Manufacturing Status 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 soft robotic arm, mounted to the top of the UGV, that extends an RGB camera, CO2 Sensor, and AHRS up to 4 meters from its base.

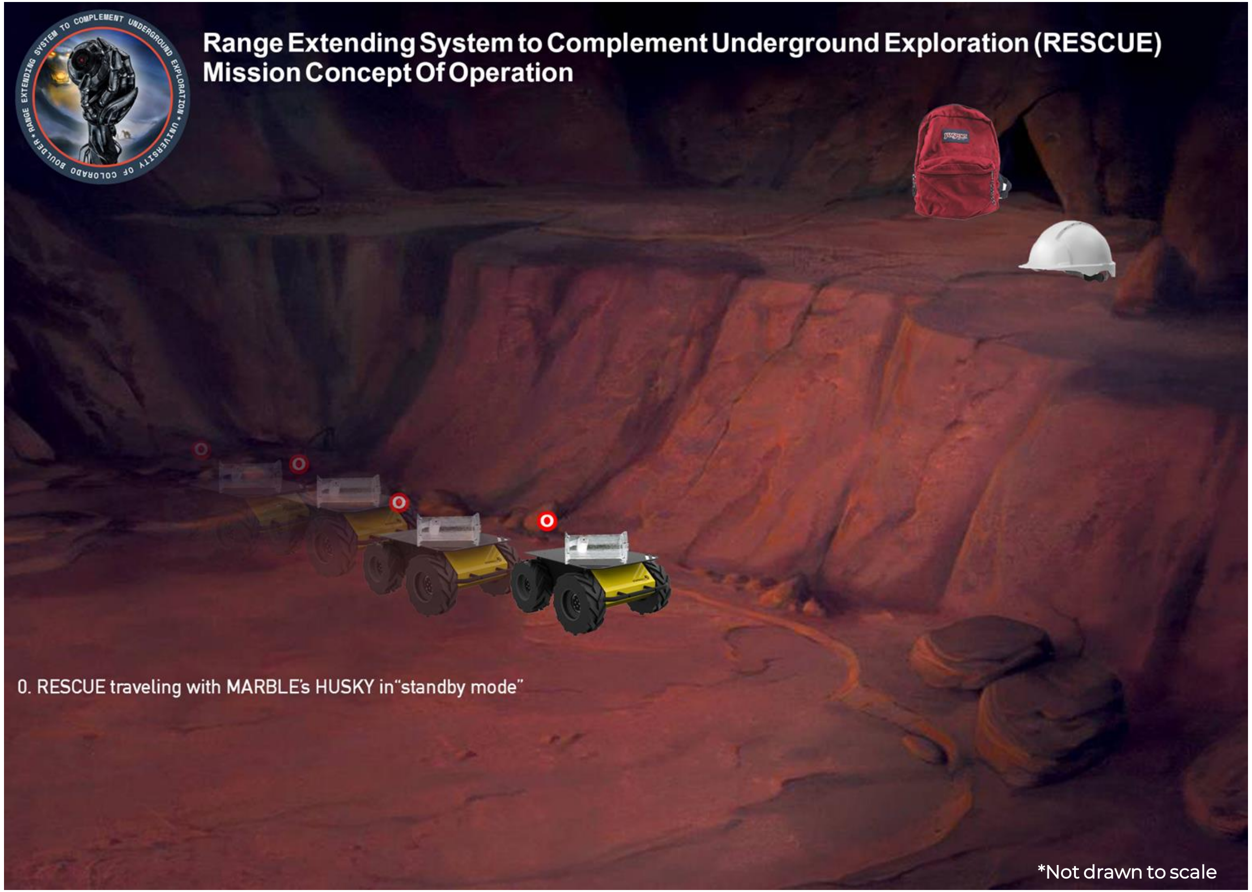
Specific Application

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

CONOPS

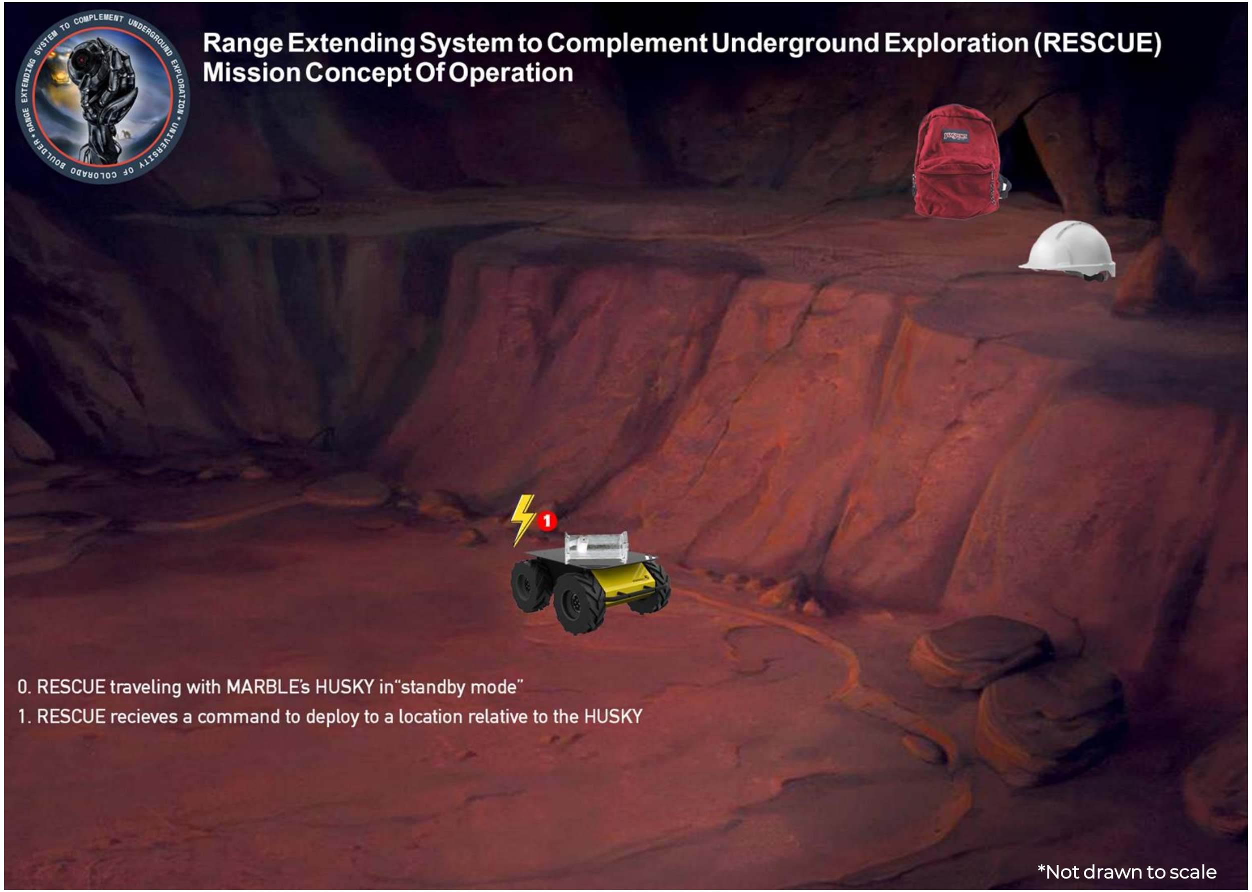


Range Extending System to Complement Underground Exploration (RESCUE)
Mission Concept Of Operation

0. RESCUE traveling with MARBLE's HUSKY in "standby mode"

*Not drawn to scale

CONOPS



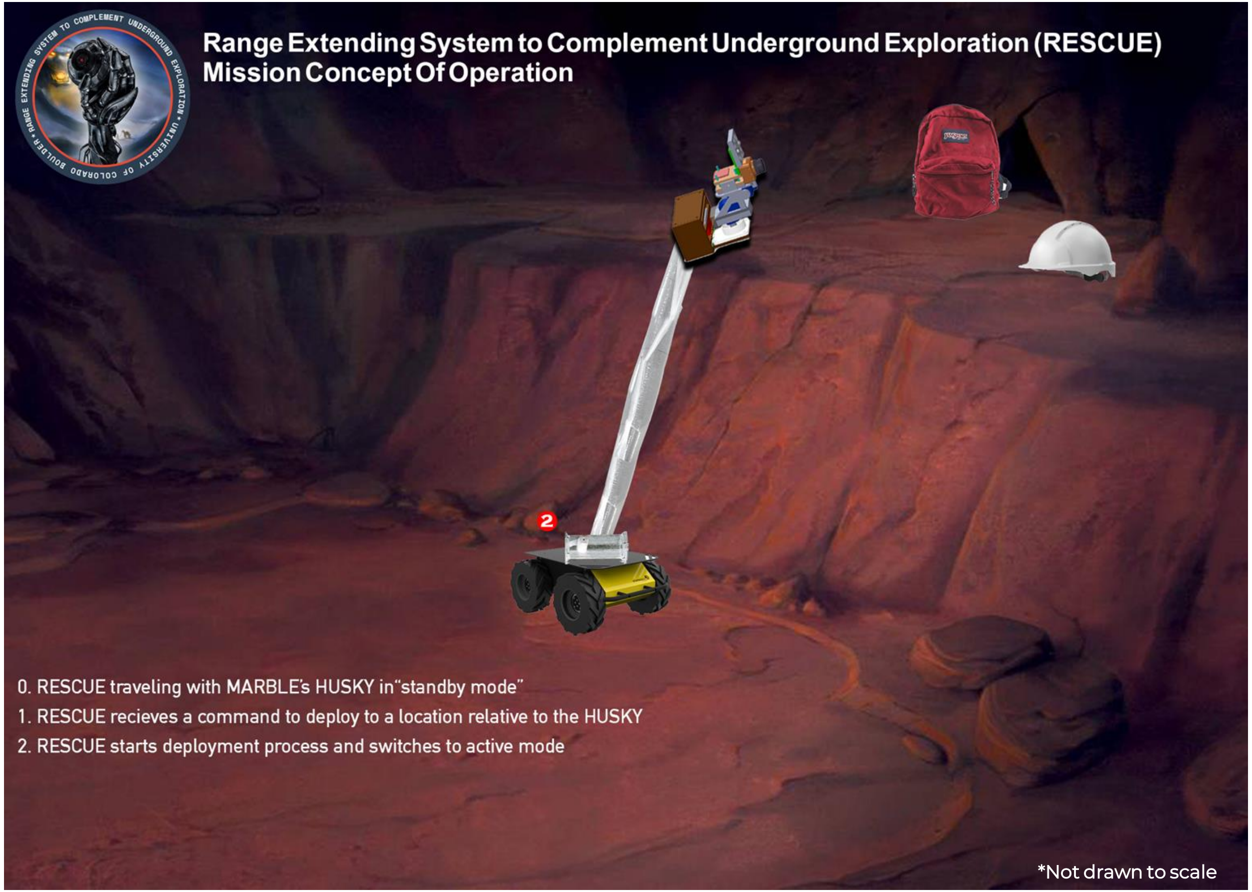
Range Extending System to Complement Underground Exploration (RESCUE)
Mission Concept Of Operation

0. RESCUE traveling with MARBLE’s HUSKY in“standby mode”

1. RESCUE recieves a command to deploy to a location relative to the HUSKY

*Not drawn to scale

CONOPS

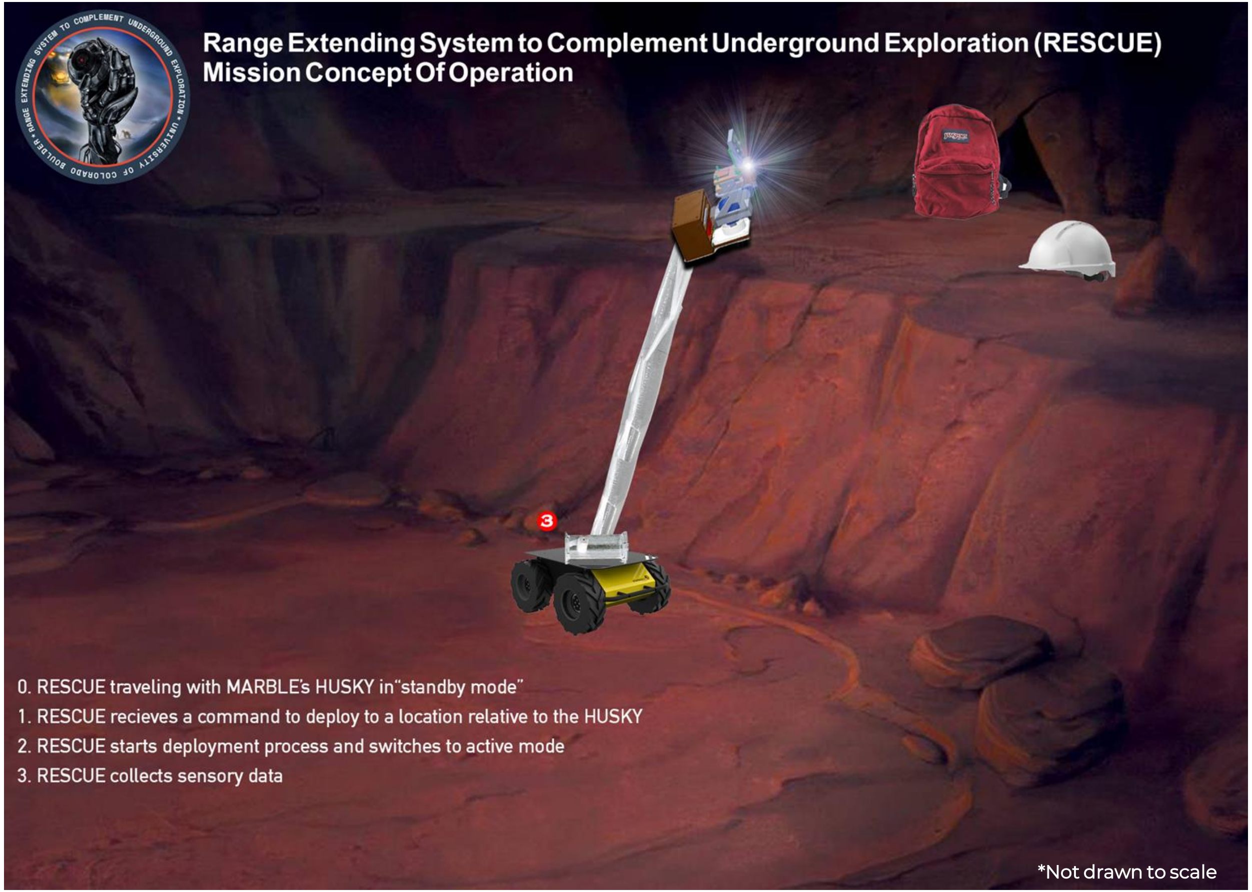


Range Extending System to Complement Underground Exploration (RESCUE) Mission Concept Of Operation

0. RESCUE traveling with MARBLE's HUSKY in"standby mode"
1. RESCUE recieves a command to deploy to a location relative to the HUSKY
2. RESCUE starts deployment process and switches to active mode

*Not drawn to scale

CONOPS



Range Extending System to Complement Underground Exploration (RESCUE) Mission Concept Of Operation

0. RESCUE traveling with MARBLE's HUSKY in"standby mode"
1. RESCUE recieves a command to deploy to a location relative to the HUSKY
2. RESCUE starts deployment process and switches to active mode
3. RESCUE collects sensory data

*Not drawn to scale

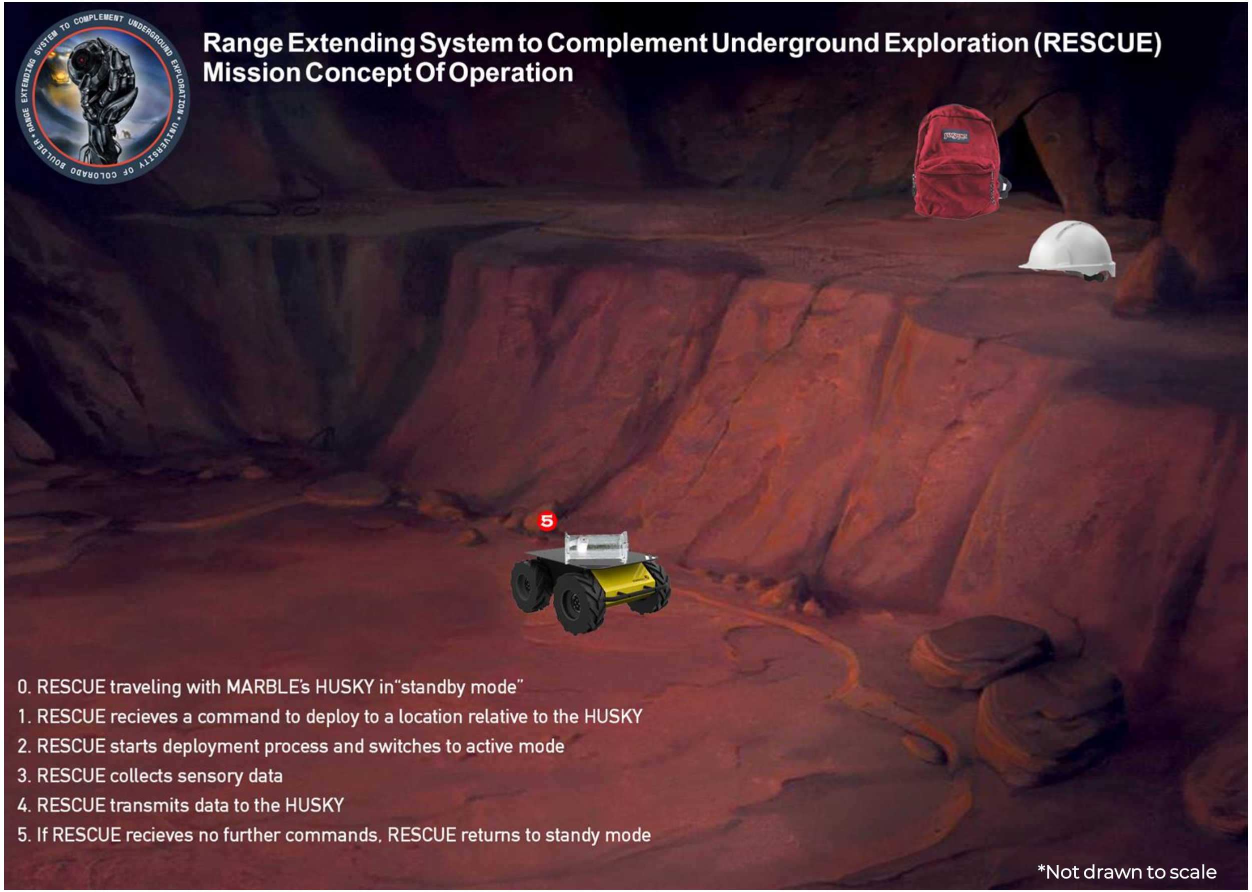
CONOPS

Range Extending System to Complement Underground Exploration (RESCUE) Mission Concept Of Operation

0. RESCUE traveling with MARBLE’s HUSKY in“standby mode”
1. RESCUE recieves a command to deploy to a location relative to the HUSKY
2. RESCUE starts deployment process and switches to active mode
3. RESCUE collects sensory data
4. RESCUE transmits data to the HUSKY

*Not drawn to scale

CONOPS

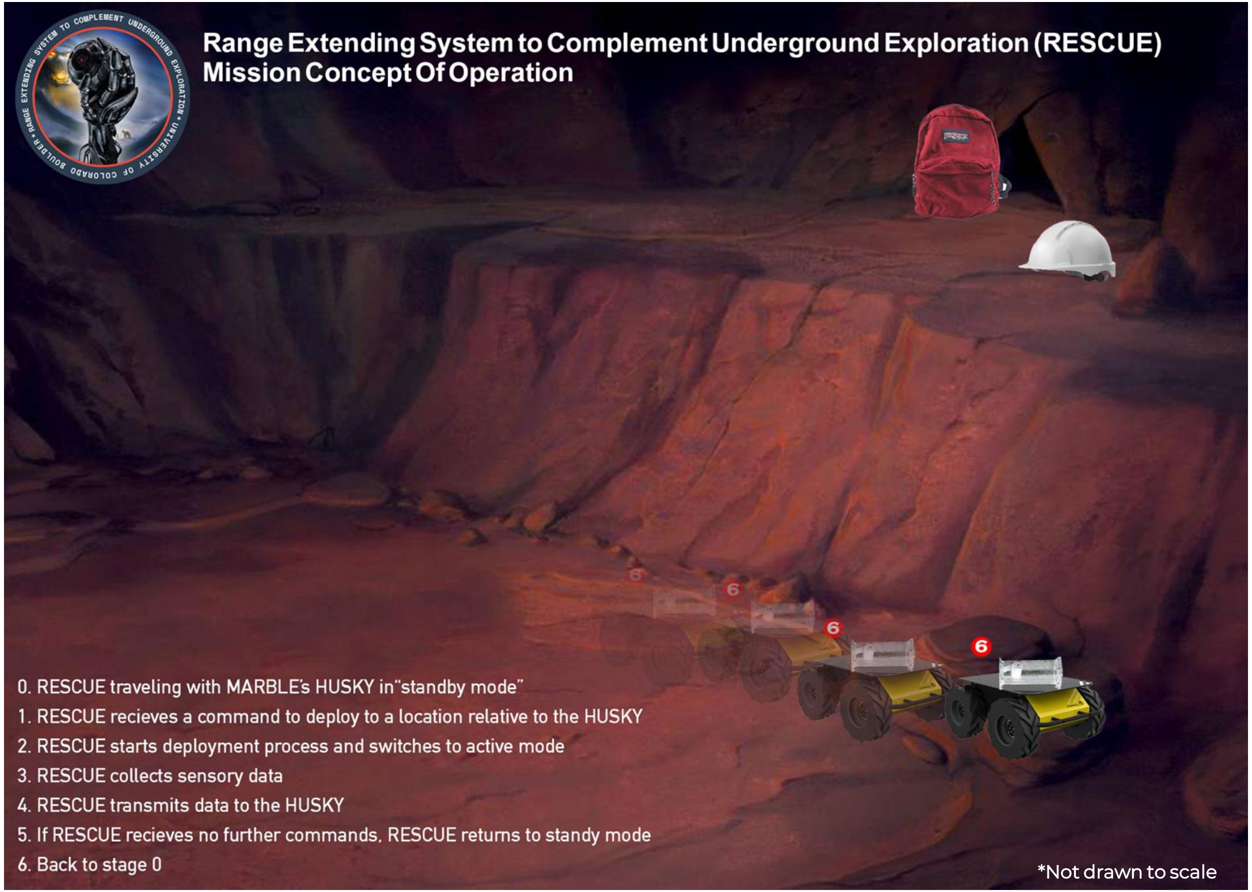


Range Extending System to Complement Underground Exploration (RESCUE) Mission Concept Of Operation

0. RESCUE traveling with MARBLE’s HUSKY in“standby mode”
1. RESCUE recieves a command to deploy to a location relative to the HUSKY
2. RESCUE starts deployment process and switches to active mode
3. RESCUE collects sensory data
4. RESCUE transmits data to the HUSKY
5. If RESCUE recieves no further commands, RESCUE returns to standy mode

*Not drawn to scale

CONOPS



Range Extending System to Complement Underground Exploration (RESCUE) Mission Concept Of Operation

0. RESCUE traveling with MARBLE's HUSKY in"standby mode"
1. RESCUE recieves a command to deploy to a location relative to the HUSKY
2. RESCUE starts deployment process and switches to active mode
3. RESCUE collects sensory data
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

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

Project Overview: High Levels of Success & CPEs

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 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).**

Project Design

- **Basic components (figure 2):**
  - Extension System: inflatable tube
  - Pressurization System: paintball tanks to provide pressurized air
  - Pointing System: base capable of pointing the extension system
  - End Effector: housing sensors (camera, CO_2 sensor, and AHRS)
- **Key characteristics:**
  - **Total Mass:** 7.453 kg (below limit)
  - **Total Power Consumption:** 272.3W (below limit)
  - **Extension distance:** 4 m (satisfies requirements)
  - **Number of Deployments:** up to 14 times.
  - **Communication:** wireless communication between RESCUE's subsystem and wired connection to the mother rover: MARBLE.
  - **Mounting space:** 15" x 18" x 12"
- **Changes since CDR/FFR:**
  - None.

