Critical Design Review

Range Extending System to Complement Underground Exploration (RESCUE)

Customer: Prof. Eric Frew

University Of Colorado Boulder

Project Purpose and Objectives

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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 or range.

Specific Application

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

Proposed Solution

A soft robotic arm, mounted to the top of MARBLE's Husky, which is capable of extending an RGB camera, CO2 Sensor, and AHRS up to 4 meters from its base.

Acronyms

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

Project 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

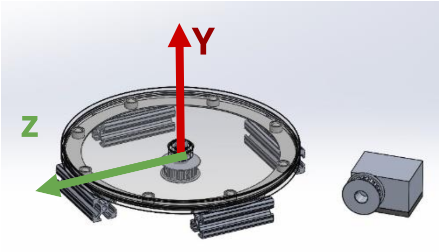
- MARBLE’s UGV has **limited sensing** capabilities in comparison to other competitors in DARPA’s Subterranean Challenge.

- 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.

Design solution

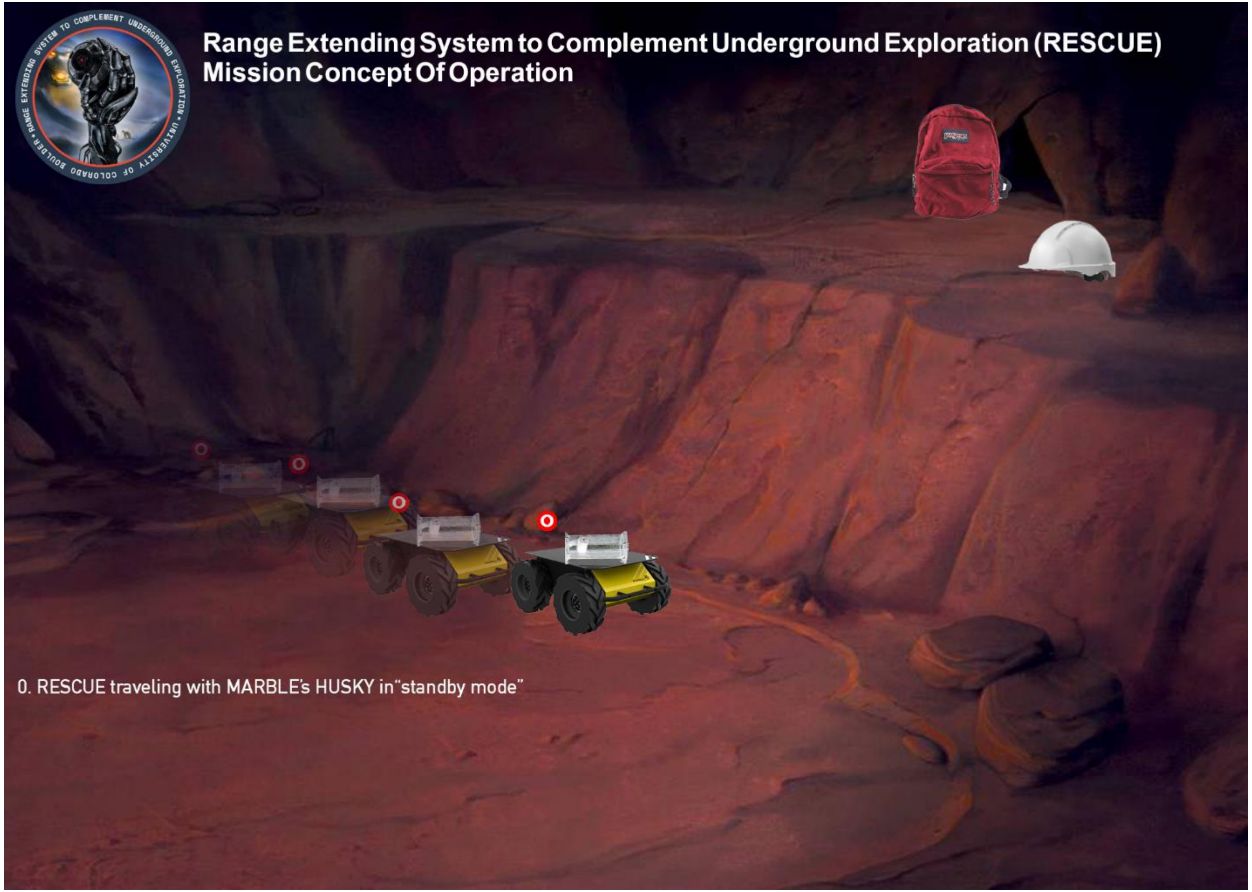
Design Solution



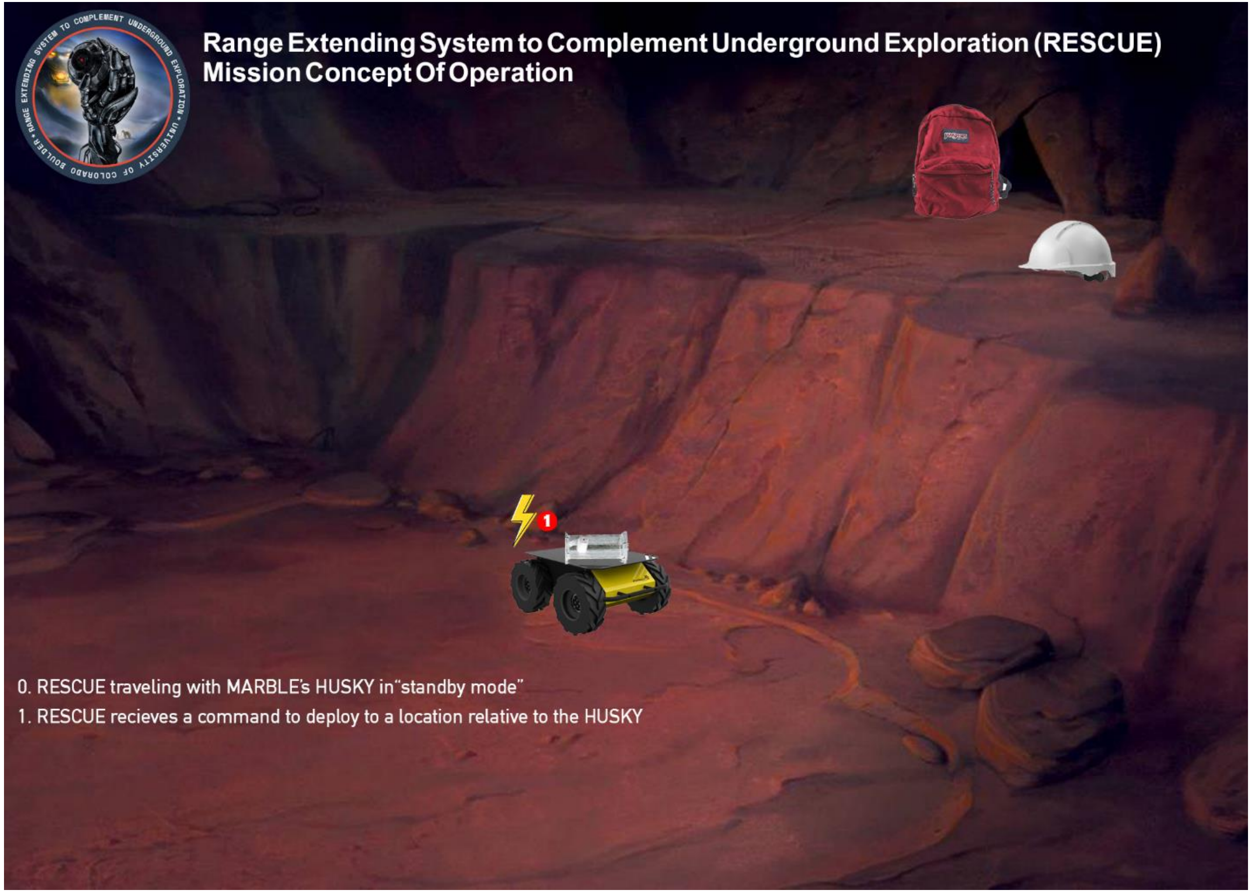
View full slide

	PDR	CDR
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	• Folding robotic arm • 3 sections • Range ≈ 1.3m	• Inflatable robotic arm • Controlled by air pressure • Range ≈ 4m (3x the original range)
End Effector	• RGB-Depth camera • CO_2 sensor • AHRS • Servos to control sensor orientation	• RGB camera • CO_2 sensor • AHRS • Servos to control sensor orientation

CONOPS


Range Extending System to Complement Underground Exploration (RESCUE)
Mission Concept Of Operation
0. RESCUE traveling with MARBLE's HUSKY in "standby mode"

CONOPS


Range Extending System to Complement Underground Exploration (RESCUE)
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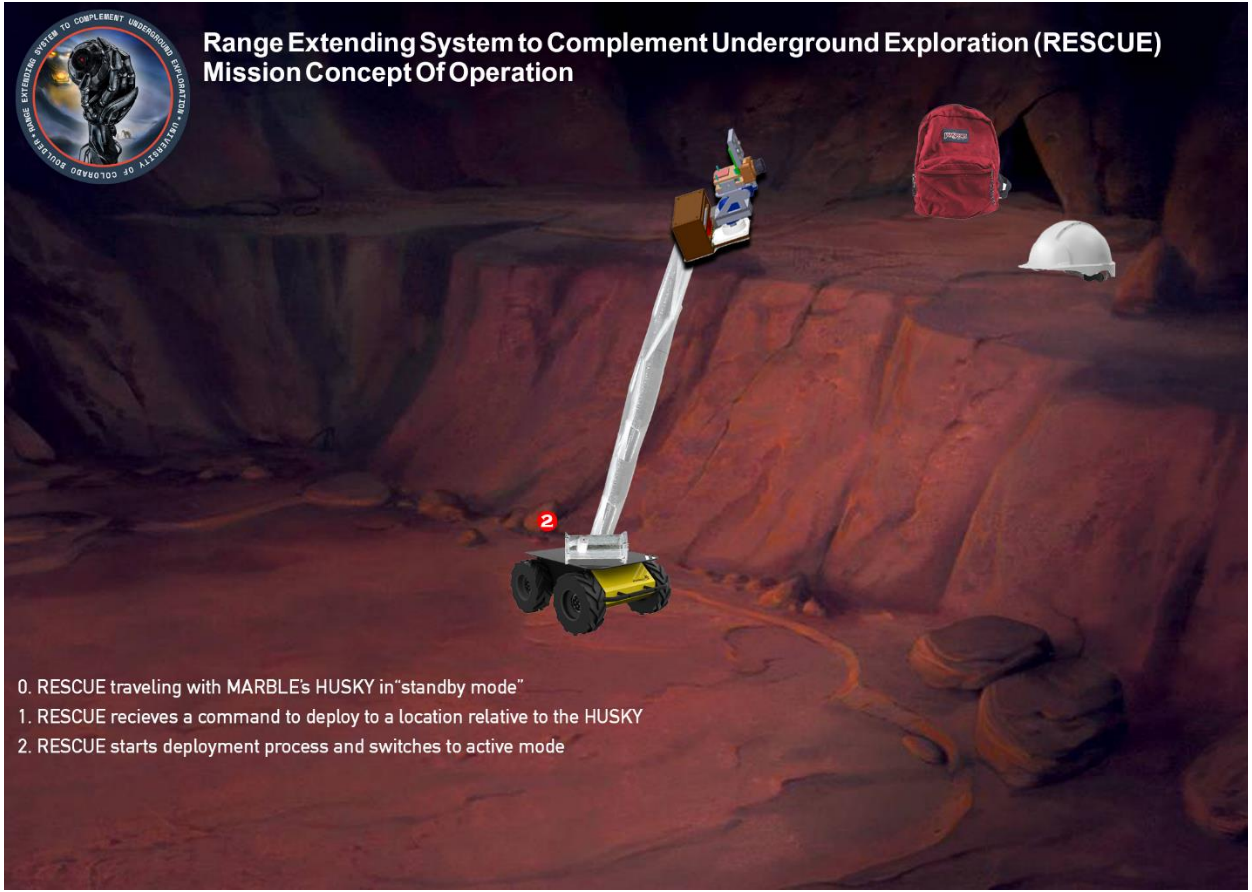
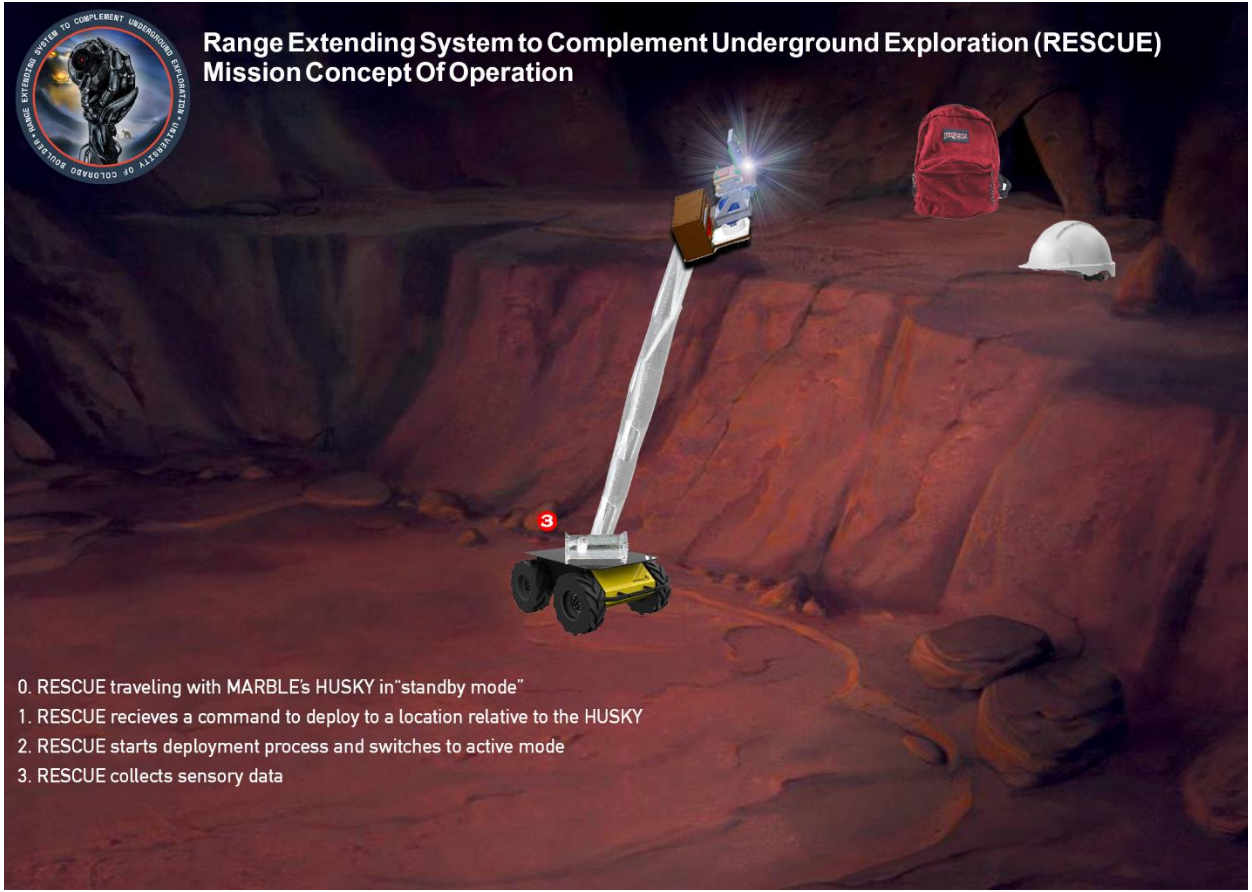
1
0. RESCUE traveling with MARBLE's HUSKY in "standby mode"
1. RESCUE recieves a command to deploy to a location relative to the HUSKY

