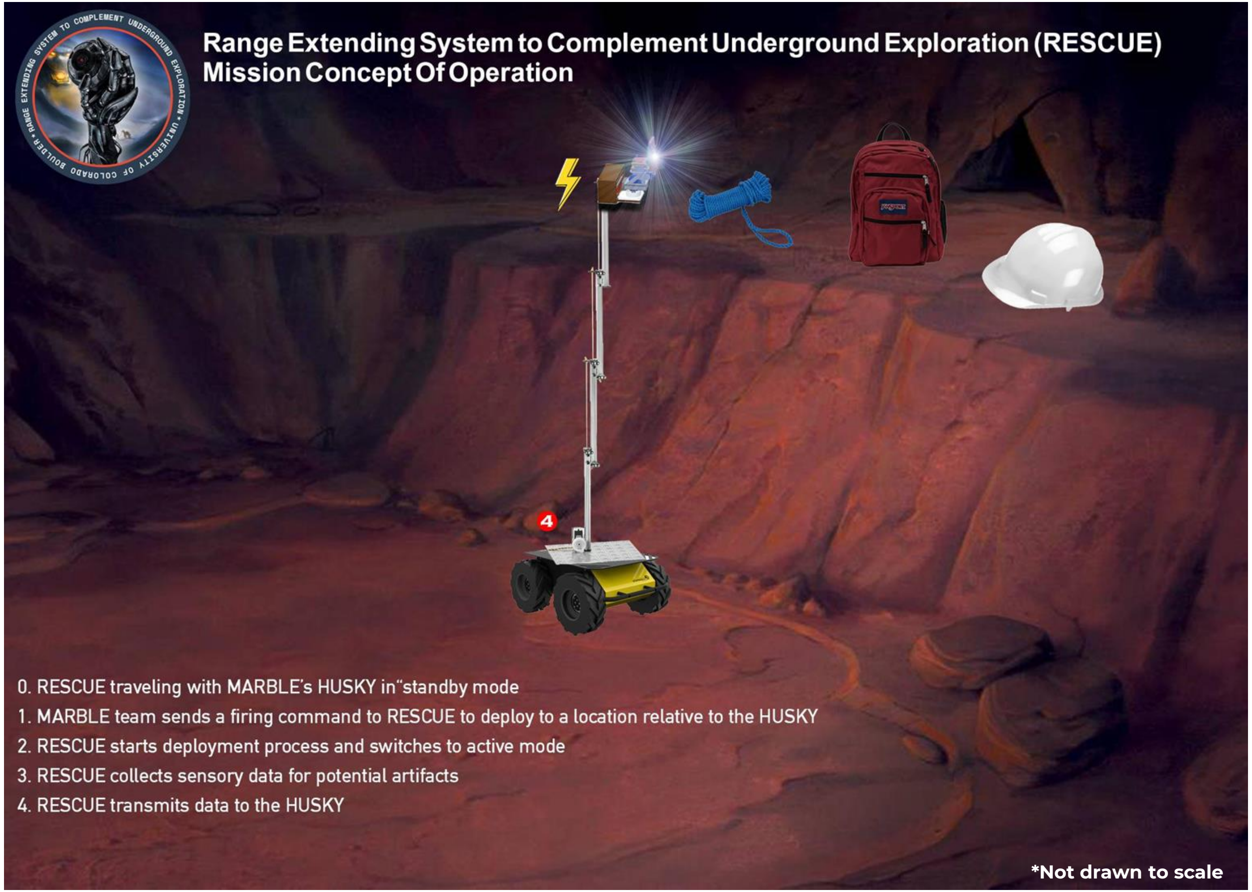
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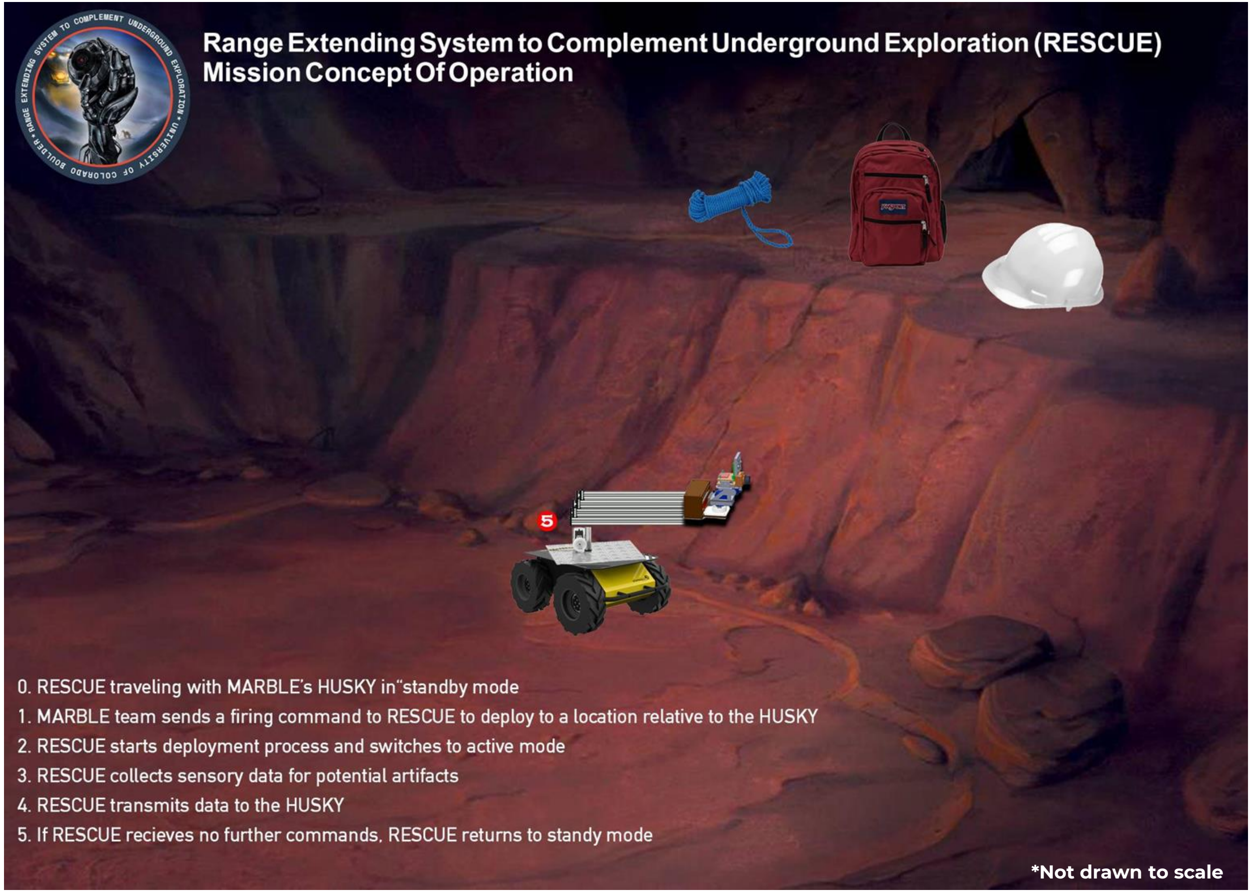
2. RESCUE starts deployment process and switches to active mode
3. RESCUE collects sensory data for potential artifacts
4. RESCUE transmits data to the HUSKY
*Not drawn to scale

CONOPS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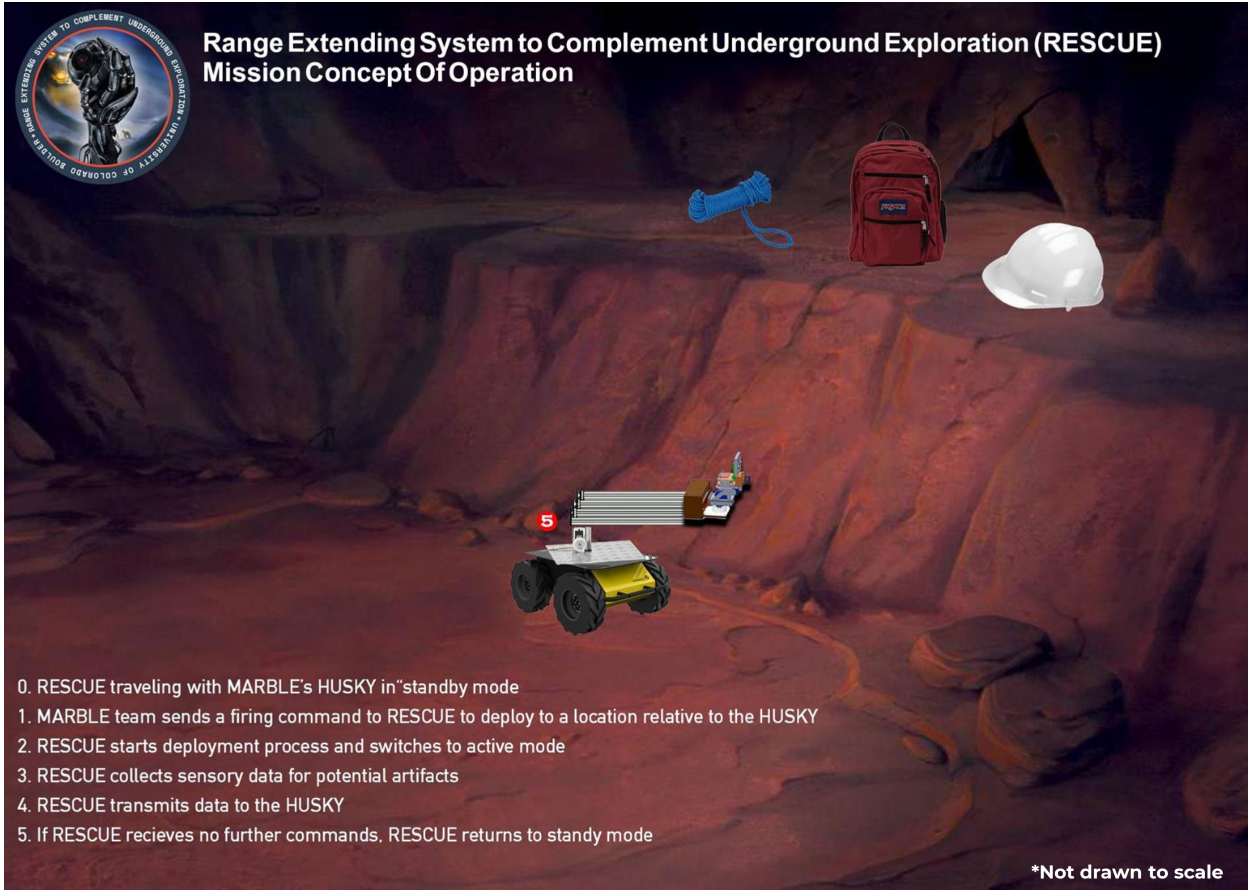
3. RESCUE collects sensory data for potential artifacts
4. RESCUE transmits data to the HUSKY
5. If RESCUE recieves no further commands, RESCUE returns to standy mode
*Not drawn to scale

CONOPS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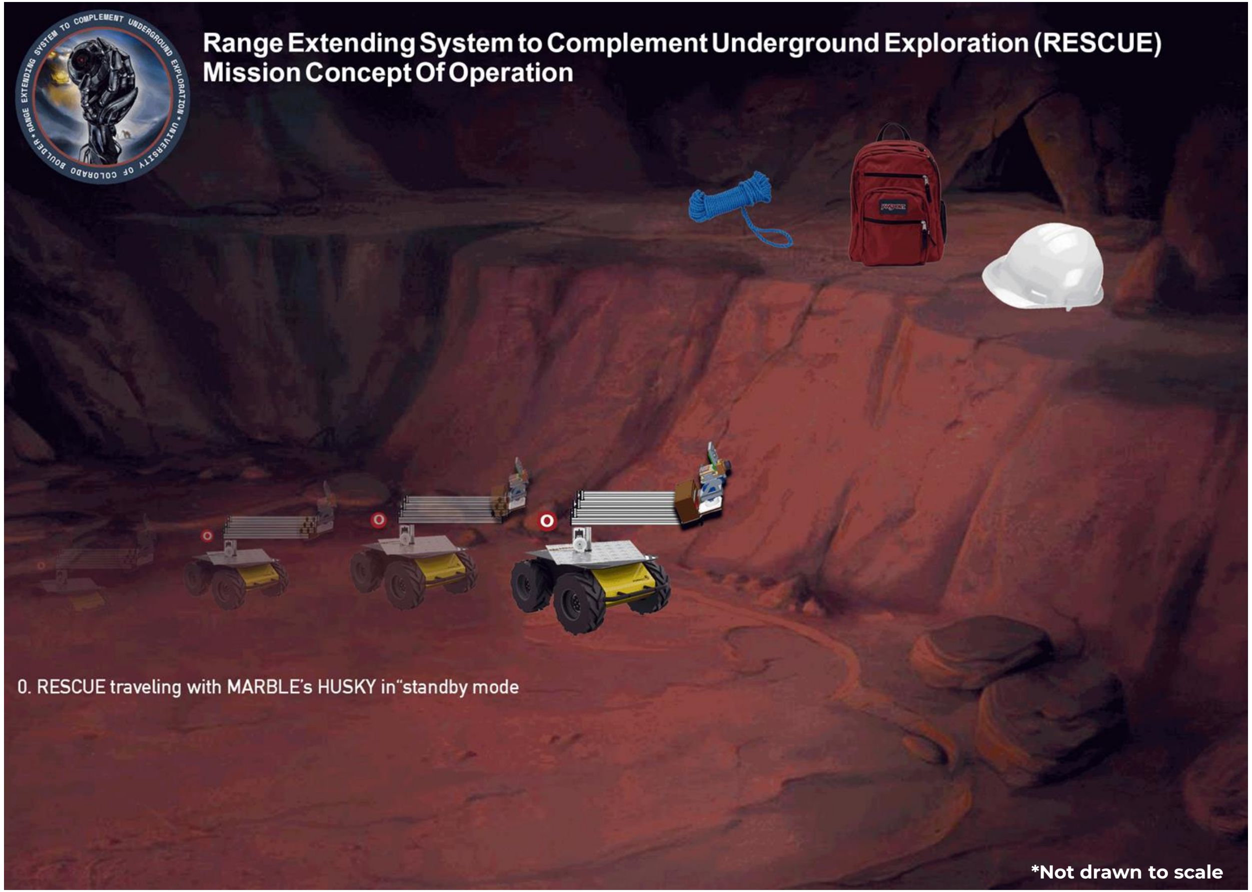

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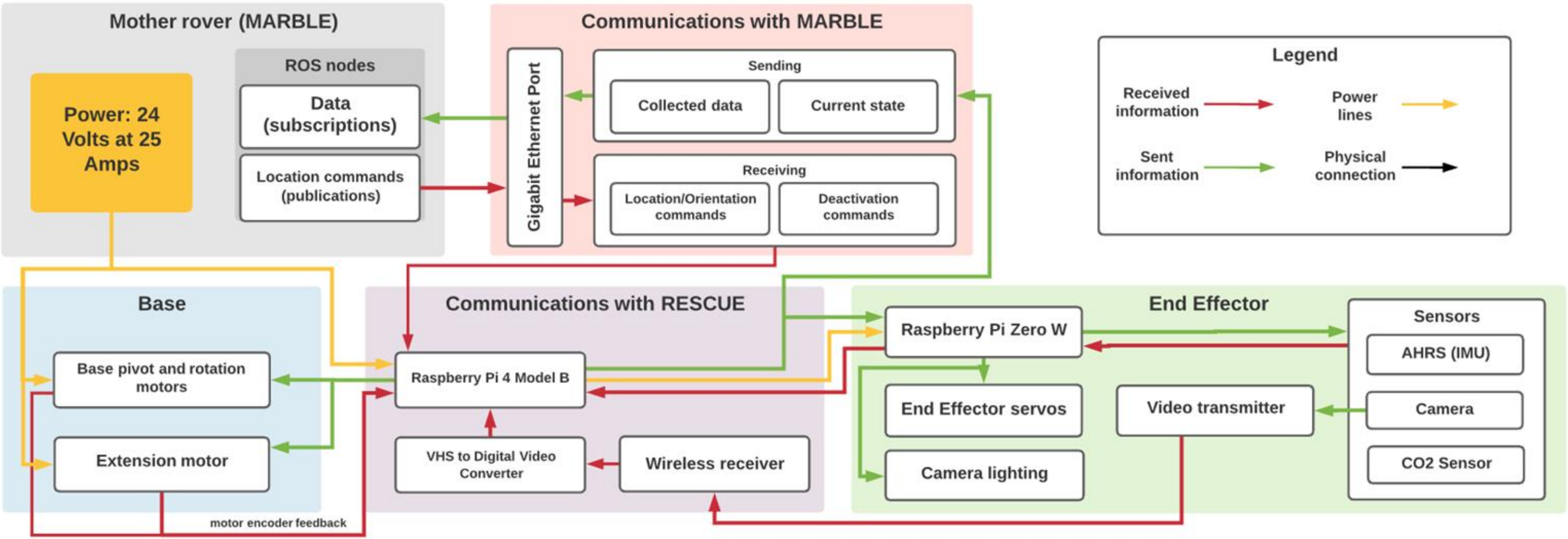
Project Overview: High Levels of Success & CPEs

Critical Project Elements

Physical reach	Data collection	Communication	Deployments
RESCUE shall be able to reach a position in an upper hemisphere within 1-5 m from 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).