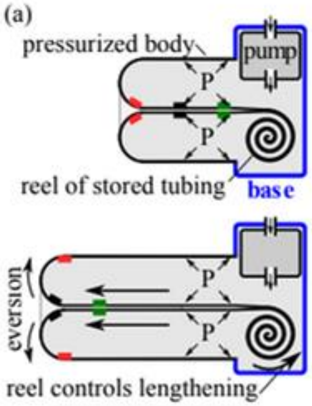


Figure 3: Schematic of the concept, courtesy of Stanford.

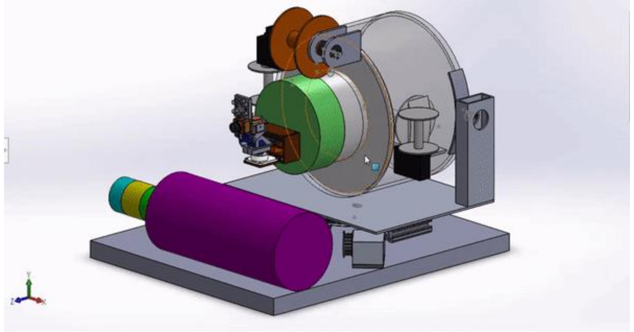
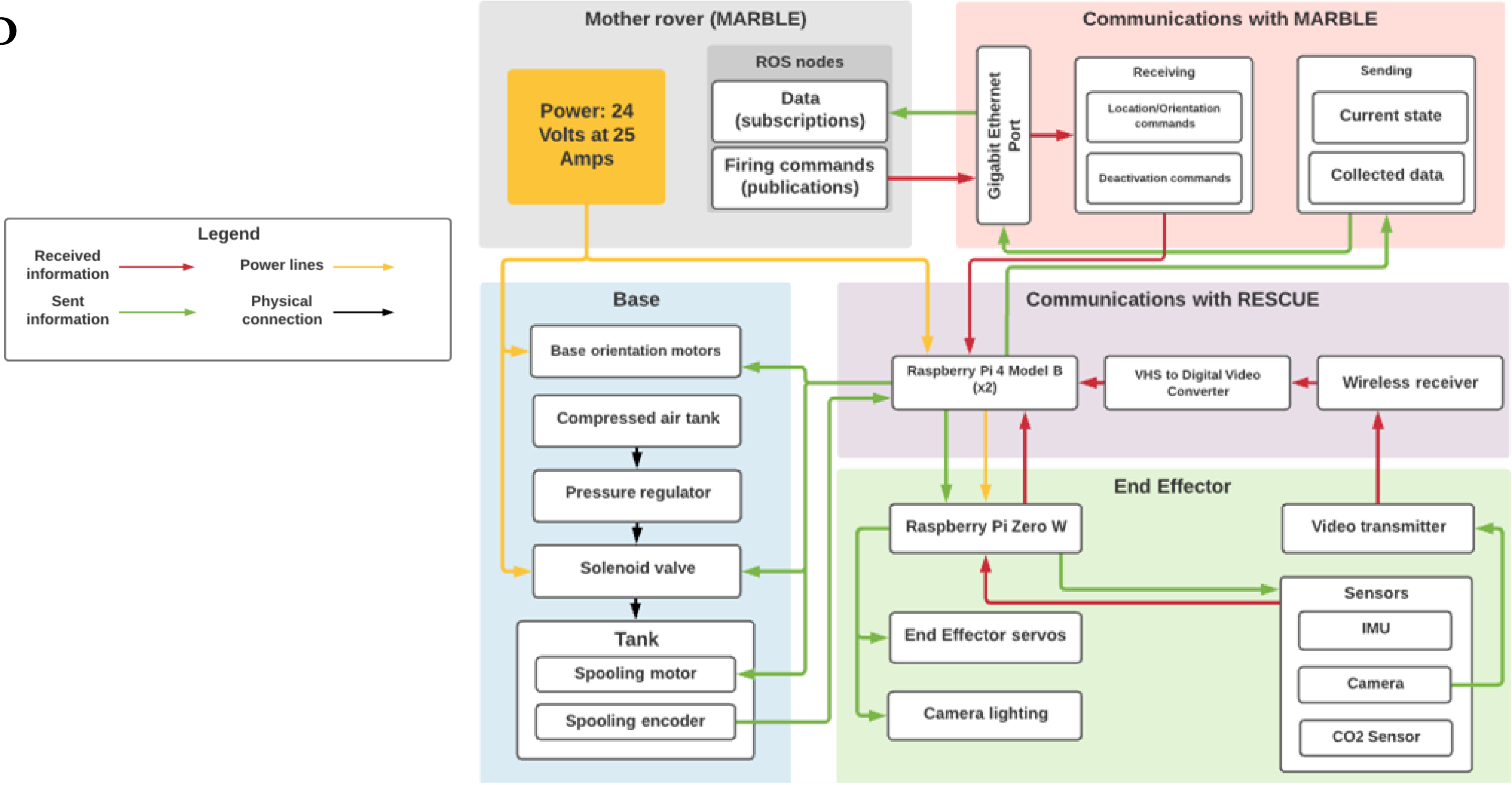


Figure 2: CAD of RESCUE's version of the same concept

Figure 1: The arm design tested by RESCUE

FBD



Legend

Received information

Power lines

Sent information

Physical connection

Mother rover (MARBLE)

Power: 24 Volts at 25 Amps

ROS nodes

Data (subscriptions)

Firing commands (publications)

Communications with MARBLE

Gigabit Ethernet Port

Receiving

Location/Orientation commands

Deactivation commands

Sending

Current state

Collected data

Base

Base orientation motors

Compressed air tank

Pressure regulator

Solenoid valve

Tank

Spooling motor

Spooling encoder

Communications with RESCUE

Raspberry Pi 4 Model B (x2)

VHS to Digital Video Converter

Wireless receiver

End Effector

Raspberry Pi Zero W

Video transmitter

End Effector servos

Camera lighting

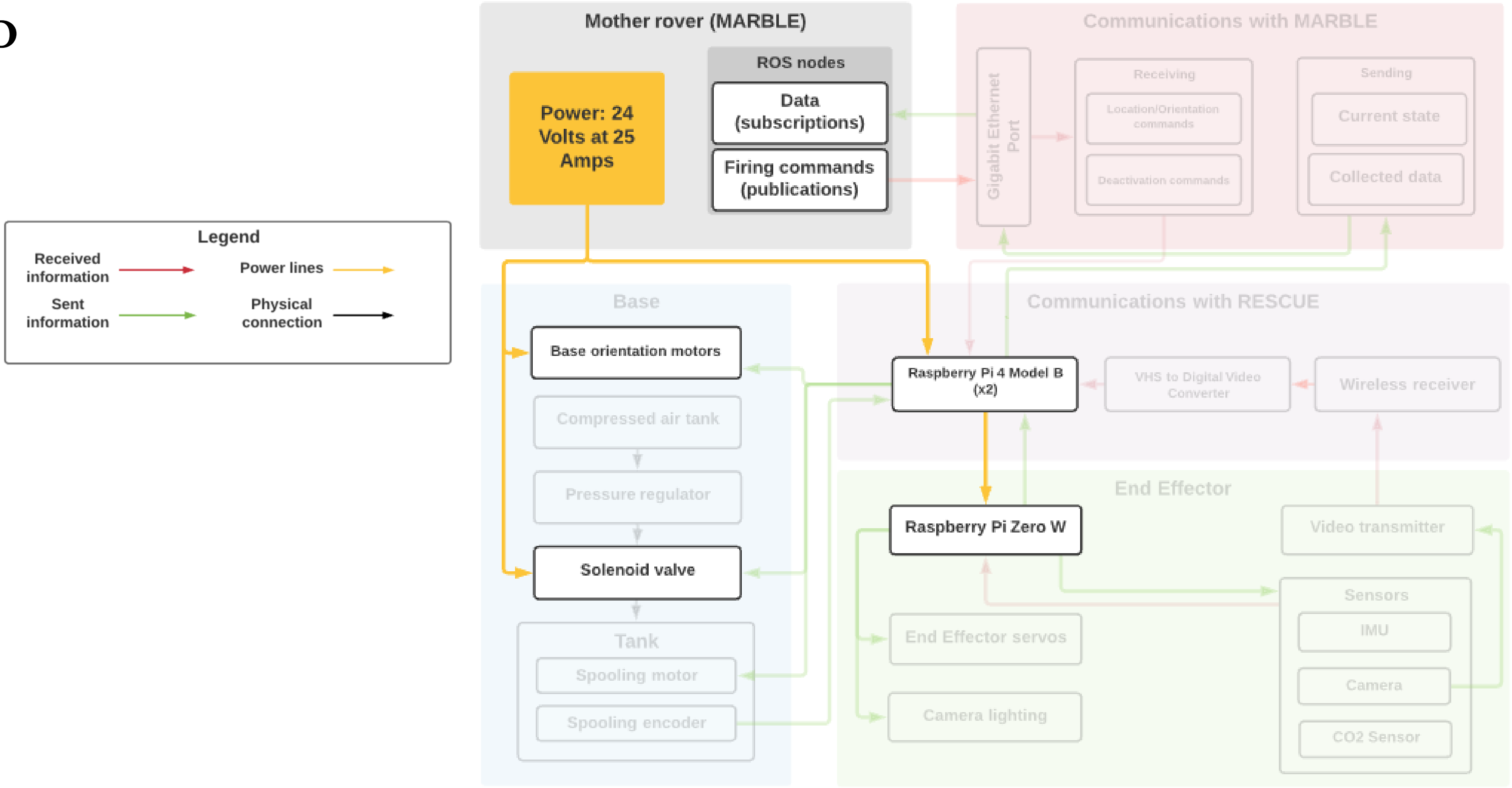
Sensors

IMU

Camera

CO2 Sensor

FBD



Legend

Received information

Power lines

Sent information

Physical connection

Mother rover (MARBLE)

Power: 24 Volts at 25 Amps

ROS nodes

Data (subscriptions)

Firing commands (publications)

Communications with MARBLE

Gigabit Ethernet Port

Receiving

Location/Orientation commands

Deactivation commands

Sending

Current state

Collected data

Base

Base orientation motors

Compressed air tank

Pressure regulator

Solenoid valve

Tank

Spooling motor

Spooling encoder

Communications with RESCUE

Raspberry Pi 4 Model B (x2)

VHS to Digital Video Converter

Wireless receiver

End Effector

Raspberry Pi Zero W

Video transmitter

End Effector servos

Camera lighting

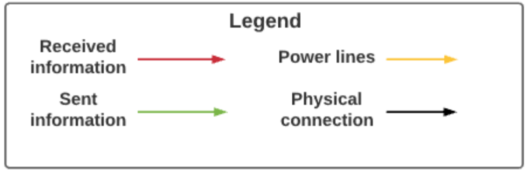
Sensors

IMU

Camera

CO2 Sensor

FBD



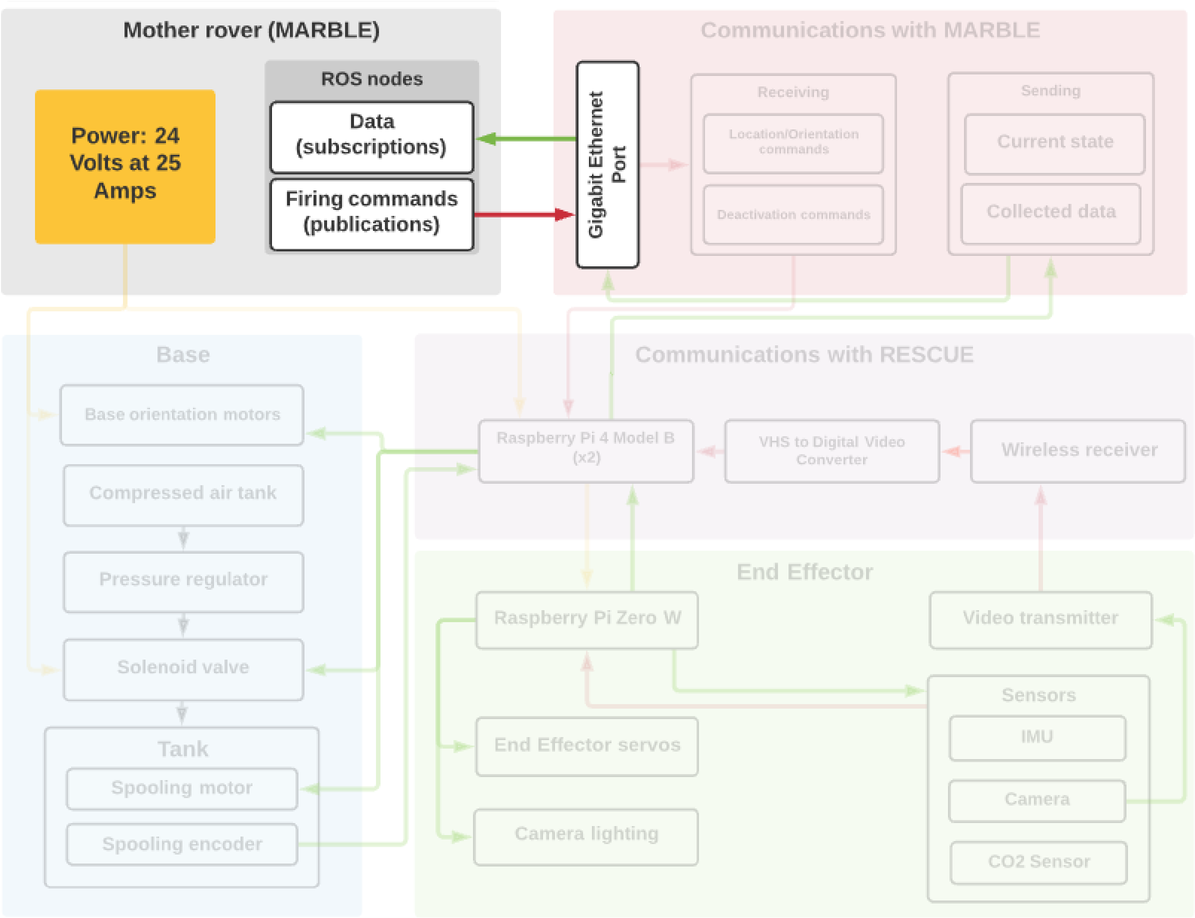
Legend

Received information

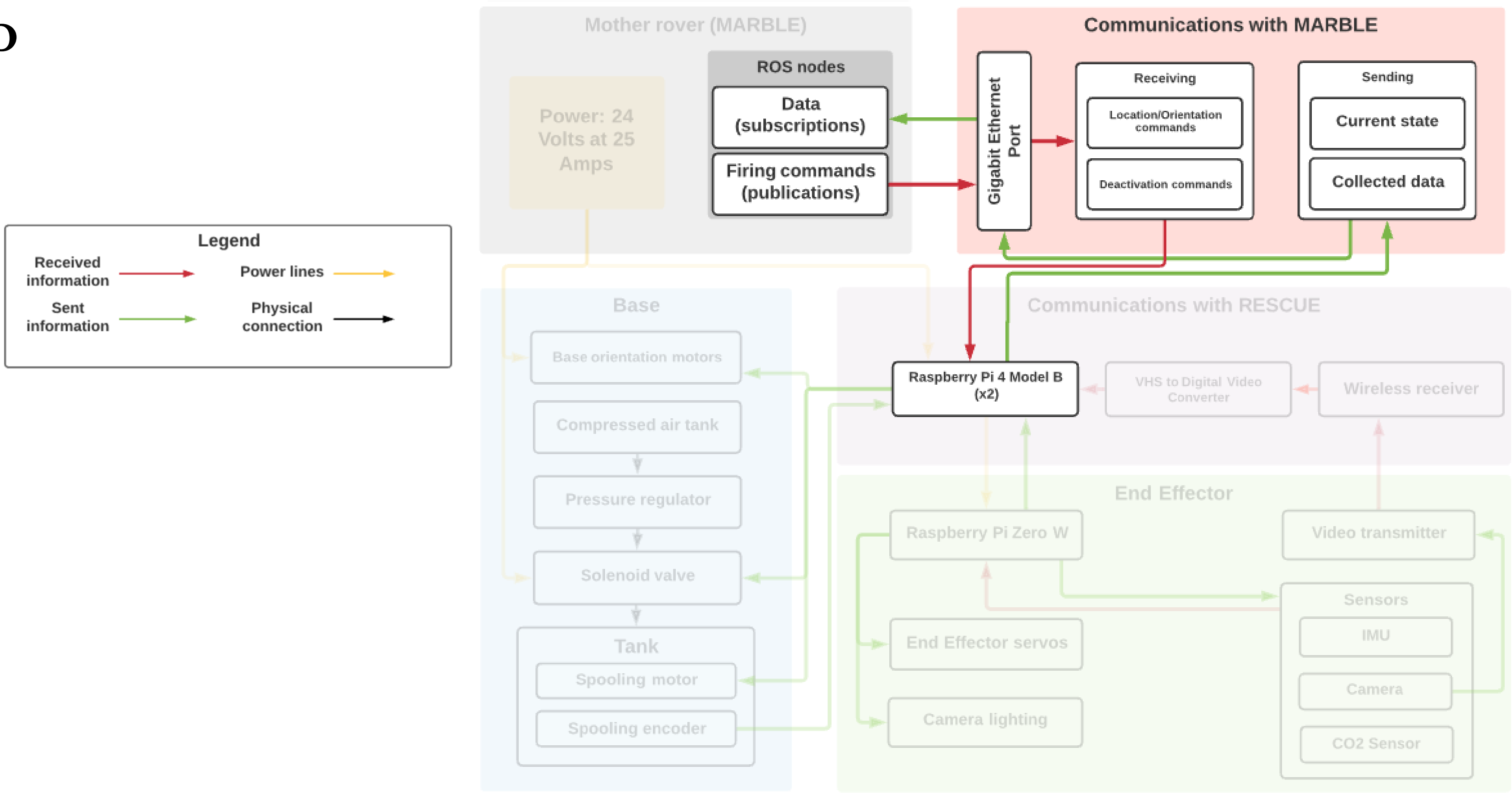
Power lines

Sent information

Physical connection



FBD



Legend

Received information

Power lines

Sent information

Physical connection

Mother rover (MARBLE)

Power: 24 Volts at 25 Amps

ROS nodes

Data (subscriptions)

Firing commands (publications)

Communications with MARBLE

Gigabit Ethernet Port

Receiving

Location/Orientation commands

Deactivation commands

Sending

Current state

Collected data

Base

Base orientation motors

Compressed air tank

Pressure regulator

Solenoid valve

Tank

Spooling motor

Spooling encoder

Communications with RESCUE

Raspberry Pi 4 Model B (x2)

VHS to Digital Video Converter

Wireless receiver

End Effector

Raspberry Pi Zero W

Video transmitter

End Effector servos

Camera lighting

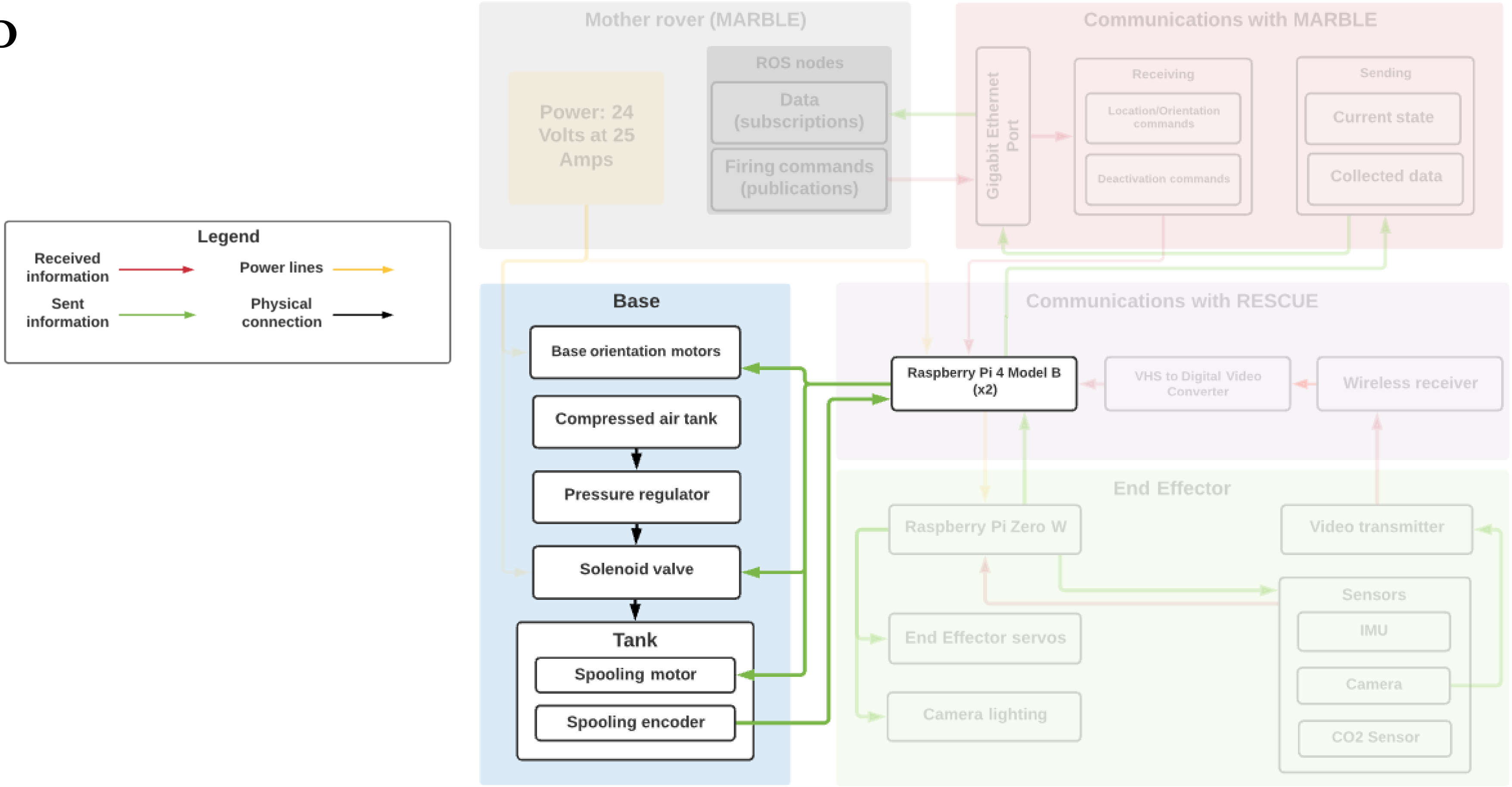
Sensors

IMU

Camera

CO2 Sensor

FBD



Legend

Received information

Power lines

Sent information

Physical connection

Mother rover (MARBLE)

Power: 24 Volts at 25 Amps

ROS nodes

Data (subscriptions)

Firing commands (publications)

Communications with MARBLE

Gigabit Ethernet Port

Receiving

Location/Orientation commands

Deactivation commands

Sending

Current state

Collected data

Base

Base orientation motors

Compressed air tank

Pressure regulator

Solenoid valve

Tank

Spooling motor

Spooling encoder

Communications with RESCUE

Raspberry Pi 4 Model B (x2)