CONOPS



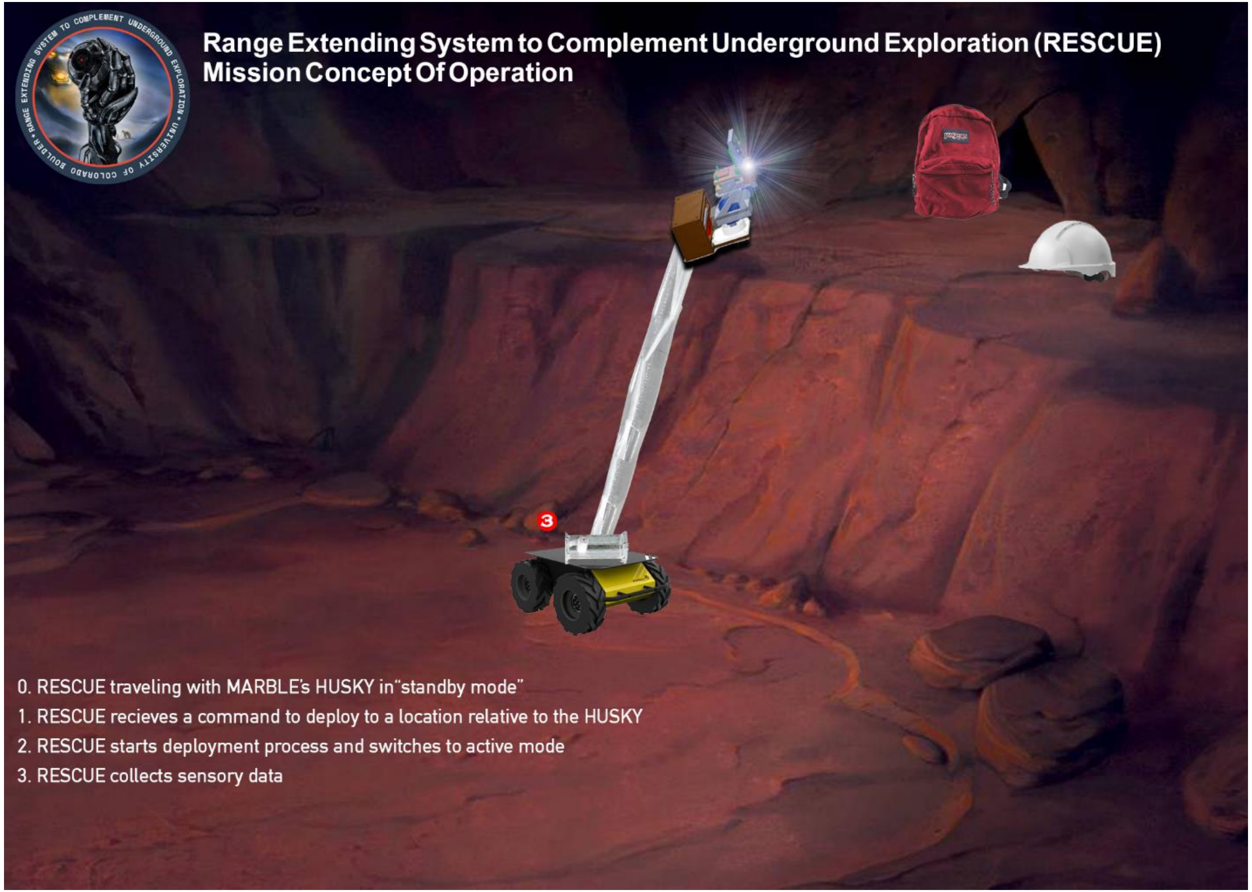
Range Extending System to Complement Underground Exploration (RESCUE)
Mission Concept Of Operation
2
0. RESCUE traveling with MARBLE's HUSKY in "standby mode"
1. RESCUE recieves a command to deploy to a location relative to the HUSKY
2. RESCUE starts deployment process and switches to active mode

CONOPS



Range Extending System to Complement Underground Exploration (RESCUE)
Mission Concept Of Operation
RANGE EXTENDING SYSTEM TO COMPLEMENT UNDERGROUND EXPLORATION • UNIVERSITY OF COLORADO BOULDER •
3
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

CONOPS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CONOPS


Range Extending System to Complement Underground Exploration (RESCUE)
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4
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1. RESCUE recieves a command to deploy to a location relative to the HUSKY
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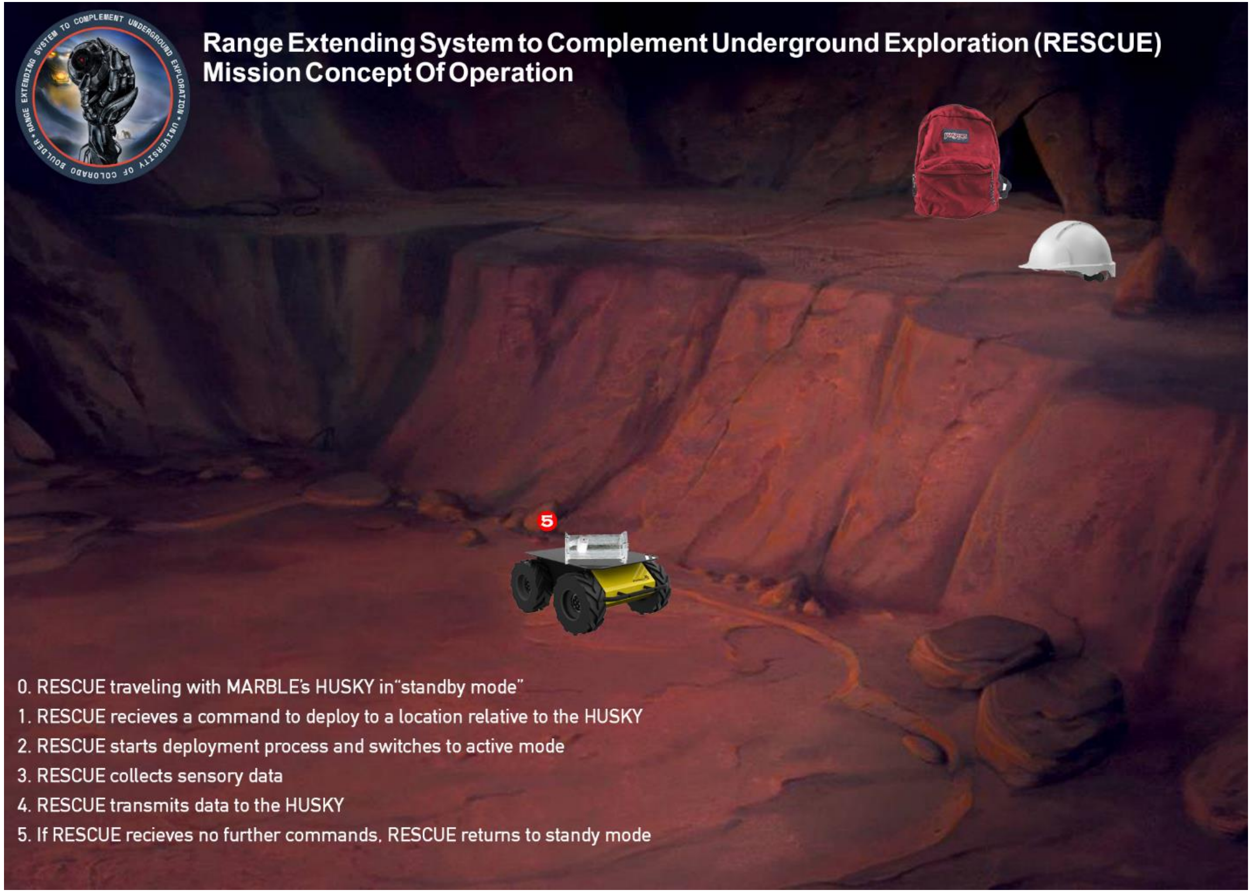
3. RESCUE collects sensory data
4. RESCUE transmits data to the HUSKY

CONOPS


Range Extending System to Complement Underground Exploration (RESCUE)
Mission Concept Of Operation
5
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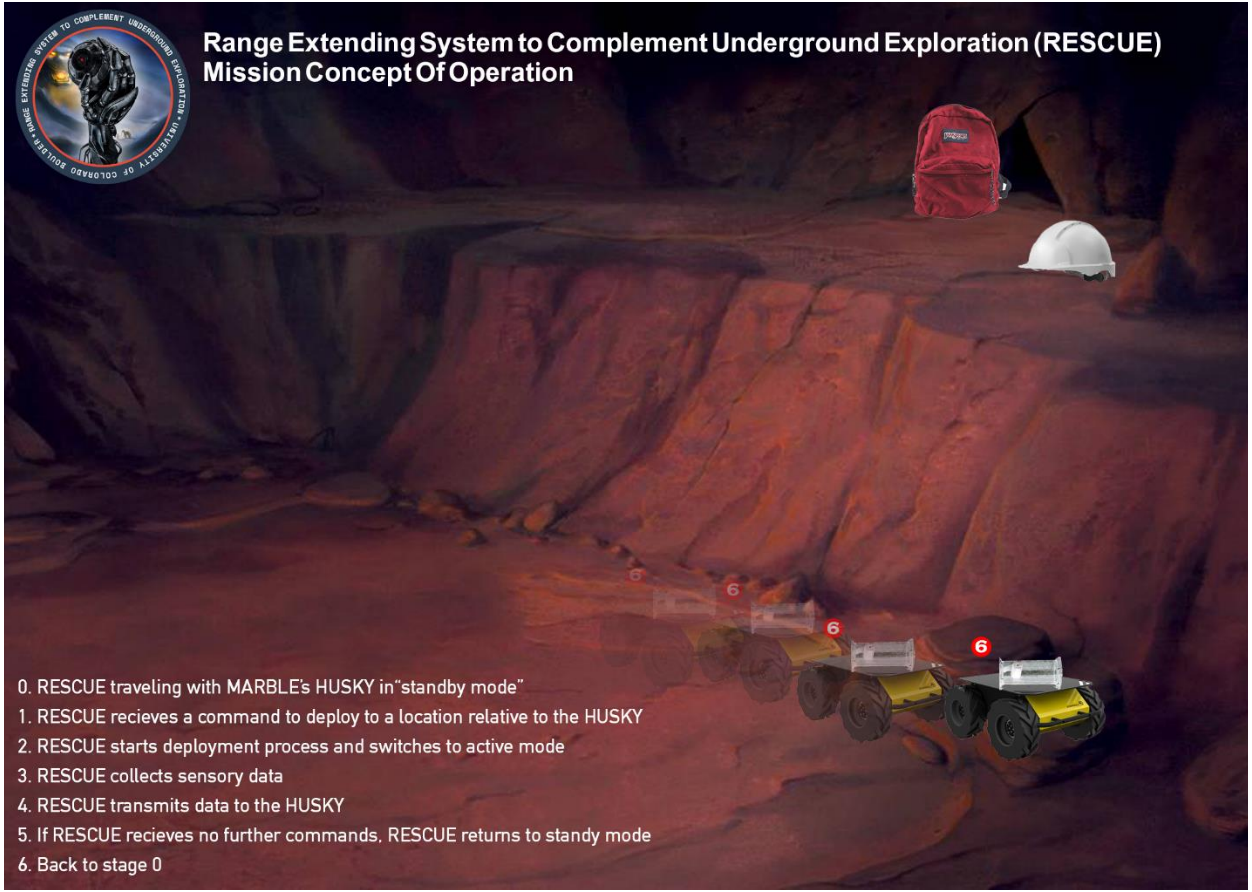
1. RESCUE recieves a command to deploy to a location relative to the HUSKY
2. RESCUE starts deployment process and switches to active mode
3. RESCUE collects sensory data
4. RESCUE transmits data to the HUSKY
5. If RESCUE recieves no further commands, RESCUE returns to standy mode