The success of RESCUE

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
VHS to Digital Video Converter
Wireless receiver
End Effector
Raspberry Pi Zero W
End Effector servos
Camera lighting
Video transmitter
Sensors
AHRS (IMU)
Camera
CO2 Sensor

Old FBD

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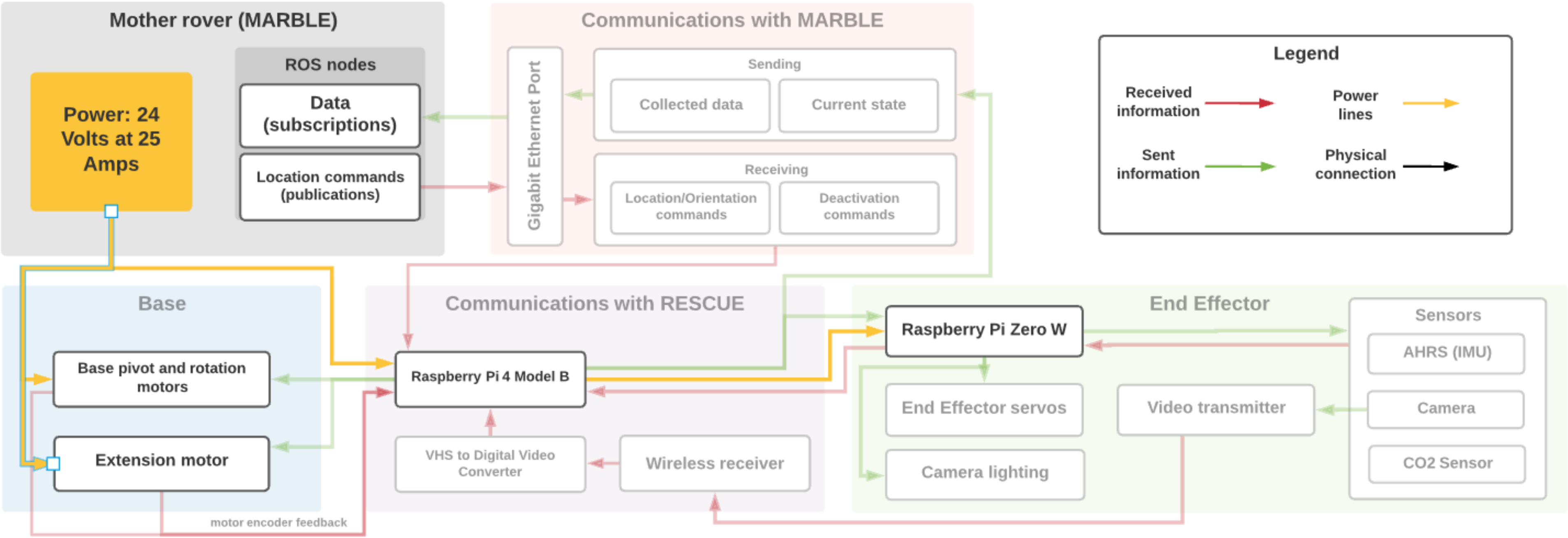
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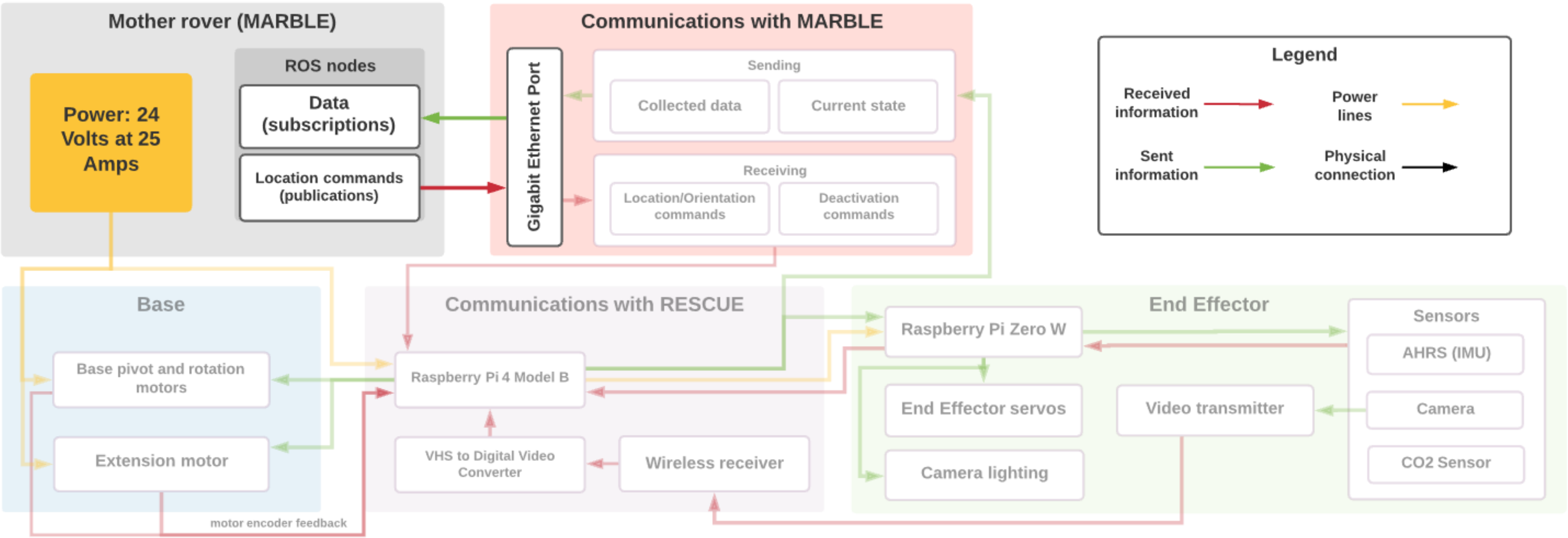

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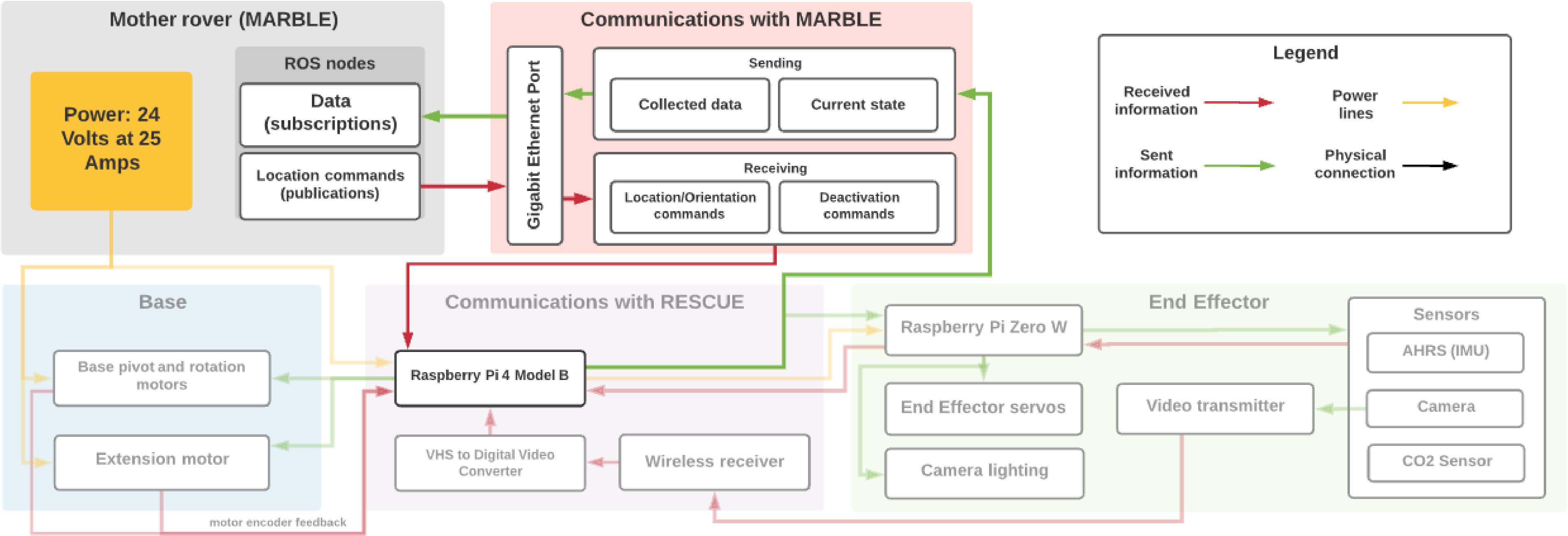
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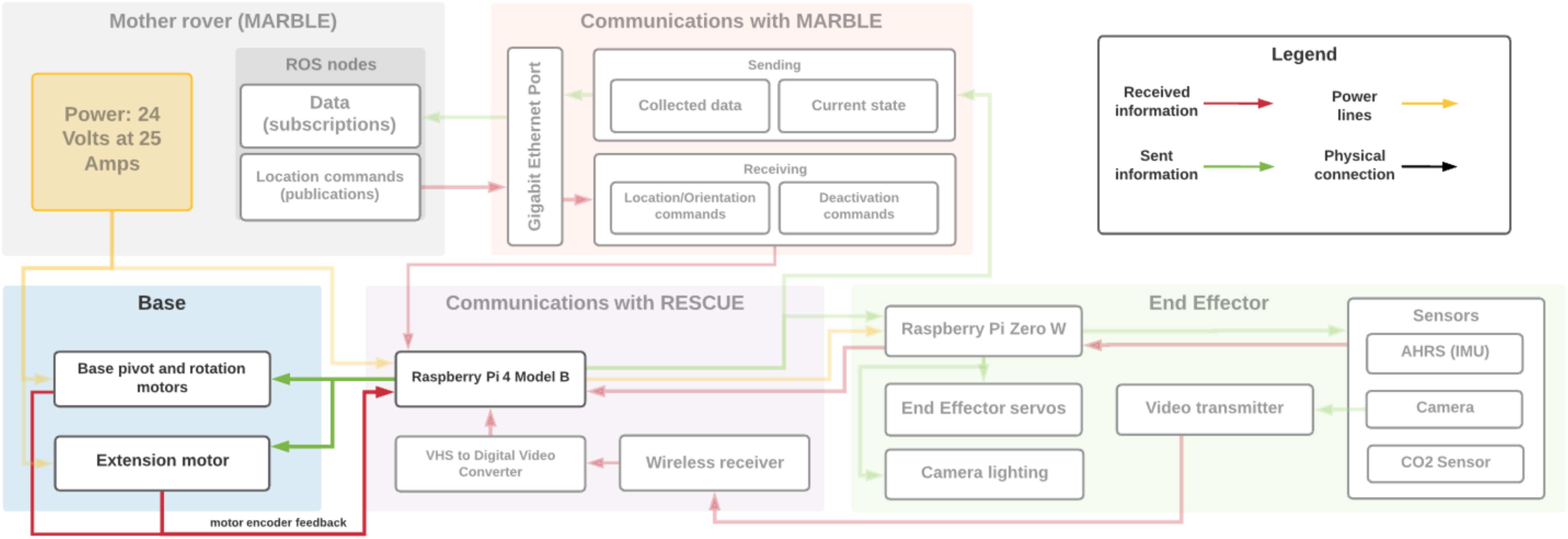
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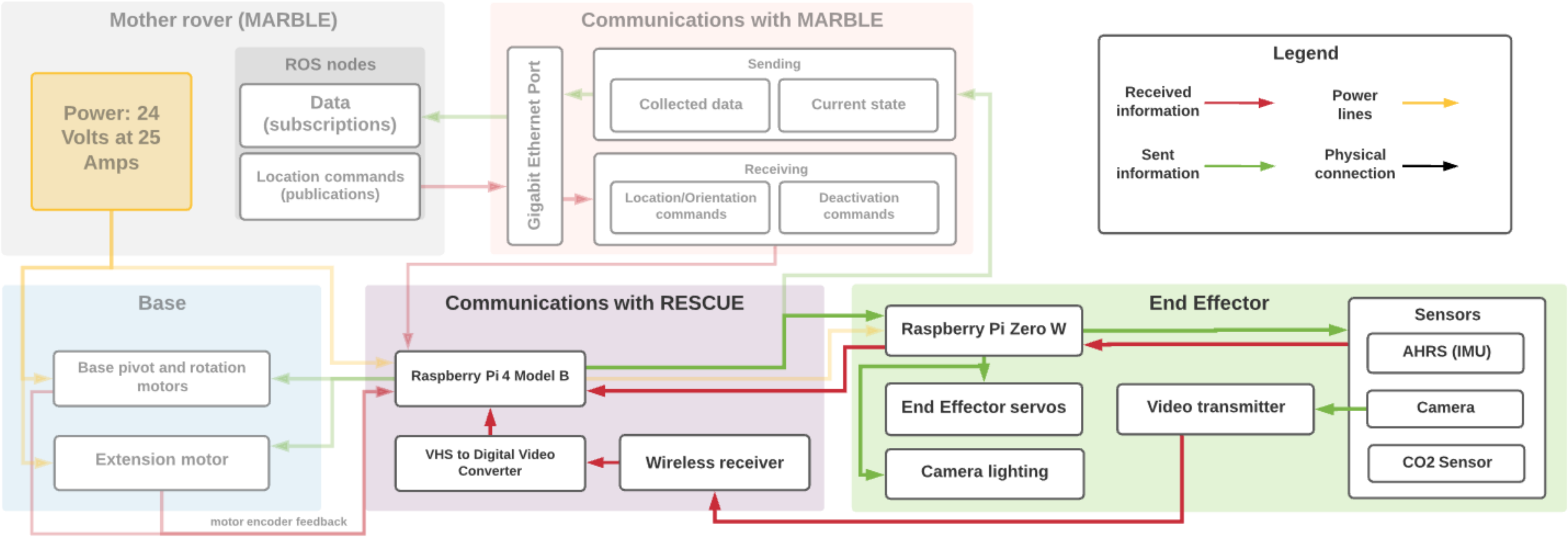

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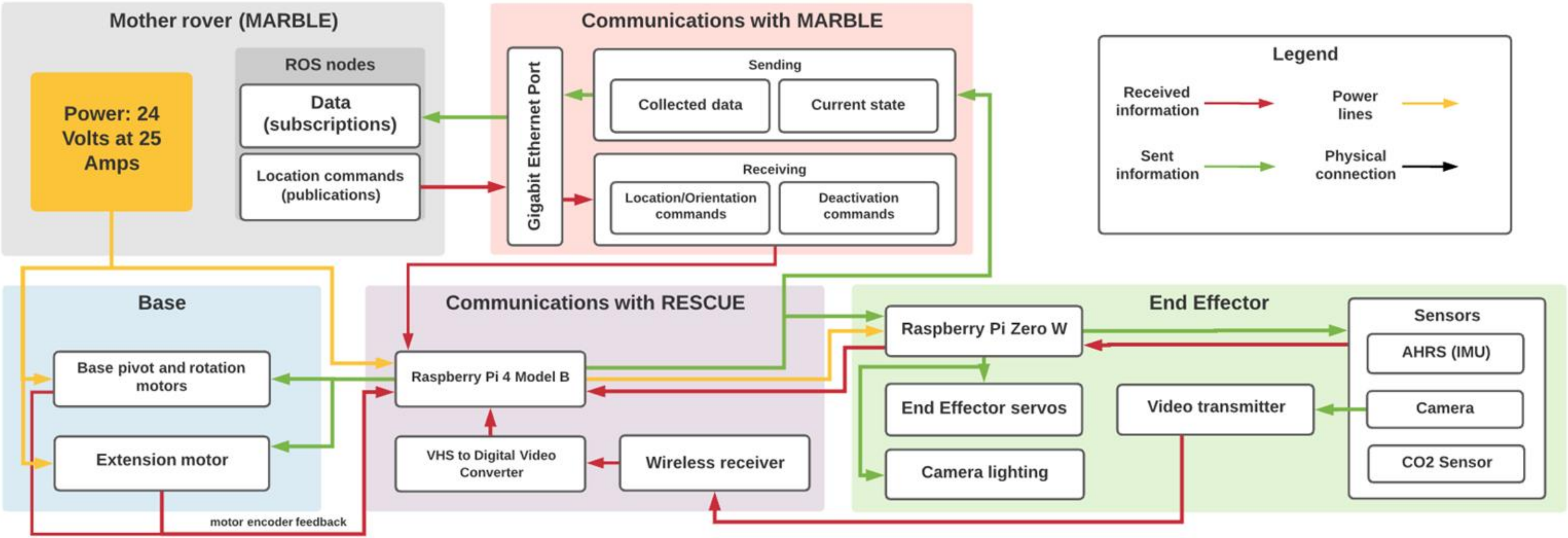

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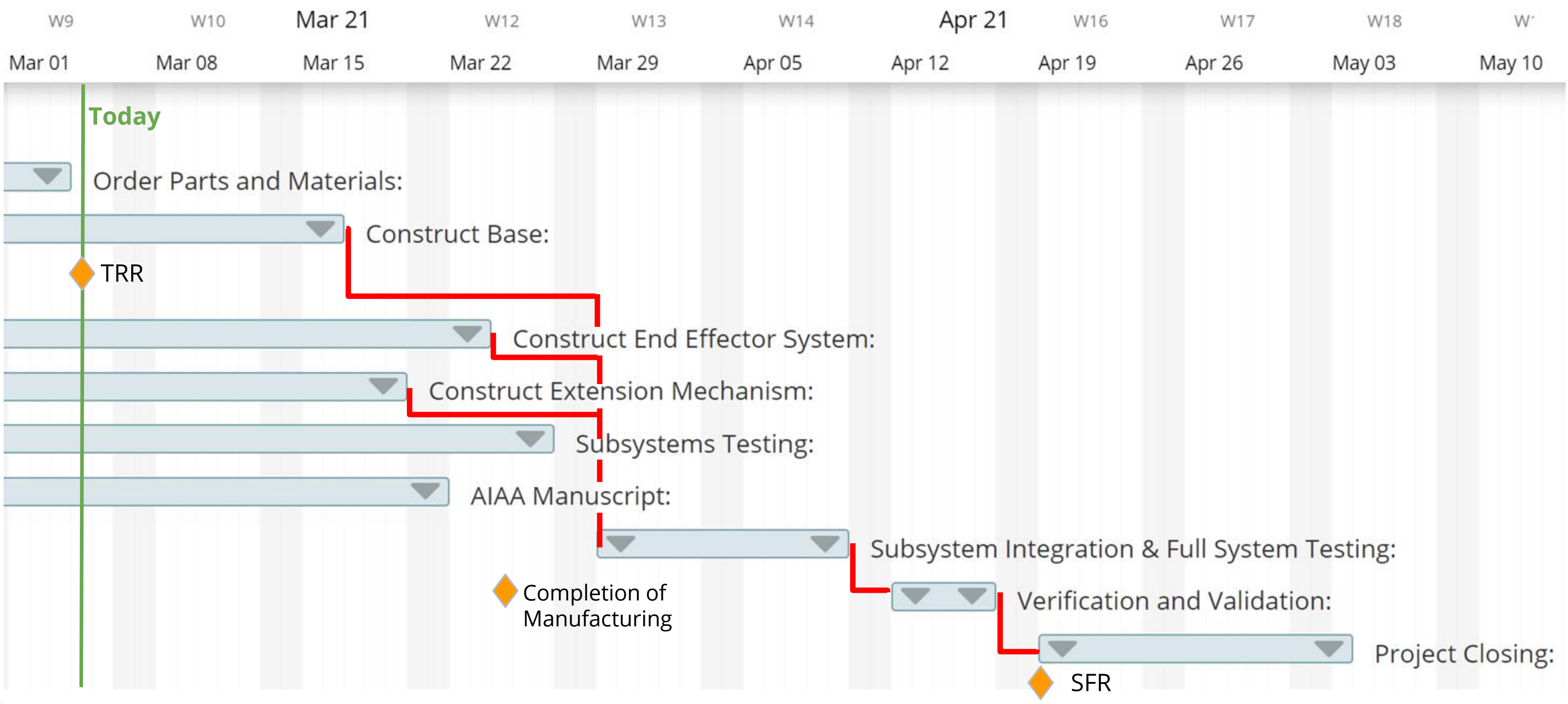
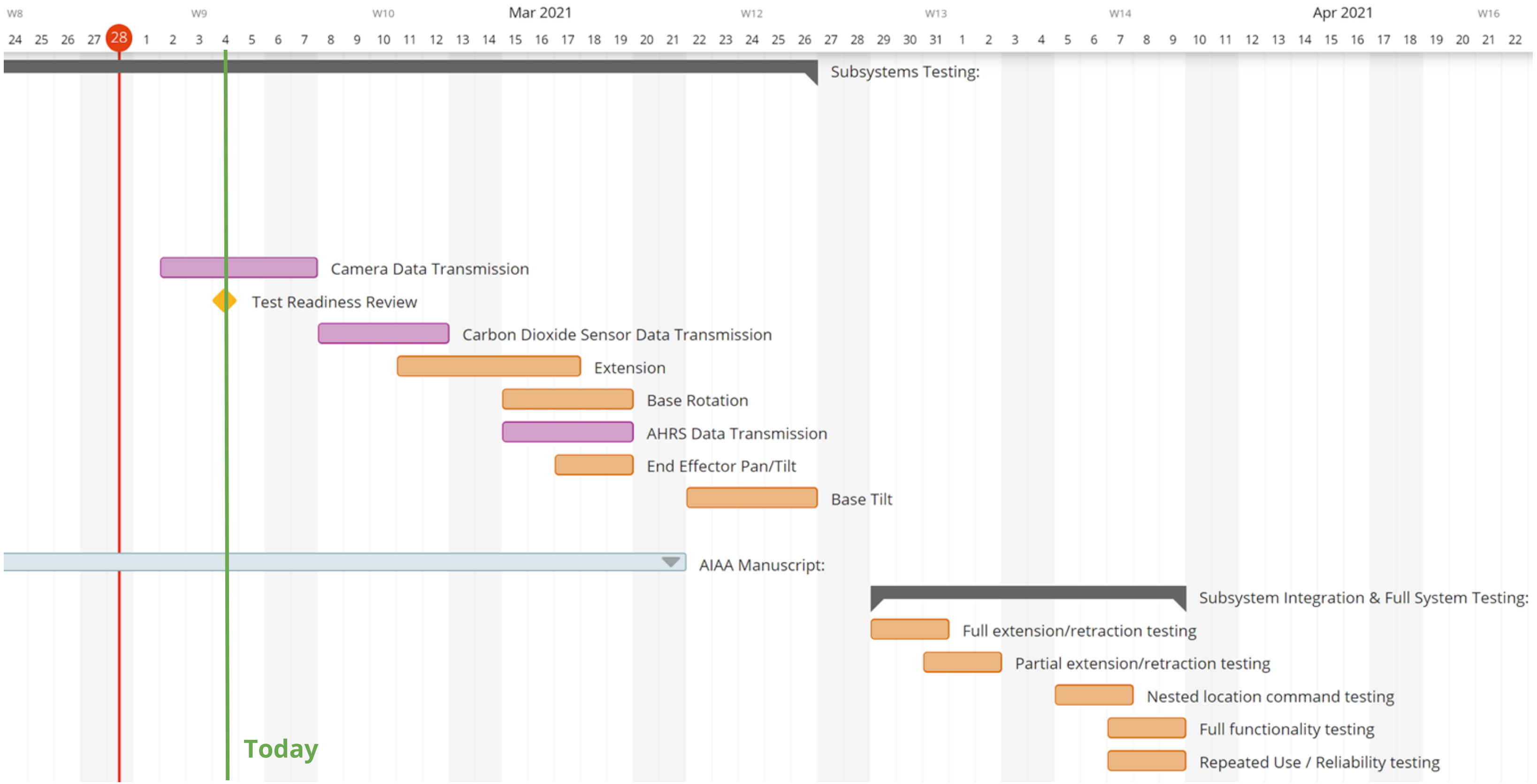
Project Schedule