VHS to Digital Video Converter

Wireless receiver

End Effector

Raspberry Pi Zero W

Video transmitter

Sensors

IMU

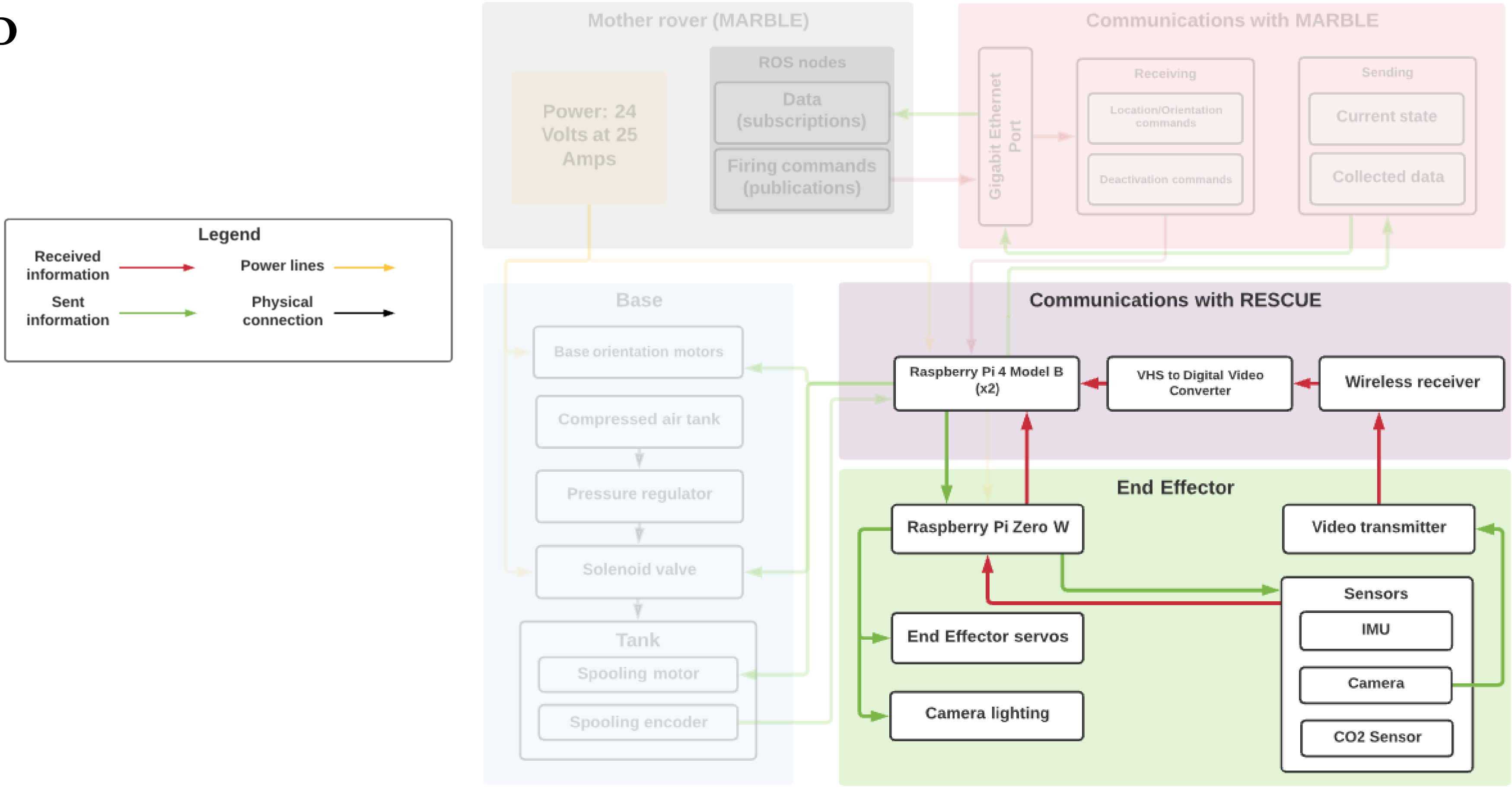
Camera

CO2 Sensor

End Effector servos

Camera lighting

FBD



Legend

Received information

Power lines

Sent information

Physical connection

Mother rover (MARBLE)

Power: 24 Volts at 25 Amps

ROS nodes

Data (subscriptions)

Firing commands (publications)

Communications with MARBLE

Gigabit Ethernet Port

Receiving

Location/Orientation commands

Deactivation commands

Sending

Current state

Collected data

Base

Base orientation motors

Compressed air tank

Pressure regulator

Solenoid valve

Tank

Spooling motor

Spooling encoder

Communications with RESCUE

Raspberry Pi 4 Model B (x2)

VHS to Digital Video Converter

Wireless receiver

End Effector

Raspberry Pi Zero W

Video transmitter

End Effector servos

Camera lighting

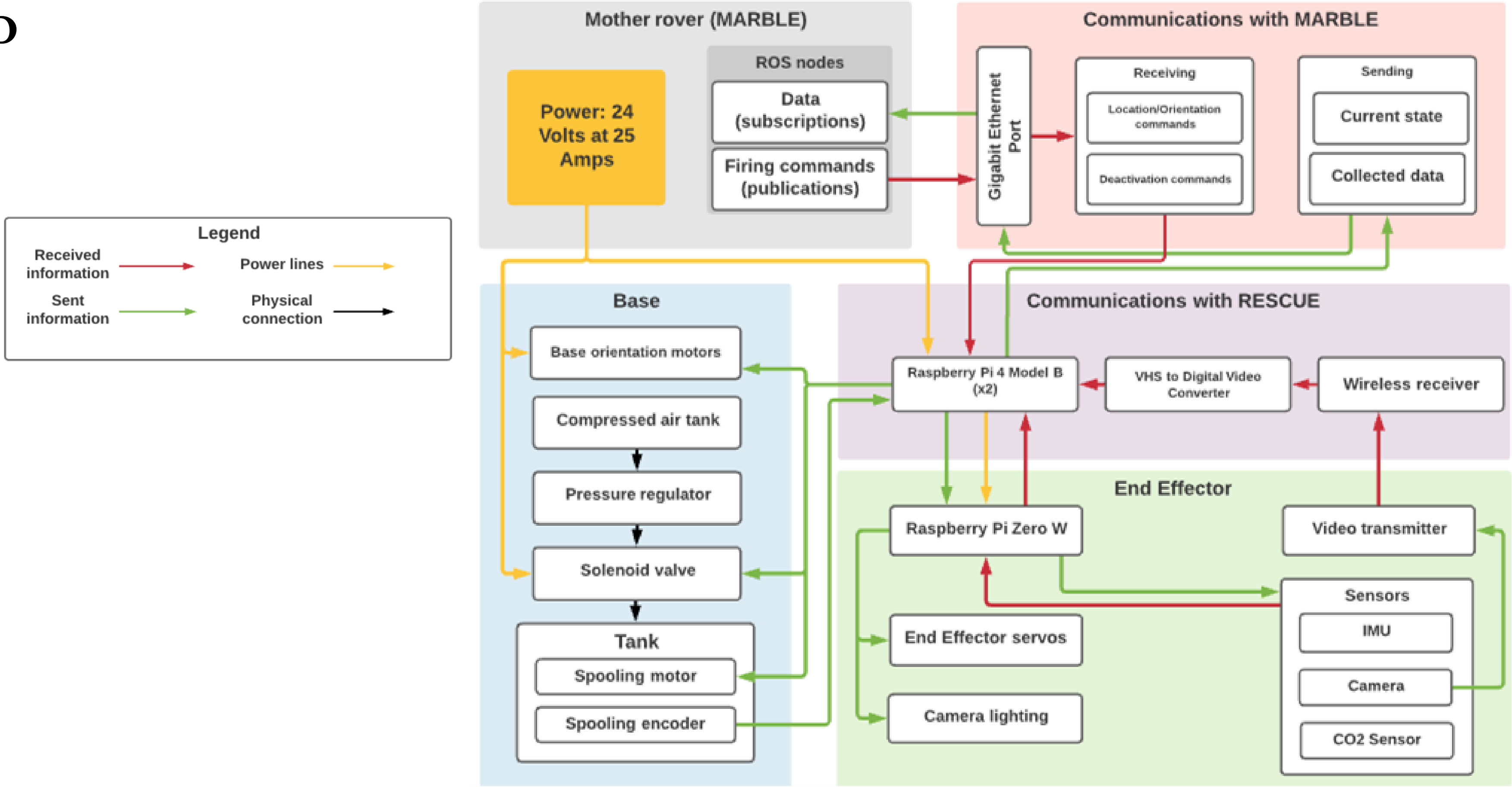
Sensors

IMU

Camera

CO2 Sensor

FBD



Legend

Received information

Sent information

Power lines

Physical connection

Mother rover (MARBLE)

Power: 24 Volts at 25 Amps

ROS nodes

Data (subscriptions)

Firing commands (publications)

Communications with MARBLE

Gigabit Ethernet Port

Receiving

Location/Orientation commands

Deactivation commands

Sending

Current state

Collected data

Base

Base orientation motors

Compressed air tank

Pressure regulator

Solenoid valve

Tank

Spooling motor

Spooling encoder

Communications with RESCUE

Raspberry Pi 4 Model B (x2)

VHS to Digital Video Converter

Wireless receiver

End Effector

Raspberry Pi Zero W

Video transmitter

End Effector servos

Camera lighting

Sensors

IMU

Camera

CO2 Sensor

Project Schedule

Project Schedule: Overview

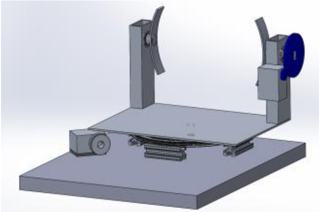


Figure 1

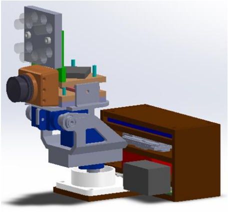


Figure 2

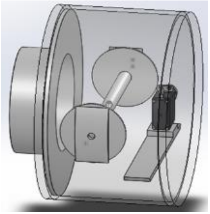
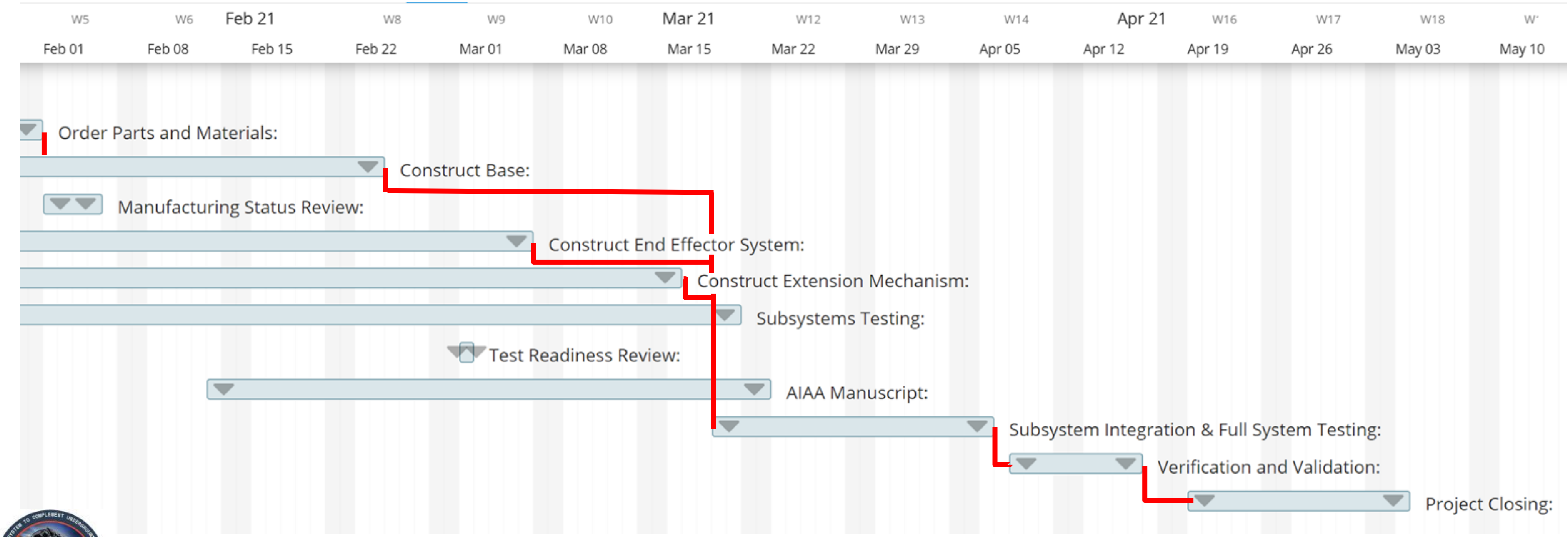
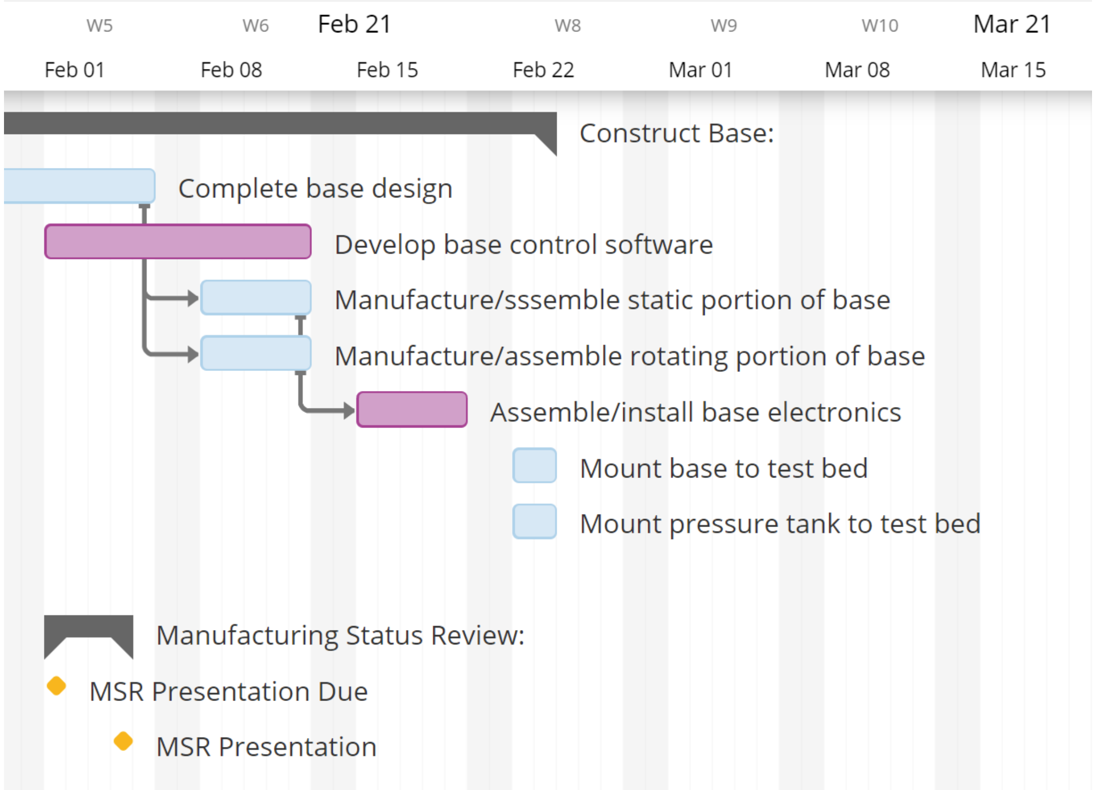


Figure 3



Project Schedule: Base Manufacturing



Construct Base:

Complete base design

Develop base control software

Manufacture/sssemble static portion of base

Manufacture/assemble rotating portion of base

Assemble/install base electronics

Mount base to test bed

Mount pressure tank to test bed

Manufacturing Status Review:

MSR Presentation Due

MSR Presentation

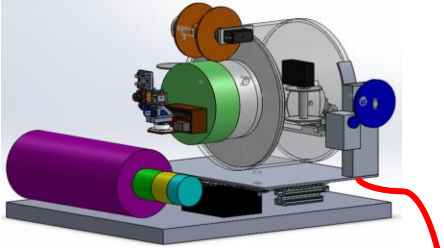


Figure 1. Complete System

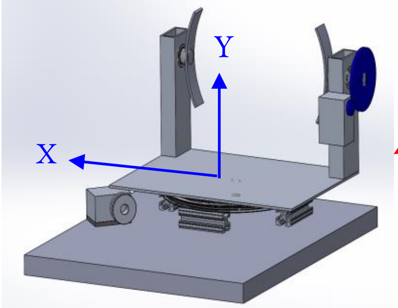
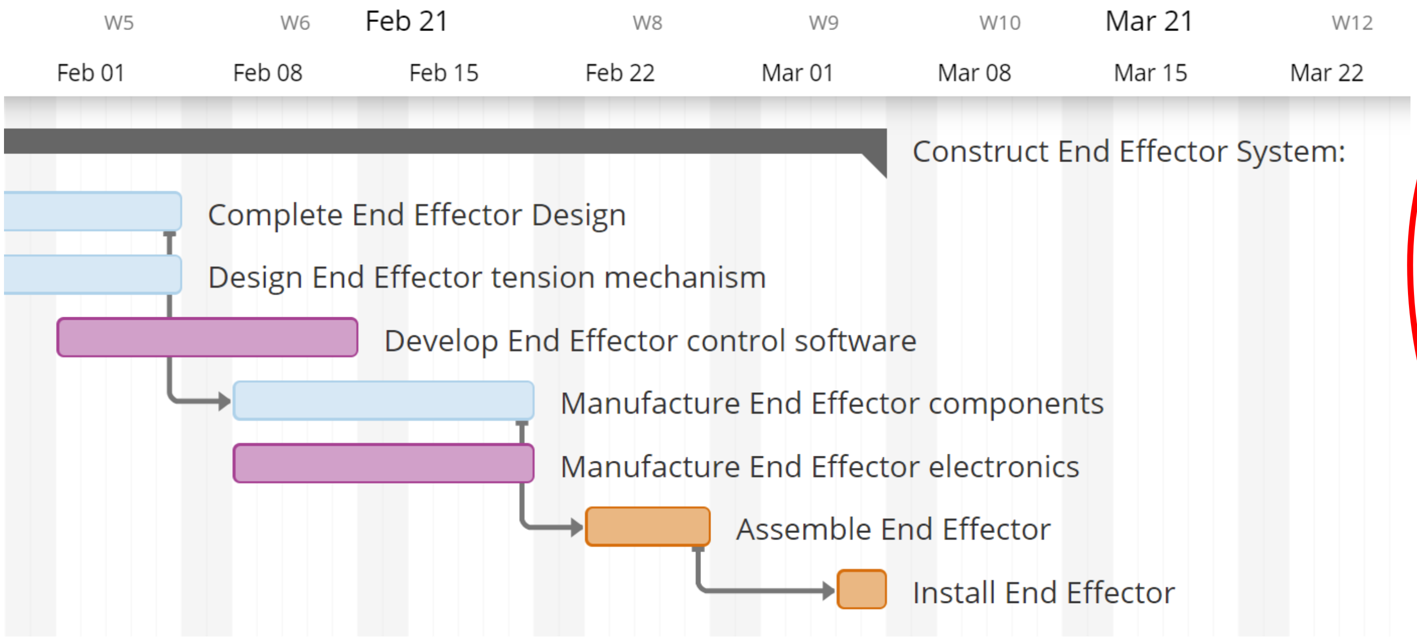


Figure 2. The rotating base

Project Schedule: End Effector Manufacturing



Construct End Effector System:

Complete End Effector Design

Design End Effector tension mechanism

Develop End Effector control software

Manufacture End Effector components

Manufacture End Effector electronics

Assemble End Effector

Install End Effector

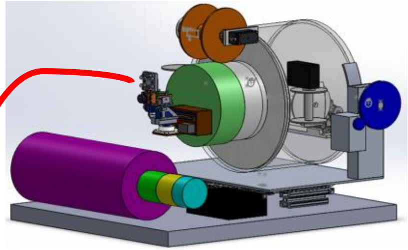


Figure 1. Complete System

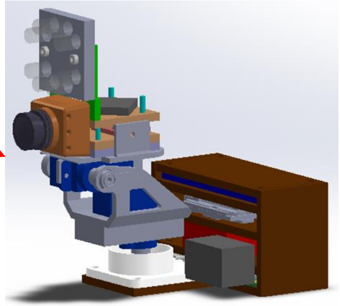
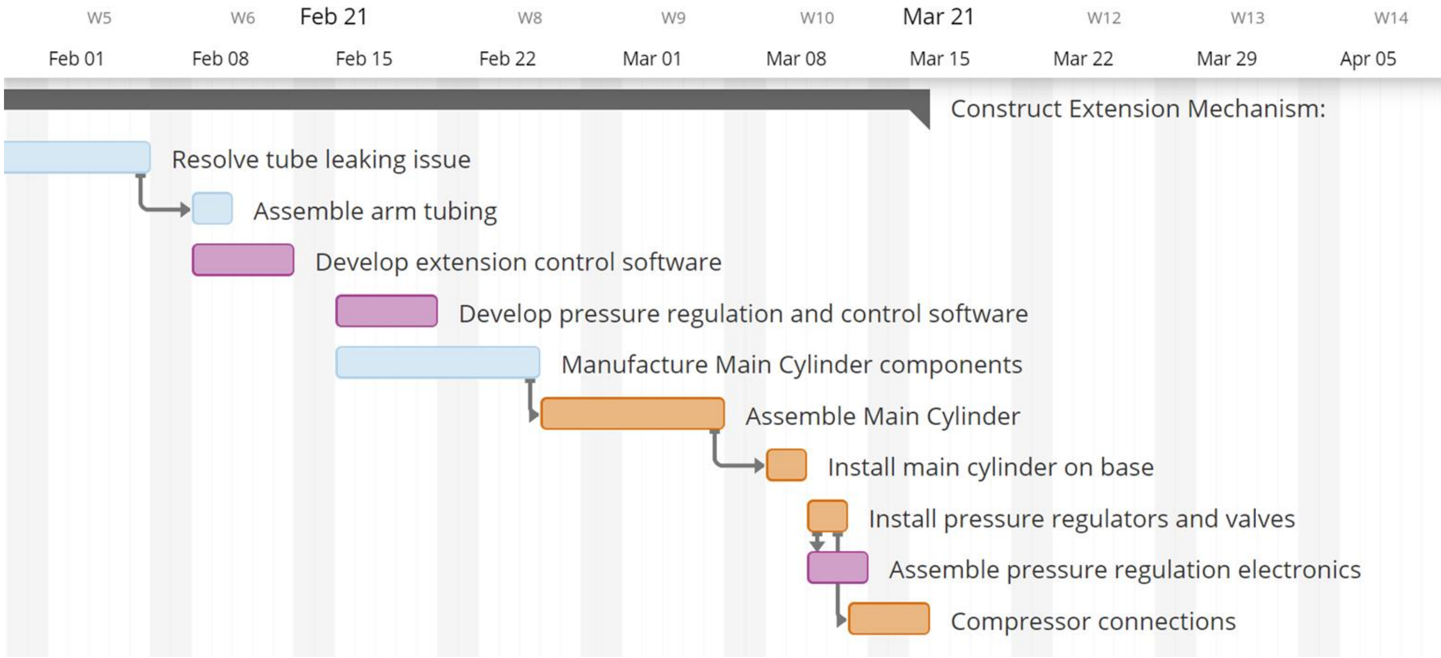


Figure 2. End Effector

Project Schedule: Extension Mechanism Manufacturing



Construct Extension Mechanism:

- Resolve tube leaking issue
- Assemble arm tubing
- Develop extension control software
- Develop pressure regulation and control software
- Manufacture Main Cylinder components
- Assemble Main Cylinder
- Install main cylinder on base
- Install pressure regulators and valves
- Assemble pressure regulation electronics
- Compressor connections