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

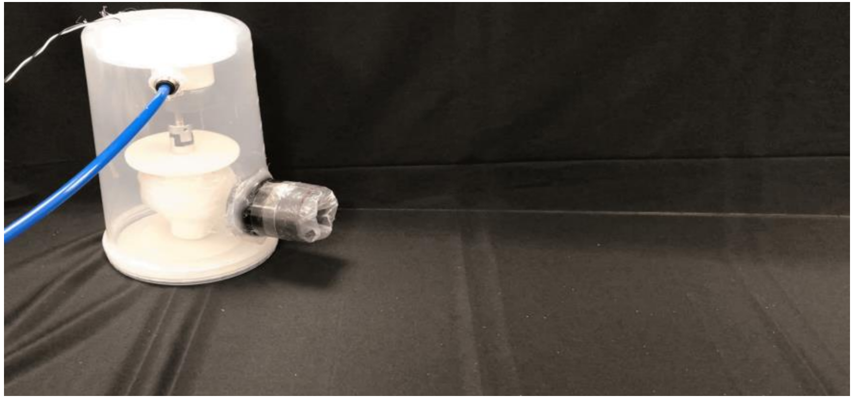
CONOPS

Range Extending System to Complement Underground Exploration (RESCUE)
Mission Concept Of Operation
0. RESCUE traveling with MARBLE's HUSKY in "standby mode"

Design Solution: Leverage research

Research done by Collaborative Haptics and Robotics in Medicine Lab at Stanford University (CHARM Lab) led to the development of:

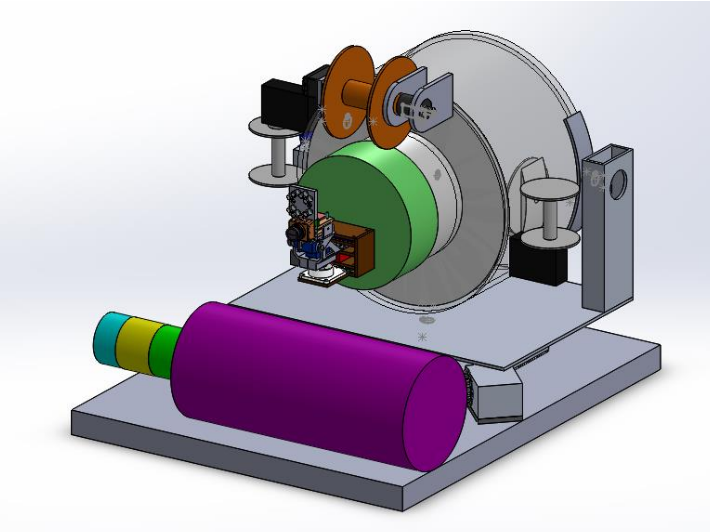
Vine Robots.



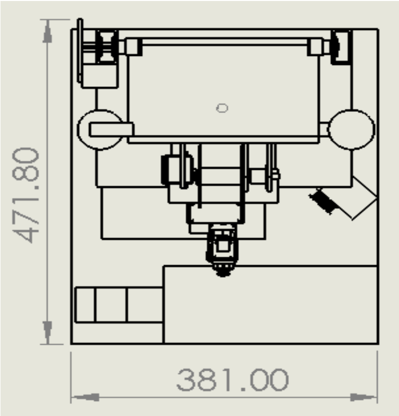
Pressure driven plastic tubes, spool outward from a base, which is connected to an air source. [Courtesy of Stanford's CharmLab]

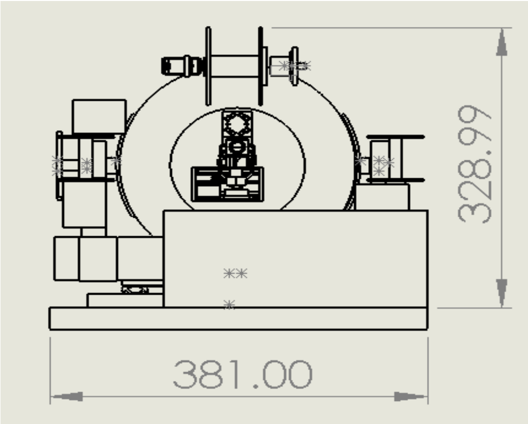
Design Solution

- Basic summary:
  - Extension System
  - Pressurization System
  - Pointing System
  - End Effector



- **Total Mass:** 7.453 kg
- **Total Power Consumption:** 272.3W
- **Extension distance:** 4 m





Dimensions (mm)

Design Solution: Additional CAD

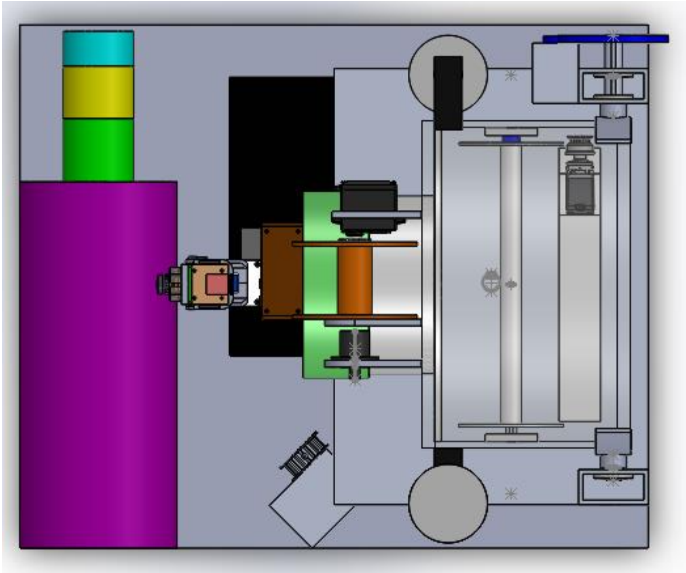


Figure 1: Top View

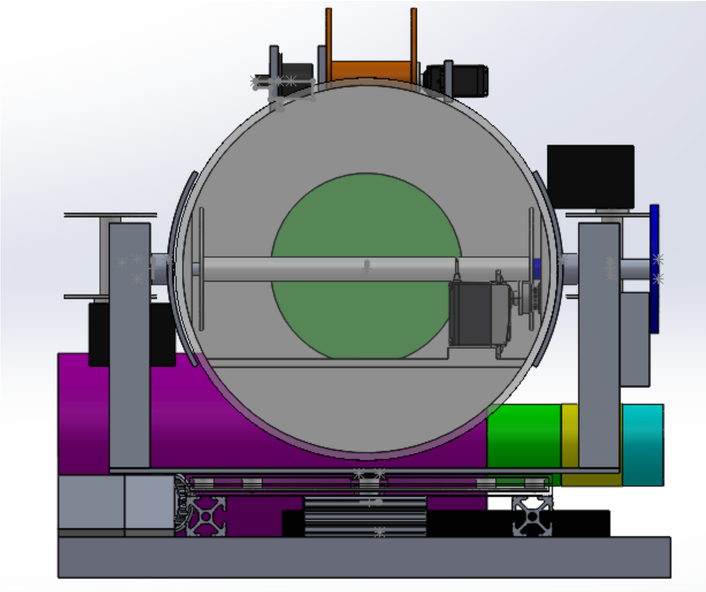
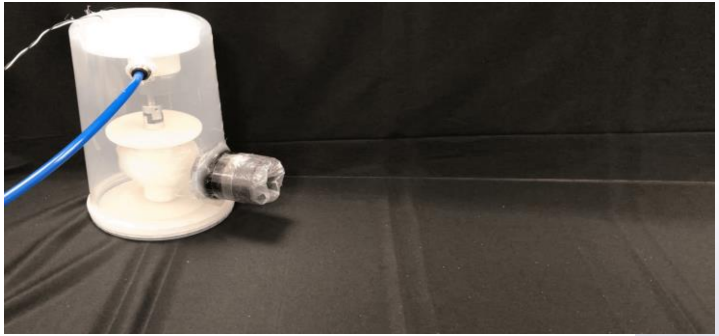
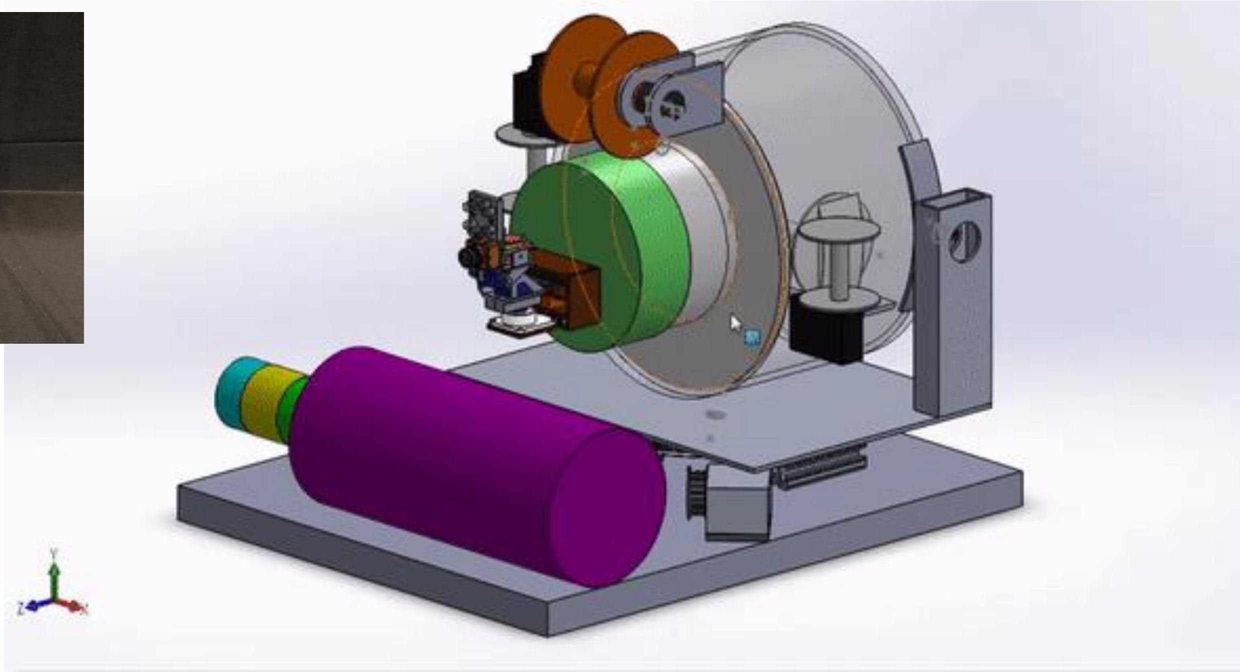