Project Schedule: Overview



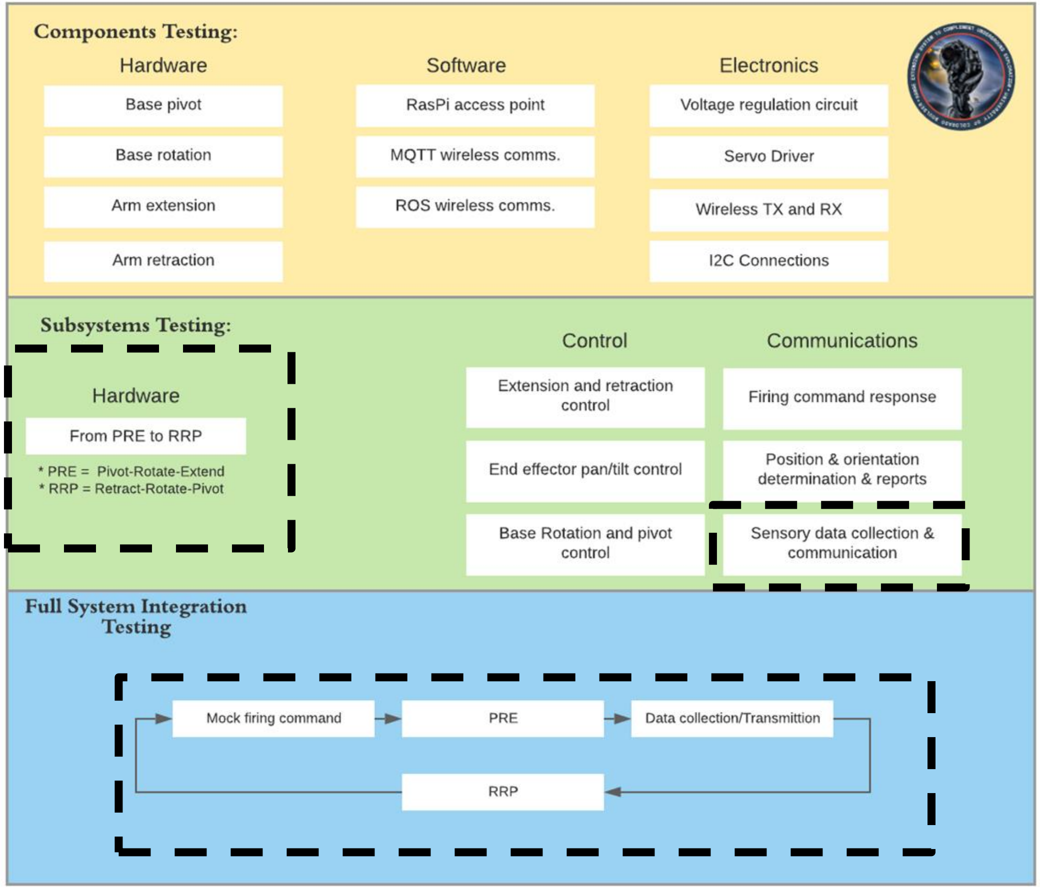
More Detail in Schedule Backup Slides

Project Schedule: Testing Schedule



Test Readiness - Overview

Testing overview:



In black box tests covered in the presentation

Test Readiness - Hardware

Hardware Test Readiness: PRE and RRP Test Overview

FR2.1 - RESCUE shall have the ability to physically reach any location along an unobstructed linear path that is at least 1 meter but no more than 5 meters in an upper hemisphere from RESCUE's stowing position on the MARBLE Clearpath Husky.

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

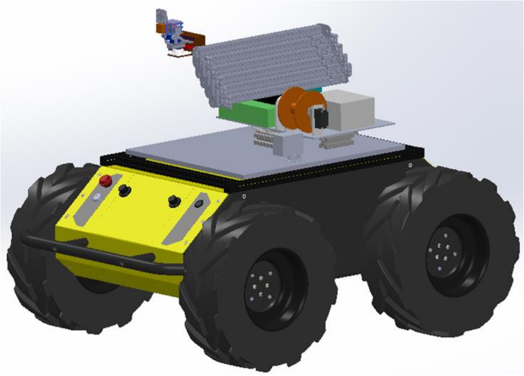
- **Test Purpose:** Demonstrate RESCUE's ability to Pivot, Rotate, and Extend (PRE) as well as Retract, Rotate, Pivot (RRP) in all directions and to various distances in timely manner.
- **Risk Mitigation**: Reduce risk of inaccurately pointing the system and/or missing target location. Verifies the system speed and mobility.
- **Test Status**: Planned to begin upon completion of base and extension mechanism assembly. (March 29th)
- **Expected Results (success criteria)**: Orientation of system achieved to within 5° (TDR 3.1.2) of commanded angles, 1m (TDR 3.1.1) of commanded extension, and within 30 seconds (TDR 4.3.1).
- **Model Validation**: Measured results within analytical model's' error tolerance in orientation and position to within 5% of differences. Compare encoders performance to measurements taken by protractor and tape measures.

Hardware Test Readiness: Rotate, Pivot, Extend Test

Facility: A plate to attach RESCUE to.

Equipment:

- Rescue Base and Extension Subsystems (hardware and electronics)
- Stopwatch
- Tape Measure
- Protractor



Procedure Overview:

1) Send mock location and orientation command to RESCUE
2) Pivot, Rotate, and Extend to the commanded location. Record total time.
3) Once rescue is stationary, measure the angles or pivoting and rotation via protractor and extension range via tape measure.
4) Retract, pivot, rotate back to stowing configuration, record time.
5) Repeat for different orientations and distances

Test Readiness - Electronics

Electronics Test Readiness: Communication Overview

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.
- **Test Status**: Incomplete but on schedule - needs to be performed by March 12th.
- **Model Validation**: Test will validate the link budget model.
- **Expected Results(success criteria)**: Expected data transfer rate of about 10.37 Mbps.

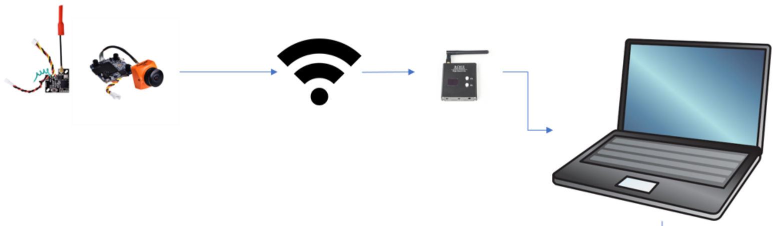
Electronics Test Readiness: Communication

Facility:

- **Electronics Shop**

Equipment:

- Laptop
- FPV Wireless Transmitter
- FPV Wireless Receiver
- FPV Camera



$$Z = \frac{Data\ Transmitted\ in\ bits}{Time\ to\ Transmit\ in\ seconds}$$

Procedure Overview:

1) Ensure the wireless transmitter and receiver are on the same band and channel.
2) Connect the receiver to the laptop through the NTSC to digital capture card.
3) Connect the camera to the transmitter.
4) Turn on the camera and begin the video data transfer to the receiver.
5) Measure the data rate using the total amount of data transferred and the time taken to transfer it.

Test Readiness - Software

Software Test Readiness: Full Commands & Data Transmission Test

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

FR6.1 - RESCUE shall receive commands from & communicate sensed data with MARBLE and these processes shall not interfere with MARBLE's communication systems.

- **Test Purpose:** Ensure successful integration of software components
- **Risk Mitigation**: Build confidence in command-handling and data transmission functionalities of the system
- **Test Status**: Scheduled to begin upon completion of manipulation testing (PRE, RRP) (March 31^{st})
- **Expected Results (Success Criteria)**:
    - Activate operational state within 30 seconds of command transmission (TDR's 4.3.2, 4.3.3)
    - Correct interpretation of location command (TDR 6.1.1)
    - Data transmission within 60s of retraction (TDR 6.1.2)
    - Accurate RESCUE status reports (TDR 6.1.4)
- **Model Validation**: Test will validate the expected behavior outlined in system architecture definition.

ROS Node Map

Component Tests

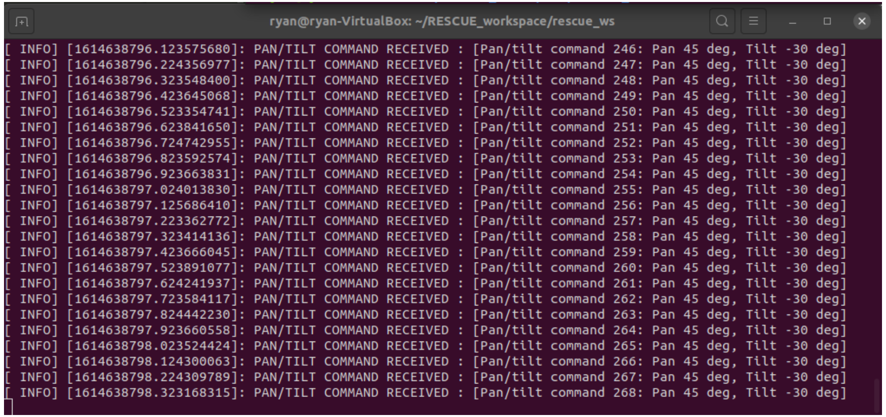
Software Test Readiness: Full Commands & Data Transmission Test

Facility:

- Personal computer

Equipment:

- Two Raspberry Pi's
- Personal computer



Relayed output of "dummy" pan/tilt commands sent to *pan_tilt_servos* node for component-level node testing

Procedure Overview:

1) Send location command to extend X-rail mechanism
2) Collect sensory data & transmit from end effector Pi to base Pi
3) Send status report from end effector Pi, to base Pi
4) Transmit sensory data and status report from base Pi to MARBLE imitator via Ethernet

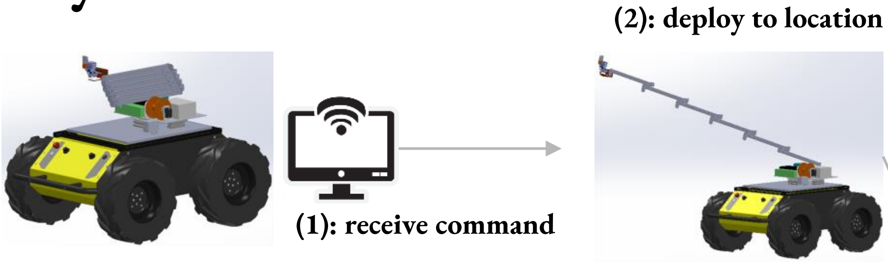
Test Readiness - Subsystems Integration

Full System Test Readiness: Day In The Life Test Overview

All FRs and TDRs.

- **Test Purpose:** Test RESCUE's functionality comprehensively and ensure subsystems compatibility.
- **Risk Mitigation**: Ensure that RESCUE is going to function as desired and reduce risk of integration with MARBLE.
- **Test Status**: Planned to begin upon finishing subsystems testing and integrating all subsystems together. (April 7th)
- **Expected Results**: Reaching the desired position in timely manner, collecting and transmitting all data, and retracting back. Success determined by meeting all TDRs and FRs.
- **Model Validation**: Validating all measure of performance and measures of effectiveness against all TDRs and FRs.

Full System Test Readiness: Day In The Life Test



Facility:

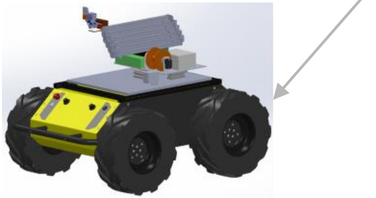
- **No special facilities needed.**

Equipment:

- Fully assembled RESCUE system
- Personal computer
- A static plate to attach RESCUE to to mimic being attached to the HUSKY.

Procedure Overview:

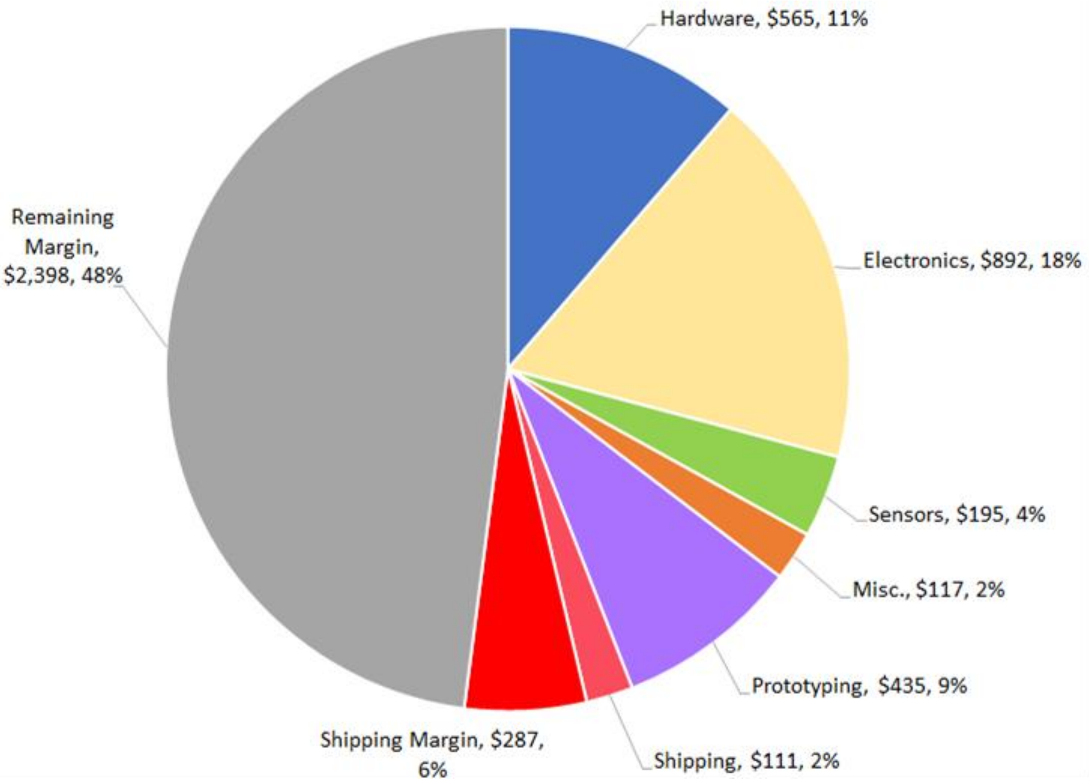
1) Send a mock firing command that contains a location and an orientation
2) Pivot, Rotate, Extend (PRE)
3) Collect data
4) Transmit data
5) Retract, Rotate, Pivot (RRP).



***Note: for all of these step, all relevant measure of performance will be recorded to compare to requirements,**

Budget/Procurement

Budget Status



Category	Planned	Margin, Margin %
Hardware	$565	$719, 30%
Electronics	$892	$719, 30%
Sensors	$195	$192, 8%
Misc.	$117	$288, 12%
Prototyping	$435	$480, 20%
Shipping	$111	N/A
Shipping Margin	$287	Factored into planned
Totals (Planned)	**$2,602**	**$2,398**
Total (Spent)	**$1,278**	

Procurement Status

	Sensors	Testing Equipment/ Components	Raw Materials/Misc.
Received	- All: IMU, CO_2, camera	- Inflatable Arm prototyping components/equipment (all)	- 1.75mm/3mm PLA - 1.75mm PTEG - Gantt software
Pending			
Planned		- High pressure LDPE Return	- Gantt software subscriptions
Critical/Concerns	- Sensor damage during testing		

Procurement Status, Cont.

	Hardware	Electronics
Received	- End effector pan/tilt kit - Base turntable/mounting parts - 4 Section X Rail slide kit	- End effector sensor supporting components (All) - FPV transmitter/receiver - End effector servo drivers
Pending		- End effector connector cables - Base wiring boards - 24V to 12V Transformer
Planned	- End effector fasteners - Base rotation attachment (all) - 2 X Rail mid sections - Pivot mounting/gears (all) - Extension motor mounting (all) - Power spooling (all)	- Base pivot/rotation servos/motors, controllers - Power wire spooling wire, slip ring - Extension motor, controller
Critical/Concerns	- Pivot gearing system - End effector redesign	- Base rotation/pivot motor availability - Extension winch motor selection - End effector assembly with mech components - Power spooling

Questions?