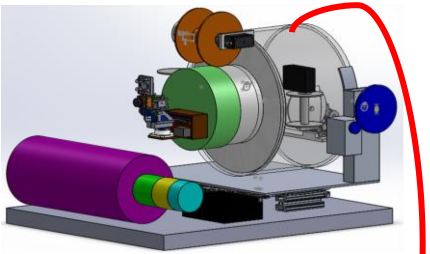


Figure 1. Complete System

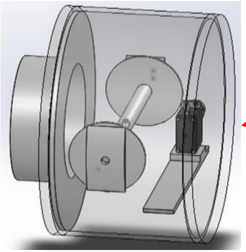
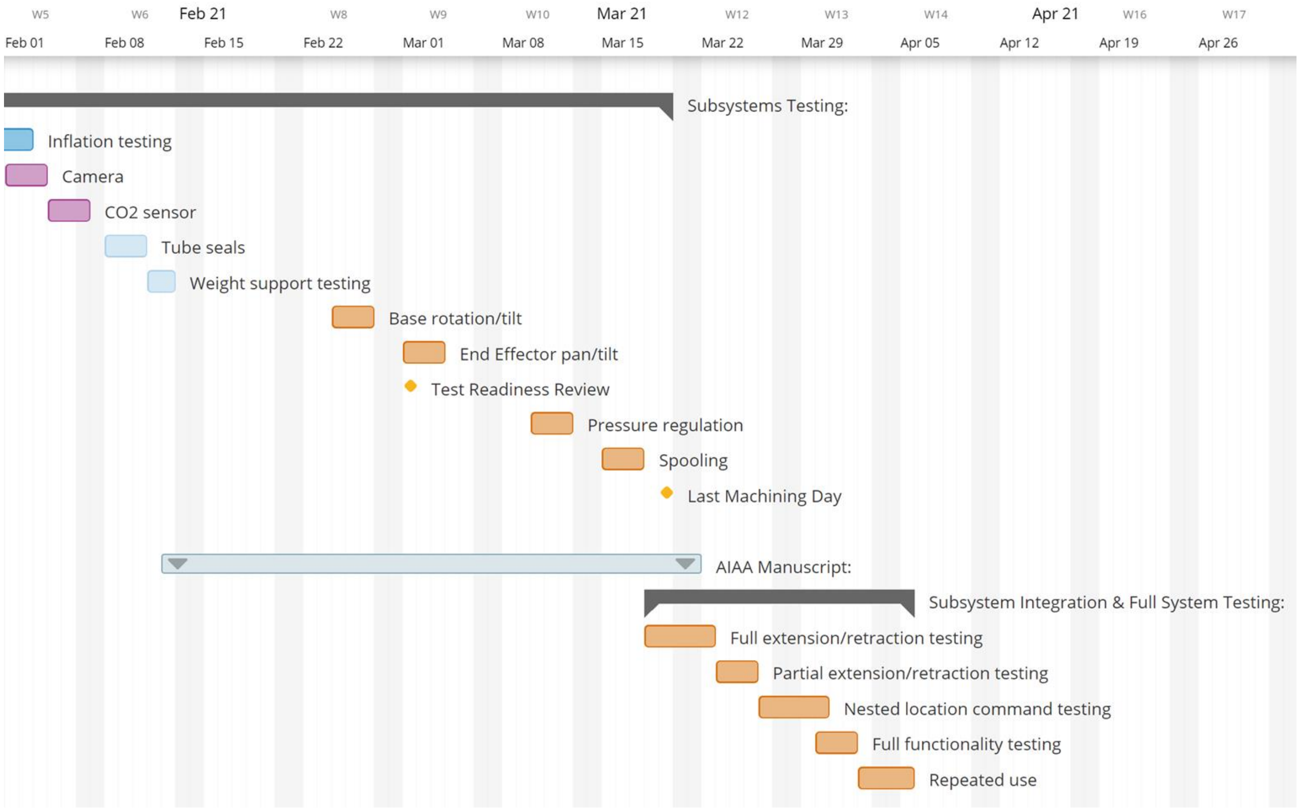


Figure 2. Main Cylinder/Material Spool Container

Project Schedule: Testing Schedule



Manufacturing: Testing Manufacturability

The beginning of the semester:

- The team conducted extensive prototyping to test the extension mechanism mechanics and the payload capacity

Fig. 1 : extension mechanism

Fig. 2 : material failure

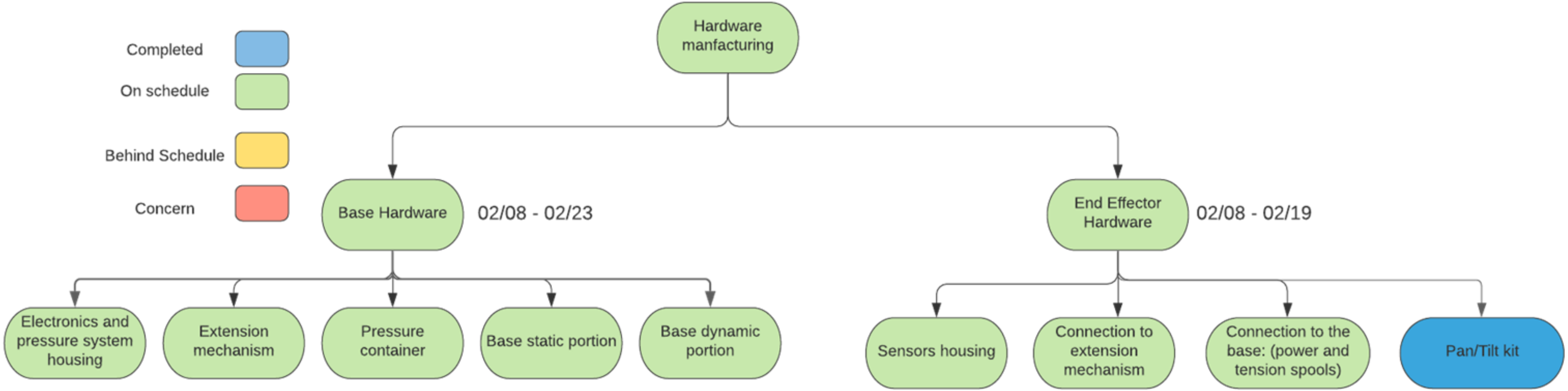
Fig. 3 : payload capacity

Main outcomes:

- Understood the mechanisms of extension and time of extension.
- Due to material inaccurate properties (from manufacturer), the tubes would burst at a lower pressure than expected.
- Bursting at lower pressure means that RESCUE cannot support the mass at the end of the arm.
- Currently in the process of purchasing material from another supplier that provides material with more technical details.
- The process of prototyping took long time because the team could not access necessary tools in timely manner due to COVID

Manufacturing: Hardware

Hardware Manufacturing: Overview



Completed 🟦

On schedule 🟩

Behind Schedule 🟨

Concern 🟥

Hardware manfacturing

- Base Hardware 02/08 - 02/23
  - Electronics and pressure system housing
  - Extension mechanism
  - Pressure container
  - Base static portion
  - Base dynamic portion
- End Effector Hardware 02/08 - 02/19
  - Sensors housing
  - Connection to extension mechanism
  - Connection to the base: (power and tension spools)
  - Pan/Tilt kit

- 33.33% will be purchased:
  - Within budget limits
- 66.67% will be manufactured
  - **Facility needed**: machine shop, and 3D printer (3D printer is available off-campus for the team to use with proper health precautions)

Hardware Manufacturing: Material Spool Container

Functionality:	- Pressurizes to 48.3 kPa (7 psi) to evert arm tube - Contains material spooling system - **End Cap Pressurization**: - Design point: 21 psi (144.8 kPa); (Operational 7 psi (48.3 kPa), 3 FOS) - **Main Tube Pressurization:** - Design point: 8.4 psi (57.9 kPa); (Operational 7 psi (48.3 kPa), 3 FOS)
Integration/Access:	- Clamped into base pivot/rotation system (backup slides) - Arm material sealed to nozzle end - Material spooling system installed during initial assembly
Materials/Procurement:	- 0.953 cm (0.375 in.) cast acrylic caps - 119mm (9.375 in.) OD PVC tube - Glenmarc G5000 Epoxy: 7600 psi (52.4 MPa) - PLA printed material nozzle - Pressurization connections (quick disconnect)

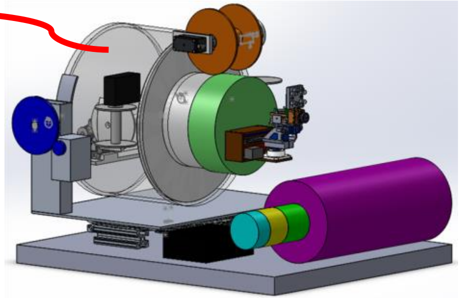


Figure 1. Complete System

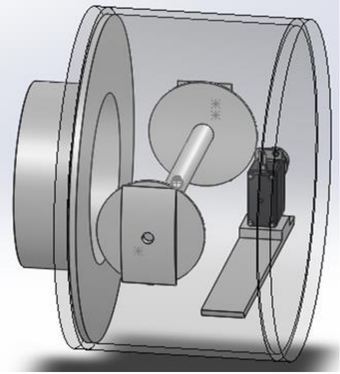


Figure 2. Material Spool Container

Figure 3. Material Spooling Example (Credit: Stanford CHARM Lab)

Hardware Manufacturing: Material Spool Container, Cont.

Manufacturing:	- Main tube: jigsaw cut to length from 122cm section - Endcaps: Epilog Fusion M2 laser cut - Nozzle: LulzBot Taz 6 printed - Nozzle-material seal: TBD - Epoxy sealed endcaps/nozzle connections
Tolerances:	- Airtight epoxy sealing for endcaps/nozzle - ± 1mm endcap radii
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

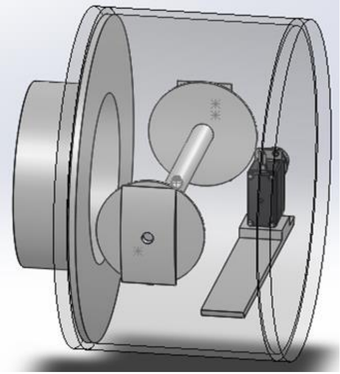
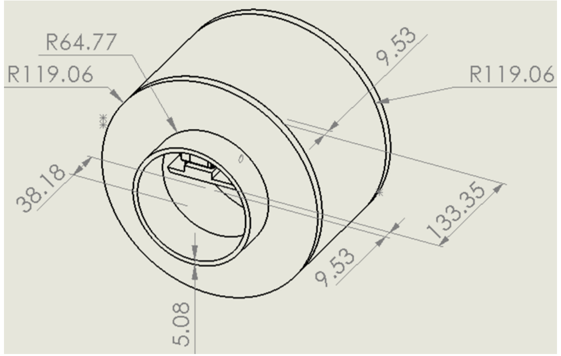


Figure 1. Material Spool Container

Figure 2. Material Spool Container Dim. (mm)



Hardware Manufacturing: Extension mechanism (Material LDPE)

Functionality:	**The material that makes the body of the robotic arm. Made out of LDPE**
Integration/Access	- Mounted to a spool inside the pressure container - Connects to the nozzle outside the pressure container.
Materials/Procurement	- 6 Mil LDPE tubes to be bought from vendors. - Theoretically should be tolerate up to 138 kPa (20 psi)
Manufacturing	- Material procured from manufacturer and inverted and attached to the spool via glue and to the nozzle via tape.
Challenges	- Finding a material that tolerates high pressures and vendors that provide more technical details in small quantities.
Manufacturing Status	- The first patch obtained bursted at a lower pressure than expected - Currently ordered a new material from a different supplier that has more technical details.

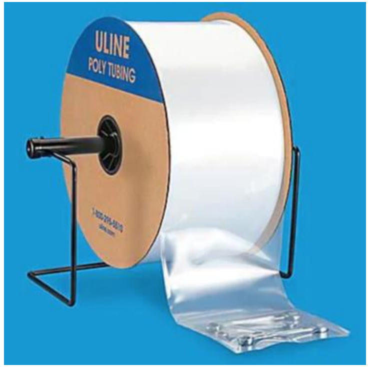


Figure 1: LDPE tubing from the original supplier ULINE

6 Mil Black Poly Tubing

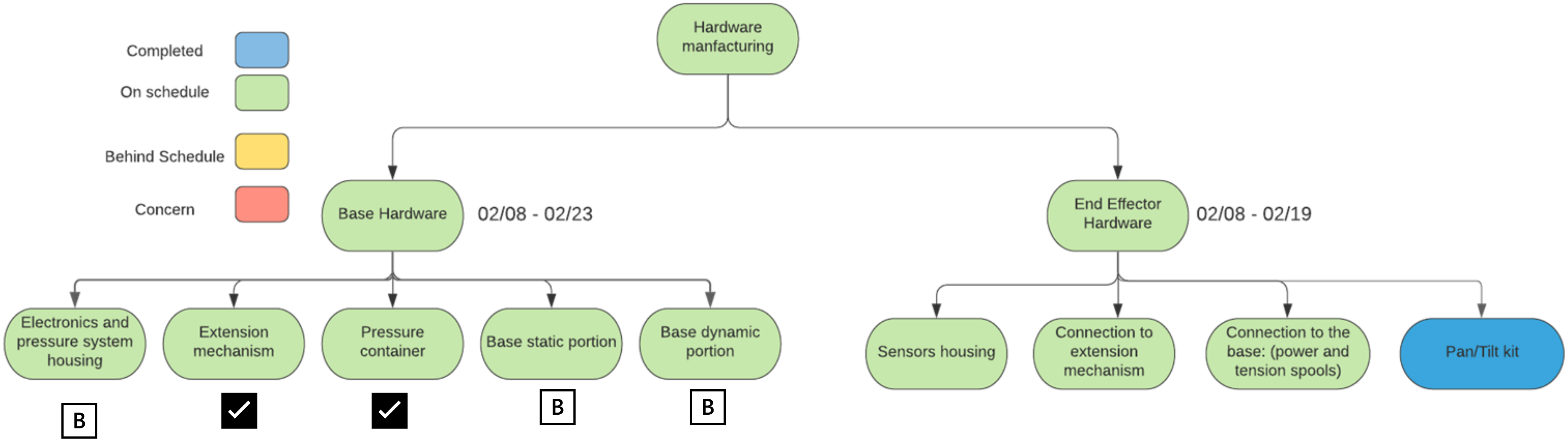
.006 Black Poly Tubing on Rolls

Constructed of super heavy duty 6 mil black Low Density Polyethylene (LDPE) film. Opaque, all virgin poly is great for light-sensitive products. Neatly wound on a 3 core with 1 diameter core plug. Manufactured to exact specification to ensure even wall thickness. Can be heat sealed, tied, stapled or taped shut. See our Tubing Dispensers and Thermal Sealers for making your own custom static control bags.

- Extended shelf life
- Tensile strength: 2000 PSI.
- Tearing strength: 400 PSI.
- Elongation (MD%): greater than 150
- Dart impact - 250 to 700 gms
- Burst (Mullen) - 20 to 60 PSI.
- **Heat Sealing Properties:**
- Temperature 250 to 375 degrees Fahrenheit.
- Time 0.5 to 3.5 seconds.
- Pressure 30 to 70 PSI.

Figure 2: New LDPE tubing from International Plastics Inc. with more technical information

Hardware Manufacturing: Overview



Completed 🟦
On schedule 🟩
Behind Schedule 🟨
Concern 🟥

Hardware manfacturing

Base Hardware 02/08 - 02/23

- Electronics and pressure system housing B
- Extension mechanism ✓
- Pressure container ✓
- Base static portion B
- Base dynamic portion B

End Effector Hardware 02/08 - 02/19

- Sensors housing
- Connection to extension mechanism
- Connection to the base: (power and tension spools)
- Pan/Tilt kit

B = Backups
✓ = covered in main presentation

Hardware Manufacturing: End Effector Sensor Mounting

Functionality:	- Mechanical assembly holding end effector sensors/electronics in place
Integration/Access	- Screwed to endcap - Power wired to base - Open assembly (unsealed, easy sensor access)
Materials/Procurement	- 1.75 mm PLA - End Effector Electronics/Sensors - Fasteners
Manufacturing	- LulzBot Taz 6 3D Printer (1.75mm PLA) - Hand Assembly, fastener hole drilling - Electronics wiring
Tolerances	- 3mm printed part thickness (Taz 6, 1.75mm PLA) - 2mm M2 fastener holes
Challenges	- Fastener length selection
Manufacturing Status	- **In Progress:** identifying fastener options to minimize cost (M2 screw standardization)

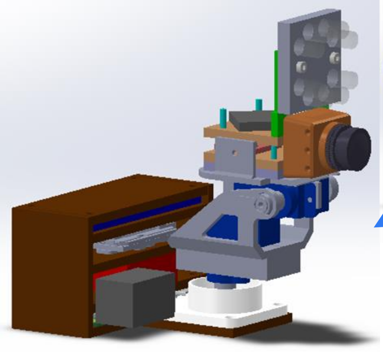


Figure 2. End Effector

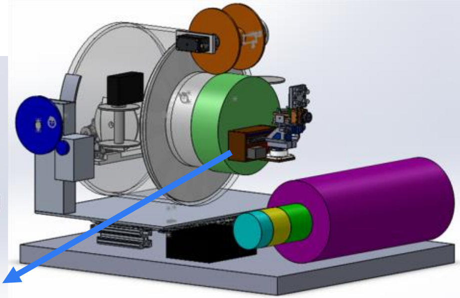


Figure 1. Complete System

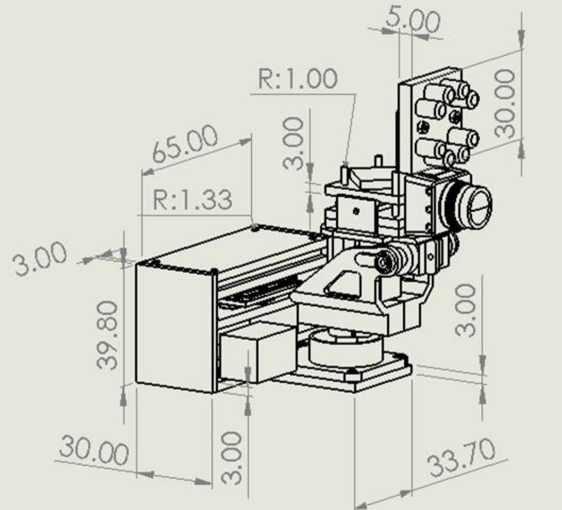


Figure 3. End Effector Dim. (mm)

Hardware Manufacturing: Tension System

Functionality:	- Provides a tension force on the end cap, holding the end effector on the tip of the arm at all times.
Integration/Access	- Mounted to material spooling container
Materials/Procurement	- 2 x HSR-2645CRH Servos - Nylon fishing line - Glenmarc G5000 Epoxy - PLA printed spools
Manufacturing	- Epoxy seal one end of the fishing line to the spool, measure and wrap 4 meters of fishing line - Epoxy seal the spools to the servo heads - Remove mounting brackets from servo (cut off with X-acto knife) so that the side is smooth - Epoxy seal the smooth side of the servos to either side of the material spooling container
Challenges	- Ensuring sufficient contact area between the round container and flat servo
Manufacturing Status	- Planned, with secondary system being designed (more detail in backup slides)

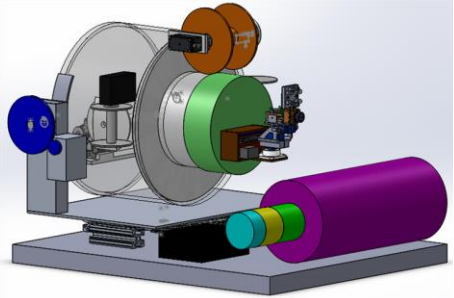


Figure 1. Complete System

Figure 2: HSR-2645CRH Servo

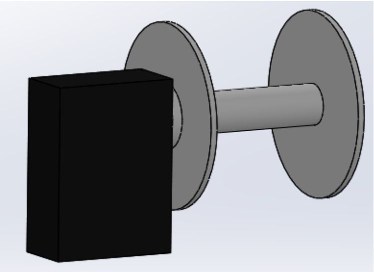


Figure 3: Servo and spool connected

Hardware Manufacturing: Power Wire Spooling

Functionality:	- Spools out end effector power and ground wires as arm extends
Integration/Access	- Unsealed, outside of arm - Mounted to material spooling container
Materials/Procurement	- 5A, 22mm Slip Ring - 20 AWG Power/Ground Wires - Parallax 900-00360-ND continuous rotation servo - Spool (3mm PLA) - Servo/Slip Ring Mounts (3mm PLA)
Manufacturing	- LulzBot Taz 6 printed parts - Slip ring/servo/power/ground connections soldered - Assembly by hand
Tolerances	- 3mm min. PLA part dimensions (Taz 6, 1.75mm filament)
Challenges	- Software for spooling rate/servo control - Mounting dependence on material spool container
Manufacturing Status	- Planned, mounting dependence will require redesign

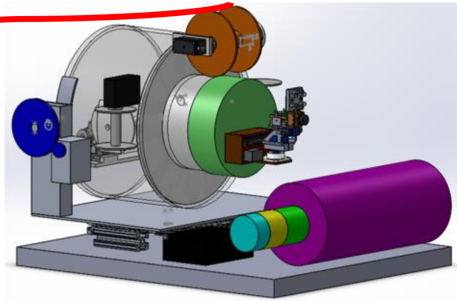


Figure 1. Complete System

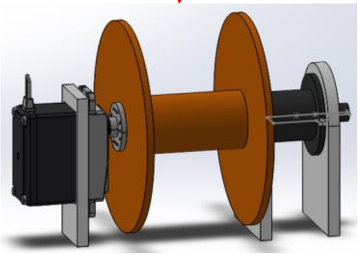


Figure 2. Power Spooling System (without wires)

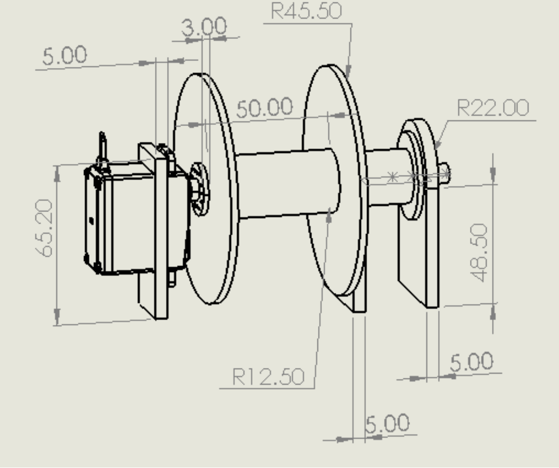
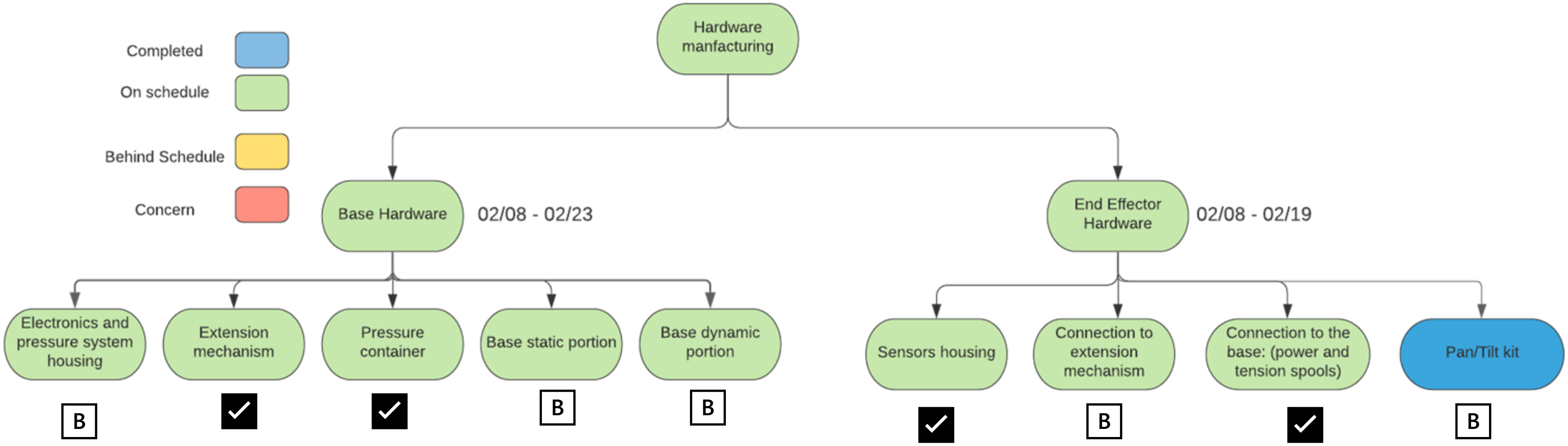


Figure 3. Power Spooling System Dim. (mm)

Hardware Manufacturing: Overview



Completed 🟦
On schedule 🟩
Behind Schedule 🟨
Concern 🟥

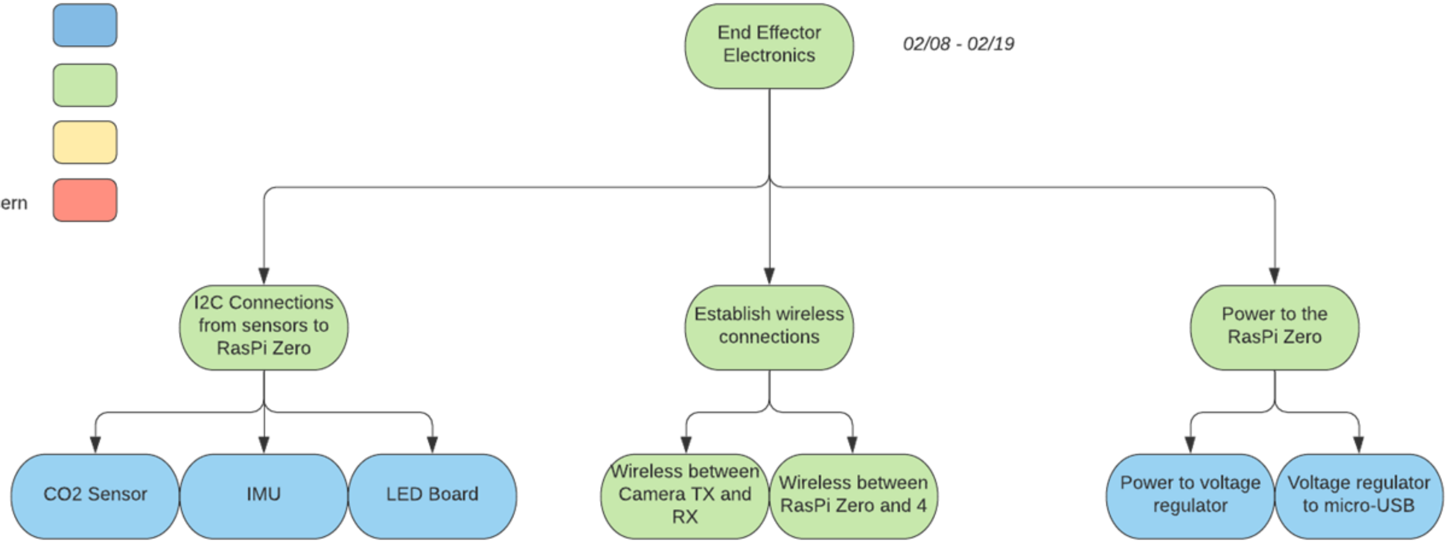
- Hardware manfacturing
  - Base Hardware 02/08 - 02/23
    - Electronics and pressure system housing B
    - Extension mechanism ✓
    - Pressure container ✓
    - Base static portion B
    - Base dynamic portion B
  - End Effector Hardware 02/08 - 02/19
    - Sensors housing ✓
    - Connection to extension mechanism B
    - Connection to the base: (power and tension spools) ✓
    - Pan/Tilt kit B

B = Backups
✓ = Covered in Main Presentation

Manufacturing - Electronics

Electronics Overview: End Effector

Complete	🟦
On Schedule	🟩
Behind	🟨
Cause for Concern	🟥



End Effector Electronics

02/08 - 02/19

I2C Connections from sensors to RasPi Zero

Establish wireless connections

Power to the RasPi Zero

CO2 Sensor

IMU

LED Board

Wireless between Camera TX and RX

Wireless between RasPi Zero and 4

Power to voltage regulator

Voltage regulator to micro-USB

Electronics Manufacturing: Wireless Connections

Component:	Wireless Connection Between FPV Camera and Base Receiver	Wireless Connection Between RasPi Zero and RasPi 4
Functionality (purpose):	Transmit the analog (NTSC) video data from the TX on the end effector to the RX on the base.	Transmit the data from the CO2 and IMU to the base Raspberry Pi 4.
Manufacturing process	Purchase the wireless TX and RX.	Purchase the Raspberry Pi Zero W and Raspberry Pi 4.
Points of integration (connects to what?)	Integrates via 5.8 GHz (5 band 40 channel) wireless.	Integrates via IEEE 802.11n WLAN.
Used tools/machines	N/A	N/A
Expected challenges	Selecting a channel that will not interfere with MARBLE.	Integrating the Message Queuing Telemetry Transport (MQTT) broker.
Manufacturing status	Both the TX and RX have been purchased and received.	Both the Raspberry Pi Zero W and Raspberry Pi 4 have been purchased and received.