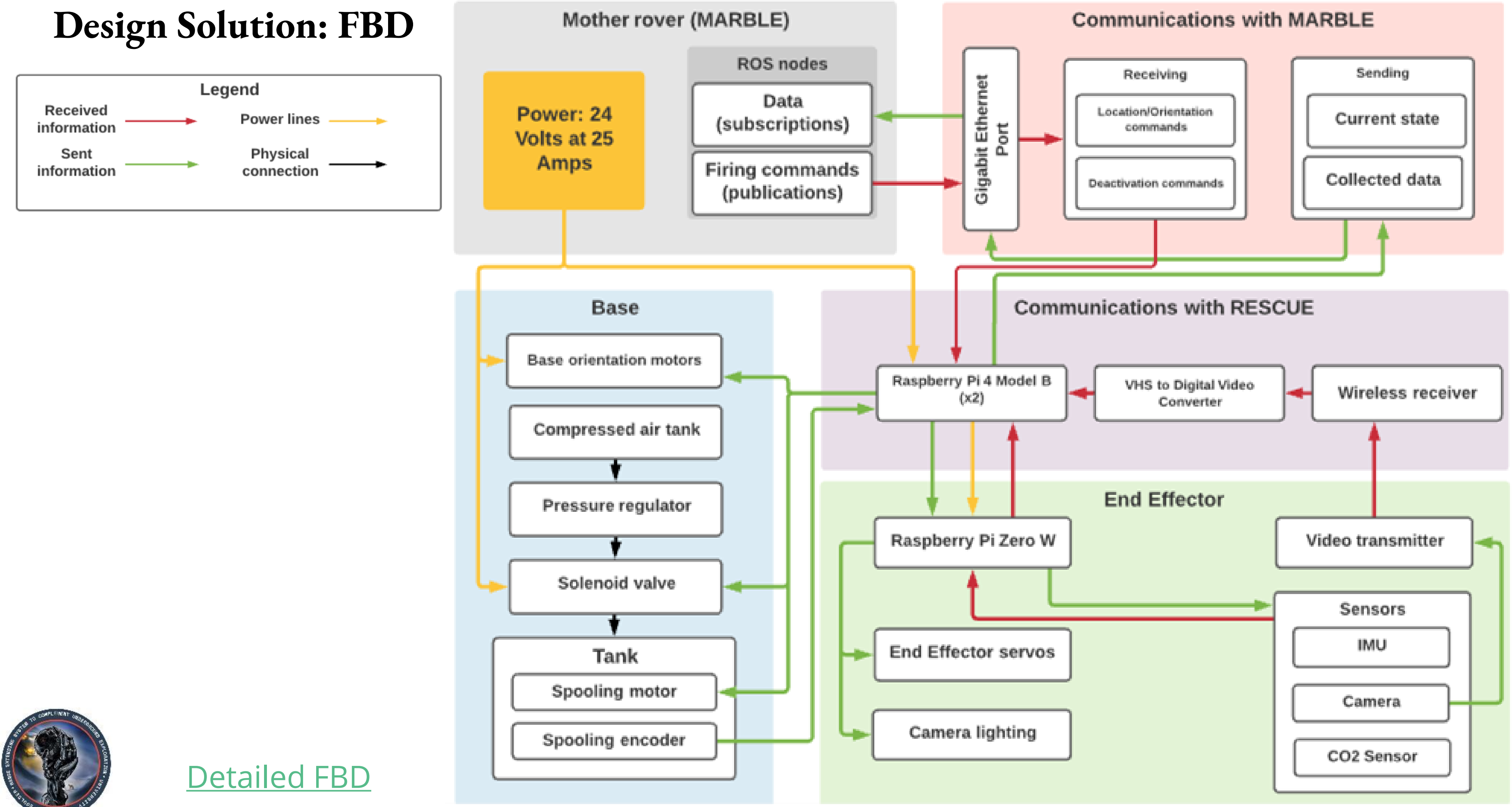
Figure 1: Back View

Design Solution: CAD



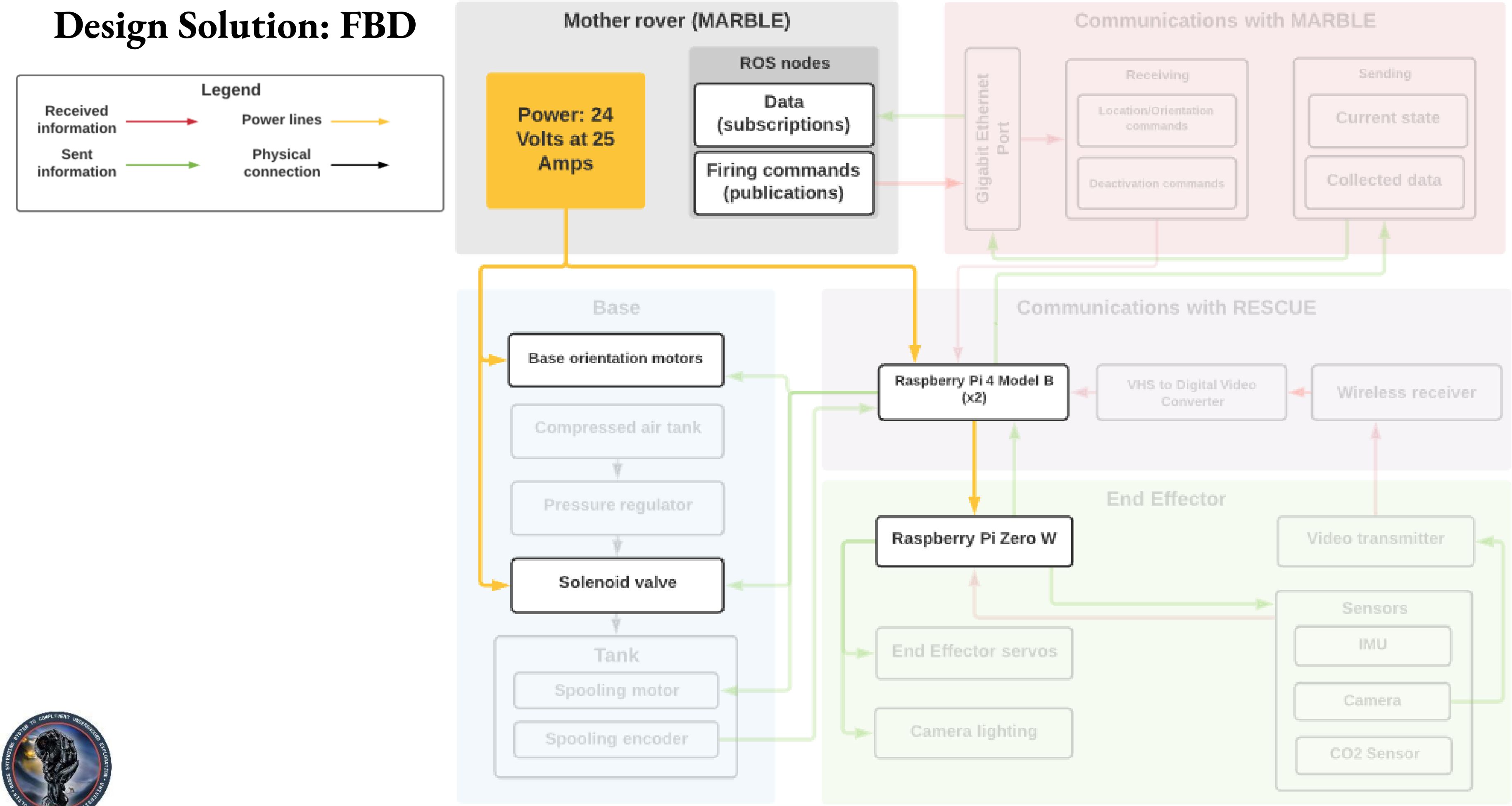


Design Solution: FBD



Detailed FBD

Design Solution: FBD



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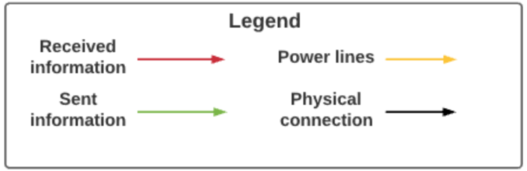