Backup Slides

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, Raspberry Pi Zero and camera 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:

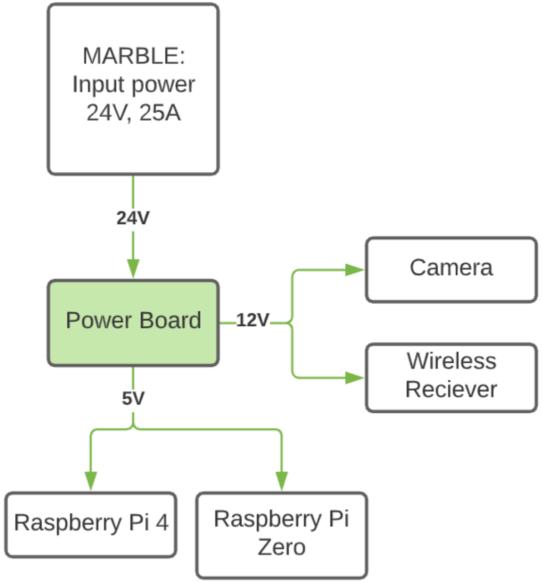
- Electronics Shop

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 Raspberry Pies' power lights are on, wireless receiver power light is on and camera is on. Maintain for 135 minutes. Also monitor current being drawn through power supply.



Electronics Test Readiness: End Effector Voltage Regulation Overview

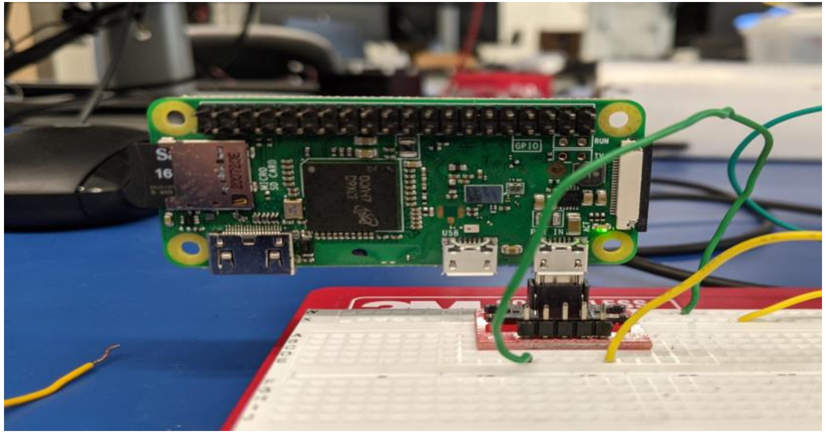
TDR 4.1.3: If RESCUE is directly connected to the Husky, power drawn from the Husky robot shall be less than or equal to 24-30 Volts at 25 Amps.

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 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) Set power supply to 12V
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".

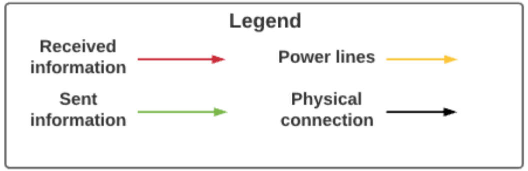
Motivation

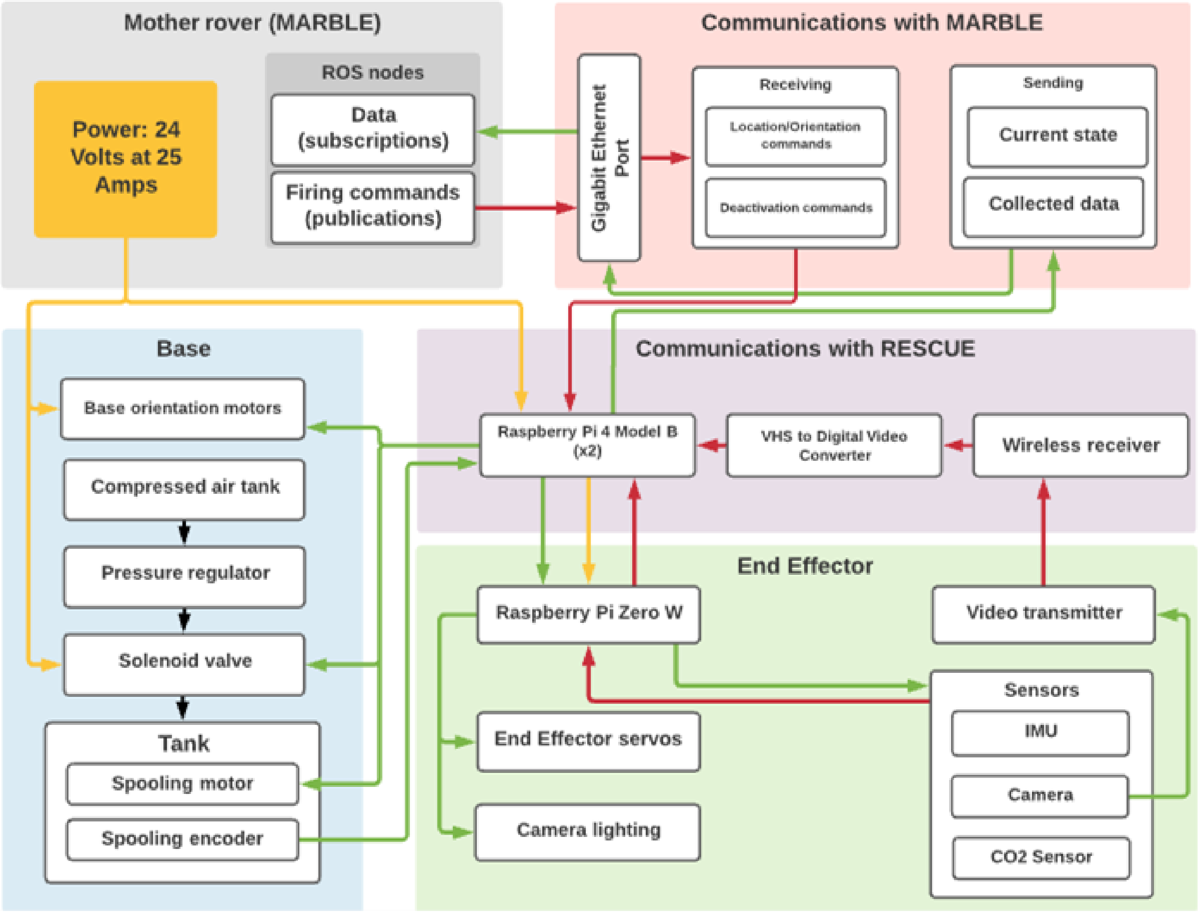
- MARBLE's UGV has **limited sensing** capabilities in comparison to other competitors in DARPA's Subterranean Challenge.

- 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.

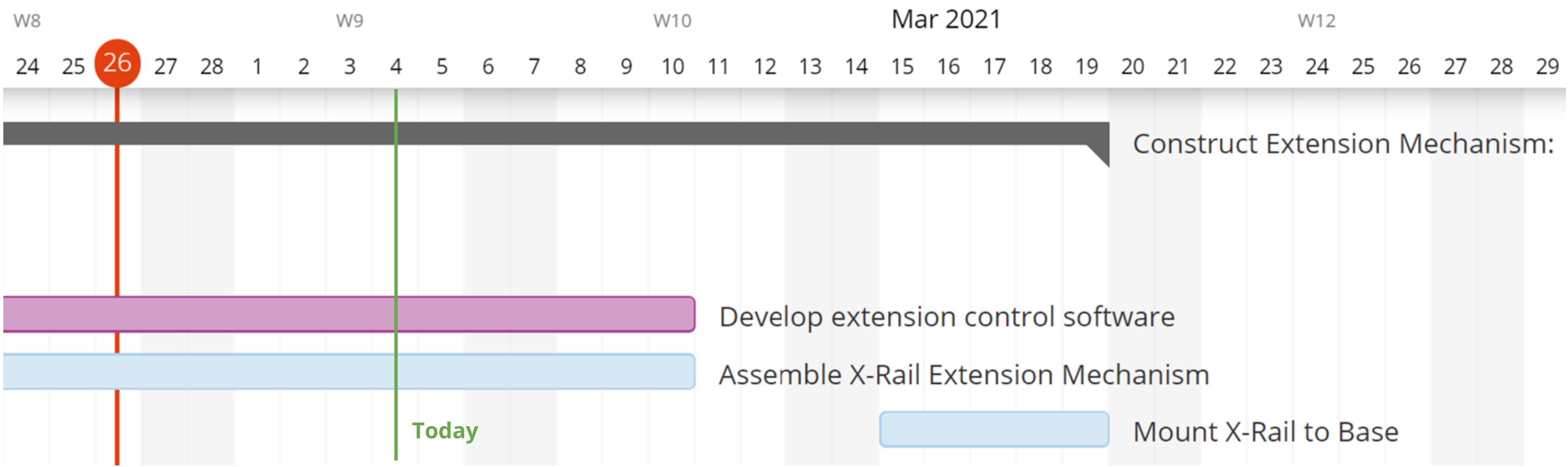
Old FBD



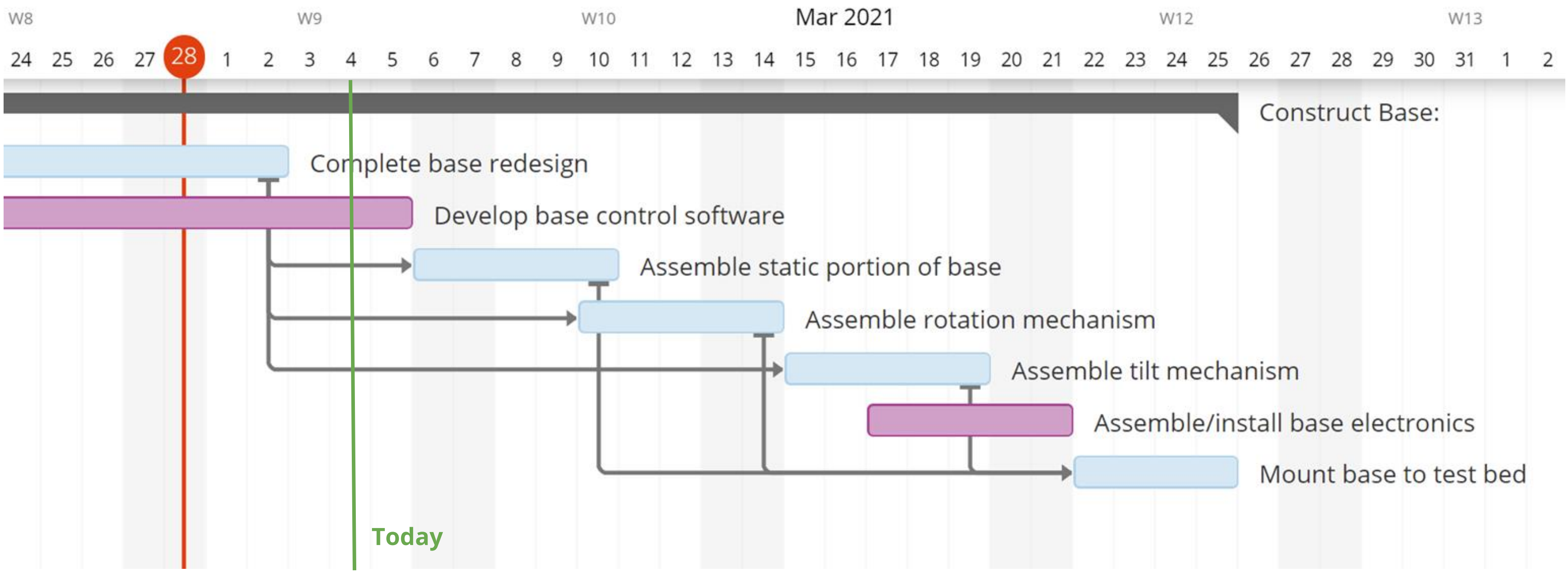


Back to new FBD

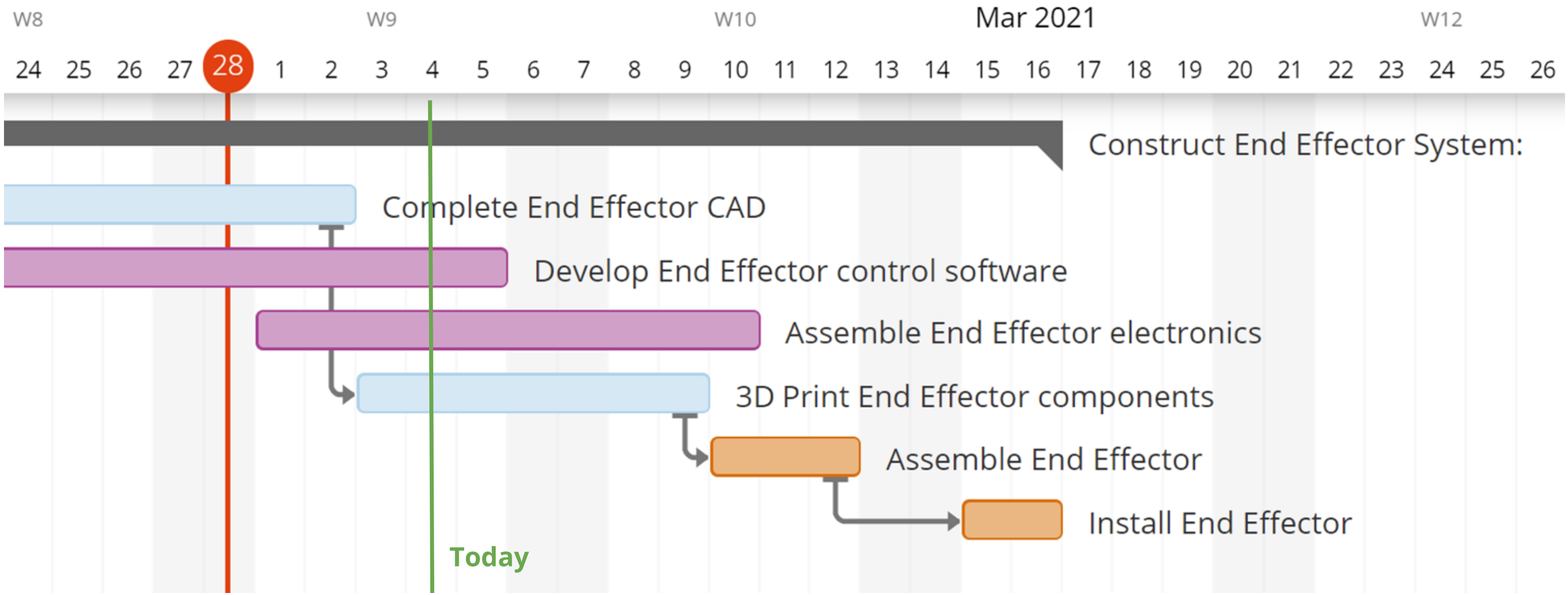
Project Schedule: Extension Mechanism



Project Schedule: Base



Project Schedule: End Effector



Test Readiness: template

Status:

Complete
Incomplete

Test	Rationale & Risk Mitigation	Design	Equipment & Facilities
Node interaction & callbacks		One publisher & any number of subscriber ROS nodes	Personal computer
Node interaction between devices	Reliable communications over ethernet connection to MARBLE		Two Raspberry Pi's, personal computer
Raspberry Pi wireless access point	Demonstration of ability to connect to RasPi offline	Raspberry Pi with wireless access point software installed	Raspberry Pi, personal computer
MQTT host & client communications	Standardized wireless communication		Two Raspberry Pi's, personal computer
MQTT automation & integration	Rapid & reliable automated data & command transmission	Two Raspberry Pi's with	Two Raspberry Pi's, personal computer

Test Readiness: Software Components

Status:

Complete
Incomplete

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

FR6.1: RESCUE shall receive commands from & communicate sensed data with MARBLE and these processes shall not interfere with MARBLE's communication systems.

Back to Software Test Readiness

Test	Rationale	Design	Equipment & Facilities
Node interaction & callbacks	Ensure expected functionality of ROS framework	One publisher & any number of subscriber ROS nodes	Personal computer
Node interaction between devices	Reliable communications over ethernet connection to MARBLE	Raspberry Pi transmitting messages to another Raspberry Pi or personal computer	Two Raspberry Pi's, personal computer
Raspberry Pi wireless access point	Demonstration of ability to connect to RasPi offline	Raspberry Pi with wireless access point software installed	Raspberry Pi, personal computer
MQTT host & client communications	Standardized wireless communication	Two Raspberry Pi's with MQTT installed & configured	Two Raspberry Pi's, personal computer
MQTT automation & integration	Rapid & reliable automated data & command transmission	Two Raspberry Pi's with MQTT installed & configured	Two Raspberry Pi's, personal computer

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.