Wireless Data Budget for Video Transmission:

- NTSC analog video transmitted at 10.37 Mbps data rate.
- 5.8 GHz band maximum data rate: 1300 Mbps

Wireless Data Budget for Sensor Data Transmission:

- CO2 data (192 kbps) and IMU data (115.2 kbps) combine for: 307.2 kbps
- 2.4 GHz band maximum data rate: 150 Mbps

Link budget backup slide

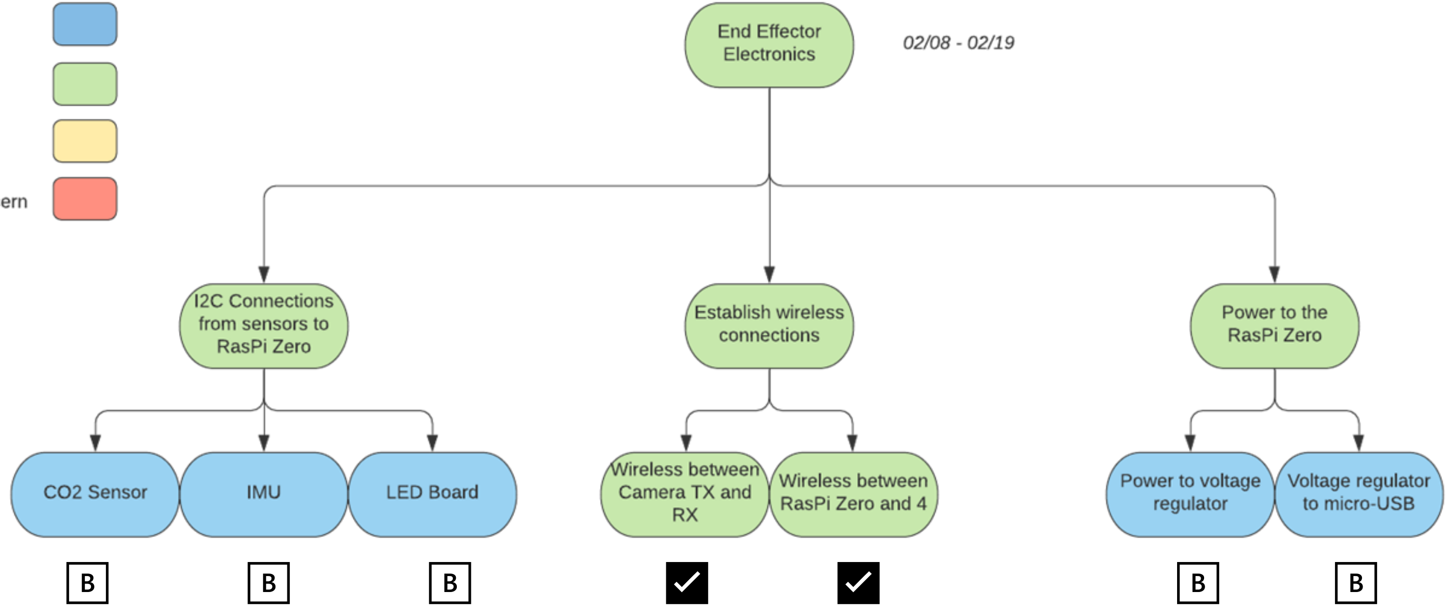
Electronics Overview: End Effector

Complete 🟦

On Schedule 🟩

Behind 🟨

Cause for Concern 🟥



- End Effector Electronics 🟩 02/08 - 02/19
  - I2C Connections from sensors to RasPi Zero 🟩
    - CO2 Sensor 🟦 B
    - IMU 🟦 B
    - LED Board 🟦 B
  - Establish wireless connections 🟩
    - Wireless between Camera TX and RX 🟩 ✓
    - Wireless between RasPi Zero and 4 🟩 ✓
  - Power to the RasPi Zero 🟩
    - Power to voltage regulator 🟦 B
    - Voltage regulator to micro-USB 🟦 B

B = Backups

✓ = Covered in Main Presentation

Backup for Sensor Connections

Backup for Voltage Regulation

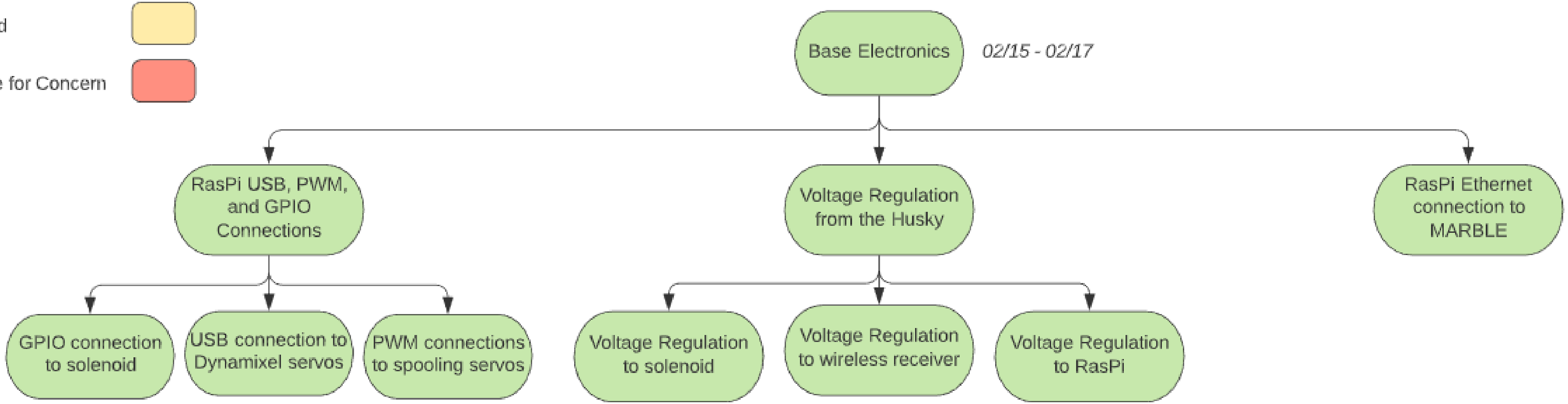
Electronics Overview: Base

Complete 🟦

On Schedule 🟩

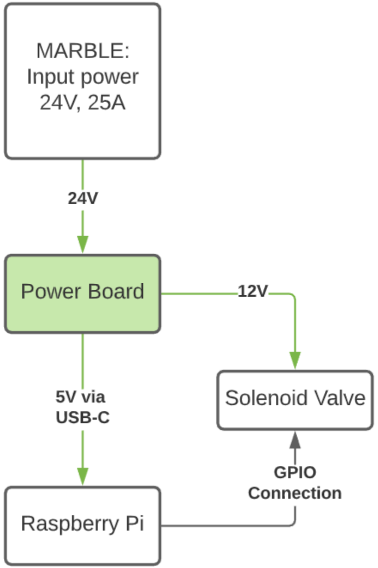
Behind 🟨

Cause for Concern 🟥



Electronics Manufacturing: Voltage Regulation

Component:	Voltage regulation to decrease available input power
Functionality (purpose):	To reduce the available power from MARBLE to the voltages that RESCUE's components require.
Manufacturing process	Designed circuit will be soldered using a solderful breadboard. Circuit includes two LM317 voltage regulators, diodes, resistors and capacitors.
Points of integration (connects to what?)	The input power from MARBLE will be regulated through a breadboard circuit. The reduced power will be connected to the RasPi, the solenoid, the wireless receiver and the RasPi Zero.
Used tools/machines	Soldering Iron
Expected challenges	The chosen voltage regulators may not be able to handle the input voltage.
Manufacturing status	The circuit is designed, has been checked with Dr. Rainville. The parts have been obtained but manufacturing has not begun. Backup for Circuit Diagram


MARBLE: Input power 24V, 25A

24V

Power Board

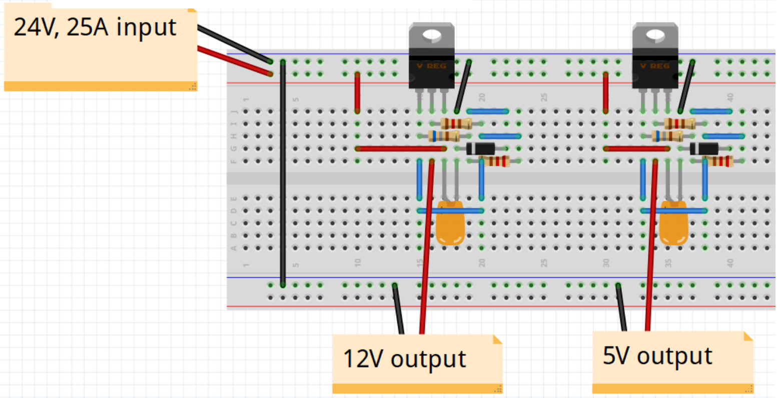
12V

Solenoid Valve

5V via USB-C

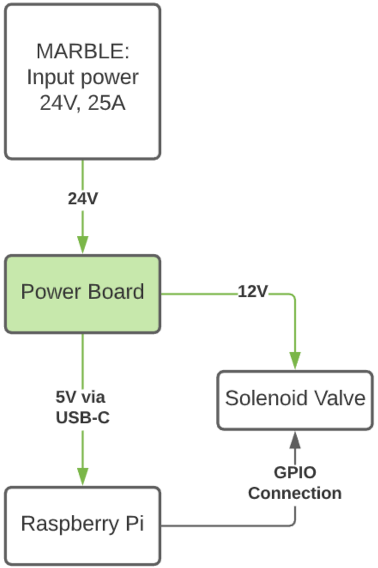
GPIO Connection

Raspberry Pi



Electronics Manufacturing: Solenoid Control

Component:	Voltage regulation to allow the RasP to control the solenoid
Functionality (purpose):	To allow the RasPi to control a component that requires a higher voltage input than the RasPi.
Manufacturing process	A circuit using a transistor, resistor and diode will be soldered to allow the RasPi to control the Solenoid.
Points of integration (connects to what?)	The solenoid valve will receive power from the voltage regulation board and will be controlled by the RasPi.
Used tools/machines	Soldering Iron
Expected challenges	Securing the wires for repeated deployment
Manufacturing status	The circuit is designed and has been checked with Dr. Rainville. The parts obtained but manufacturing has not begun.



MARBLE:
Input power
24V, 25A

24V

Power Board

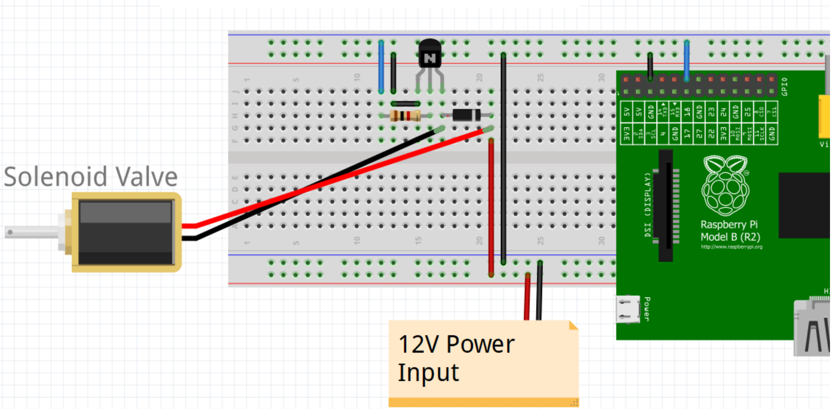
12V

Solenoid Valve

5V via
USB-C

GPIO
Connection

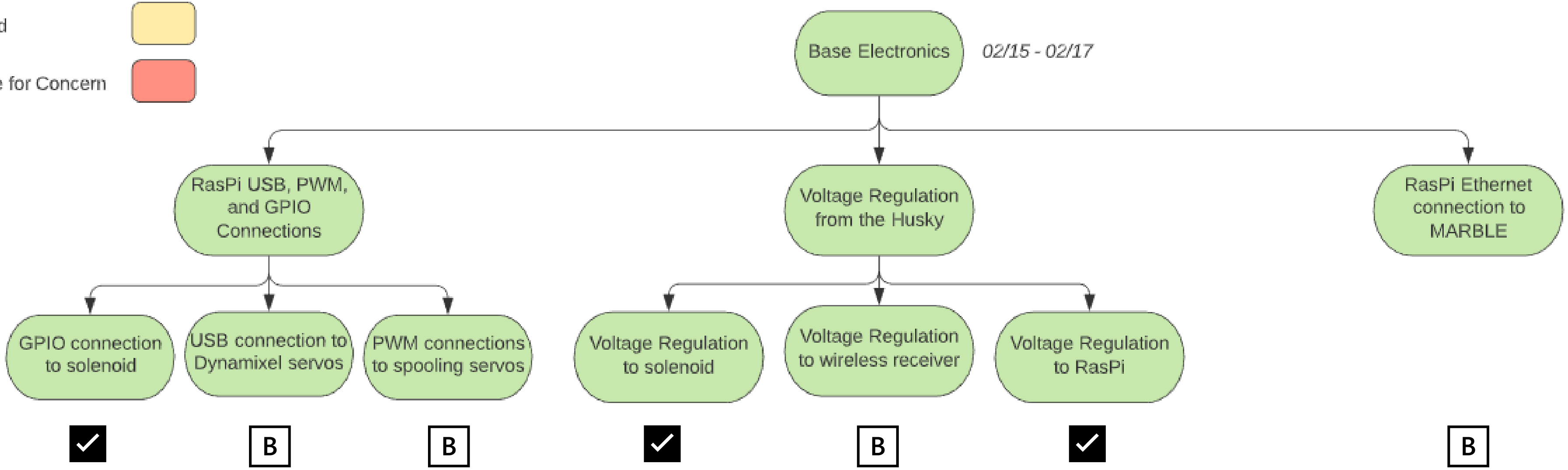
Raspberry Pi



[Backup for Circuit Diagram](#)

Electronics Overview: Base

Complete	🟦
On Schedule	🟩
Behind	🟨
Cause for Concern	🟥



Base Electronics

02/15 - 02/17

RasPi USB, PWM, and GPIO Connections

Voltage Regulation from the Husky

RasPi Ethernet connection to MARBLE

GPIO connection to solenoid ✓

USB connection to Dynamixel servos B

PWM connections to spooling servos B

Voltage Regulation to solenoid ✓

Voltage Regulation to wireless receiver B

Voltage Regulation to RasPi ✓

B

B = Backups

✓ = Covered in Main Presentation

Backup for Connections Table

Backup for Connections Diagram

Manufacturing - Software

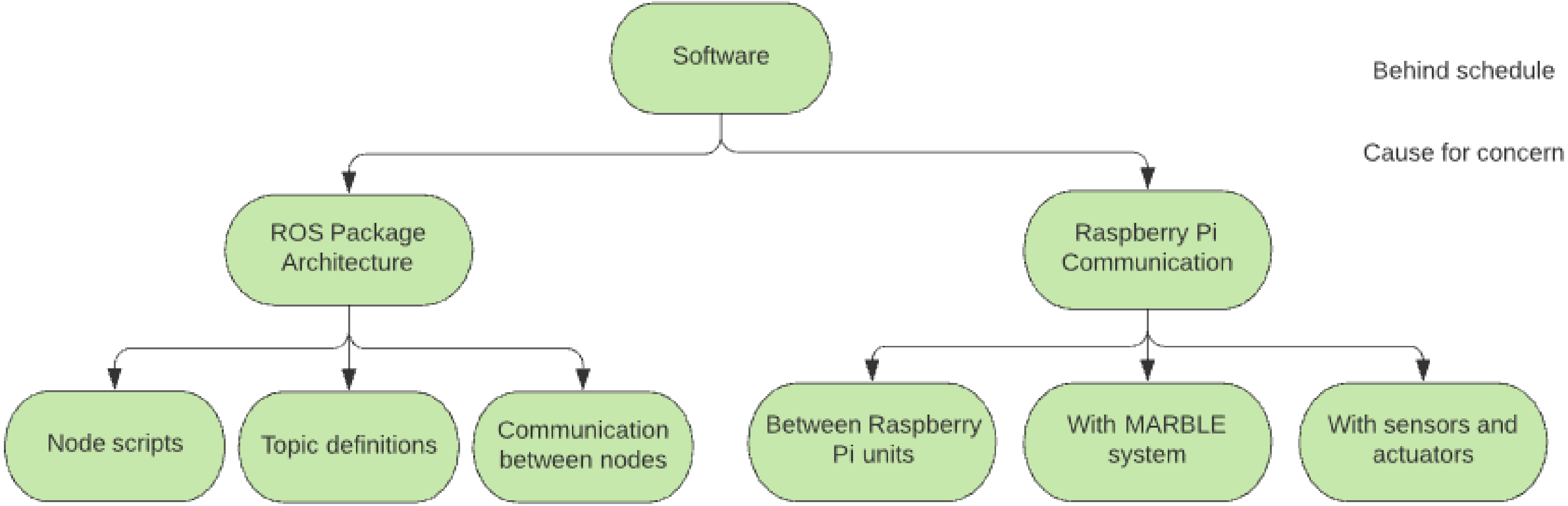
Software Manufacturing: Overview

Complete 🟦

On schedule 🟩

Behind schedule 🟧

Cause for concern 🟥



Software

ROS Package Architecture

Raspberry Pi Communication

Node scripts

In progress

Topic definitions

In progress

Communication between nodes

In progress, preliminary testing

Between Raspberry Pi units

In progress

With MARBLE system

Not started

With sensors and actuators

Not started

Most challenging: Communication between Raspberry Pi units

Backup Slide: ROS Node Map

Software Manufacturing: Tasks

	ROS Package	RasPi Communications
Functionality (purpose)	Integrate the software side of the project into a comprehensive architecture, facilitating communication, commands, and control	Relay sensor data from end effector to base, as well as pan & tilt commands from base to end effector
Points of Integration (connects to what?)	Integrated with all peripherals except for FPV camera	Interaction with RESCUE's peripherals (i.e. data acquisition, commands)
Resources Available	ROS tools & libraries, ROS wiki tutorials & forums, university faculty	ROS tools & libraries, ROS wiki tutorials & forums, VNC (Virtual Network Computing) viewer, university faculty

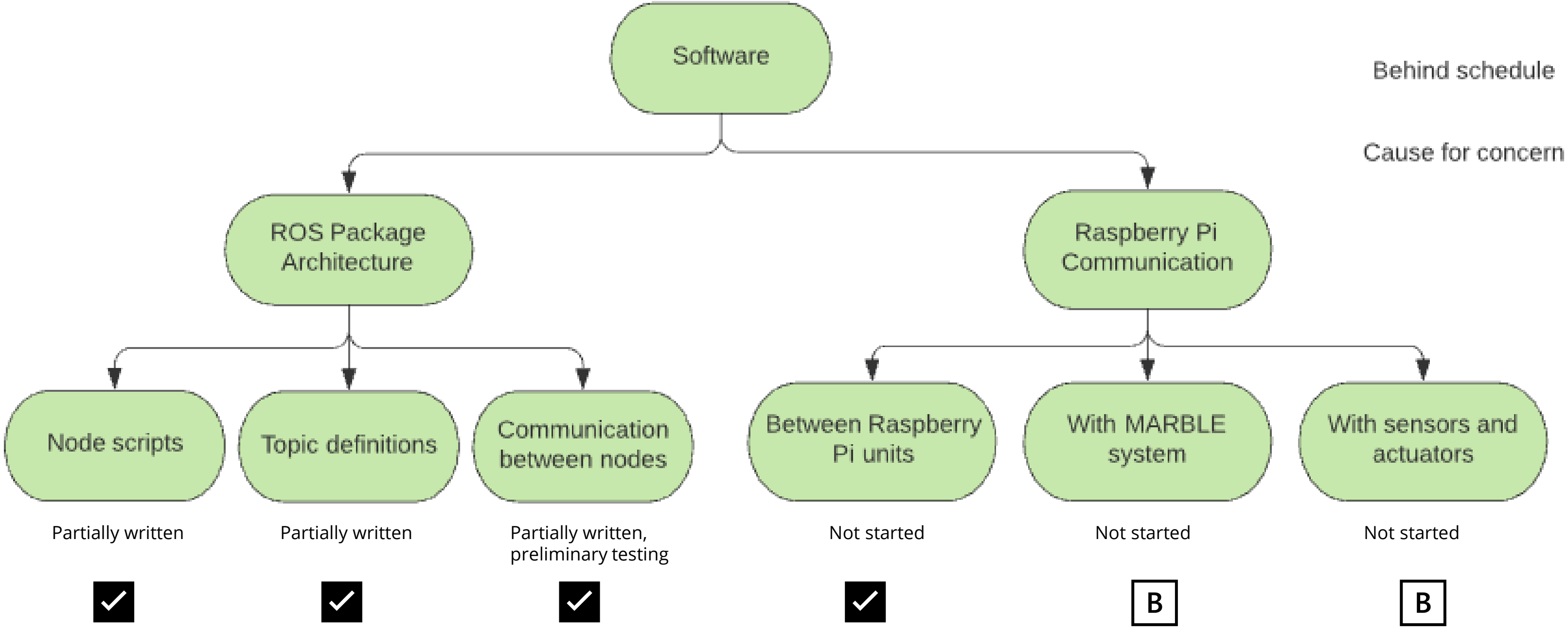
Software Manufacturing: Status

	ROS Package	RasPi Communications
Expected Challenges	Node / communication ROS architecture between RasPi (base) and RasPi Zero W (end effector)	Wireless communication without a network connection
Proposed Solutions	Separate packages for each node with independent wireless transmission	433MHz transmitter/receiver pairs integrated with RasPi and RasPi Zero W
# of Team Members Assigned	3	4
Expected Completion Date	2/15	2/8
Manufacturing Status	In progress (on schedule)	In progress (on schedule)