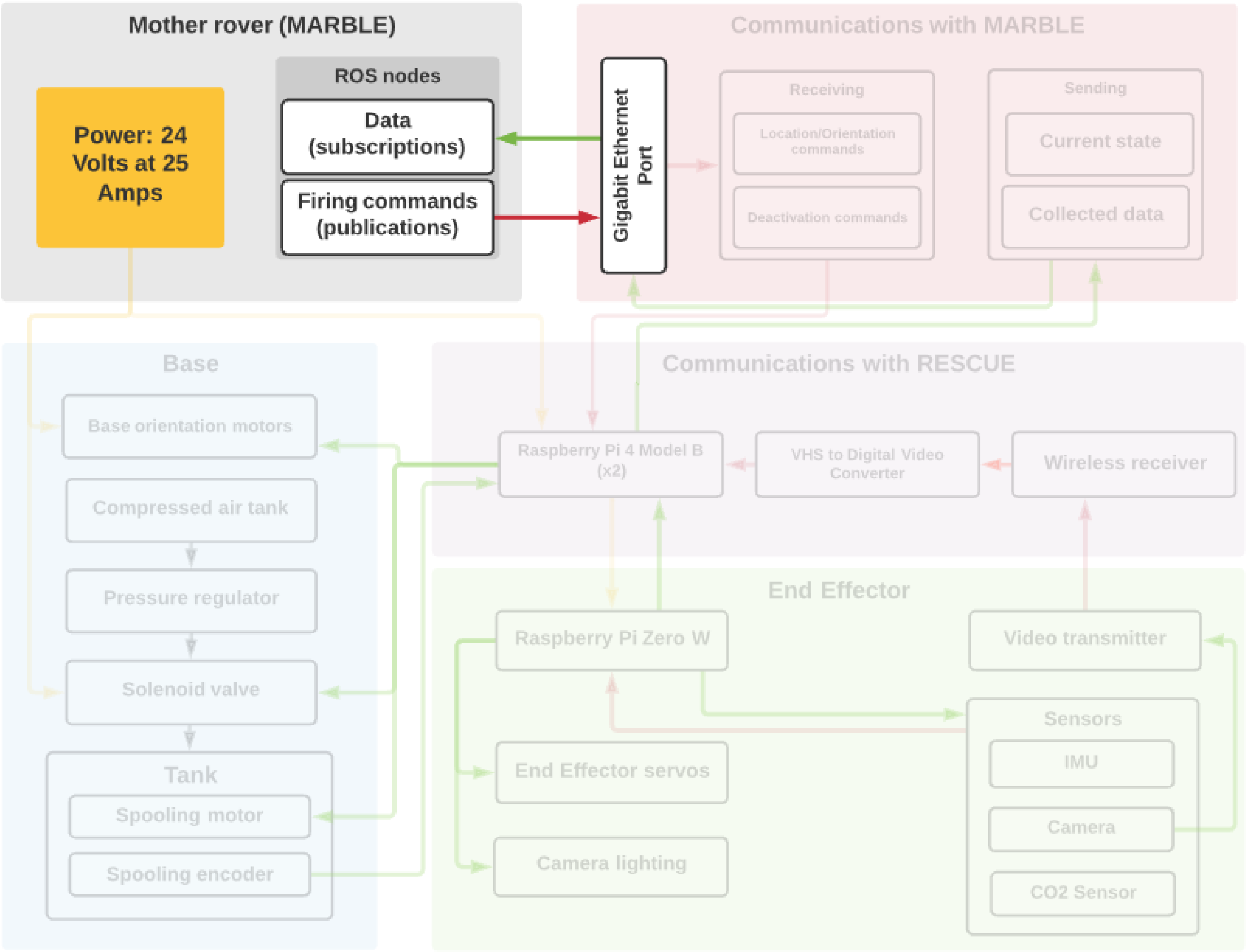

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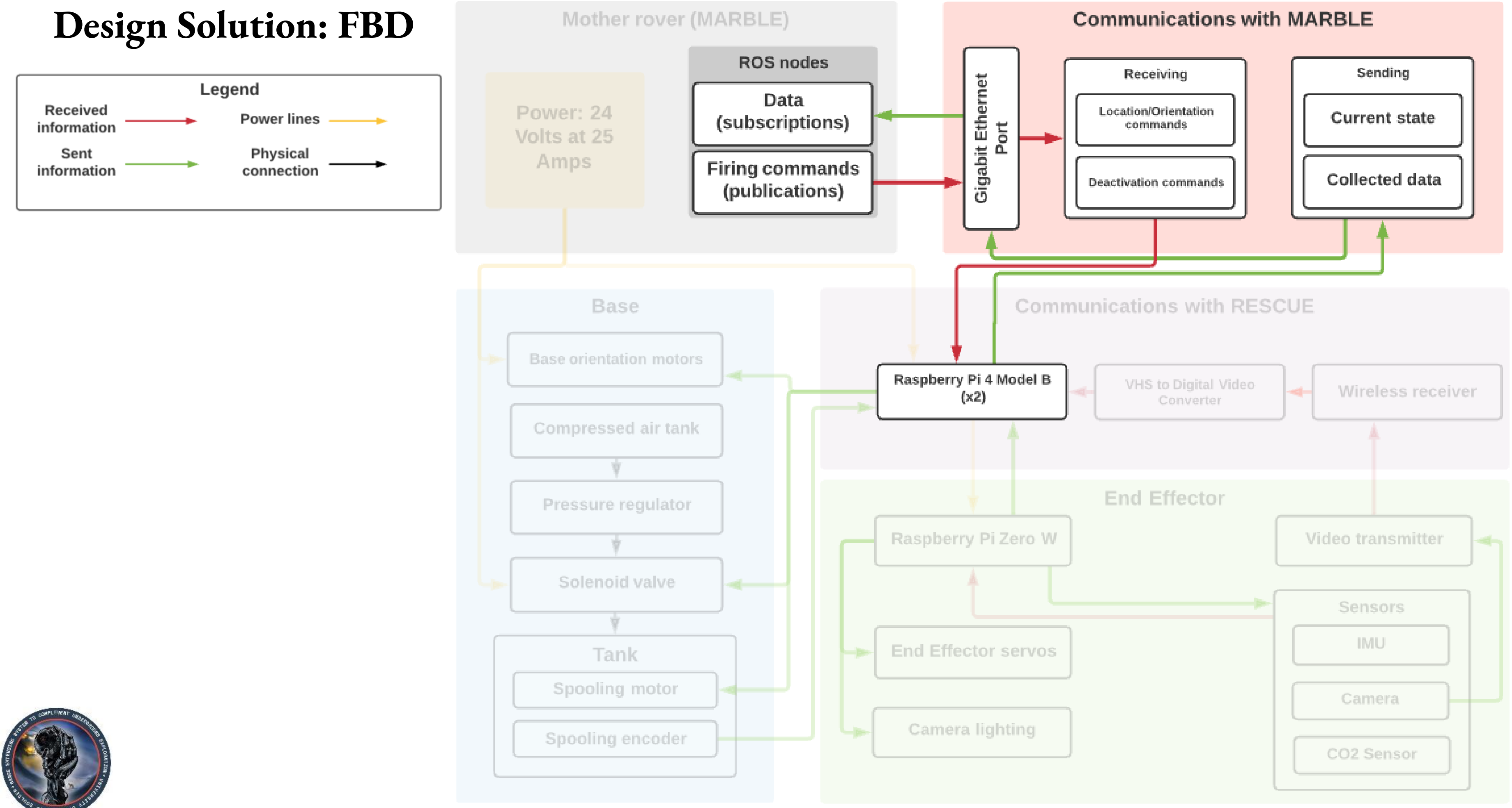

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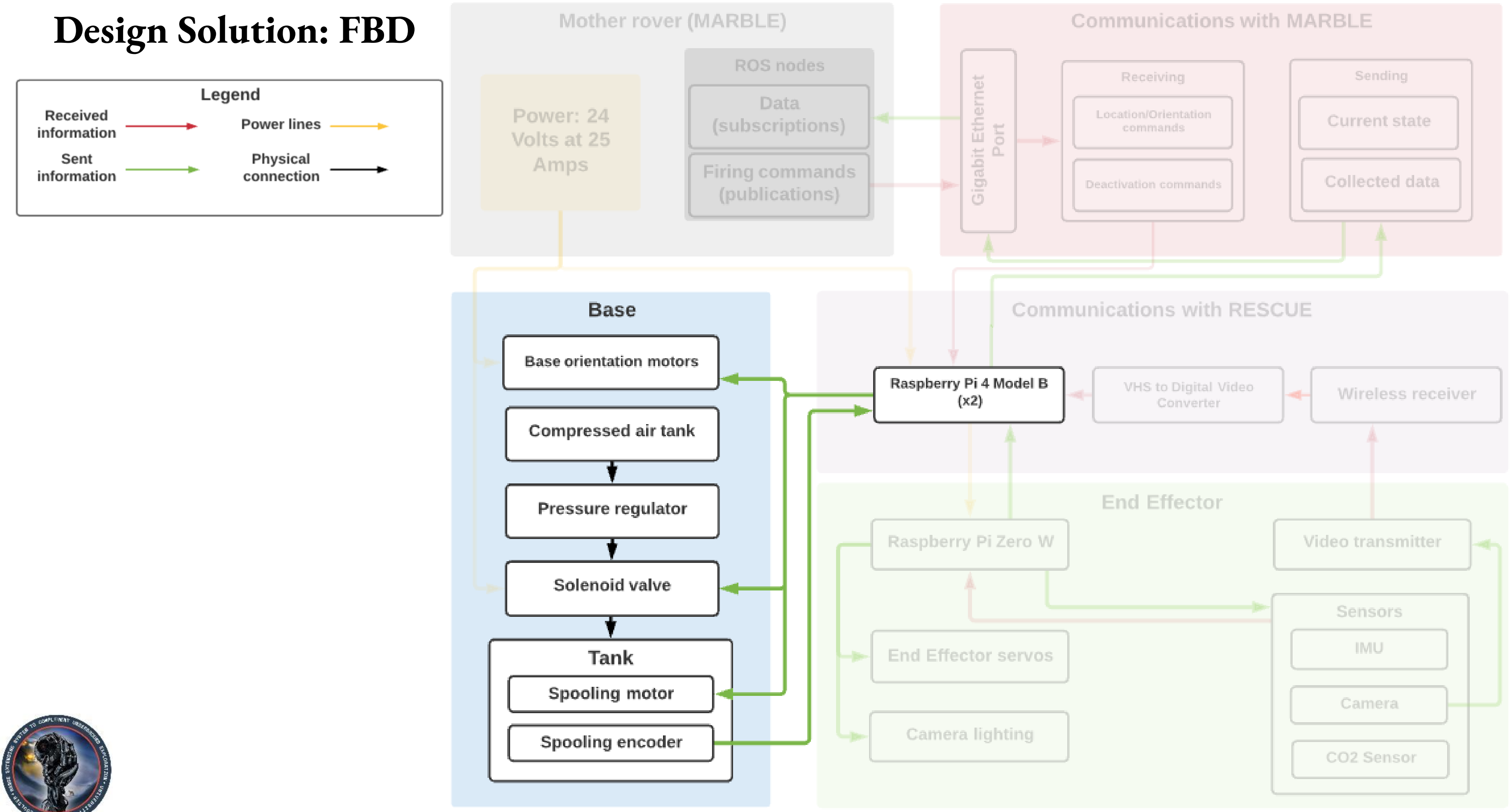

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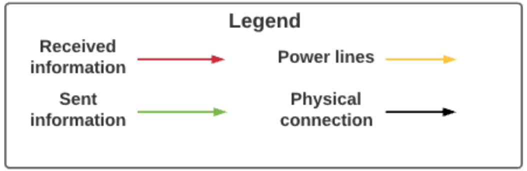

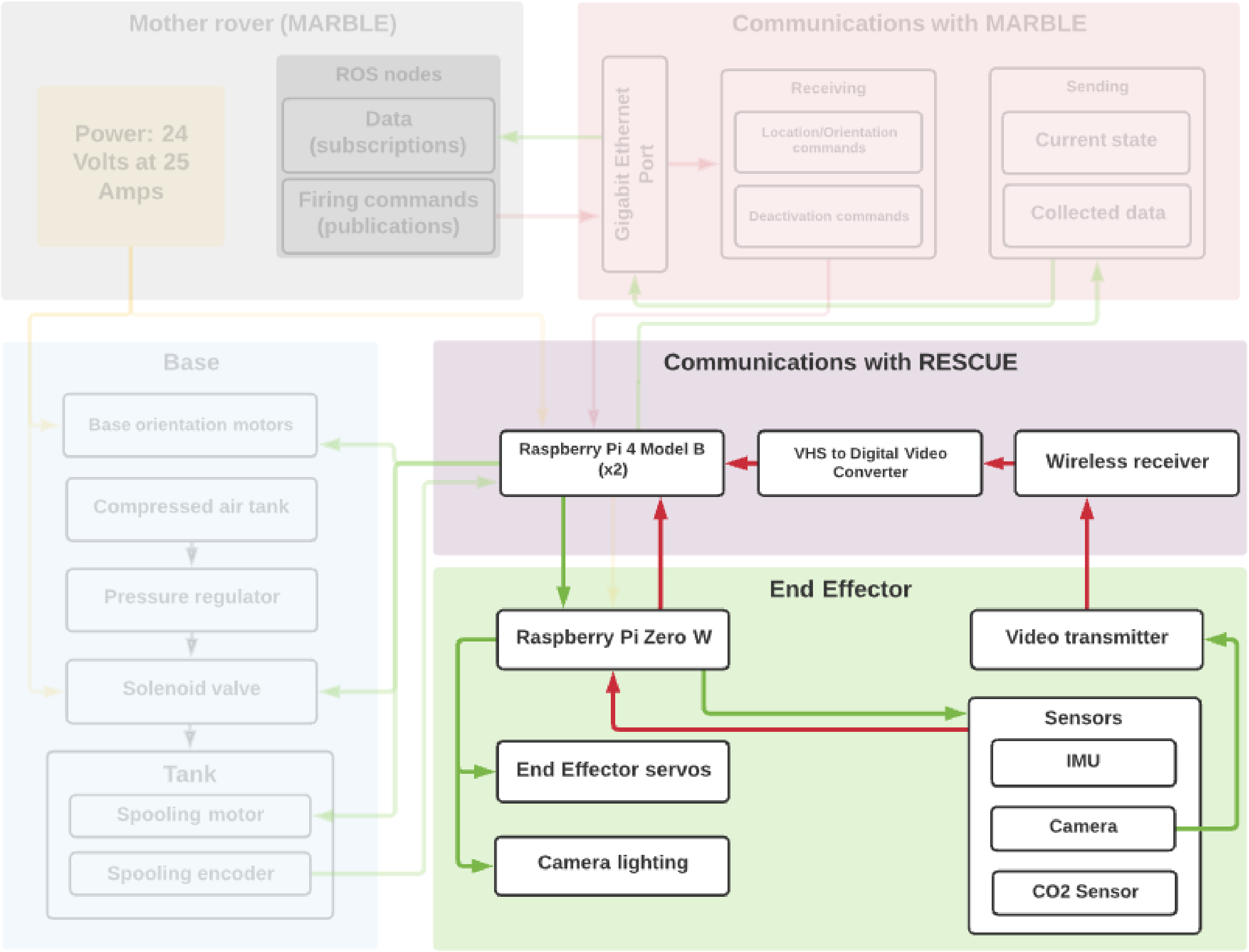

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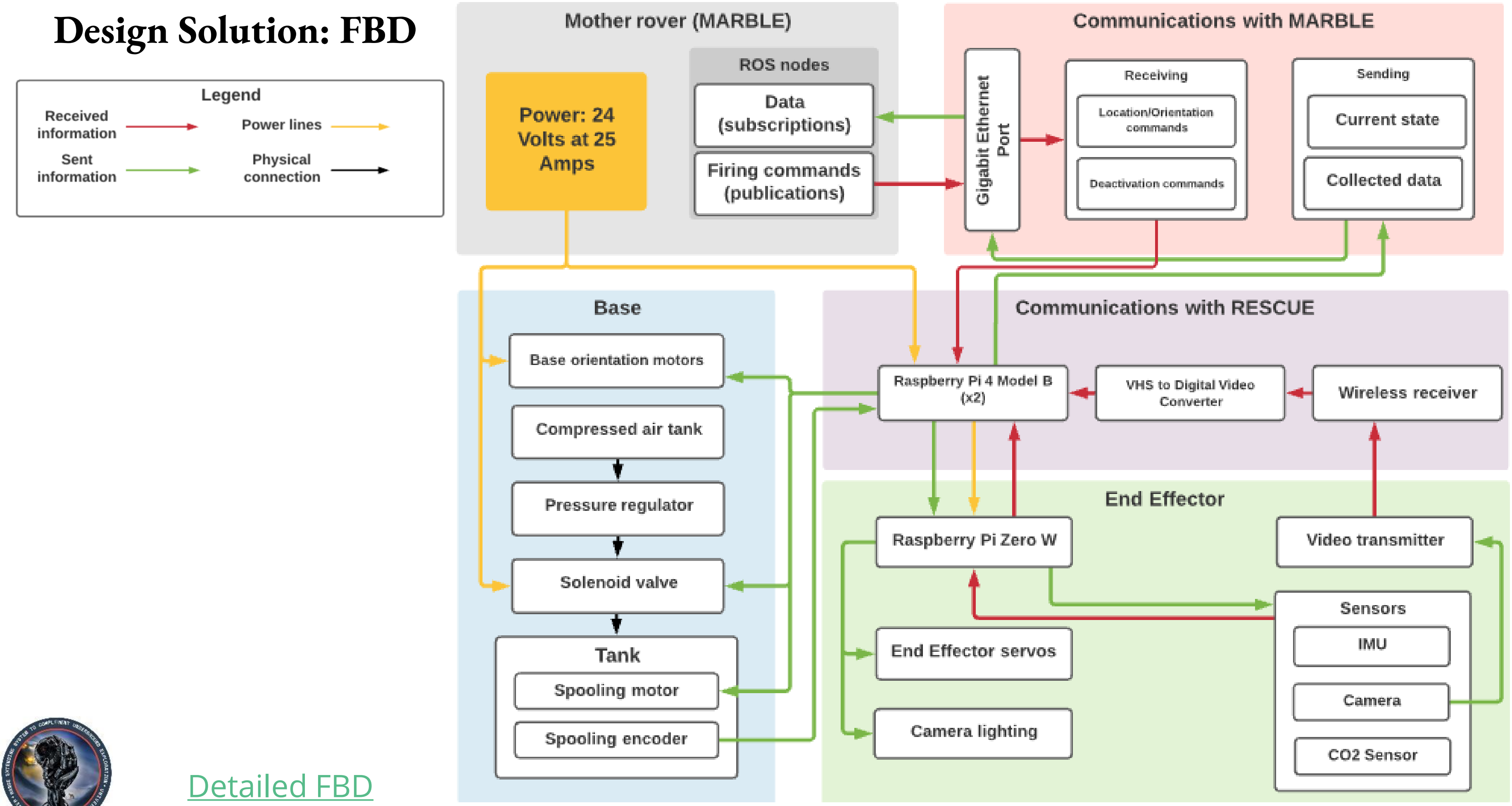