Requirements (1):

FRs	TDRs	Requirement	Functional Category
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
FR 2.1		The sensing system shall be able to sense DARPA subterranean challenge competition artifacts	Artifacts Sensing
	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
	TDR2.1.2	The sensing apparatus shall be able to sense and detect carbon dioxide (CO2) at 2000 parts per million concentration.	Artifacts Sensing
	TDR2.1.3	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.	Artifacts Sensing
FR 3.1		RESCUE shall determine and report its location and orientation relative to the ground robot	System Position and Orientation
	TDR 3.1.1	RESCUE shall be able to determine its position relative to the ClearPathHusky, within 1 meter accuracy of its ground truth location at all times	System Position and Orientation
	TDR 3.1.2	RESCUE shall be able to determine its orientation to the ClearPath Husky within 5° accuracy of its ground truth orientation at all times.	System Position and Orientation

Requirements (2):

FRs	TDRs	Requirement	Functional Category
FR 4.1		When in its standby configuration, RESCUE shall be compatible with the MARBLE team's Clearpath Husky.	Deployment: Constraints
	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: Constraints
	TDR 4.1.2	RESCUE shall not exceed a total mass of 10 kilograms	Deployment: Constraints
	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: Constraints
FR 4.2		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: Mechanical Interference
	TDR 4.2.1	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 and/or orientation of or damage the MARBLE Clearpath Husky	Deployment: Mechanical Interference
FR 4.3		RESCUE's deployment operations shall be rapid enough to incur a minimal time cost to MARBLE's total mission time.	Deployment: Time
	TDR 4.3.1	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
	TDR 4.3.2	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.	Deployment: Time

Requirements (3):

FRs	TDRs	Requirement	Functional Category
FR 5.1		RESCUE shall withstand the environment of the DARPA subterranean challenge which is to be restricted to possible water splashes and poor lighting.	Endurance: Environmental Hazard
	TDR 5.1.1	RESCUE's mechanical and electrical components shall meet at least IP04 water exposure tolerances.	Endurance: Environmental Hazard
	TDR 5.1.2	RESCUE shall have enough lighting to perform all of its sensing operations in a possibly aphotic environment.	Endurance: Environmental Hazard
	TDR 5.1.3	RESCUE shall accomplish all other design requirements in an nominal thermal environment of 50-65°F.	Endurance: Environmental Hazard
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: Time
	TDR 5.2.1	RESCUE shall have enough electrical power to maintain a standby state for at least 135 minutes.	Endurance: Time
	TDR 5.2.2	RESCUE shall have enough electrical power to maintain an operational state for at least 30 minutes.	Endurance: Time
FR 5.3		RESCUE shall withstand repeated deployments.	Endurance: Time
	TDR 5.3.1	The MARBLE team shall be able to deploy RESCUE at least 5 times during a competition run.	Endurance: Time

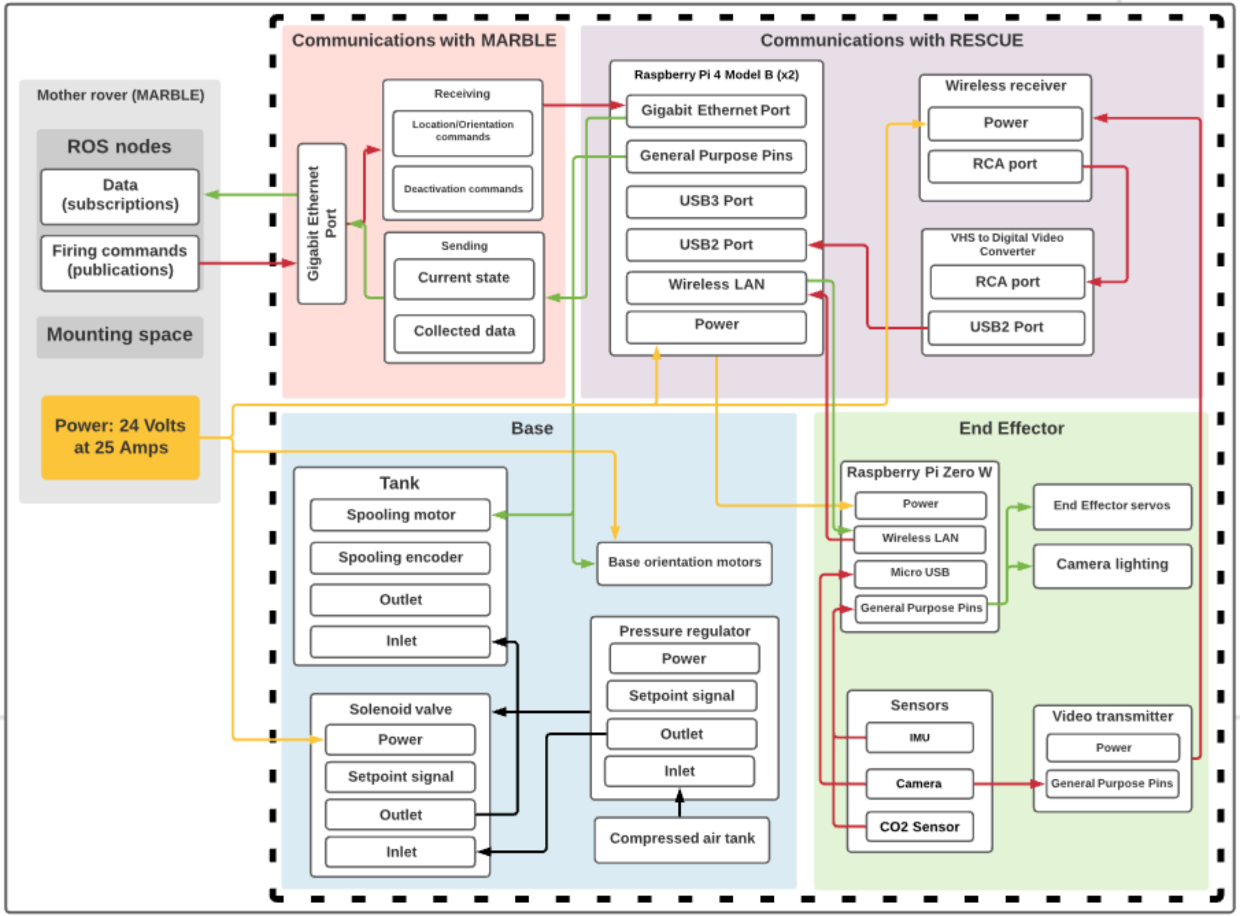
Requirements (4):

FRs	TDRs	Requirement	Functional Category
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
	TDR 6.1.1	RESCUE shall be capable of receiving firing commands from the ROS nodes in the existing MARBLE architecture.	Communications
	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
	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
	TDR 6.1.4	RESCUE shall deliver frequent status reports to the MARBLE robot regarding deployment status and data collection	Communications

Detailed FBD

Legend

Received information	→	Power lines	→
Sent information	→	Physical connection	→



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

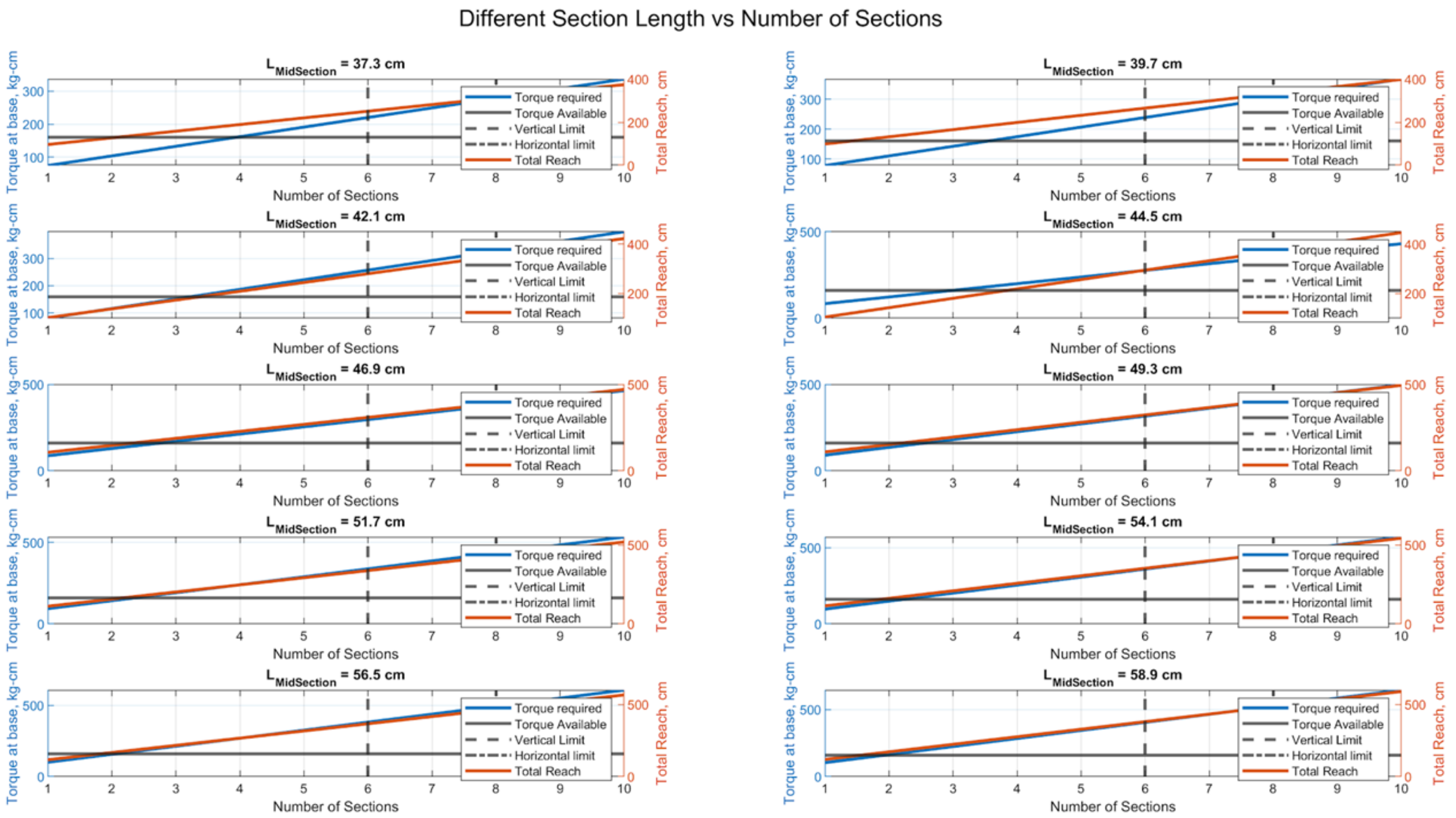
- Needs to extend 6 rail sections in 10 seconds
- Servocity (manufacturer) achieved 4 rail section extension in 8 seconds at 60 RPM
- From this, 6 section in 10 seconds equates to 72 RPM

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

FIRST TECH CHALLENGE LEGAL

Figure 1: 5202 Series Yellow Jacket Interplanetary Motor

Backup Slides: Hardware Manufacturing



Different Section Length vs Number of Sections
$L_{MidSection}$ = 37.3 cm
$L_{MidSection}$ = 39.7 cm
$L_{MidSection}$ = 42.1 cm
$L_{MidSection}$ = 44.5 cm
$L_{MidSection}$ = 46.9 cm
$L_{MidSection}$ = 49.3 cm
$L_{MidSection}$ = 51.7 cm
$L_{MidSection}$ = 54.1 cm
$L_{MidSection}$ = 56.5 cm
$L_{MidSection}$ = 58.9 cm
Torque required
Torque Available
Vertical Limit
Horizontal limit
Total Reach
Torque at base, kg-cm
Total Reach, cm
Number of Sections

Backup Hardware Manufacturing: Material Spool Container, Cont.

Challenges	- Epoxy sealed ends - Material spooling system serviceability - Pressurization testing
Manufacturing Status	- **Planned** (initial prototyping success dependence) - **Design improvements:** - Nozzle design - Nozzle sealing design - Bolted endcaps (sealing and maintenance) - Gas inflow/outflow hardware

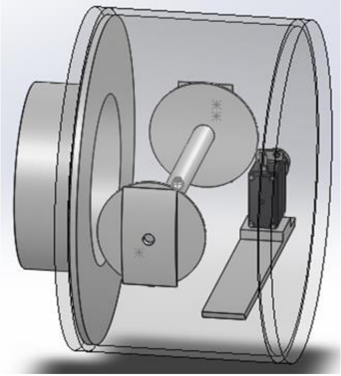


Figure 1. Material Spool Container

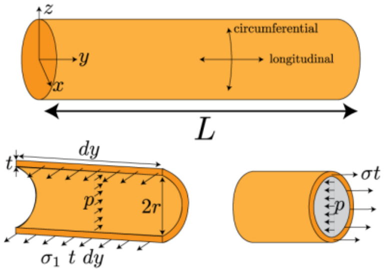


Figure 2. Body Tube Stresses

- **End Cap Pressurization**:
- Design point: 21 psi (144.8 kPa); (Operational 7 psi (48.3 kPa), 3 FOS)
- Epoxy seal: $\sigma_{seal} \approx$ 250 psi (1724 kPa)
  - G5000 Epoxy: 7600 psi (52.4 MPa) tensile strength
  - Cast acrylic yield strength: 10,000 psi (68.9 MPa) yield strength
- **Main Tube Pressurization:**
- Design point: 8.4 psi (57.9 kPa); (Operational 7 psi (48.3 kPa), 3 FOS)
- Main body tube: Hoop (max.) stress (σ1) ≈ 404.3 psi (2.79 MPa)
  - 500 psi (3.44 MPa) PVC yield strength

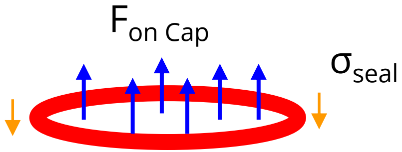


Figure 3. Endcap Stress Diagram

Hardware Manufacturing: Base Dynamic System

Functionality:	- Rotate 360° and pivot 90° to position the pressure container and inflatable arm
Integration/Access	- Screwed to base - Pivot screwed into upper plate
Materials/Procurement	- Square aluminum tube - 4:1 gears - 3D printed container attachment - Plastic 22.86cm turntable - Timing belt gears - 2.54cm t-slotted aluminum - 2 x DYNAMIXEL XM540-W270-R servos
Manufacturing	- Mill - Bandsaw
Tolerances	- Components machined to 0.08cm
Challenges	- Gears connecting the pivot system - Rotating the belt 90° underneath the upper plate
Manufacturing Status	- Planned

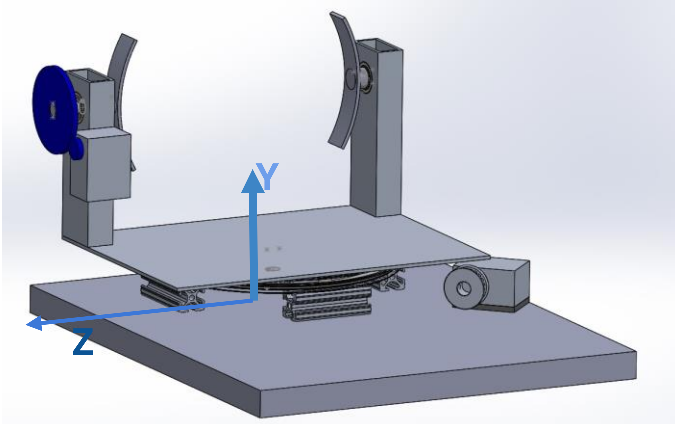


Figure 1. The rotating base

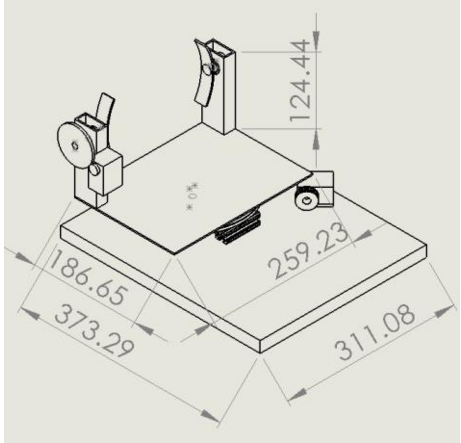


Figure 2. The rotating base Dim.(mm)

Hardware Manufacturing: Base Static Plate

Functionality:	- Supports all components and connects to the MARBLE ClearPath Husky
Integration/Access	- Open, integration for all components and connects directly to the top of MARBLE's Husky
Materials/Procurement	- 45.72cm x 38.1cm x 0.3175cm aluminum plate
Manufacturing	- Bandsaw
Tolerances	- Plate cut to 0.15cm in for length and width
Challenges	- Secure mounting to MARBLE and of components
Manufacturing Status	- Planned

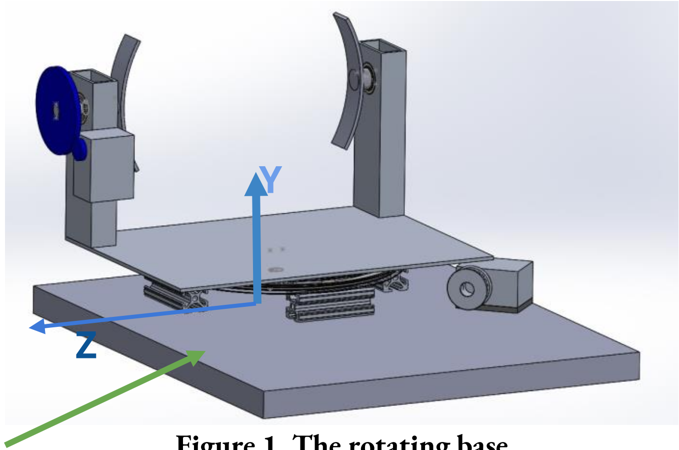


Figure 1. The rotating base

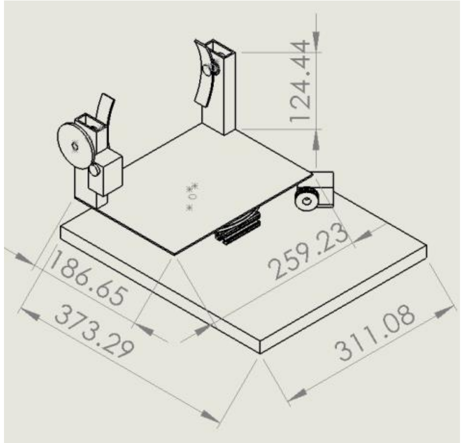


Figure 2. The rotating base Dim.(mm)

Hardware Manufacturing Backup: Base Electronics Housing

Functionality:	- Contains all base electronic components
Integration/Access	- Screwed to base as complete assembly
Materials/Procurement	- 3 mm PLA - M2 Screws (TBD) - All base electronics
Manufacturing	- LulzBot Taz 6, 3mm PLA - Component assembly by hand - Base electronics soldered as required
Tolerances	- Printed with 1.75mm PLA
Challenges	- Fitting under the turntable
Manufacturing Status	- **Planned:** - Finalize base electronics (design dependent) - determine standardized fastener sizes - CAD design - Actual print/assembly

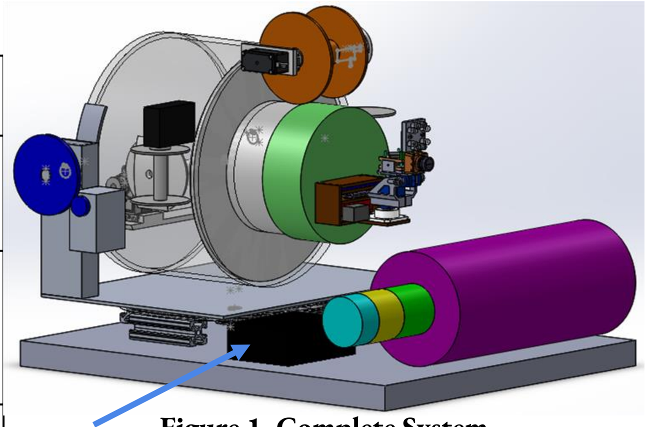


Figure 1. Complete System

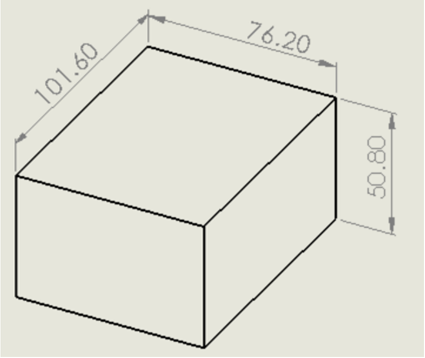


Figure 2. Estimated Base Electronics Housing Dim. (mm)

Hardware Manufacturing: Material Spooling System

Functionality:	- Provide the right amount of tubing to be inflated
Integration/Access	- Contained inside the pressurized container - Will be unable to access once the pressurized container is sealed
Materials/Procurement	- One Parallax 900-00360 servo - PLA 3D printed spool, spool end caps, servo mount - Timing belt with 1.08cm OD timing gears - Keyed axle
Manufacturing	- Slot the keyed axle through material spool - Place end caps on axle ends and tighten with set screws - Epoxy seal the end caps to the inside of the material spool container - Epoxy seal the servo to the servo mount, and the servo mount to the inside of the material spool container
Tolerances	- Filament tolerance for 3D printed parts, 1 mm for machined parts
Challenges	- Assembling inside the container
Manufacturing Status	- Planned (design dependent)