Backup for Software Status

Software Manufacturing: Overview

Complete 🟦
On schedule 🟩
Behind schedule 🟧
Cause for concern 🟥



Software

ROS Package Architecture

Raspberry Pi Communication

Node scripts
Partially written
✓

Topic definitions
Partially written
✓

Communication between nodes
Partially written, preliminary testing
✓

Between Raspberry Pi units
Not started
✓

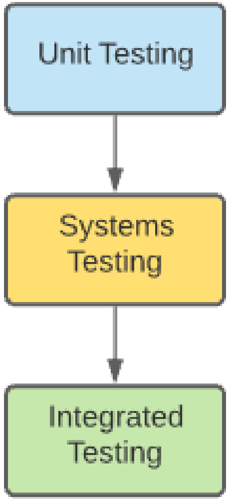
With MARBLE system
Not started
B

With sensors and actuators
Not started
B

B = Backups
✓ = Covered in Main Presentation

Manufacturing - Subsystems Integration

Subsystems Integration:



Unit 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

Systems Testing:

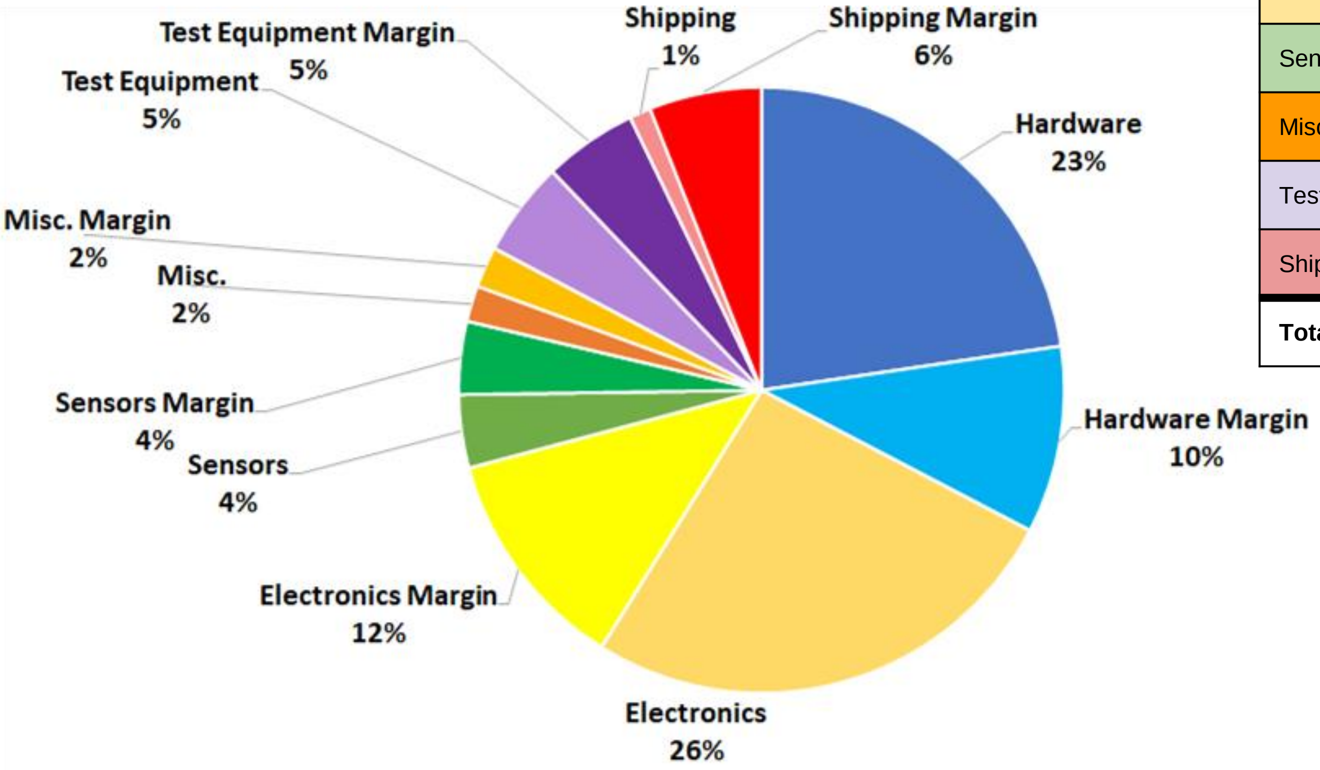
- Ensure that subsystems operate as planned
- Test subsystems separately:
    - Test the base mobility, material spooling and retraction (including pressurization and venting), sensors data collection and transmission, system response to commands and status report

Integrated Testing:

- 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.

Budget/Procurement

Budget Status



Hardware	$1,133
Electronics	$1,310
Sensors	$195
Misc.	$96
Test Equipment	$254
Shipping	$57
Total Planned (without margin)	**$3,045**

Hardware Margin	$500
Electronics Margin	$600
Sensors Margin	$195
Misc. Margin	$109
Test Equipment Margin	$250
Shipping Margin	$300
Total Margin	**$1,955**

Procurement Status

	Sensors	Testing Equipment/ Components	Raw Materials/Misc.
Received	- All: IMU, CO_2, camera	- Low pressure LDPE - Testing valves, gauge - Heat sealer	- 1.75mm/3mm PLA - Gantt software
Pending		- Pressure rated LDPE tubing	
Planned		- Material spooling test components - Material alternatives	- Gantt software subscriptions
Critical/Concerns	- Sensor damage during testing	- LDPE lead time	

Procurement Status, Cont.

	Hardware	Electronics
Received	- End effector pan/tilt kit	- End effector sensor supporting components (All) - FPV transmitter/receiver - End effector servo drivers
Pending		
Planned	- End effector fasteners - Material container (all) - Material spooling (all) - Tension system (all) - Base pivot/rotation (all) - Pressurization system (all) - Power spooling (mounts)	- Base pivot/rotation servos, controllers - Power wire spooling wire, slip ring - Material spooling servo - Pressure regulation solenoid valve, controllers
Critical/Concerns	- Prototype test dependency - Material container - Pressurization system adaptors	- Prototype test dependency - Base pivot/rotation servos - Material spooling servo - Pressure system solenoid valves

Questions?

Backup Slides

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

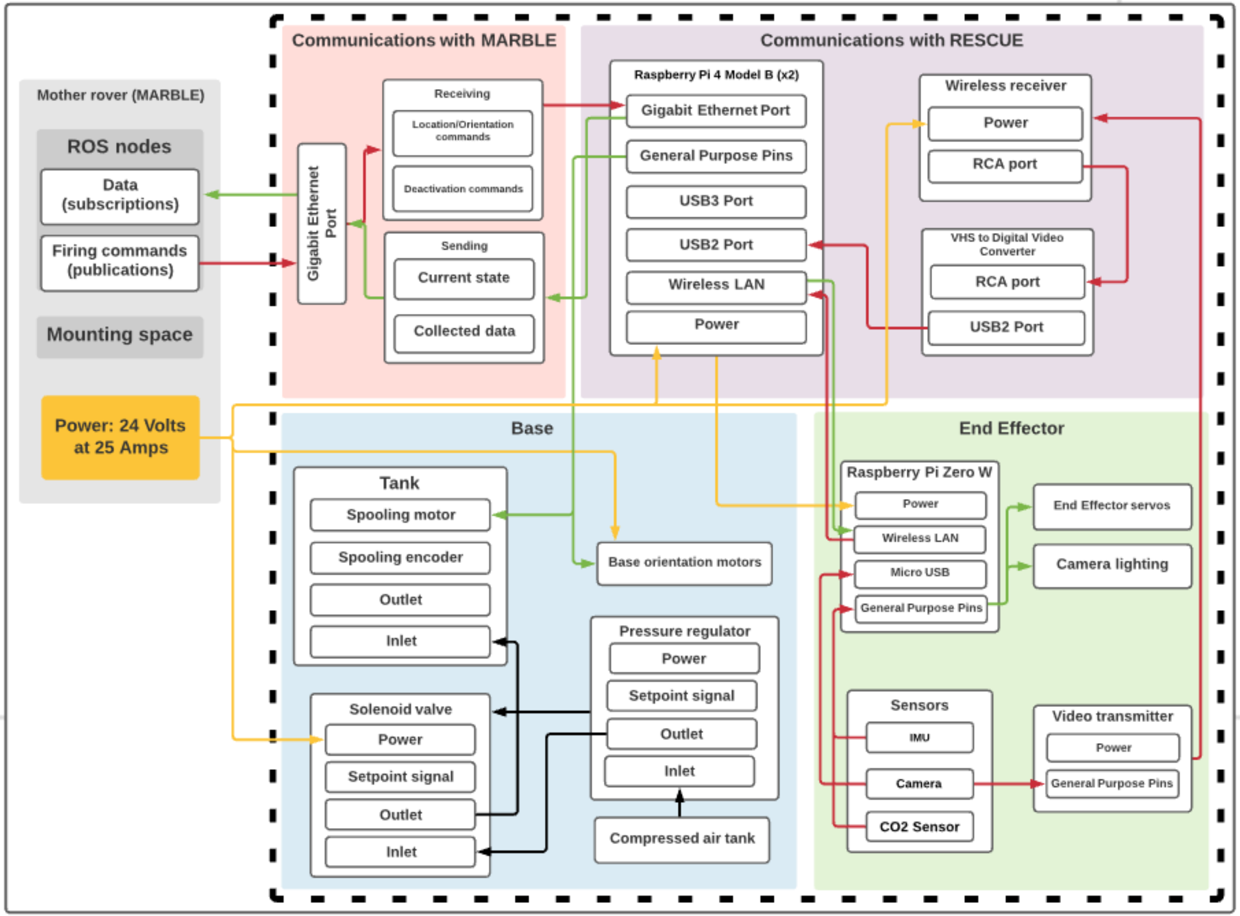
- MARBLE’s UGV has **limited sensing** capabilities in comparison to other competitors in DARPA’s Subterranean Challenge.
- UGVs offer greater endurance than UAVs, however, **field of view and mobility are limited**.
- Certain obstacles are currently **impassible** and/or out of the FOV of the UGV.

Detailed FBD

Legend

Received information 🟥→ Power lines 🟨→

Sent information 🟩→ Physical connection ⬛→



Mother rover (MARBLE)

ROS nodes

Data (subscriptions)

Firing commands (publications)

Mounting space

Power: 24 Volts at 25 Amps

Communications with MARBLE

Gigabit Ethernet Port

Receiving

Location/Orientation commands

Deactivation commands

Sending

Current state

Collected data

Communications with RESCUE

Raspberry Pi 4 Model B (x2)

Gigabit Ethernet Port

General Purpose Pins

USB3 Port

USB2 Port

Wireless LAN

Power

Wireless receiver

Power

RCA port

VHS to Digital Video Converter

RCA port

USB2 Port

Base

Tank

Spooling motor

Spooling encoder

Outlet

Inlet

Base orientation motors

Pressure regulator

Power

Setpoint signal

Outlet

Inlet

Solenoid valve

Power

Setpoint signal

Outlet

Inlet

Compressed air tank

End Effector

Raspberry Pi Zero W

Power

Wireless LAN

Micro USB

General Purpose Pins

End Effector servos

Camera lighting

Sensors

IMU

Camera

CO2 Sensor

Video transmitter

Power

General Purpose Pins

[Back to FBD](#)

Backup Slides: Hardware Manufacturing

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

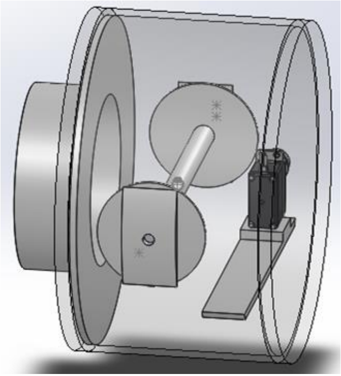


Figure 1. Material Spool Container

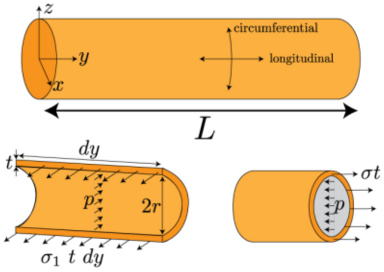


Figure 2. Body Tube Stresses

- **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

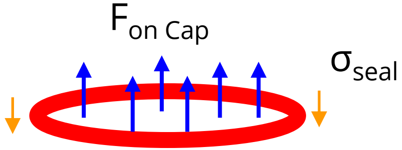


Figure 3. Endcap Stress Diagram

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

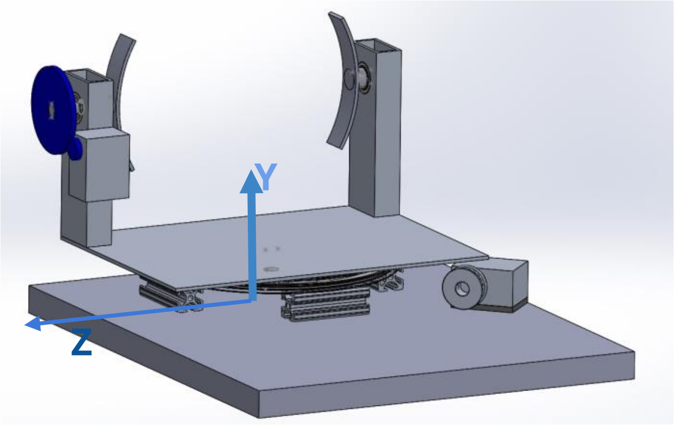


Figure 1. The rotating base

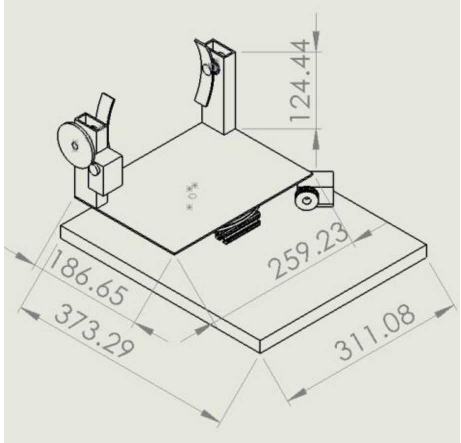


Figure 2. The rotating base Dim.(mm)

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

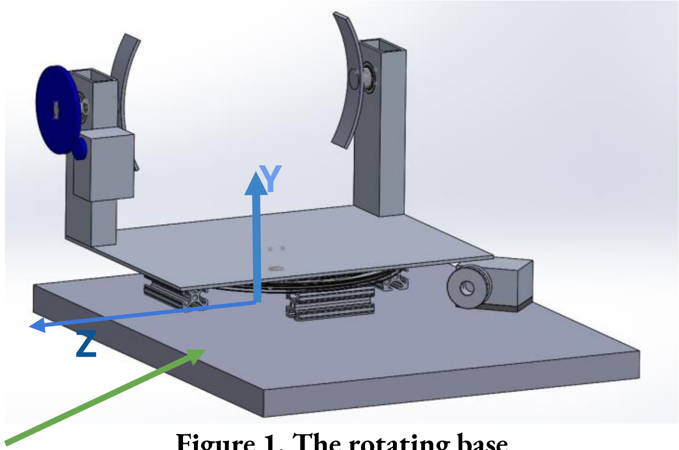


Figure 1. The rotating base

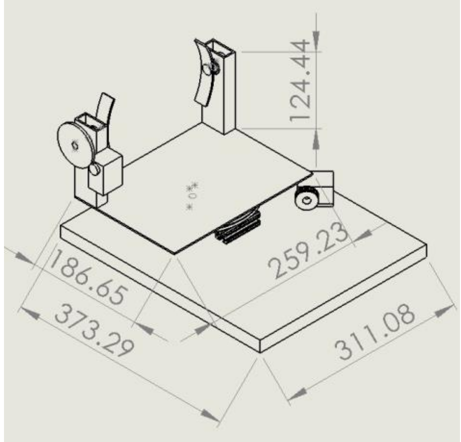


Figure 2. The rotating base Dim.(mm)

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

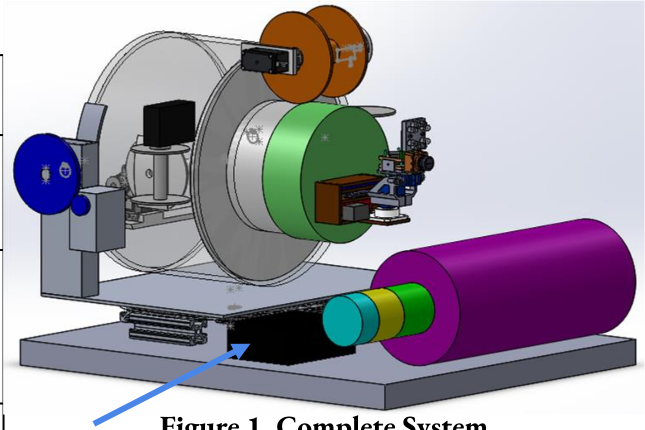


Figure 1. Complete System

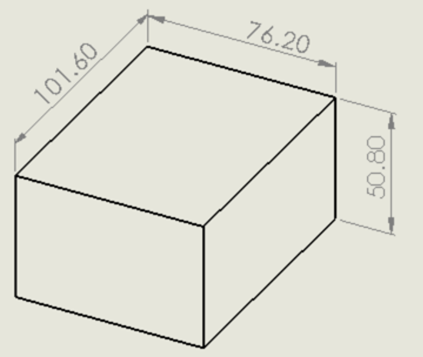


Figure 2. Estimated Base Electronics Housing Dim. (mm)

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)

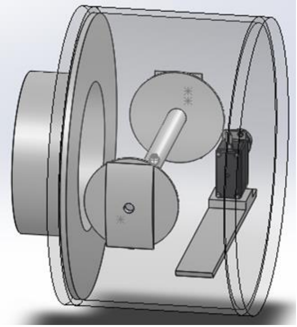


Figure 2. Material Spooling Container

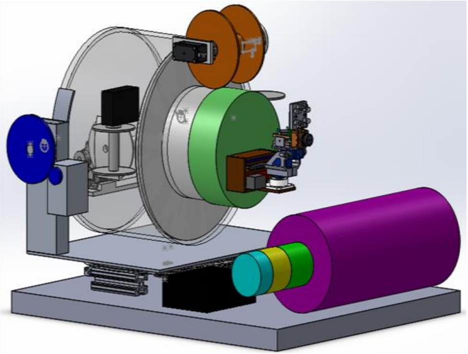


Figure 1. Complete System

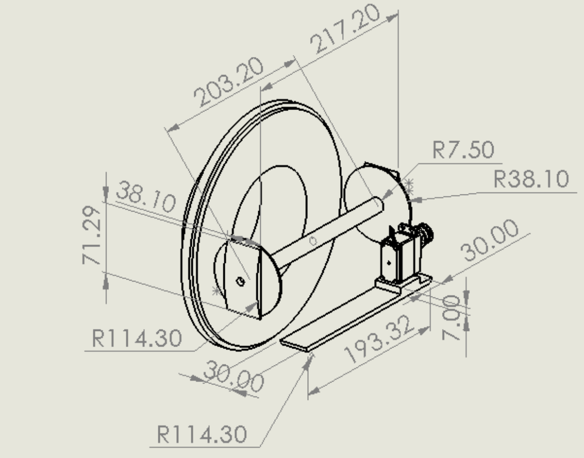


Figure 3. Material Spooling Dim. (mm)

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

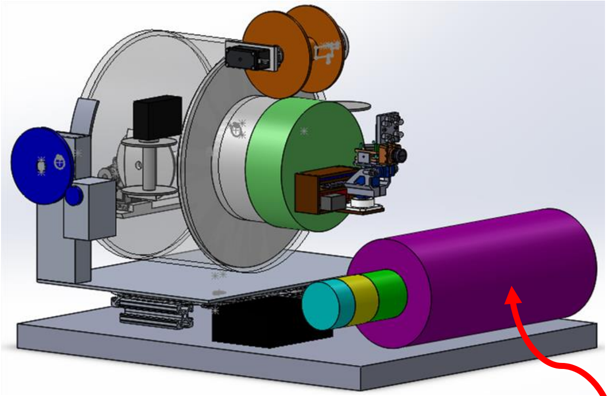


Figure 1. Complete System

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

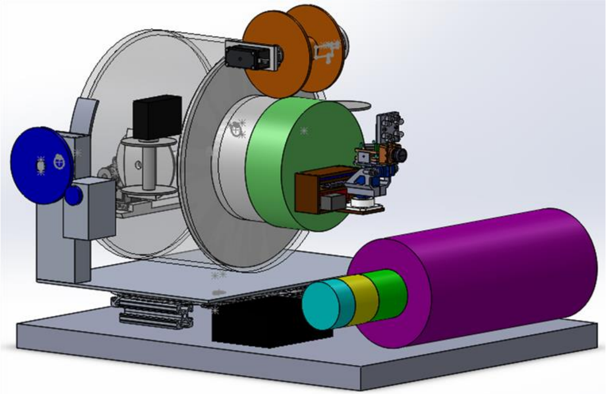
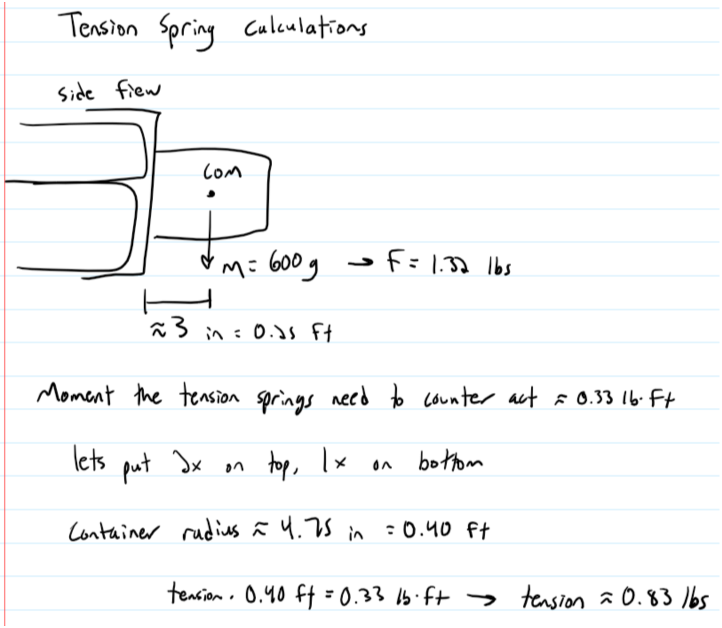