Detailed FBD

Critical Project Elements

Critical Project Elements

Main presentation

1 Artifacts sensing
- Sensor package

2 Physical reach
- Extension method
- Structural analysis

3 Endurance
- Flow control
- Spool calculations

Backups

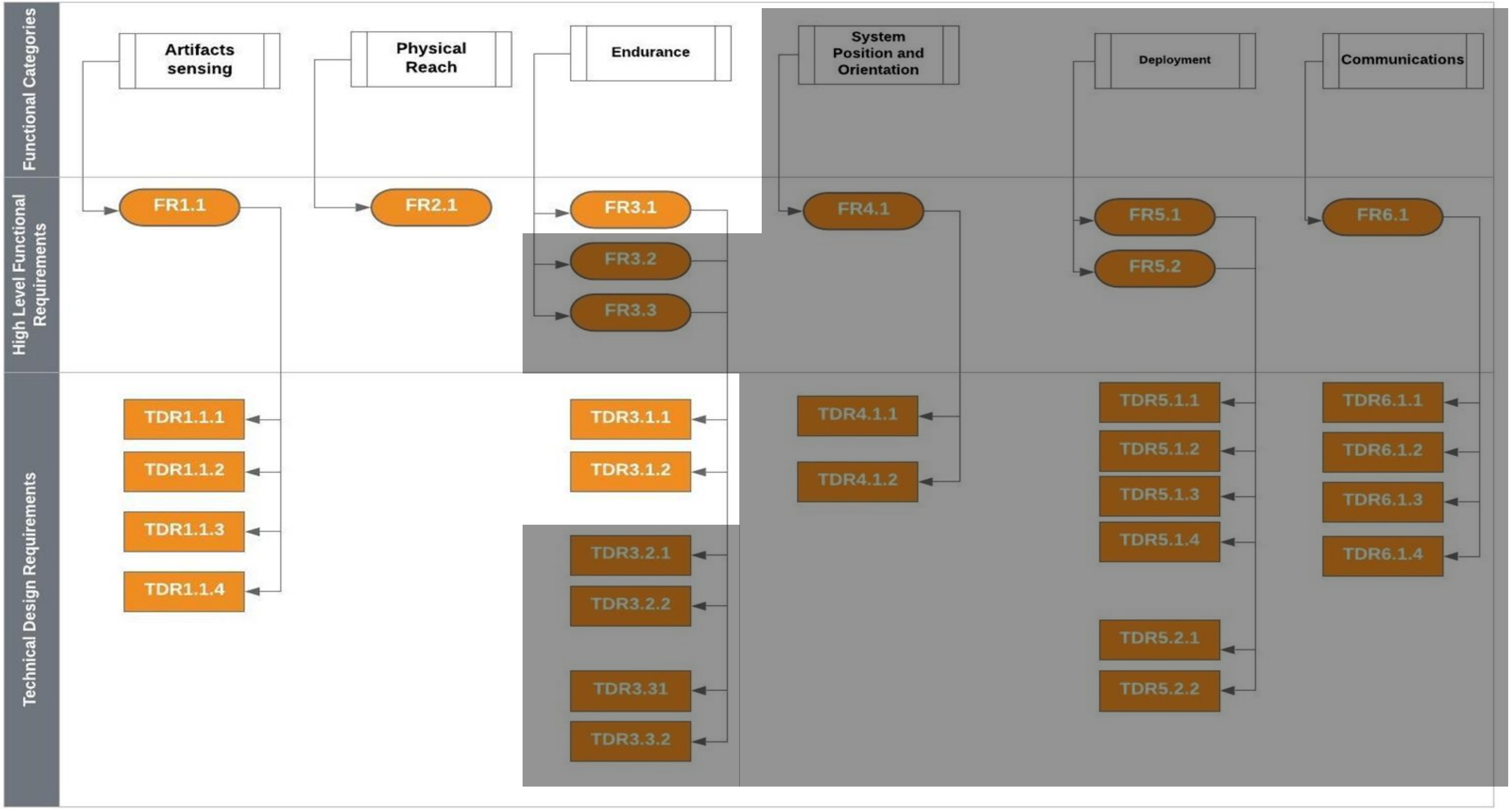
4 System position and orientation
- IMU
- Encoders
- Pointing mechanisms

5 Deployment
- Mass budget
- Volume budget
- Power budget
- Time constraints

6 Communications
- Receiving commands
- Reporting status

Design Requirements and their Satisfaction

Requirements Tree

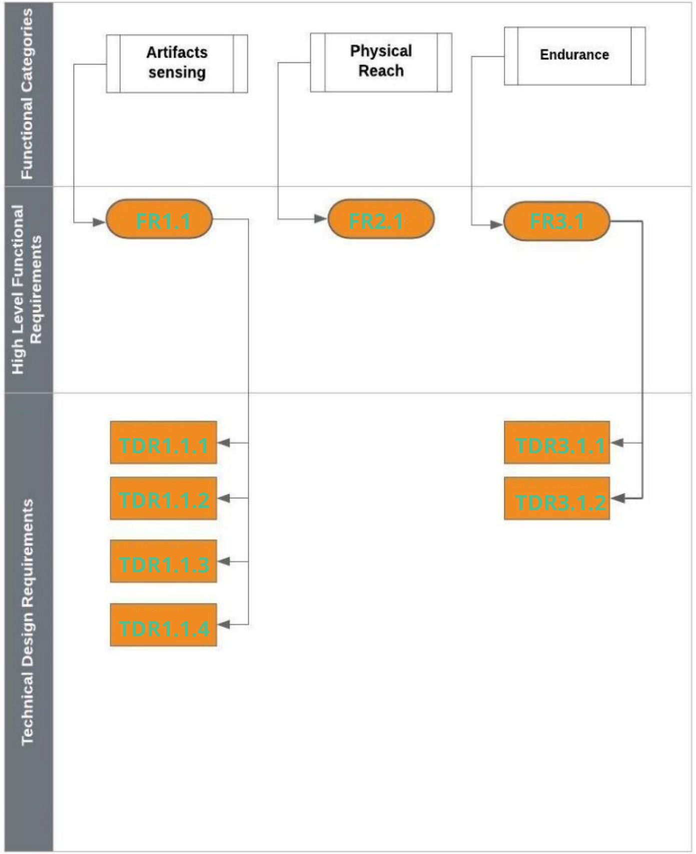


Main Presentation

Backup Slides

To Requirements in the Backups

Requirements Tree



Back to the Requirements Tree

Requirements satisfaction: Artifacts sensing

FRs	TDRs	Requirement	Functional Category
FR 1.1		The sensing system shall be able to sense DARPA subterranean challenge competition artifacts	Artifact Sensing
	TDR 1.1.1	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	Artifact Sensing
	TDR1.1.2	RESCUE shall have enough lighting to perform all of its sensing operations in a possibly aphotic environment.	Artifact Sensing
	TDR1.13	The sensing apparatus shall be able to sense and detect carbon dioxide (CO_2) at 2000 parts per million concentration.	Artifact Sensing
	TDR1.1.4	Once RESCUE is re-positioned, the mechanical mount for the visual artifact signature sensor shall be capable of rotating at least 90° or more about at least one axis.	Artifact Sensing

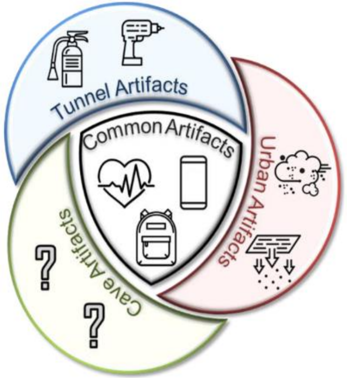


Figure 1: Possible artifacts, courtesy of DARPA

Requirement	Design	Satisfaction	FOS
Sensor apparatus is capable of sensing DARPA artifacts	Camera and LEDs and CO_2 sensor	✓	N/A

Back to the Requirements Tree

All the artifacts:

Fire Extinguisher
- Red hand-held, metal cylinder
- On ground, hanging on wall, or on work surface

Gas
- CO_2 at 2,000 ppm
- Emitted in a confined room

Vent
- Three-cone square ceiling diffuser
- 30℃ above ambient temperature

Helmet
- White caving helmet w/ headlamp on
- On ground, hanging on wall, or on a ledge

Rope
- Coiled blue climbing rope
- On ground, hanging on wall, or on a ledge

Survivor
- Thermal dummy
- High-visibility jacket
- Placed in sitting position

Cell Phone
- Samsung Galaxy smartphone
- Playing full-screen video w/ audio

Backpack
- Red JanSport
- On ground, hanging on wall, or on work surface

Drill
- Orange Black & Decker cordless drill
- On ground or work surface

Back to the Requirements Tree

Requirements satisfaction: camera and lighting

FRs	TDRs	Requirement	Functional Category
FR 1.1		The sensing system shall be able to sense DARPA subterranean challenge competition artifacts	Artifact Sensing
	TDR 1.1.1	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	Artifact Sensing
	TDR1.1.2	RESCUE shall have enough lighting to perform all of its sensing operations in a possibly aphotic environment.	Artifact Sensing

Figure 1: Runcam Split 3 Micro

Figure 2: Bright Pi Lighting Board

- **Components:**
  - Camera: Runcam Split 3 Micro (Fig. 1)
  - Lighting: Bright Pi Lighting Board (Fig. 2)
- **Purpose:**
  - Camera: collect pictures
  - Lighting: enables the collection of useful pictures

Requirement	Design	Satisfaction	FOS
Visual sensors capable of working in aphotic environment	A camera and LED lights		N/A

- **Capabilities:**
  - **Camera:**
  - 2MP, 14 g FPV
  - NTSC (720x480) Video output wired to TX200U 5.8GHz transmitter
  - WR832 5.8GHz FPV receiver combined with AIFUSI CVBS to digital video converter at base
  - **Lighting:**
  - 12 x 3.2V, 5.165 cd LEDs
  - 61.98 cd illumination total
  - I^2C Interface
  - 25g, mounted directly above camera

Back to the Requirements Tree

Requirements satisfaction: TDR 2.1.2: CO2 sensor

FRs	TDRs	Requirement	Functional Category
FR 1.1		The sensing system shall be able to sense DARPA subterranean challenge competition artifacts	Artifact Sensing
	TDR1.1.3	The sensing apparatus shall be able to sense and detect carbon dioxide (CO2) at 2000 parts per million concentration.	Artifact Sensing

- **Components:**
  - SCD30 CO_2 Sensor (Fig. 1,2)
- **Purpose:**
  - Ability to sense CO_2 -related artifacts
- **Capability:**
  - [0, 40000] ppm
  - ± 30 ppm (at 25℃ for [400, 10000] ppm)
  - 20 s Response time

Figure 1: SCD30 CO2 sensor

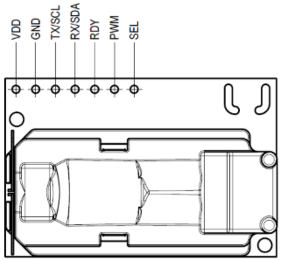


Figure 2: SCD30 CO2 sensor connection board

Requirement	Design	Satisfaction	FOS
2000 parts per million accuracy	30 parts per million accuracy		67

Back to the Requirements Tree

Requirements satisfaction: End-Effector Pan Tilt Camera Mount

FRs	TDRs	Requirement	Functional Category
FR 1.1		The sensing system shall be able to sense DARPA subterranean challenge competition artifacts	Artifact Sensing
	TDR1.1.4	Once RESCUE is re-positioned, the mechanical mount for the visual artifact signature sensor shall be capable of rotating at least 90° or more about at least one axis.	Artifact Sensing

- **Components:**
  - SG90 Micro Servo Pan Tilt Kit (Fig. 1)
- **Purpose:**
  - Rotate the camera for a better sensing capability
- **Capability:**
  - ~180° Pan and ~150° Tilt
    - Depends on Servos (alternatives exist)
  - 0.1 s/60° with 4.8 V