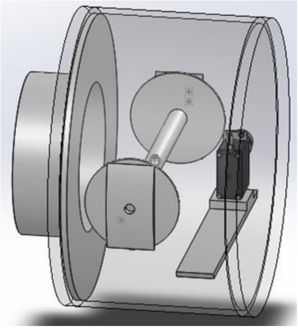


Figure 2. Material Spooling Container

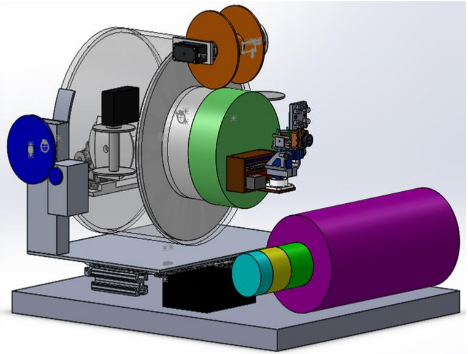


Figure 1. Complete System

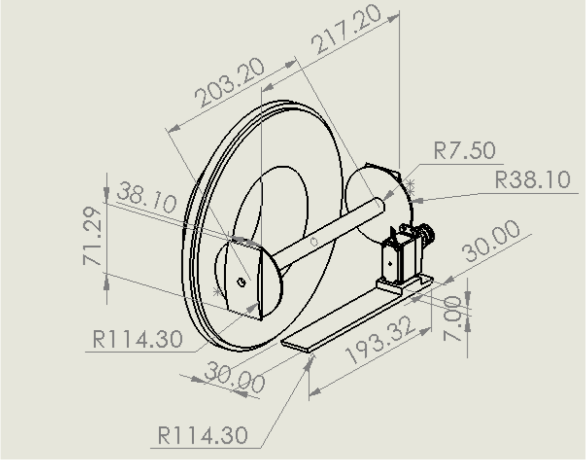


Figure 3. Material Spooling Dim. (mm)

Hardware Manufacturing: Pressurization System

Functionality:	Provides pressurized air to the tank to support the inflatable arm
Integration/Access	Open, outside of the pressurized container, easily accessible
Materials/Procurement	- Adaptors - Ninja SL2 Carbon Fiber Pressure Tank - Swagelok Pressure regulators
Manufacturing	None, assembly by hand
Tolerances	N/A
Challenges	**Pressure testing**
Manufacturing Status	Planned without the details, waiting for tests of the inflatable arm and the tension system

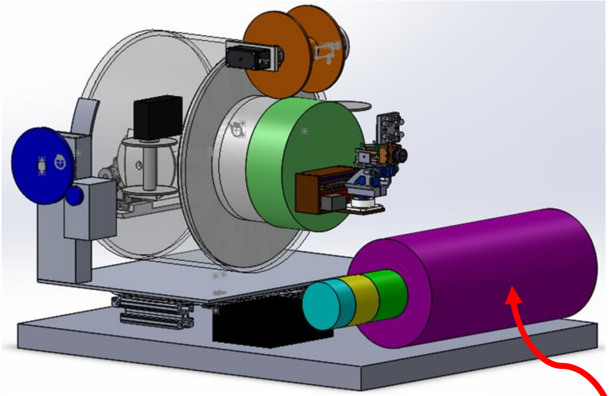


Figure 1. Complete System

Pressurization System

Hardware Manufacturing: Pressure Tank Holder

Functionality:	- Holds the pressure tank in position on the robot, providing enough security from unwanted accidental collisions
Integration/Access	- Open, away from the spooling mechanism
Materials/Procurement	- 3D printer PLA
Manufacturing	- LulzBot Taz 6 printed parts - Assembly by hand
Tolerances	- 3mm min. PLA part dimensions
Challenges	- Secure mounting to the top of the robot
Manufacturing Status	- Unplanned, depends on prior tests and possible redesigns of the entire design

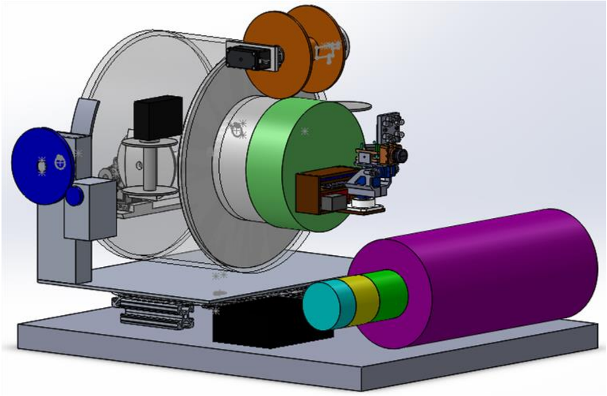


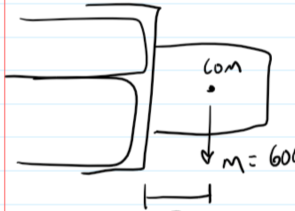
Figure 1. Complete System

Hardware Manufacturing: Tension System V2

- Constant force retractors and springs
- No motors, no software, overall a much simpler design
- Potentially two lines on top, one on bottom to balance the moment from the EE
- Difficulty: finding a 4 meter long, lightweight solution that doesn't apply too much force

Tension Spring Calculations

side view



m = 600 g → F = 1.32 lbs

≈ 3 in = 0.25 ft

Moment the tension springs need to counter act ≈ 0.33 lb·ft

lets put 2x on top, 1x on bottom

Container radius ≈ 4.75 in = 0.40 ft

tension · 0.40 ft = 0.33 lb·ft → tension ≈ 0.83 lbs

Backup Slides: Budget/Procurement

Procurement Status Backup: Received

Hardware	Electronics		Sensors	Testing Equipment/ Components	Raw Materials/Misc.
Micro Pan-Tilt Servo Kit	Bright PI Raspberry Pi Lighting System	SparkFun DC/DC Converter Breakout	Yost Labs 3 Space Embedded IMU	ULINE 6 mil heavy duty poly tubing roll - 9" x 1,000'	Gantt Chart Software subscription reimbursement (Nov, Dec, Jan)
	Raspberry Pi Model 4 B 8 GB	Block Power Plug	SCD30 Co2 Sensor	Plastic Bag Heat Sealer	2.85 mm PLA, 1 kg
	Adafruit 16-Channel 12-bit PWM Servo Driver	USB Micro B Plug Breakout connection	RunCam Split 3 Micro FPV Camera	1/4 NPT Quick Disconnect Hose Coupling	1.75 mm PLA, 1kg
	Raspberry Pi Zero WH (Zero W with Headers)	Analog to digital video converter		1/4 NPT Ball valve	
	SparkFun Snappable Protoboard	Wireless FPV Transmitter and Receiver For Drones		0-15 PSI Mechanical Pressure gage	
		RunCam TX200U FPV Transmitter			

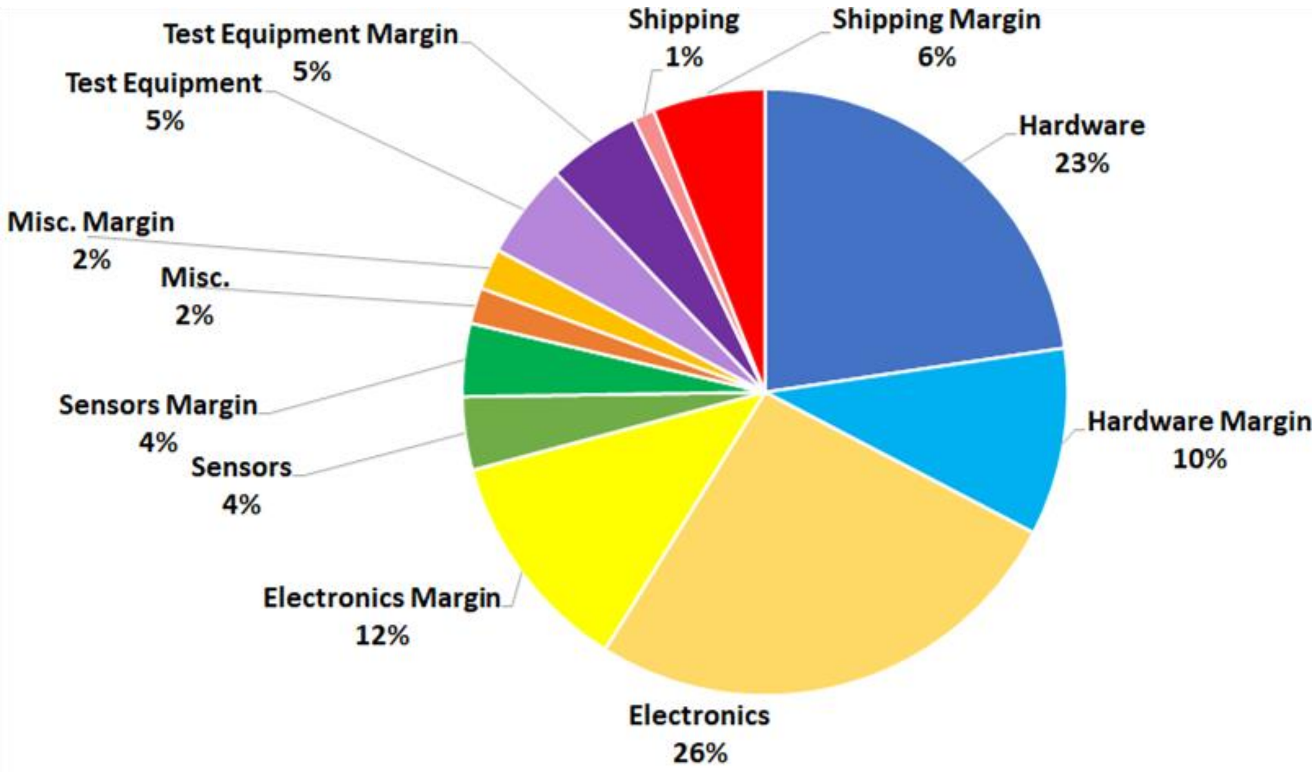
Procurement Status Backup: Planned Hardware (Nothing Pending)

End Effector	Material Container	Material Spooling	Tension System	Pivot System	Rotation System	Pressurization System	Power Spooling System
End Effector Mounting Fasteners	Material Container Tube	Material Spool Mounts	Tension spools	Pivot Supports Rectangle	Rotation Belt	Paintball Pressure Tank	Slip Ring
End Effector Printed Frame	Material Container Caps	Material Spool Axle	Tension Spool Motors (2)	Pivot Bearings	rotation gears	Hose	Slip ring mounting parts
IMU Breakout Mounting Board	Material Container Nozzle	Material Spool	Tension Spool Attachment System	Pivot Axle	rotation shaft	Pressure Regulator	Power Spooling System Mounting
End Effector Cap	Epoxy/Container Sealing	Material Spool Servo Mount		Pivot System Gears (1 2cm D and 4 8cm D)	Rotation Crown gears	Solenoid	Power Spool
		Material Spool Belt		Pivot to Container Connection		Adaptors	
		Material Spool Belt gears		Pivot System Turntable			
				Al Pivot Support Plate			
				Pivot Base Offsets			

Procurement Status Backup: Planned Continued (Nothing Pending)

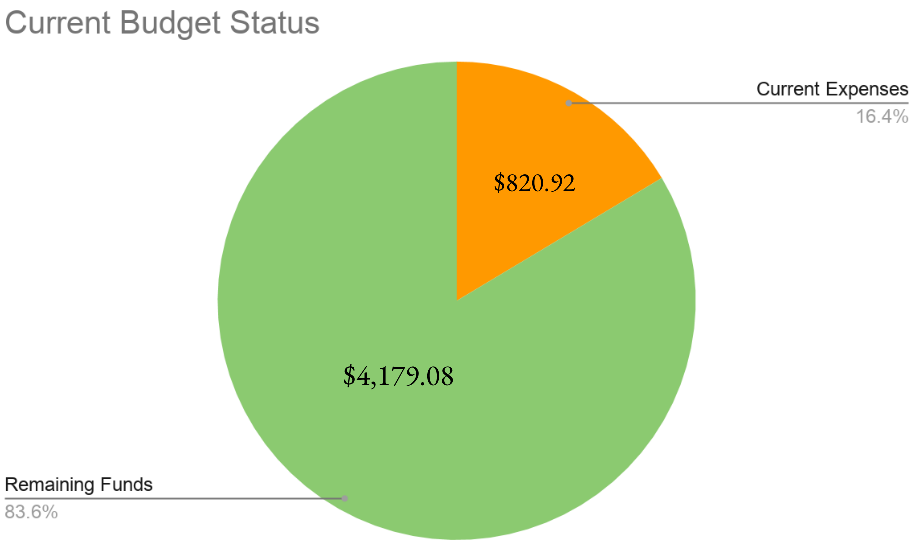
Electronics		Sensors	Testing Equipment/Components	Raw Materials/Misc.
PWM Servo Controller	Pivot servo		Higher Pressure LDPE Tubing	Insta Gantt Subscriptions
Arm Power Wiring	Rotation servo			
Solderfull Breadboard	Material Spool Servo			
LM317(x2)	Power wire servo			
Solenoid Valve	Raspberry Pi DYNAMIXEL Servo Controller Board			

Budget Status (Backup)

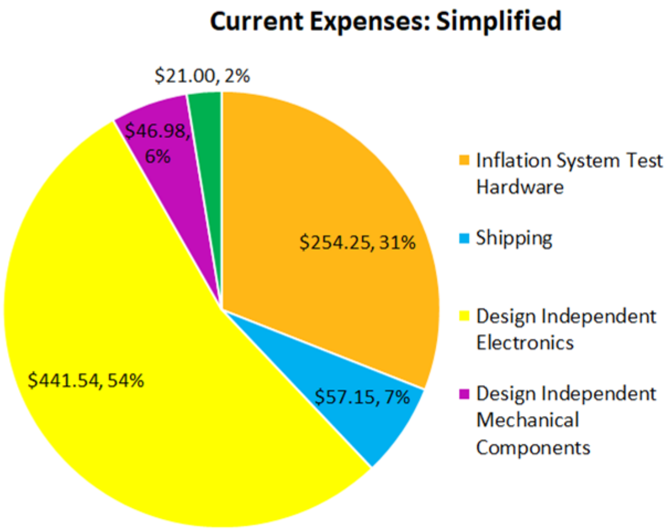


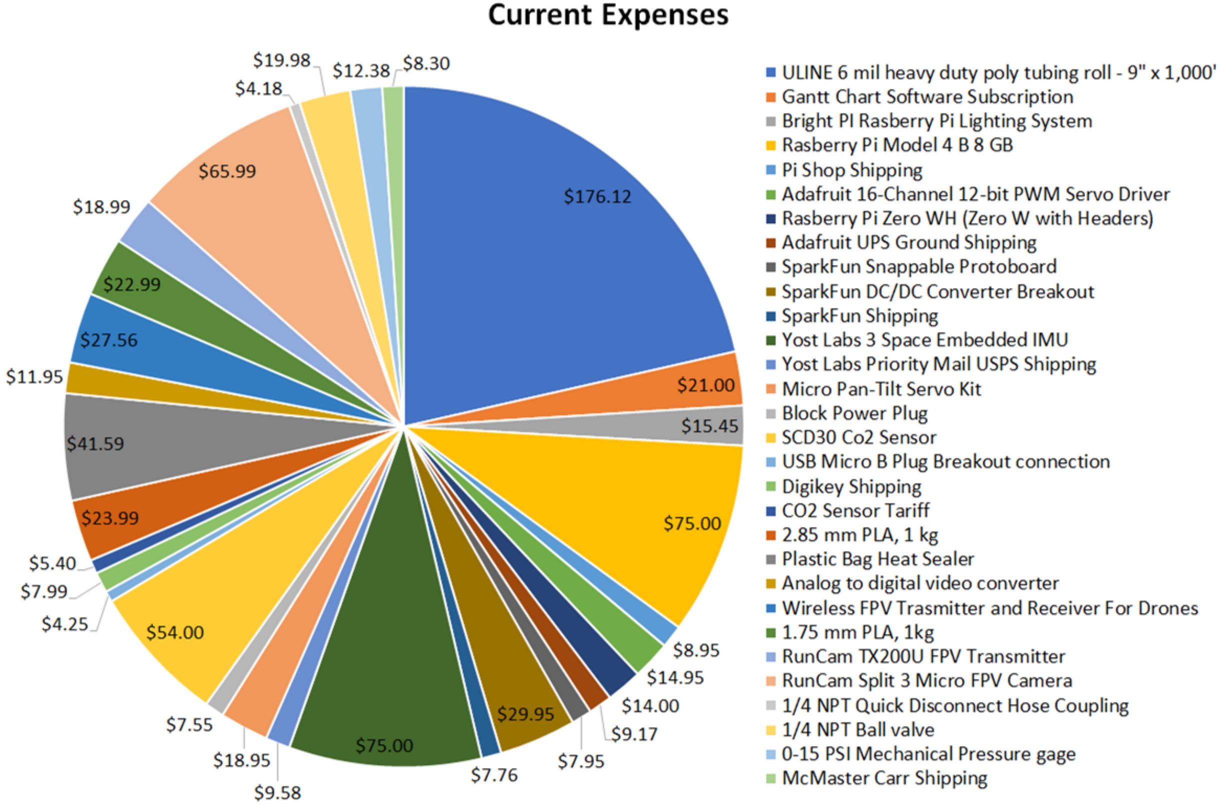
Hardware	$1,133
Hardware Margin	$500
Electronics	$1,310
Electronics Margin	$600
Sensors	$195
Sensors Margin	$195
Misc.	$96
Misc. Margin	$109
Test Equipment	$254
Test Equipment Margin	$250
Shipping	$57
Shipping Margin	$300
Total	**$5,000**

Budget Backup: Current Expenses: $820.92

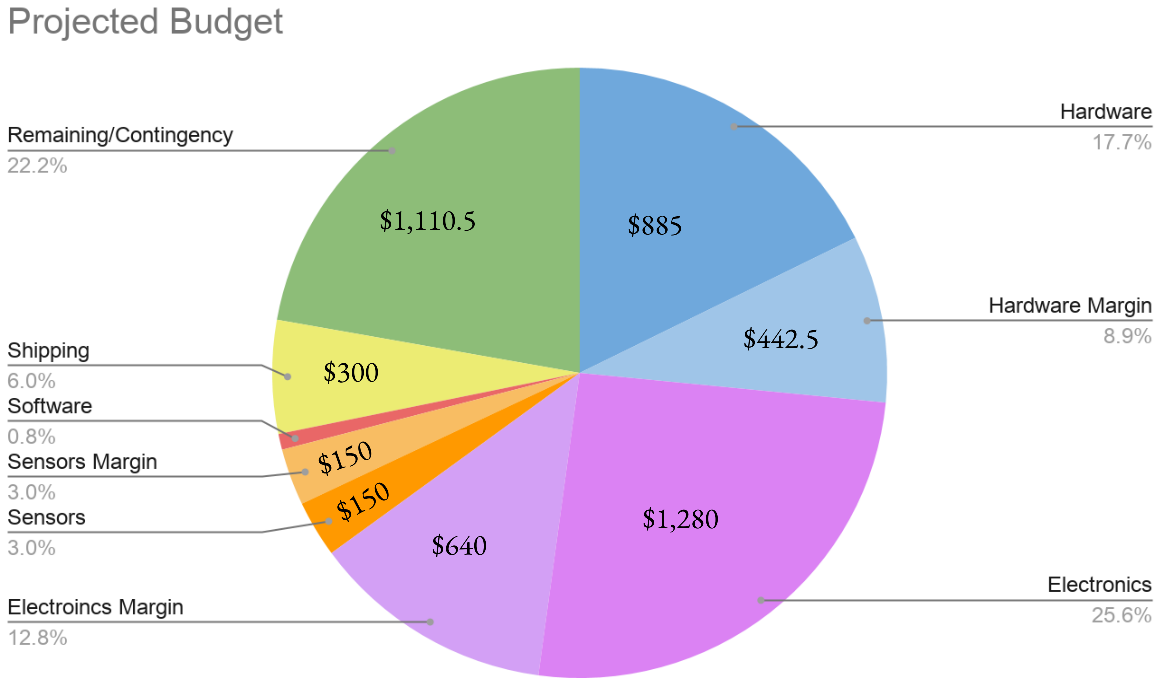


Budget Backup: Current Expenses: $820.92





Budget Backup: Overview (Previous Estimate)