Figure 1. Complete System

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			

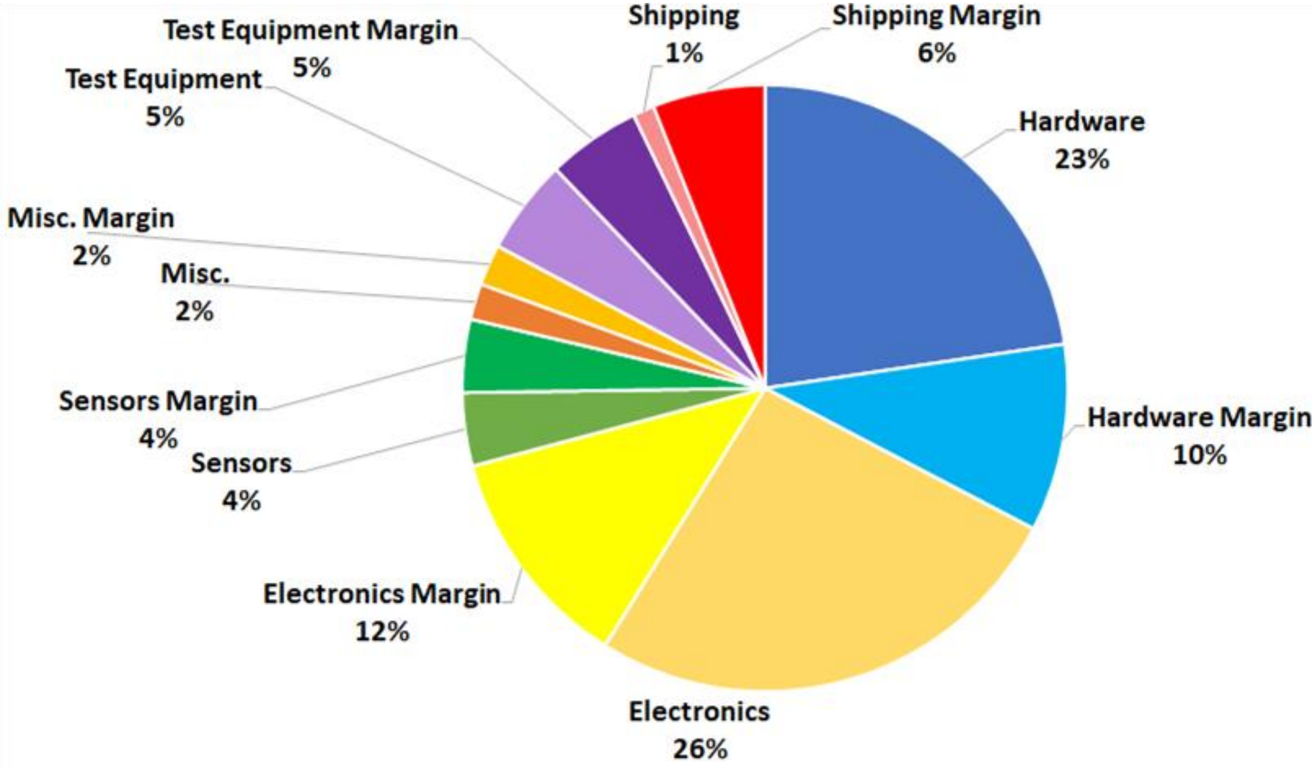
Procurement Status Backup: Planned Hardware (Nothing Pending)

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)

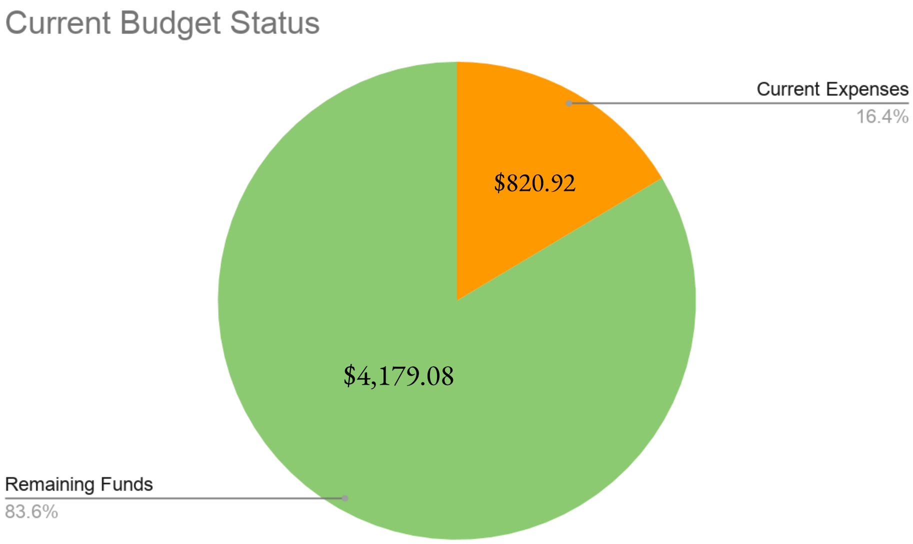
Electronics		**Sensors**	**Testing Equipment/Components**	**Raw Materials/Misc.**
PWM Servo Controller	Pivot servo		Higher Pressure LDPE Tubing	Insta Gantt Subscriptions
Arm Power Wiring	Rotation servo			
Solderfull Breadboard	Material Spool Servo			
LM317(x2)	Power wire servo			
Solenoid Valve	Raspberry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

Budget Status (Backup)

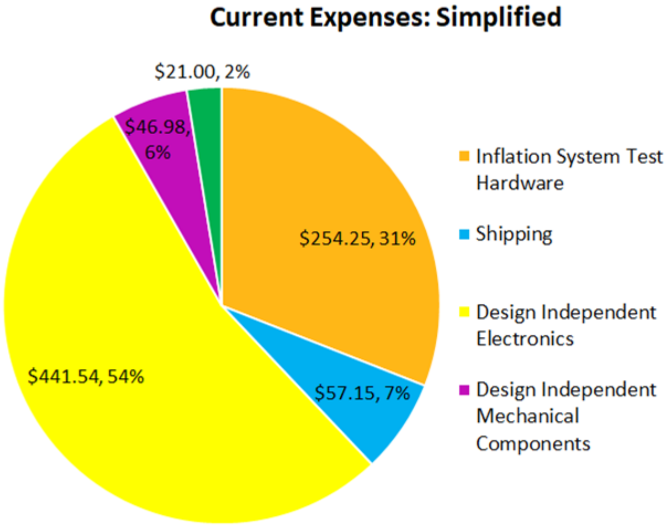


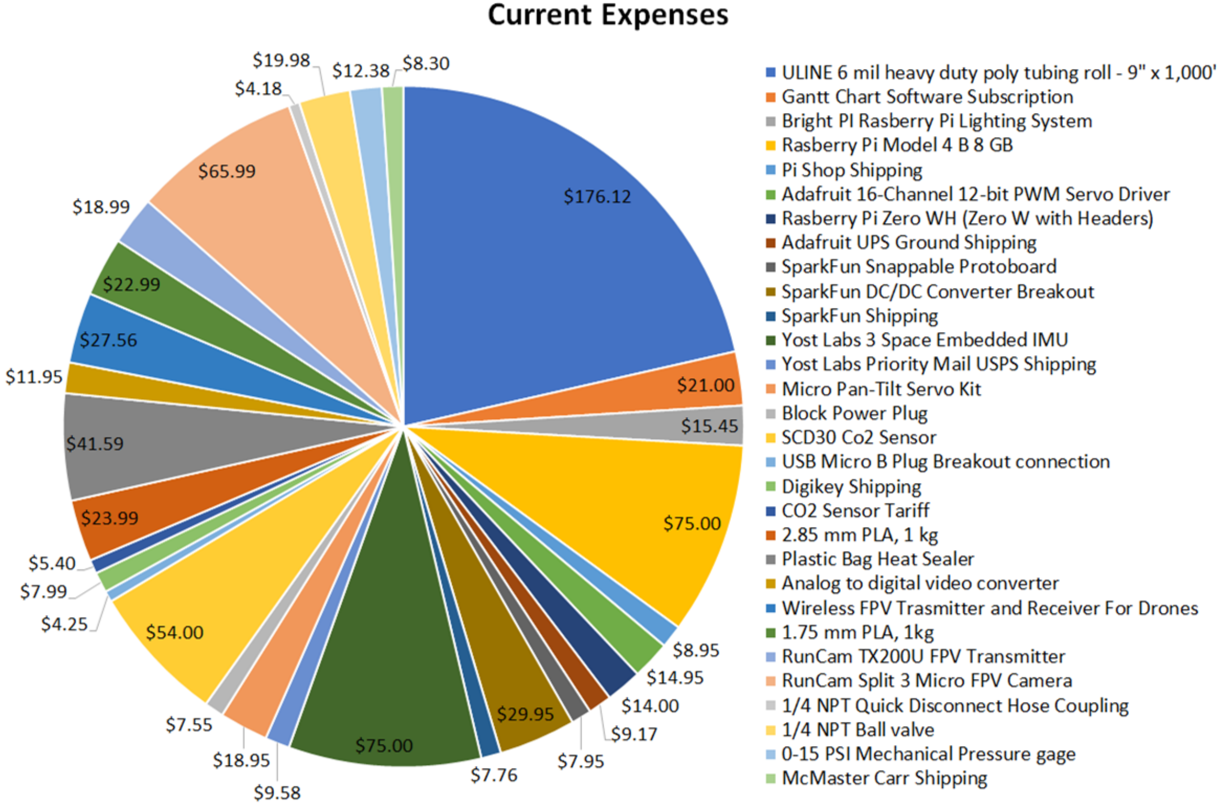
Hardware	$1,133
Hardware Margin	$500
Electronics	$1,310
Electronics Margin	$600
Sensors	$195
Sensors Margin	$195
Misc.	$96
Misc. Margin	$109
Test Equipment	$254
Test Equipment Margin	$250
Shipping	$57
Shipping Margin	$300
Total	**$5,000**

Budget Backup: Current Expenses: $820.92

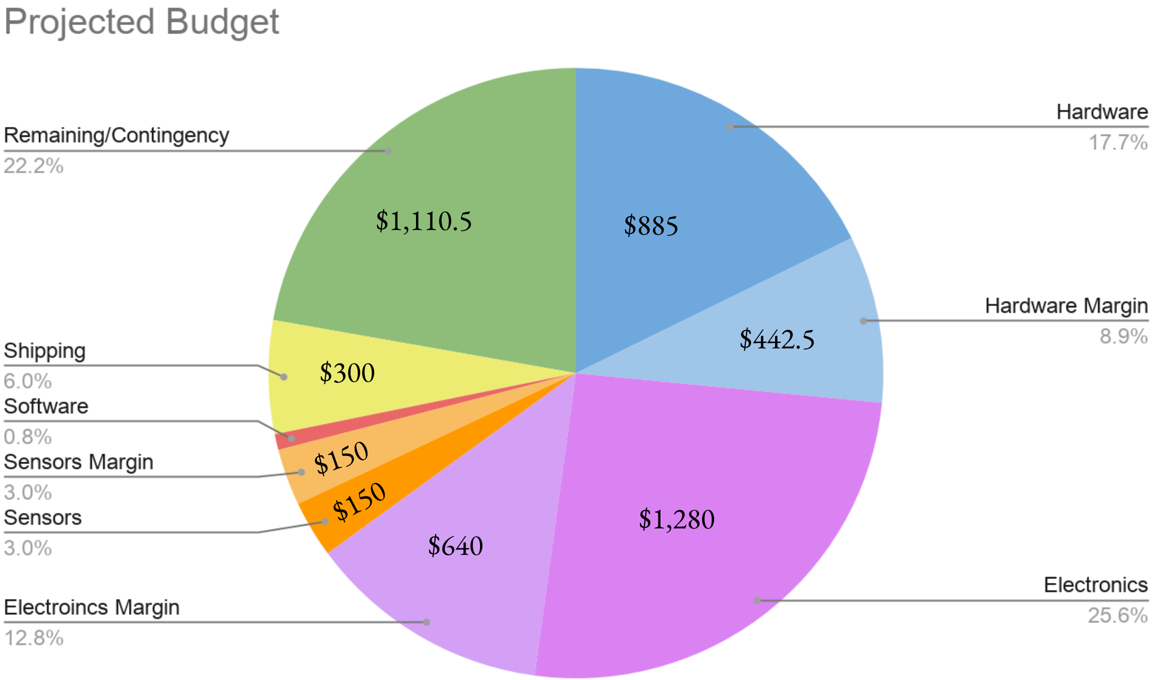


Budget Backup: Current Expenses: $820.92


Current Expenses: Simplified


Current Expenses

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

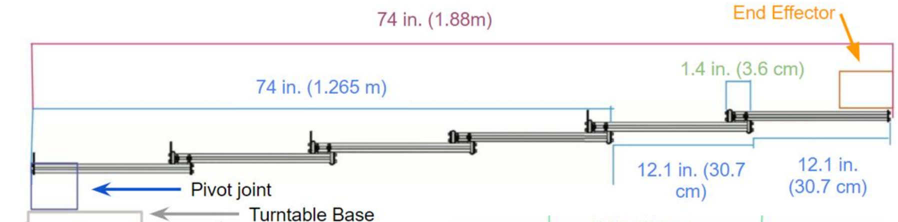


Figure 1. X Rail Arm on UGV

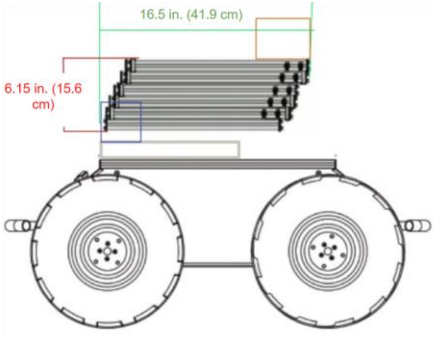


Figure 2. Collapsed X Rail on UGV

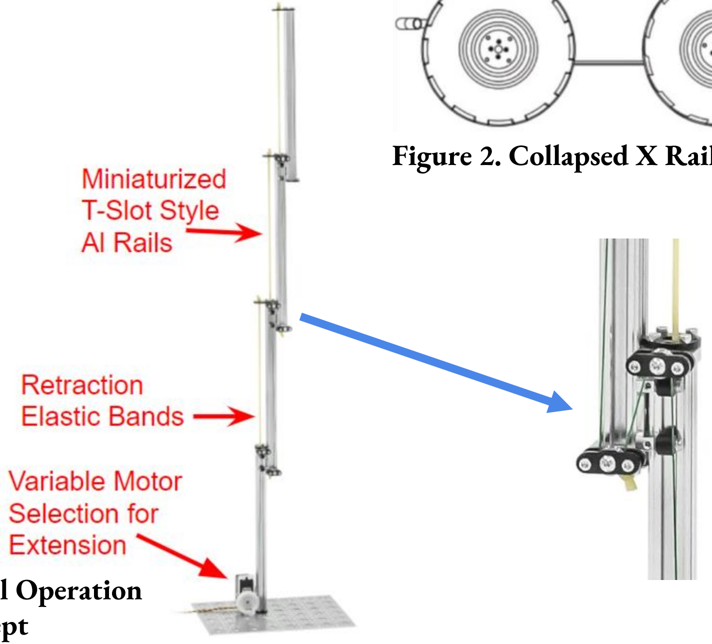
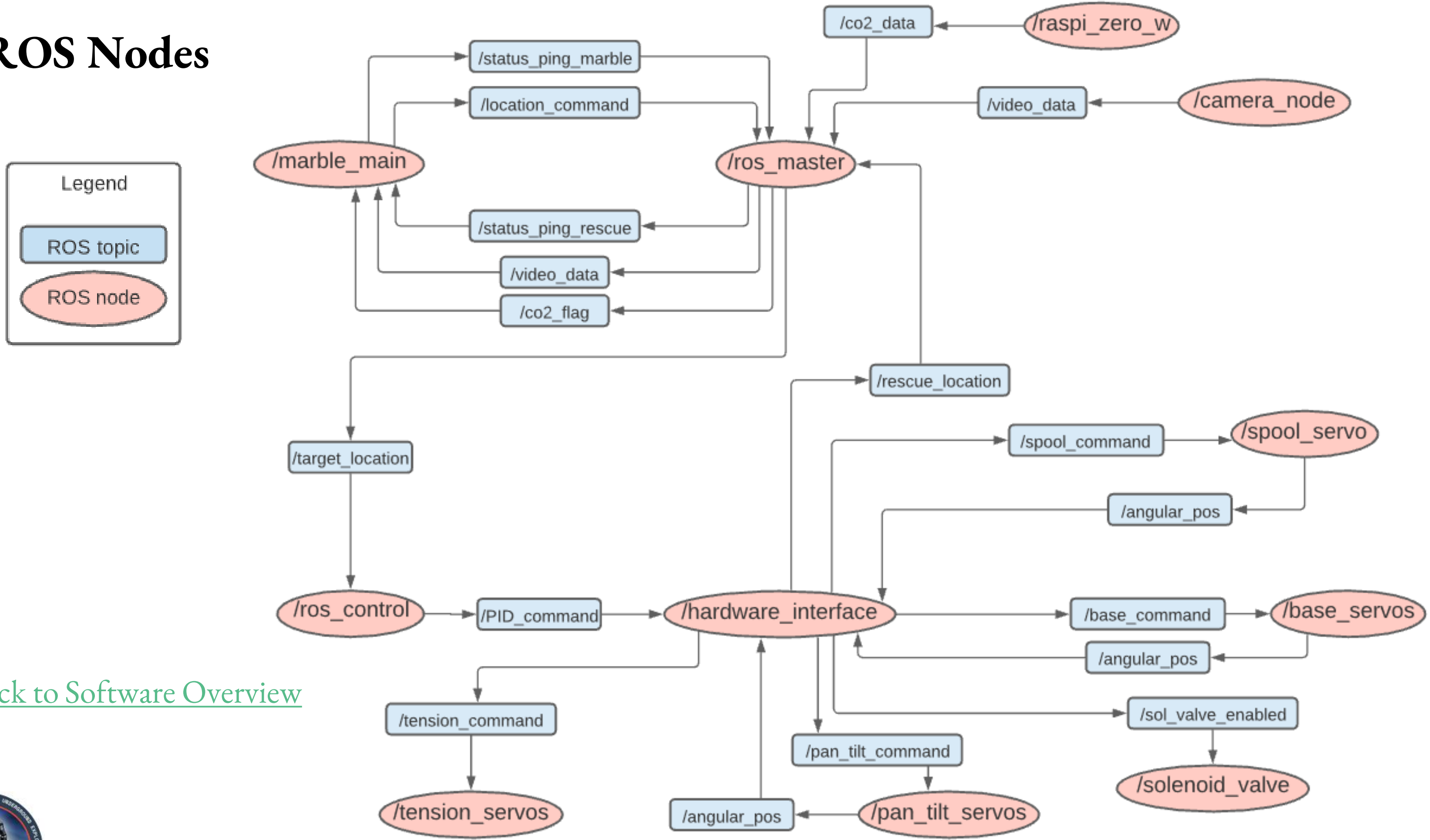


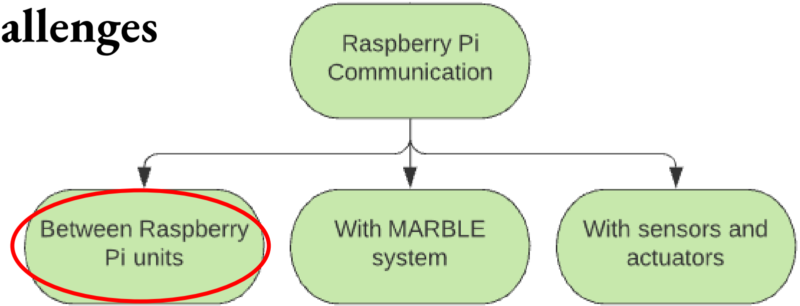
Figure 3. X Rail Operation Concept

ROS Nodes



Back to Software Overview

Software Overview - Challenges



Raspberry Pi Communication

Between Raspberry Pi units

With MARBLE system

With sensors and actuators

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

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

Back to Software Overview

Detailed Software Status

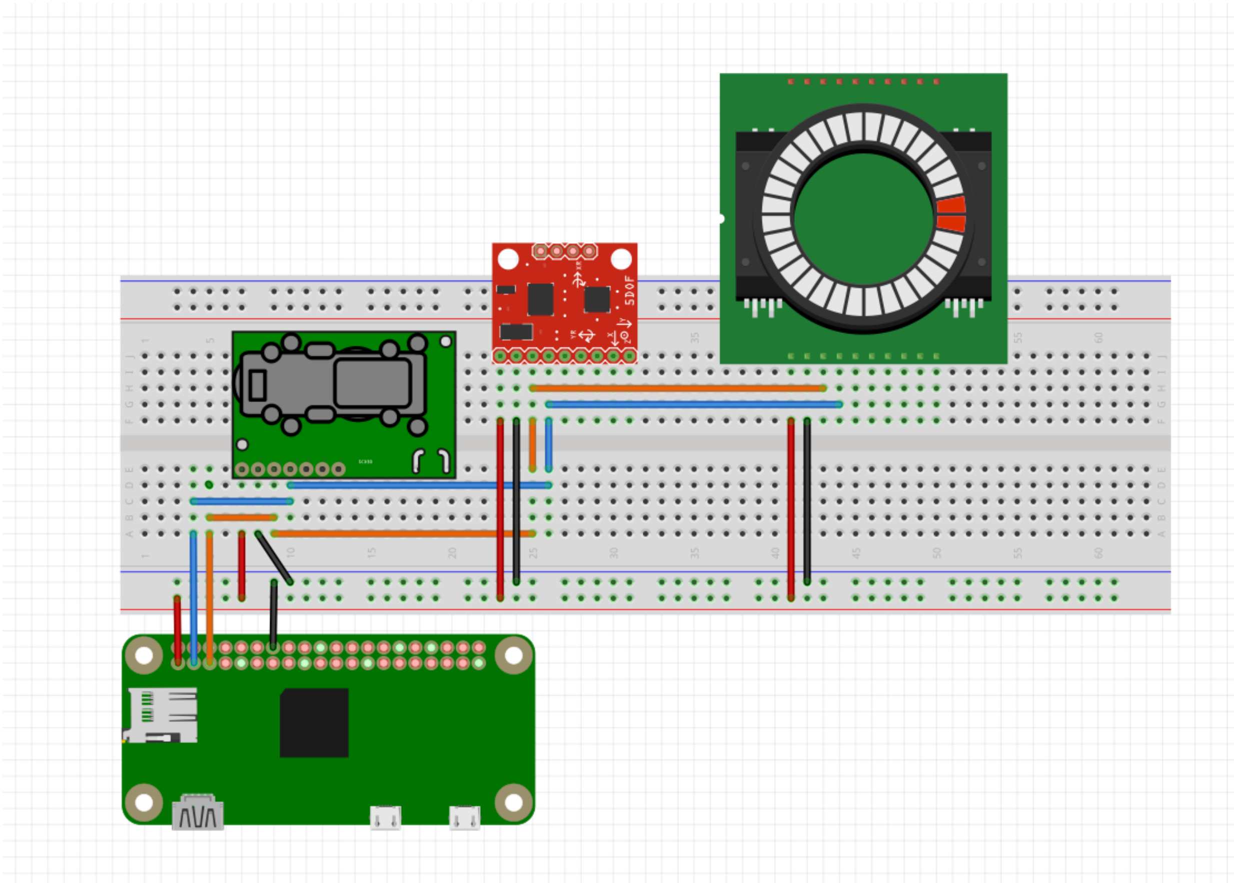
Software Component	Expected Challenges	# of Team Members Assigned	Resources Available	Projected Completion Date
Inter-RasPi Communication	ROS-based communication without wireless internet connection	4	Raspberry Pi tutorials, ROS documentation	2/8
ROS Package	Possibility of separate packages for RasPi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

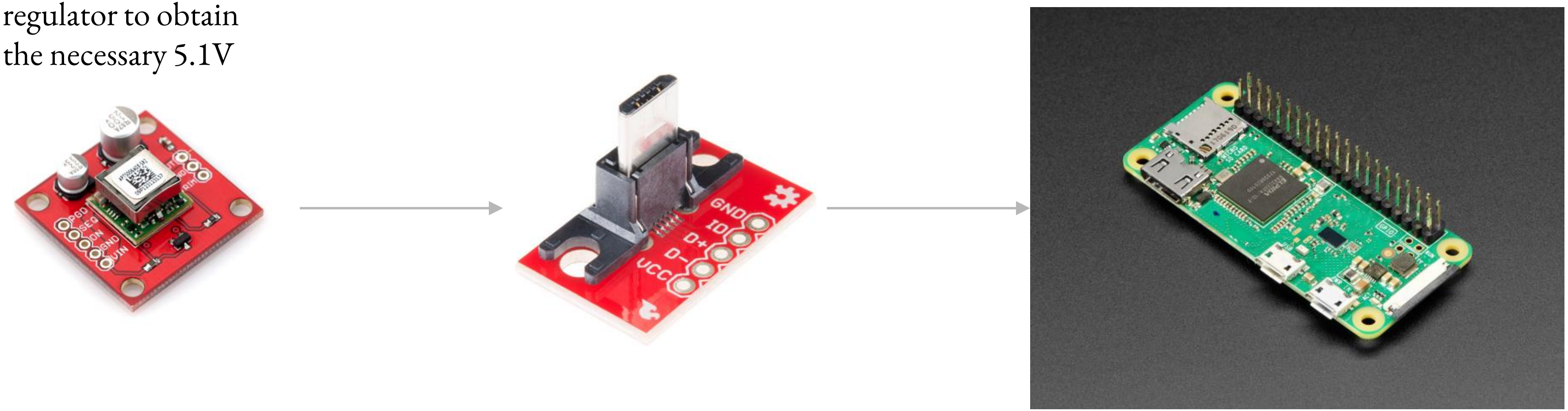


Electronics Manufacturing: Voltage Regulation Circuit to RasPi Zero

	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]:

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

$$P_{TX} = 23.01029995$$

$$G_{TX} = 2.2$$

$$L_{TX} = 0.5$$

$$L_{FS} = 57.48795996$$

$$L_M = 10$$

$$G_{RX} = 2$$

$$L_{RX} = 0.5$$

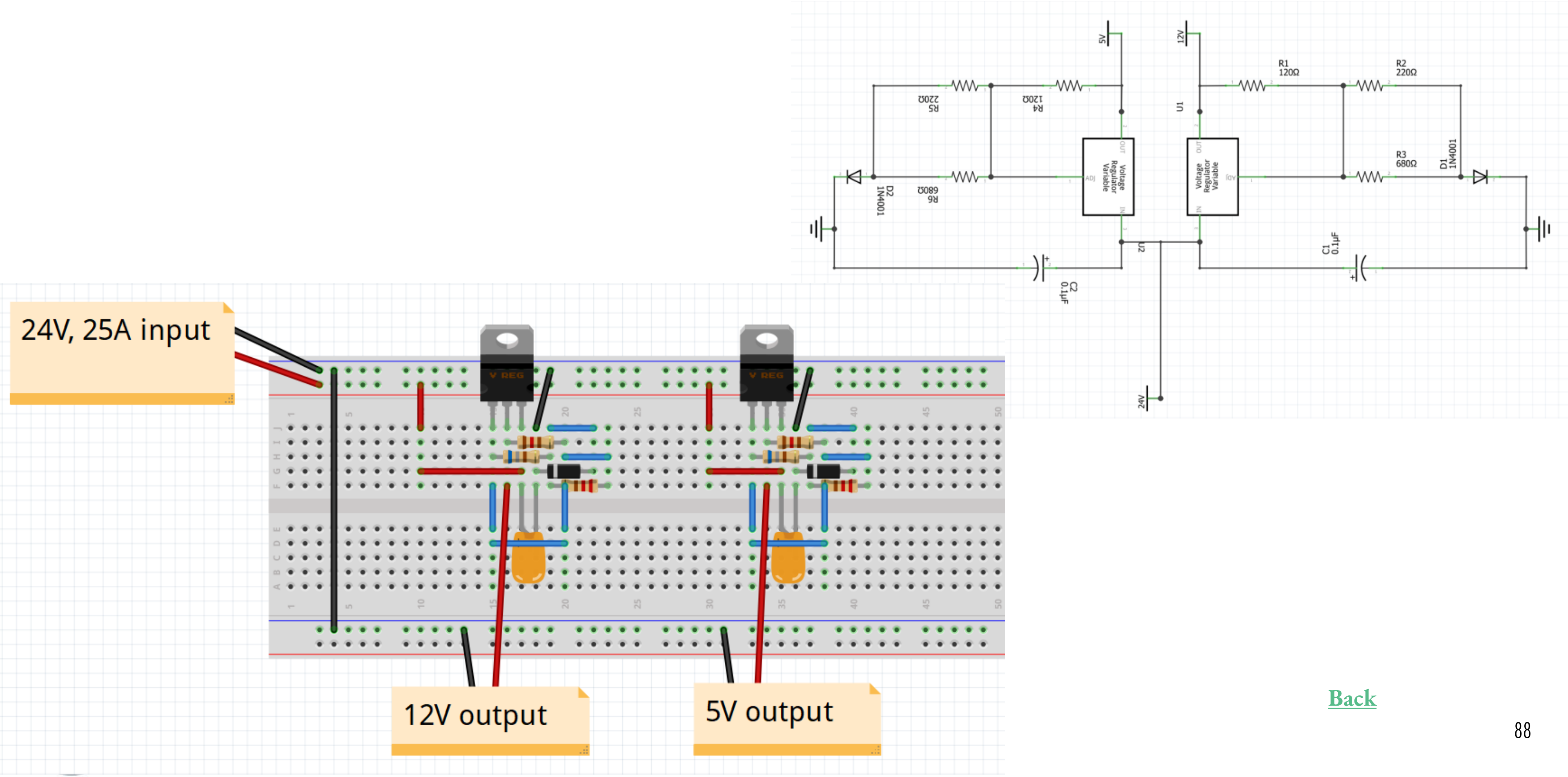
$$P_{RX} = -41.27766$$

Signal to noise ratio [dB]:

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

$$SNR = 39.2841$$

Base Electronics : Voltage Regulation Circuits



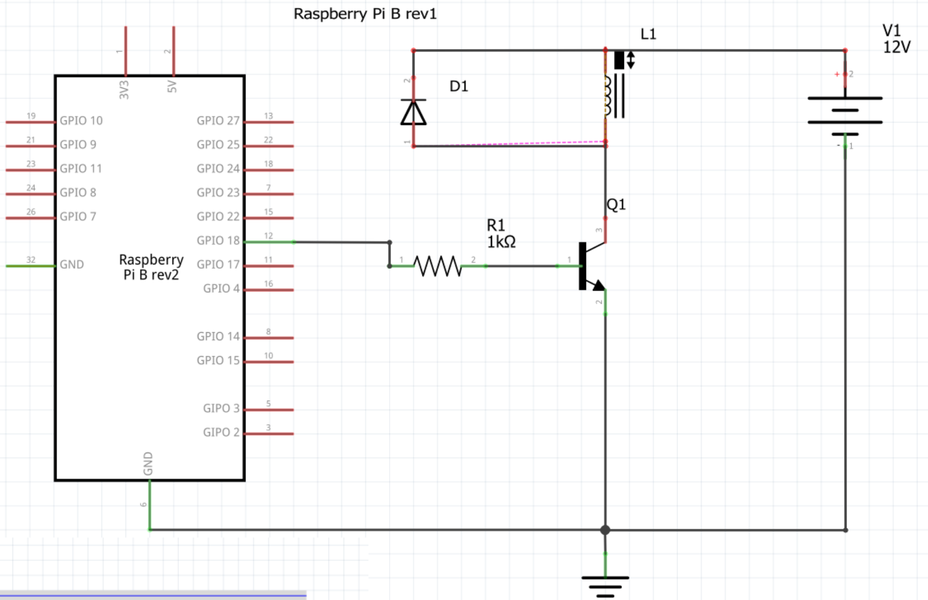
24V, 25A input

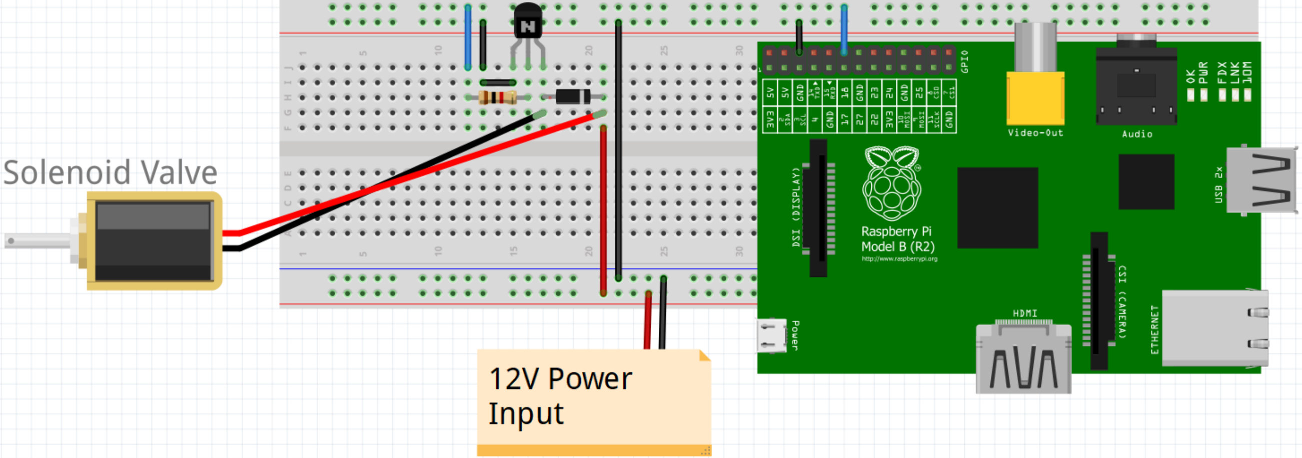
12V output

5V output

Back

Base Electronics: Solenoid Circuit



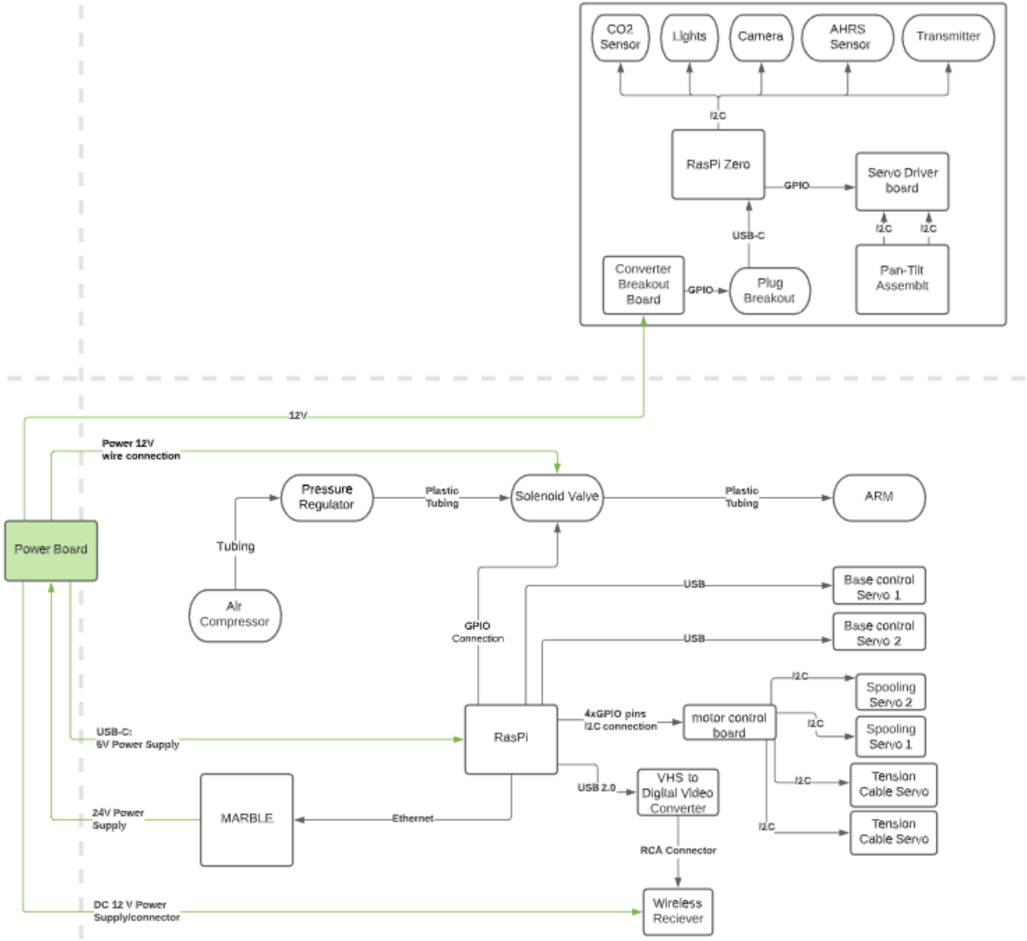


Back

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 CO2 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

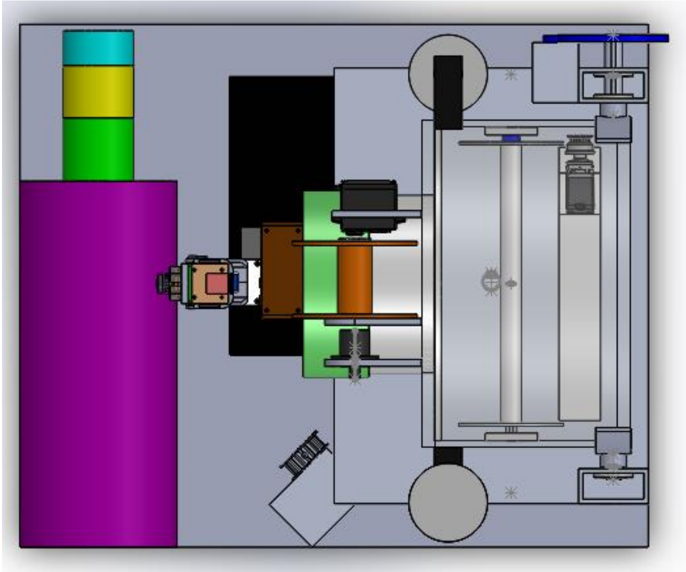


Figure 1: Top View

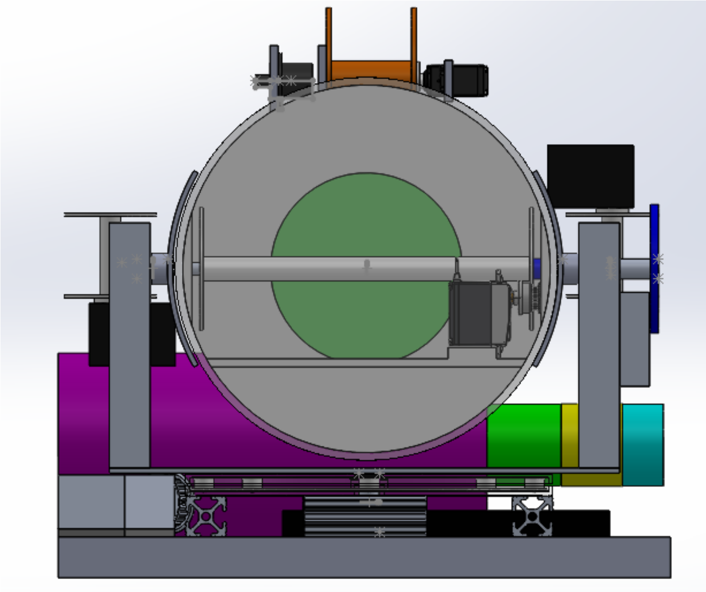
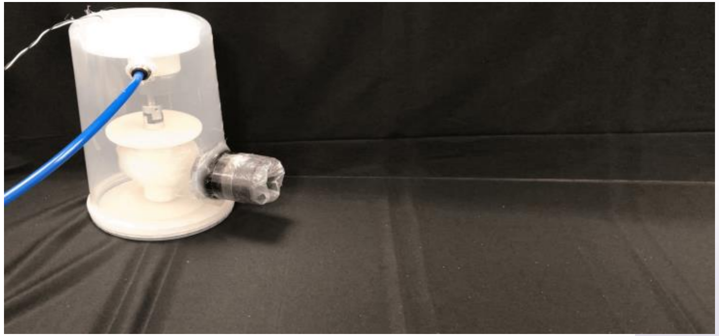
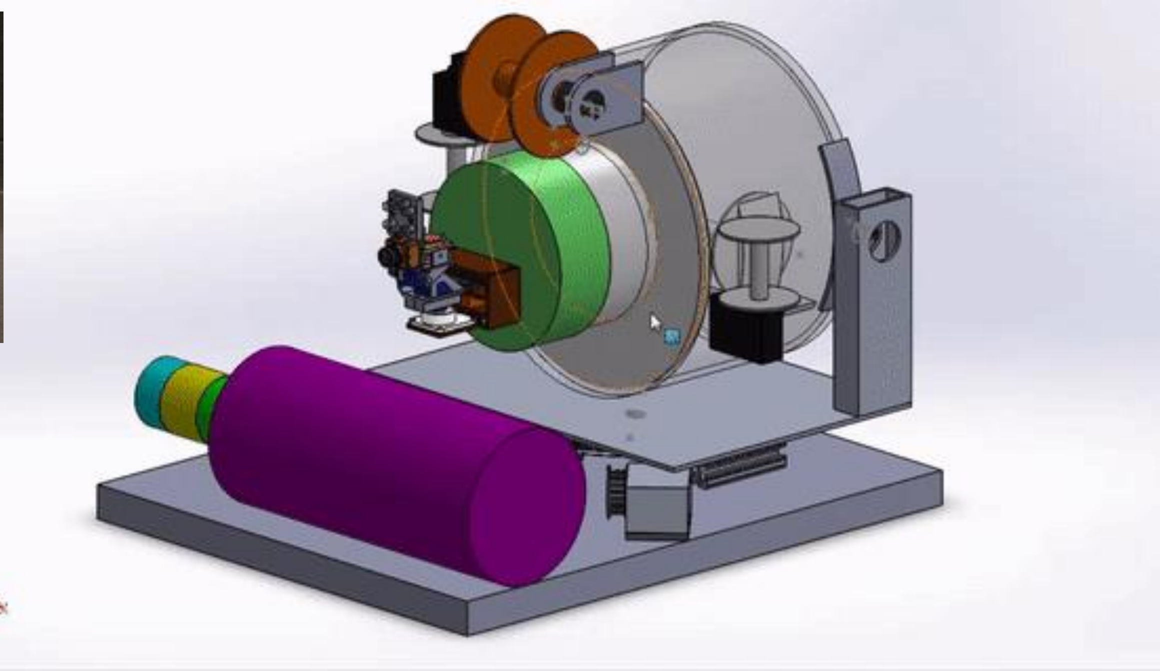


Figure 2: Back View

Design Solution: CAD





Levels of success: detailed

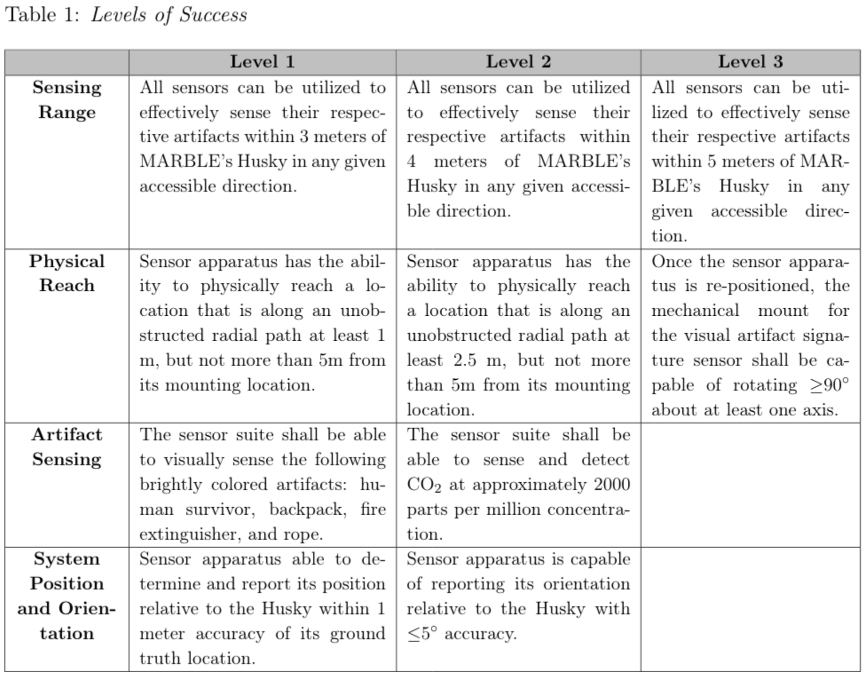
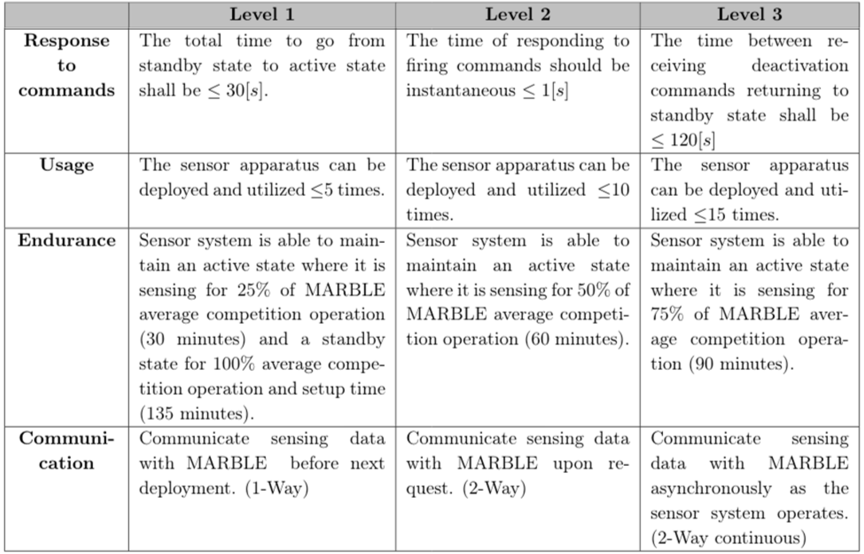


Table 1: *Levels of Success*

	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.	

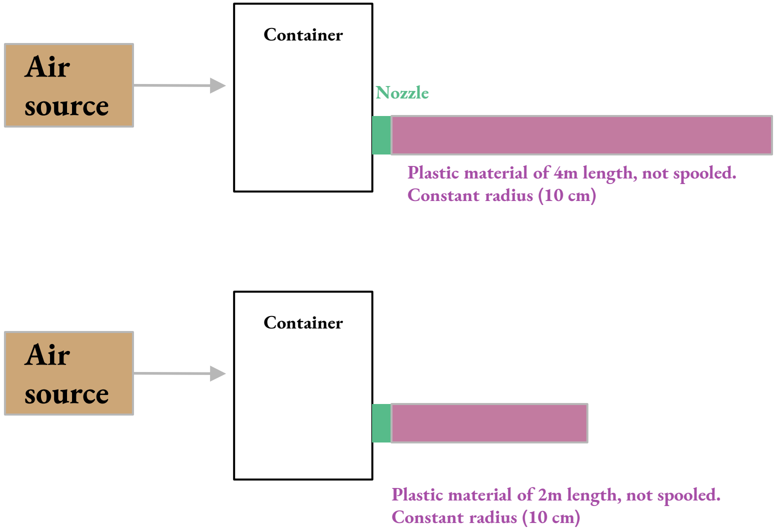


	Level 1	Level 2	Level 3
Response to commands	The total time to go from standby state to active state shall be $\leq 30[s]$.	The time of responding to firing commands should be instantaneous $\leq 1[s]$	The time between receiving deactivation commands returning to standby state shall be $\leq 120[s]$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

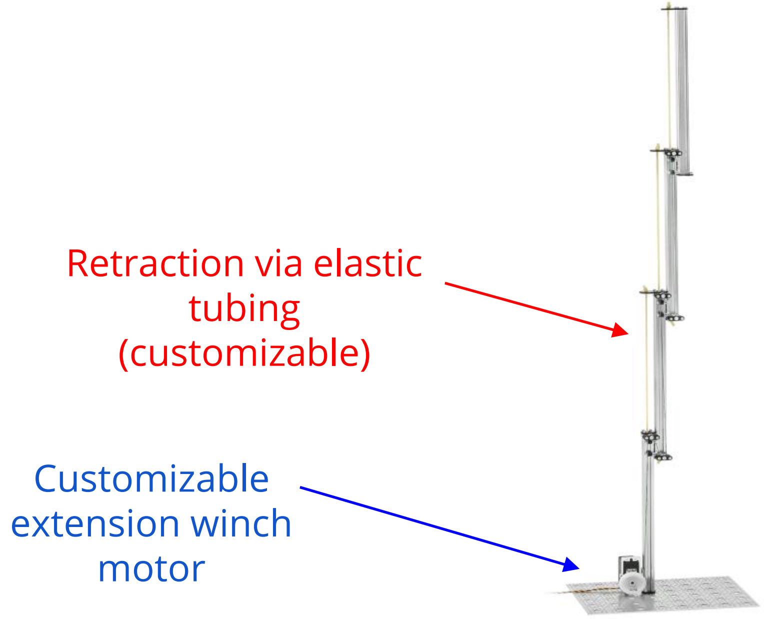
RESCUE will decrease the overall length of the tube causing:

- 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



Retraction via elastic tubing (customizable)

Customizable extension winch motor