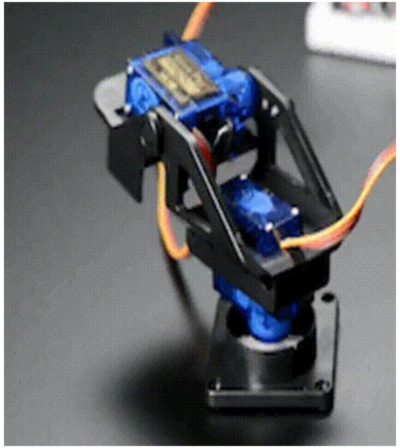


Figure 1: Pan Tilt Operation

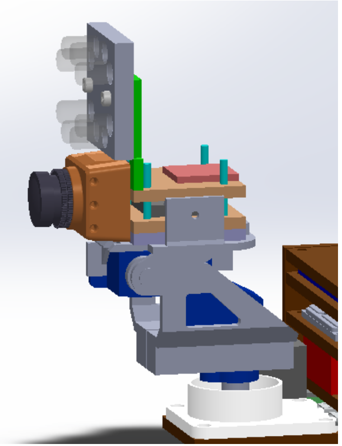
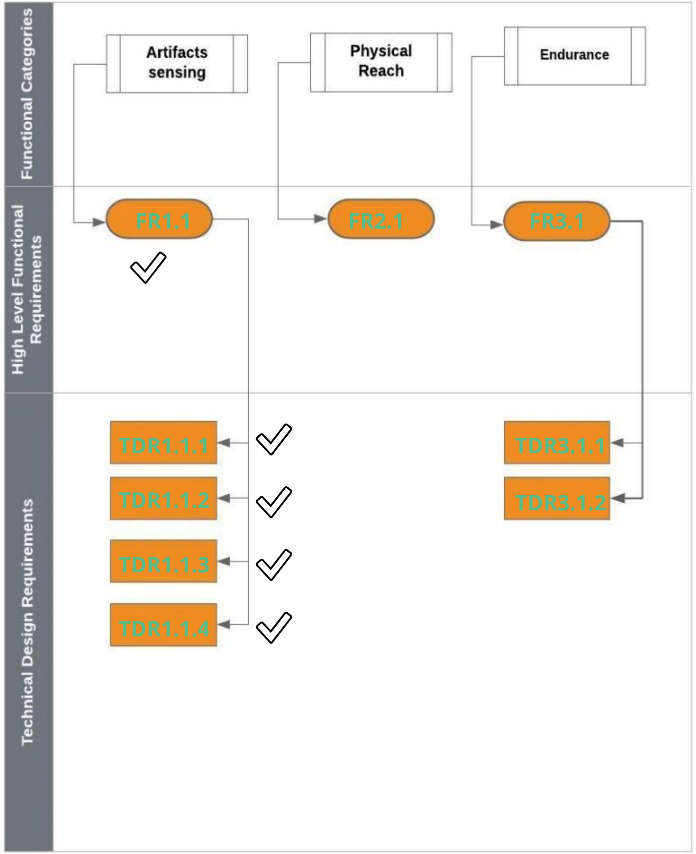


Figure 2: CAD with Instruments Mounted

Requirement	Design	Satisfaction	FOS
One axis of rotation, at least 90°	≈180° Pan ≈150° Tilt	✓	N/A

Back to the Requirements Tree

Requirements Tree



Back to the Requirements Tree

Requirements satisfaction: Extension Mechanism

FRs	TDRs	Requirement	Functional Category
FR 2.1		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 in an upper-half hemisphere.	Physical Reach

- **Component:**
  - The rotating base
- **Purpose:**
  - Provide the FOV required for the inflatable arm
- **Capability**
  - Provides a 360° about the y axis.
  - Provides a 90° about the z axis.
  - Reposition the arm into any location within the hemisphere.

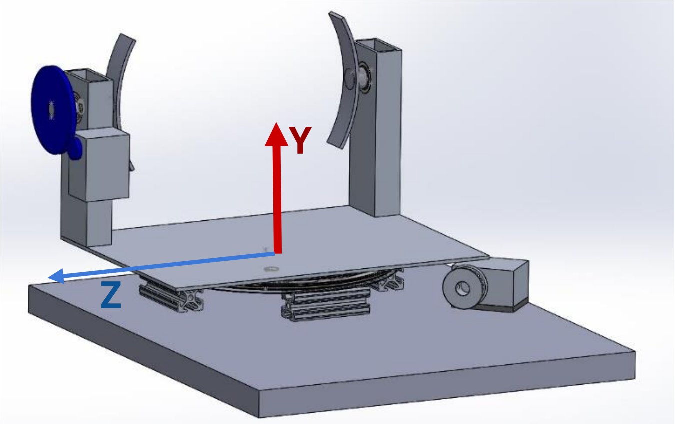


Figure 1. The rotating base

[Back to the Requirements Tree](#)

Requirements satisfaction: Extension Mechanism (The Arm)

FRs	TDRs	Requirement	Functional Category
FR 2.1		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 in an upper-half hemisphere.	Physical Reach

- **Components:**
  - Low-Density Polyethylene (LDPE) tubing (Material property in backups)
- **Purpose:**
  - Inflatable arm for sensing extension
  - Tube will be unspooled, inflated, and pressurized to reach the desired extension
- **Capability:**
  - 152 μm thick, 12.7 cm diameter
  - 4 m extension with 1.2 FOS for inflation pressure

Figure 1. ULINE roll of LDPE tubing

Back to the Requirements Tree

Requirements satisfaction: Extension Mechanism (End Effector Tension Lines)

FRs	TDRs	Requirement	Functional Category
FR 2.1		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 in an upper-half hemisphere.	Physical Reach

- **Components:**
  - Two HSR-2645CRH Servos, with spools and tension lines
- **Purpose:**
  - Keep the end effector on the tip of the arm at all times
  - As the tube is extended and inflated, the tension lines will unspool
  - As the tube is retracted, the tension lines will spool up and hold the end effector in place
- **Capability:**
  - 4 m extension in less than 30 seconds

Figure 1: servos used

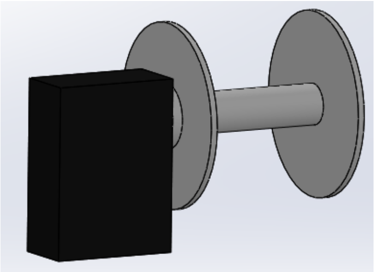


Figure 2: spool configuration

Requirements satisfaction: Extension Mechanism, Material Spool Container

FRs	TDRs	Requirement	Functional Category
FR 2.1		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 in an upper-half hemisphere.	Physical Reach

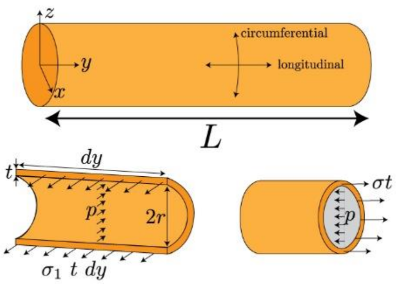


Figure 1: The tube nomenclature

- **Component:**
  - PVC Tube
  - Acrylic End Caps
- **Purpose:**
  - House the material and spooling mechanism
- **Capability:**
  - 3 FOS on maximum stress value (hoop stress)
  - 237.7 mm OD, 4.75 mm side wall
  - 133.35mm Length
  - Cap analysis in backup slides

Parameter	Value (PSI)	Value (MPa)
Hoop stress (σ1)	336.9 (PSI)	2.32 (MPa)
Longitudinal stress (σ2)	168.4 (PSI)	1.161 (MPa)
t/r	0.021	0.021
PVC Yield tensile strength (matweb min.)	500 (PSI)	3.44 (MPa)

Requirements satisfaction: Payload capacity

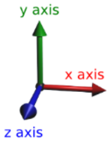
FRs	TDRs	Requirement	Functional Category
FR 2.1		RESCUE shall have the ability to physically reach a location along an unobstructed linear path that is at least 1 meter but not more than 5 meters away from RESCUE's stowing position on the MARBLE Clearpath Husky within an upper half hemisphere.	Physical Reach

How far RESCUE can go (safely) is a function of the payload capacity!

This leads to: Structural analysis

Back to the Requirements Tree

Requirements satisfaction: Structural analysis



Assumptions:

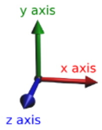
- Isotropic material
- Constant cross sectional area
- Fixed support on one end (inflatable cantilever beam)
- $F_{tendon} = 0$ (The supporting structure does not pull on the material)
- Small strain.
- Modeling as thin walled pressure vessel as a cantilever beam

Figure 1: failure due to Buckling (horizontal (parallel) loading)

Figure 2: failure due to bending (yielding) (vertical (perpendicular) loading)

Back to the Requirements Tree

Requirements satisfaction: Structural analysis



Governing equations

Maximum vertical that could be applied before the collapse of the structure [1,2]: $F_{collapse} = \frac{\pi R^3 P}{2L}.$

Maximum horizontal that could be applied before the collapse of the structur

$$F_{cr} = \frac{(E + \frac{P}{S}) I \Omega^2}{1 + \Omega^2 \frac{I}{S} + \Omega^2 \frac{\left(E + \frac{P}{S}\right) I}{P + kGS}},$$

Longitudinal stress: $\sigma_L = PR/2t\,.$

Circumferential (Hoop) stress: $\sigma_\theta = \frac{PR}{t}.$

From force balance, which results in the same exact expressions used in ASEN 3112, Spring 2019, Lecture 3.

Yield stress: σ_y The hoop stress is higher than the longitudinal stress $\sigma_\theta \leq \sigma_y$, thus we need $P \leq \frac{\sigma_y t}{R}$

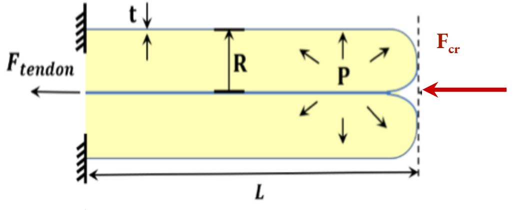


Figure 1: Bar subject to horizontal loading

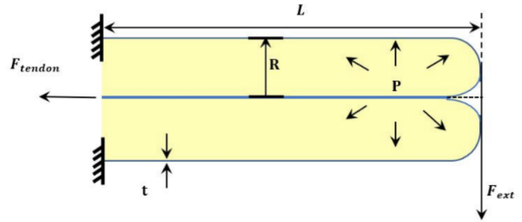


Figure 2: Bar subject to vertical loading

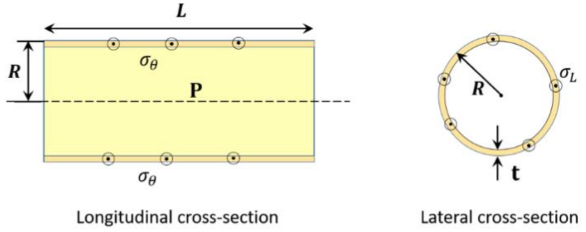
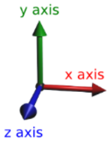
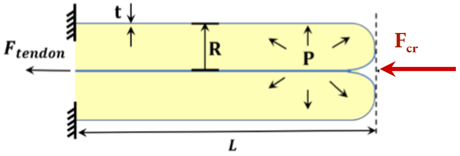


Figure 3: cross sectional views.

Back to the Requirements Tree



Requirements satisfaction: Structural analysis



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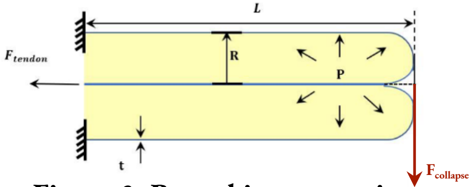
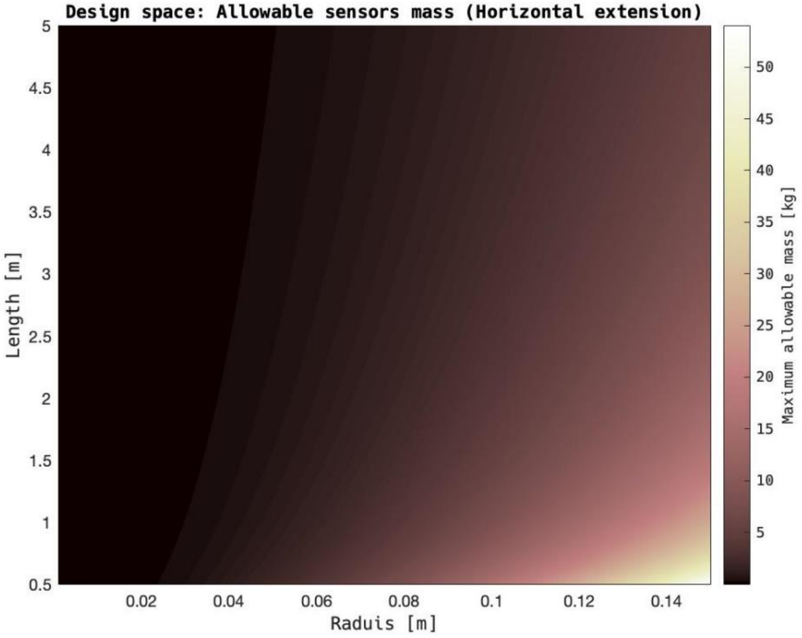


Figure 2: Bar subject to vertical loading

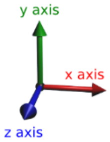
$$F_{collapse} = \frac{\pi R^3 P}{2L}.$$

- It turns out that a structure like this can tolerate way higher $\mathbf{F_{cr}}$ than $\mathbf{F_{collapse}}$
- Thus, the failure criteria is $\mathbf{F_{collapse}}$ criteria
- We can convert the force into an equivalent mass, and thus figure out the maximum possible mass that we can have given a radius and length combination.
- More detailed analysis in the backups.