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

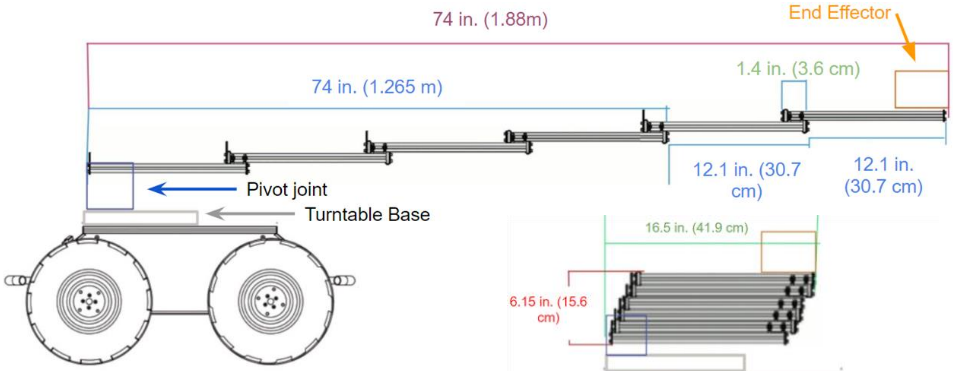


Figure 1. X Rail Arm on UGV

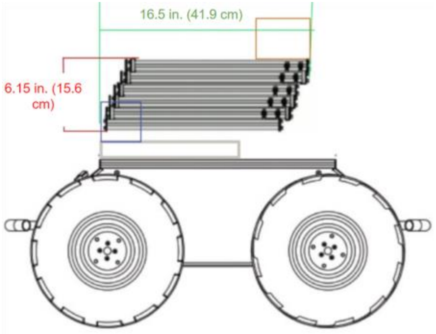


Figure 2. Collapsed X Rail on UGV

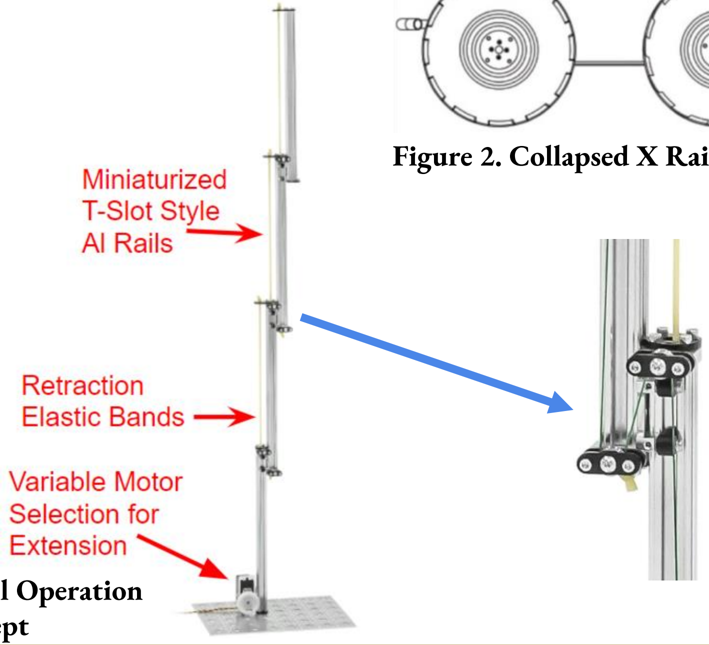
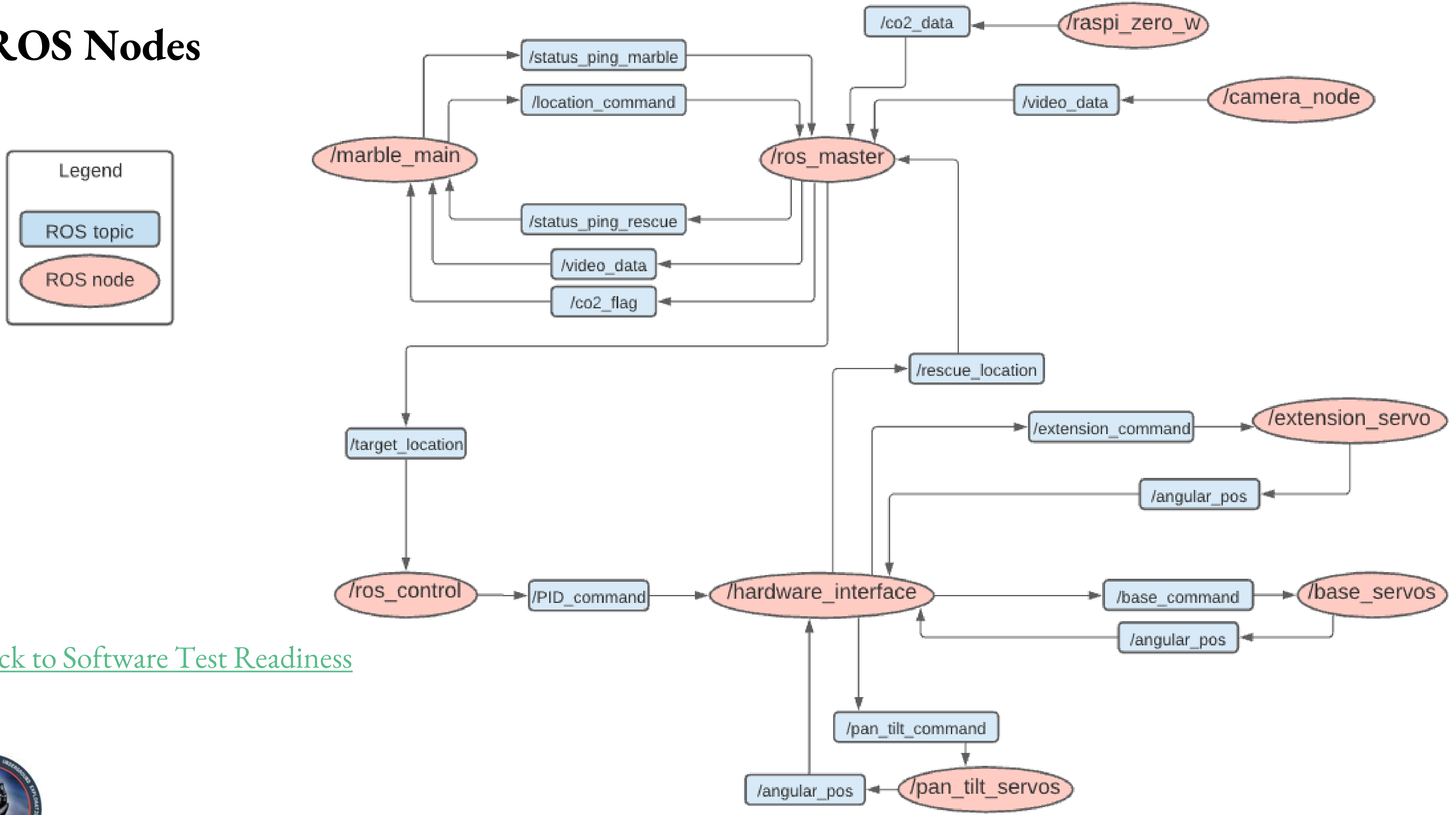


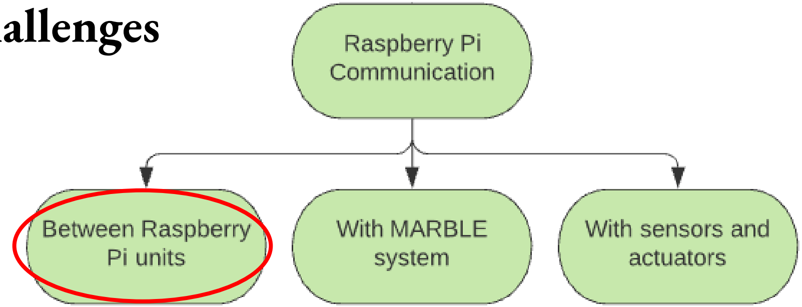
Figure 3. X Rail Operation Concept

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

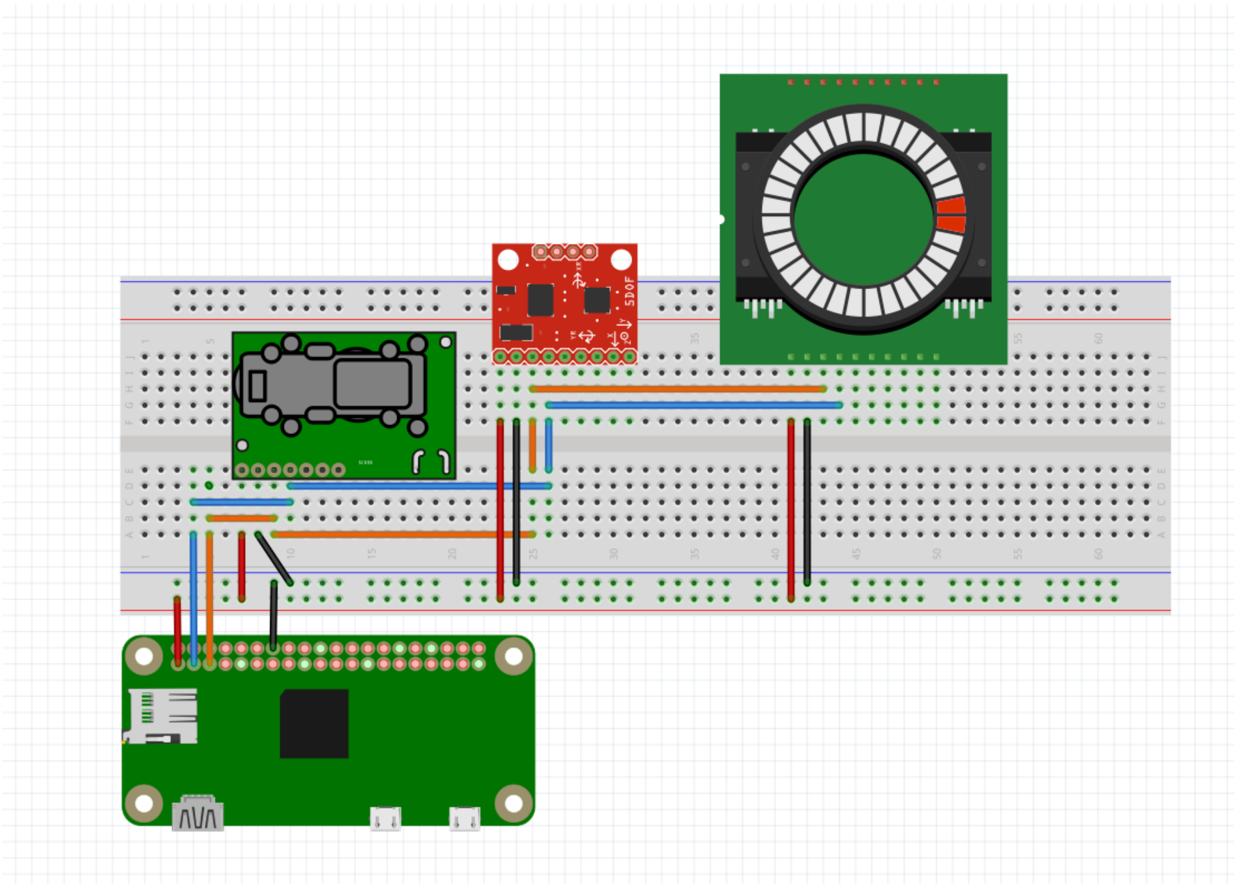
Software Component	Expected Challenges	# of Team Members Assigned	Resources Available	Projected Completion Date
Inter-RasPi Communication	ROS-based communication without wireless internet connection	4	Raspberry Pi tutorials, ROS documentation	2/8
ROS Package	Possibility of separate packages for RasPi 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

	CO_2 Sensor	IMU	LED Board
Functionality (purpose):	The purpose of this sensor is to provide readings of the CO_2 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 CO_2 sensor is purchased and received.	The IMU is purchased and received.	The LED board is purchased and received.

End Effector Electronics: Sensor Diagram

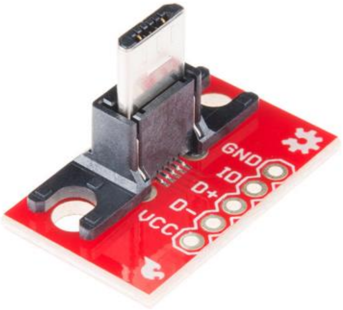


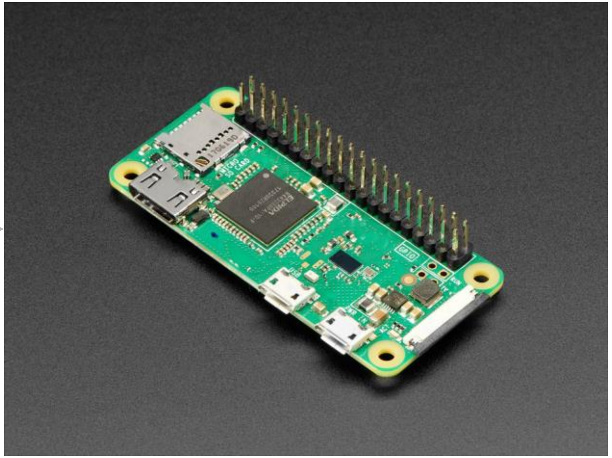
Electronics Manufacturing: Voltage Regulation Circuit to RasPi Zero

	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]:

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

$$P_{TX} = 23.01029995$$

$$G_{TX} = 2.2$$

$$L_{TX} = 0.5$$

$$L_{FS} = 57.48795996$$

$$L_M = 10$$

$$G_{RX} = 2$$

$$L_{RX} = 0.5$$

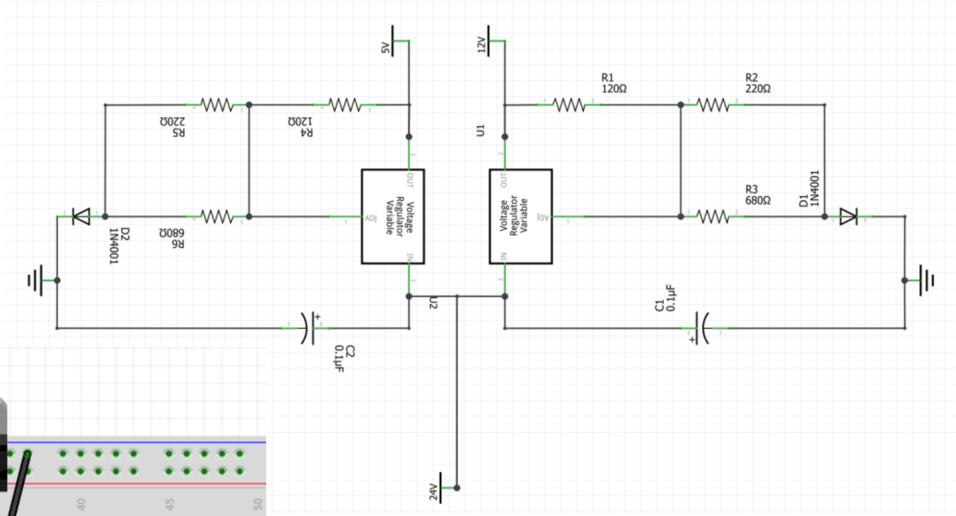
$$P_{RX} = -41.27766$$

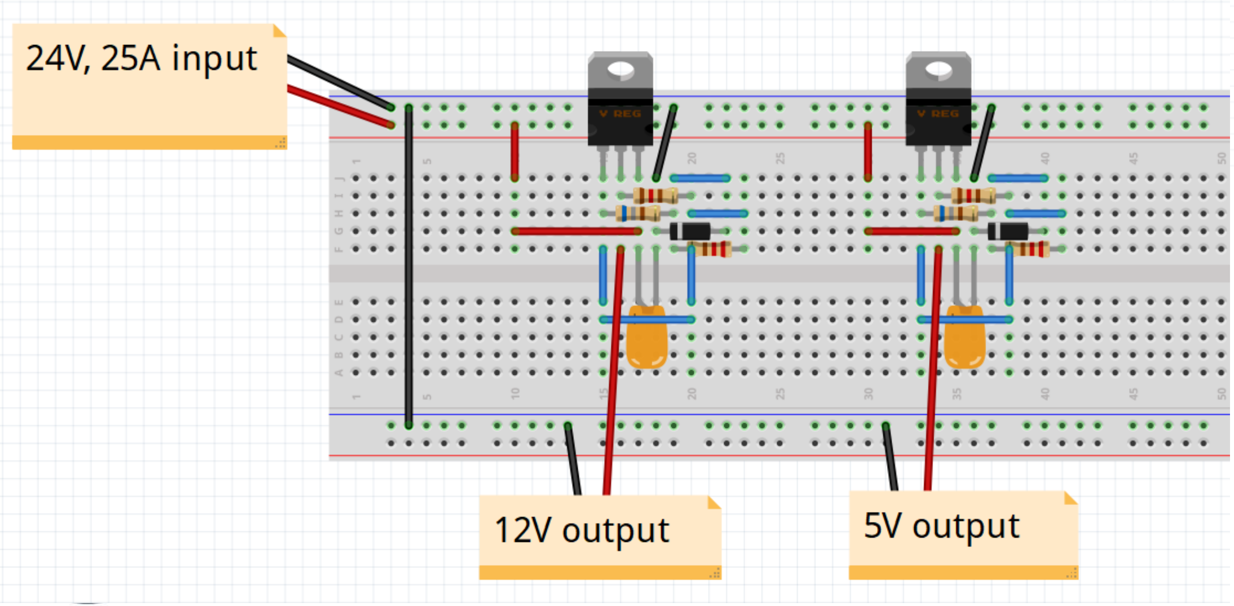
Signal to noise ratio [dB]:

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

$$SNR = 39.2841$$

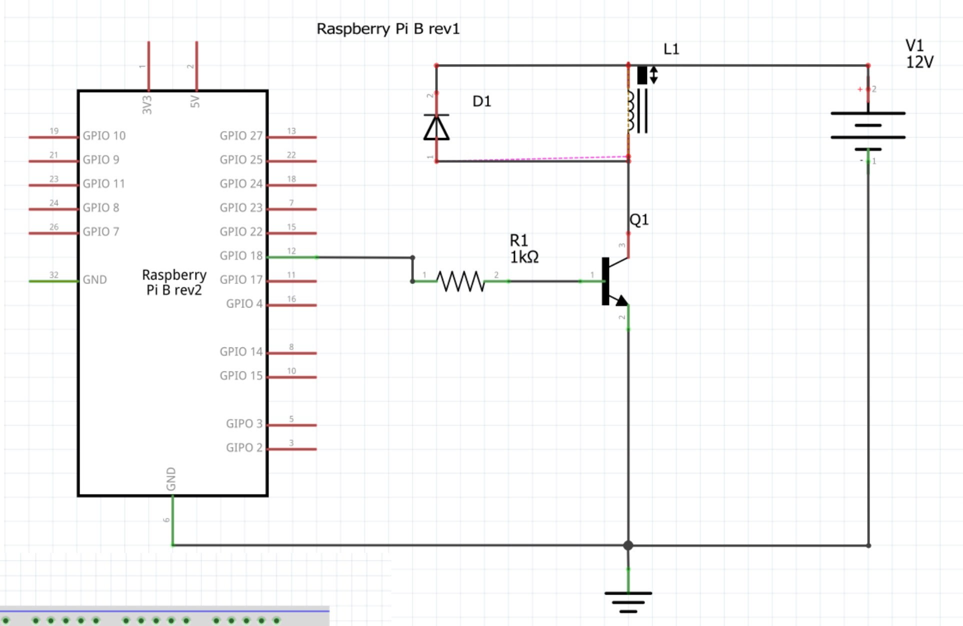
Base Electronics : Voltage Regulation Circuits

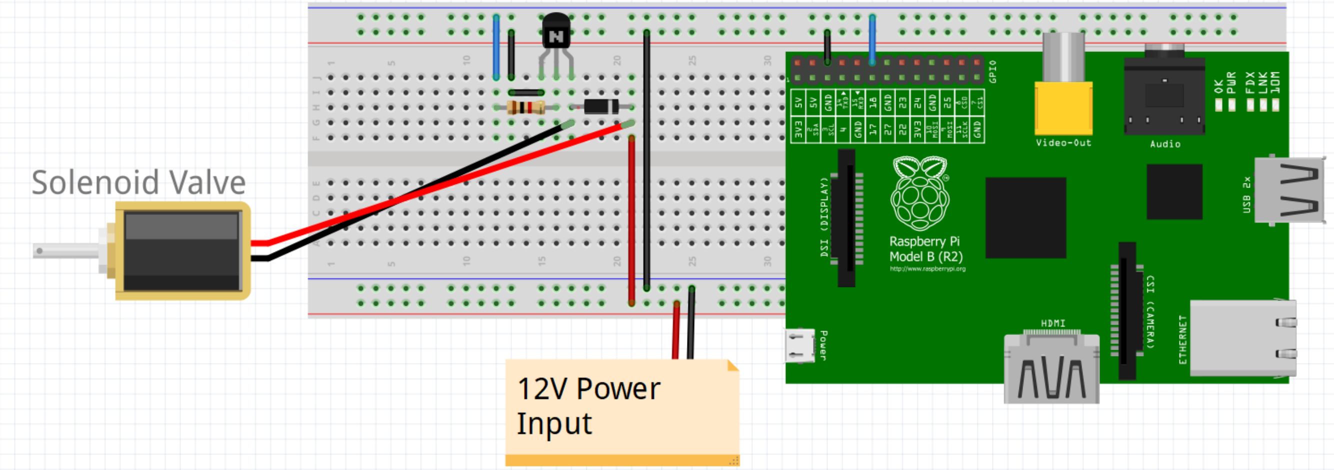




Back

Base Electronics: Solenoid Circuit





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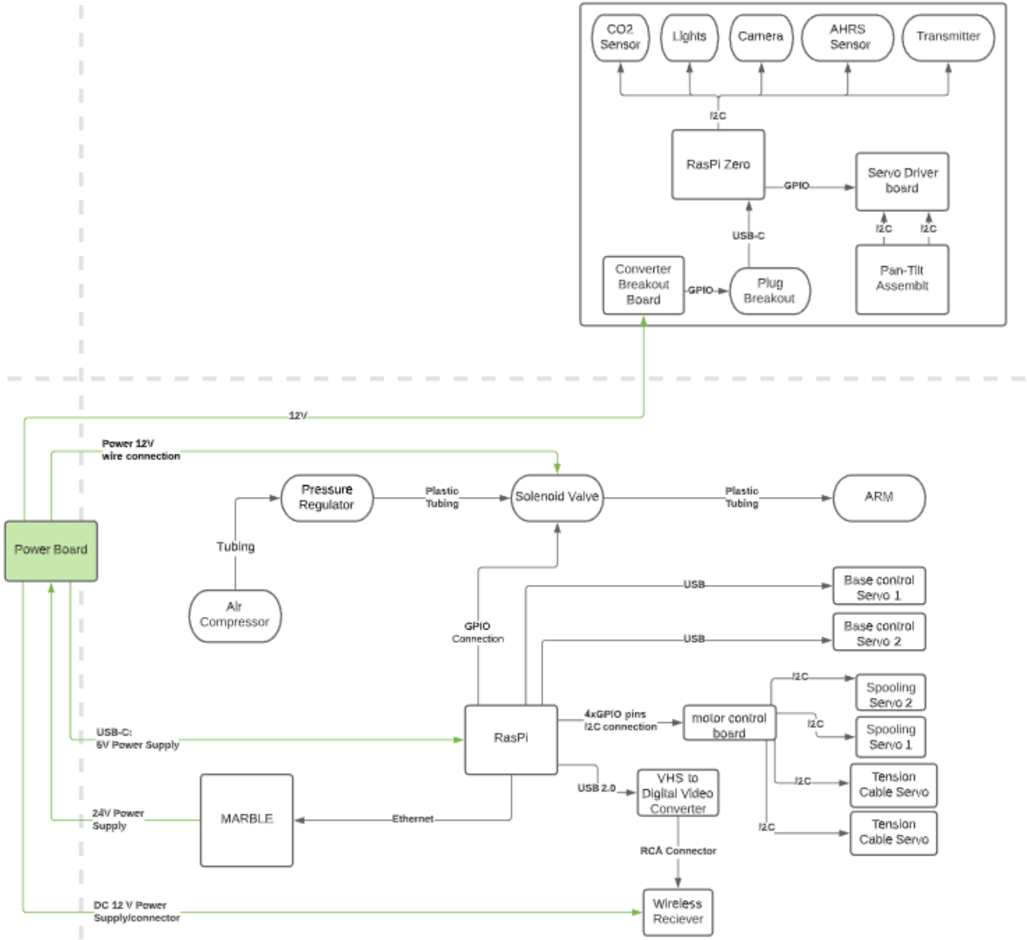
Electronics Manufacturing: USB, PWM, GPIO & Ethernet Connections to RasPi

	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



Back

Design Solution: Additional CAD

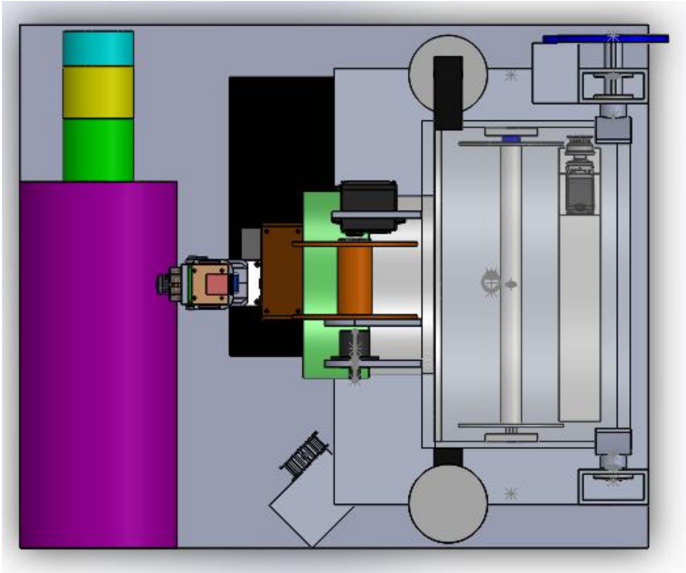


Figure 1: Top View

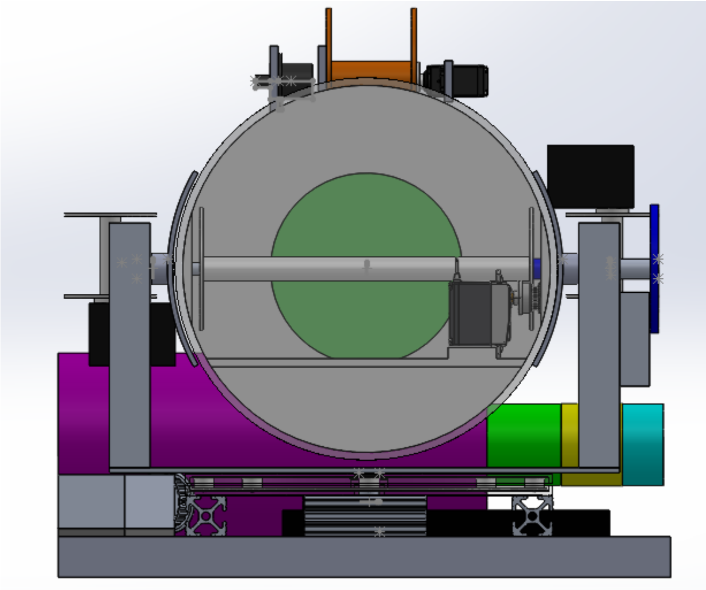
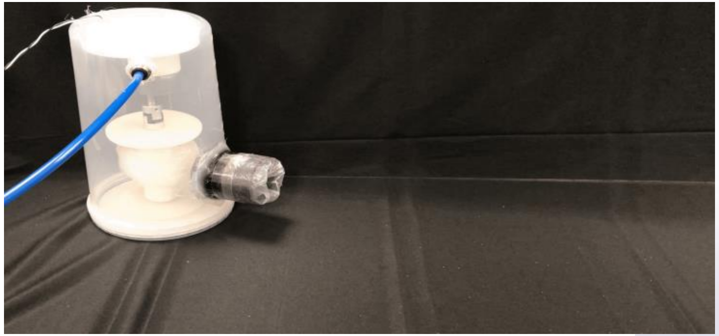
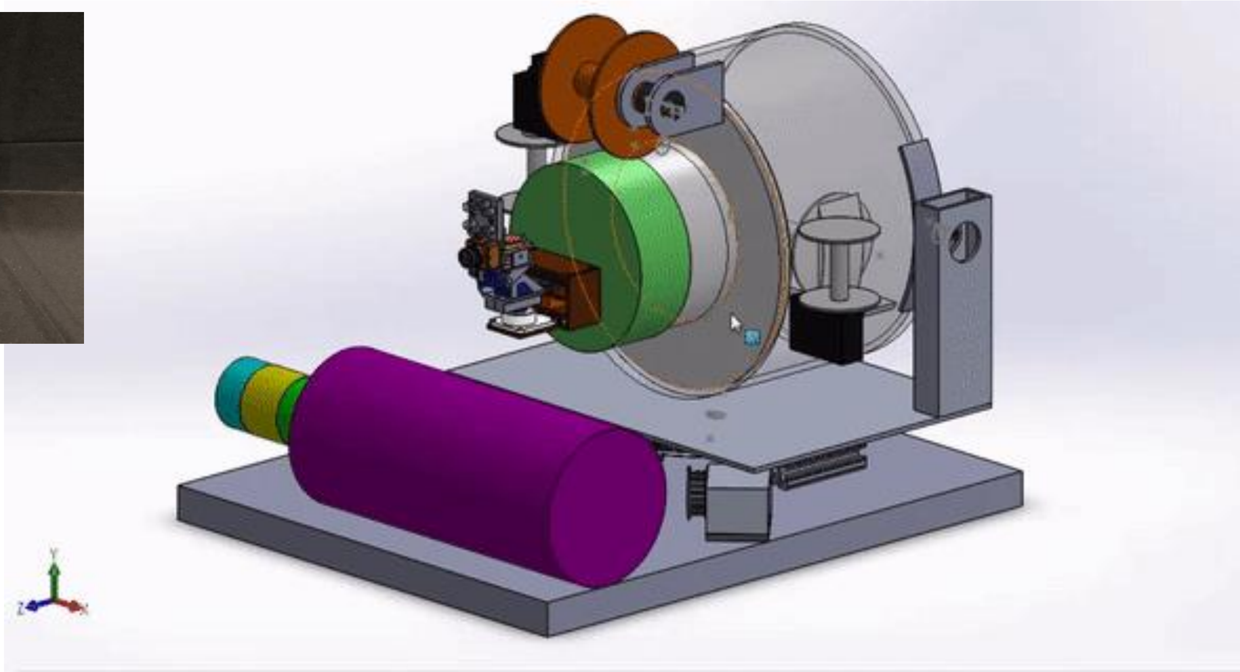


Figure 2: Back View

Design Solution: CAD





Levels of success: detailed

Table 1: *Levels of Success*

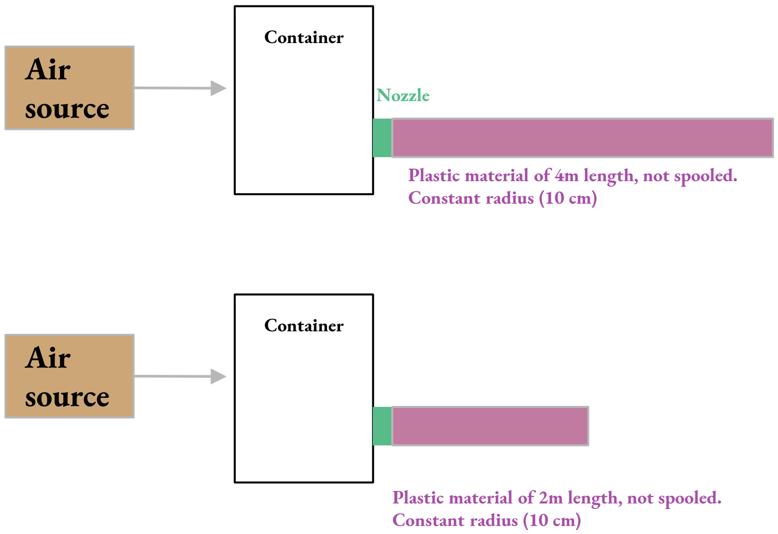
	Level 1	Level 2	Level 3
Sensing Range	All sensors can be utilized to effectively sense their respective artifacts within 3 meters of MARBLE's Husky in any given accessible direction.	All sensors can be utilized to effectively sense their respective artifacts within 4 meters of MARBLE's Husky in any given 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 1: Eversion Arm, Reduced Length

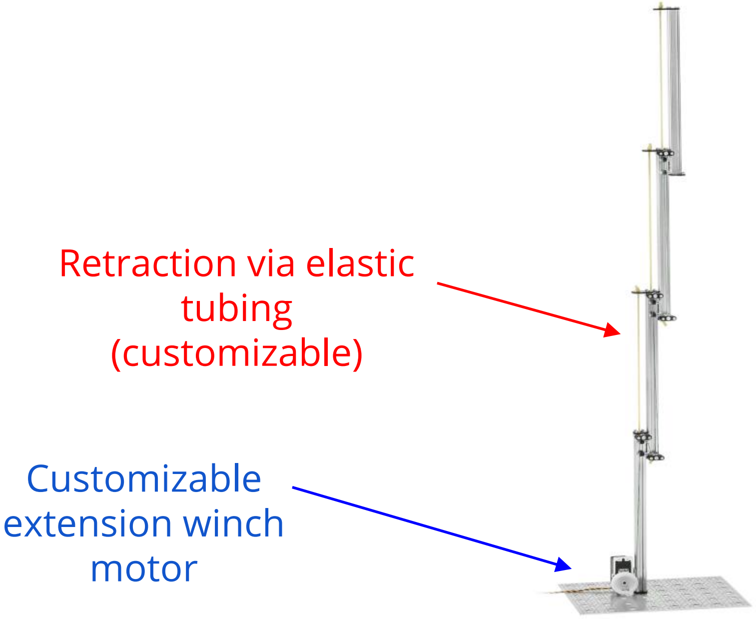
RESCUE will decrease the overall length of the tube causing:

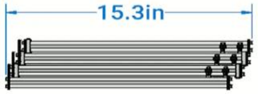
- Reduced risk of buckling
- Decrease overall tube mass
- Increase payload mass capability - greater FOS
- Faster reach

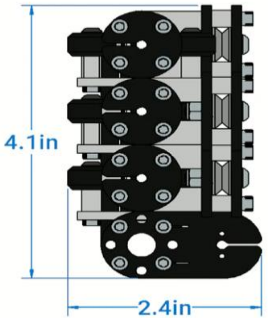


Extension Method Off Ramp 2: X Rail System

- 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







Xrail Tipping Analysis

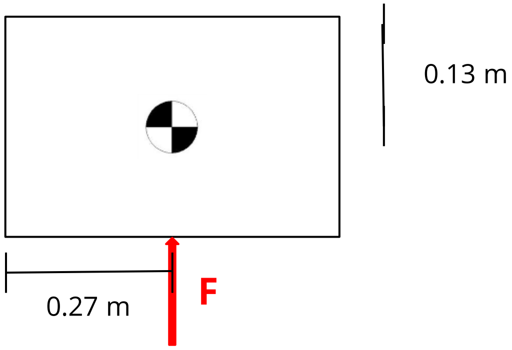
Counterclockwise Moment = Clockwise Moment

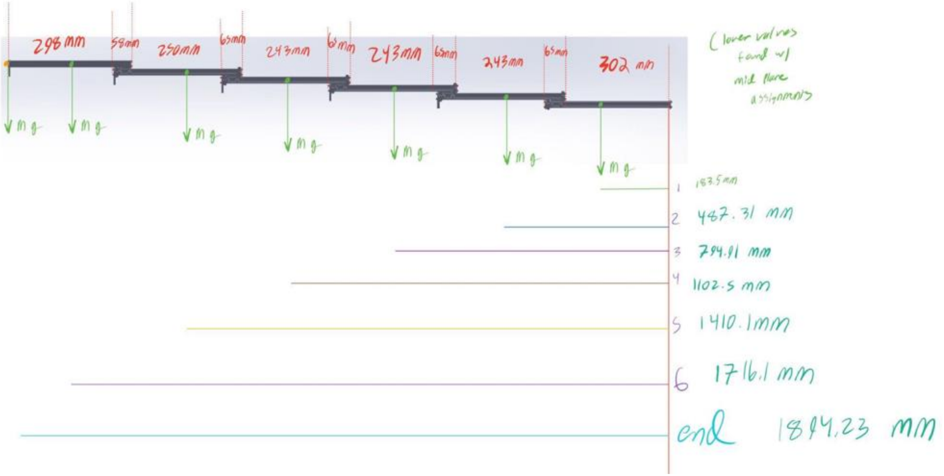
$F*d_{ccw} = F*d_{cw}$

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

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

FOS = 3.63





Section masses

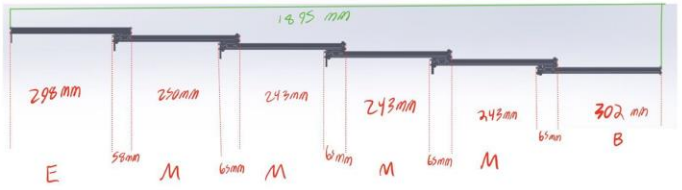
1x end	143g
1x base	136g
1x mid	176g
EE	450g

assume ee is decent for over est (125g cap + 50g margin)

EE as point mass

to nearest mm

E = end
M = mid
B = base



(total 1897 mm)

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