Design space

Back to the Requirements Tree



Requirements satisfaction: Structural analysis

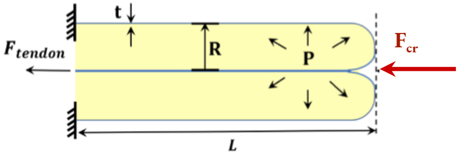


Figure 1: Bar subject to horizontal loading

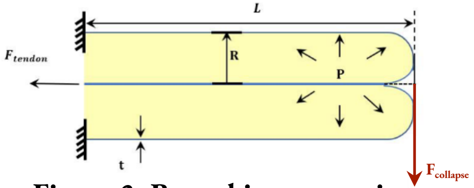
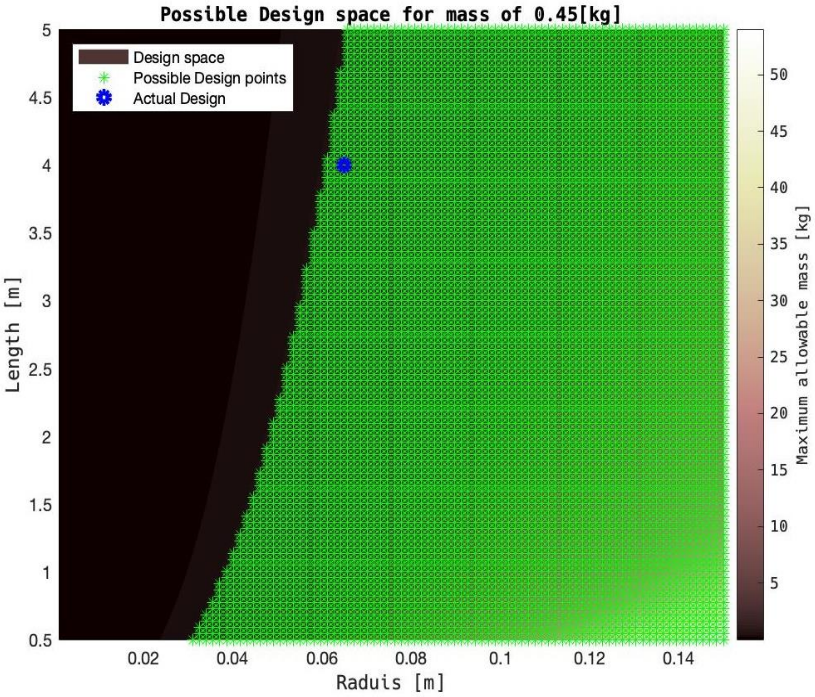


Figure 2: Bar subject to vertical loading

$$F_{collapse} = \frac{\pi R^3 P}{2L}.$$

- It turns out that a structure like this can tolerate way higher $\mathbf{F_{cr}}$ than $\mathbf{F_{collapse}}$
- Thus, the failure criteria is $\mathbf{F_{collapse}}$ criteria
- We can convert the force into an equivalent mass, and thus figure out the maximum possible mass that we can have given a radius and length combination.
- More detailed analysis in the backups.

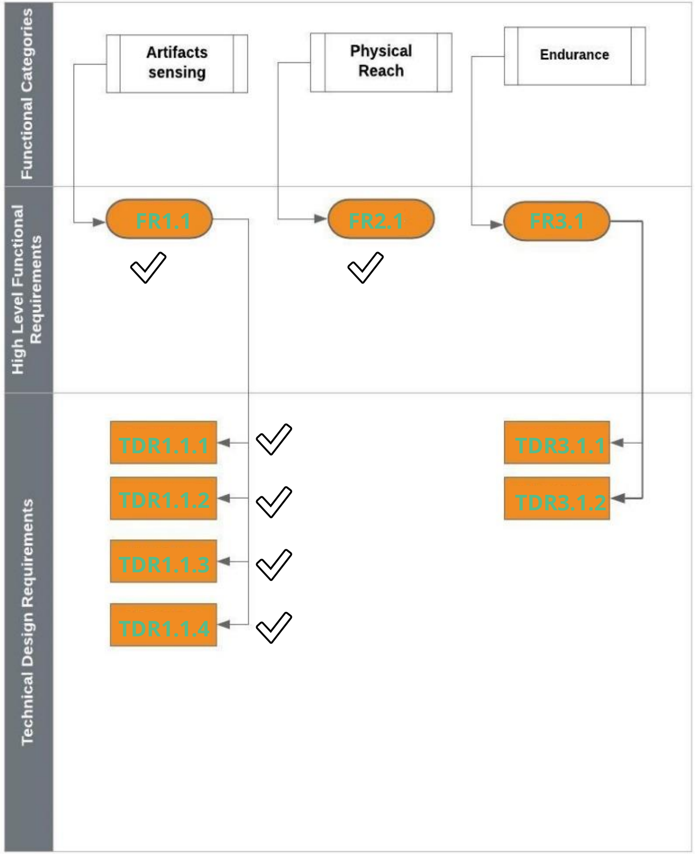
Requirement	Design	Satisfaction	FOS
Physical reach between 1m to 5m	4m	✓	N/A



The design has a tube radius of 6.5cm, and could go up to 4m or higher

Back to the Requirements Tree

Requirements Tree



Back to the Requirements Tree

Requirements satisfaction: Endurance

FRs	TDRs	Requirement	Functional Category
FR3.1		RESCUE shall withstand repeated deployments.	Endurance: Deployment capabilities
	TDR3.1.1	The MARBLE team shall be able to deploy RESCUE at least 5 times during a competition run.	Endurance: Deployment capabilities

- **Components:**
  - NinjaPaintball 68 ci/4500 psi HPA compressed air tank
  - Controls in the backups
- **Purpose:**
  - Provide the necessary air for the inflation of the arm
- **Capability:**
  - 1114 cm^3 at 31 MPa
  - 5.51 MPa outlet pressure
  - Provides 13 full deployments to full extension length (4 m)

Requirement	Design	Satisfaction	FOS
5 Deployments	13.5 Deployments	✓	2.7

Figure 1. NinjaPaintball Ultralite compressed air tank

Plot of Deployments

Pressure System Diagram

Back to the Requirements Tree

Requirements satisfaction: Endurance

FRs	TDRs	Requirement	Functional Category
FR3.1		RESCUE shall withstand repeated deployments.	Endurance: Deployment capabilities
	TDR 3.1.2	Upon receiving an firing command from the MARBLE team when in standby configuration, RESCUE shall reach an active state in 40 seconds or less.	Endurance: Deployment capabilities

- **Components:**
  - Parallax 900-00360
- **Purpose:**
  - Unspool the LDPE tube to match the tube unraveling at 27 cm/s
  - Spool: average diameter = 5 cm; 103 RPM; 8 m of tube unraveled
- **Capability:**
  - Continuous rotation up to 120 RPM
  - Incremental 6 VDC control

Requirement	Design	Satisfaction	FOS
103 RPM	Controlled up to 120 RPM	✓	N/A

Figure 1. Parallax 900-00360 servo

Back to the Requirements Tree

Risk Management

Risk management: Risk Matrix Ranking

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

Risk management: Significant Risks (Pre-Mitigation)

Risk	Subsystem(s) at Risk	Original Severity	Original Probability	Original Risk Level	Mitigation Strategy
Buckling	Structures	Undesirable	Very Likely	Extreme 9	Anti-buckling motors in end effector that assist in even retraction of tubing.
Arm Rigidity	Structures, Hardware, Sensors	Intolerable	Unlikely	High 7	Factors of safety for end effector mass and tube pressure. Extensive testing.
End Effector Detaching	Hardware, Sensors	Intolerable	Unlikely	High 7	Tensioning wires with high-precision servos controlling spooling.
Communications Interference	Software	Undesirable	Unlikely	Medium 6	Choose a wireless receiver and transmitter combo that has a variety of channels to avoid interference.
Delays Due to COVID	All	Tolerable	Likely	Medium 6	Establish a manufacturing team that is able to go on campus to use campus based resources. Wide margins on manufacturing schedule.

Risk management: Significant Risks (Post-Mitigation)

Risk	Subsystem(s) at Risk	New Severity	New Probability	New Risk Level
Buckling	Structures	Undesirable	Unlikely	Medium 6
Arm Rigidity	Structures, Hardware, Sensors	Tolerable	Unlikely	Medium 4
End Effector Detaching	Hardware, Sensors	Intolerable	Very Unlikely	Medium 5
Communications Interference	Software	Acceptable	Unlikely	Low 2
Delays Due to COVID	All	Acceptable	Likely	Medium 3

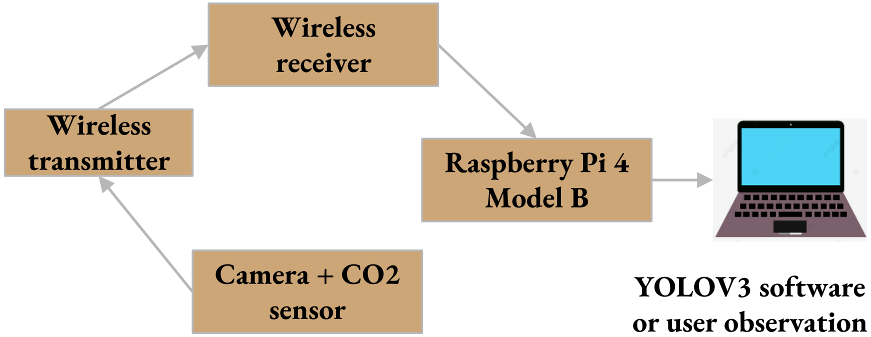
Risk management: Risk Matrix Before and After Mitigation Strategies

Before		Probability			
		Very Unlikely	Unlikely	Likely	Very Likely
Severity	Intolerable		Arm Rigidity, End Effector Detaching		
	Undesirable		Communications Interference		Buckling
	Tolerable			Delays Due to COVID	
	Acceptable				

After		Probability			
		Very Unlikely	Unlikely	Likely	Very Likely
Severity	Intolerable	End Effector Detaching			
	Undesirable		Buckling		
	Tolerable		Arm Rigidity		
	Acceptable		Communications Interference	Delays due to COVID	

Verification and Validation

Verification and Validation: Artifact Sensing



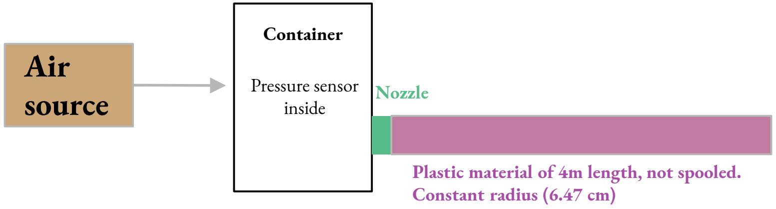
TDR 1.1.1 & 1.1.3: The sensing system shall be able to sense DARPA subterranean challenge competition artifacts.

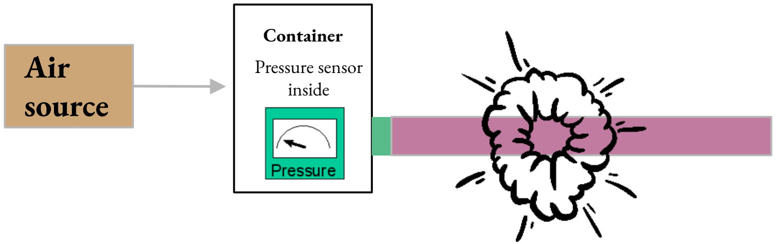
- **Test purpose:**
  - Ensure that sensor suite will be able to pick up signatures of artifacts for identification by the MARBLE team
- **Test components:**
  - Camera
  - CO_2 sensor
  - YOLOV3 image recognition software
- **Measured values:**
  - Video quality
  - Accuracy of collected CO_2 measurements.
- **Expected values:**
  - Video output at 1920x1080 pixels, 30-60 FPS
  - Video output discernible to the human eye and/or YOLOV3
  - 410 ppm CO_2 concentration for atmospheric air.

- **Tolerated uncertainties:**
  - Video resolution as low as 640x480 pixels
    - Key criteria is human/YOLOV3 recognition
  - CO_2 measurement accuracy within ± 30 ppm
- **Key measurement issues:**
  - Configuring YOLOV3 software
  - Determining actual CO_2 concentration (vs altitude)
- **Safety concerns:**
  - Decreased oxygen concentration in CO_2 vessel
  - Possible use of pressurized gas

Verification and Validation: Burst Pressure

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

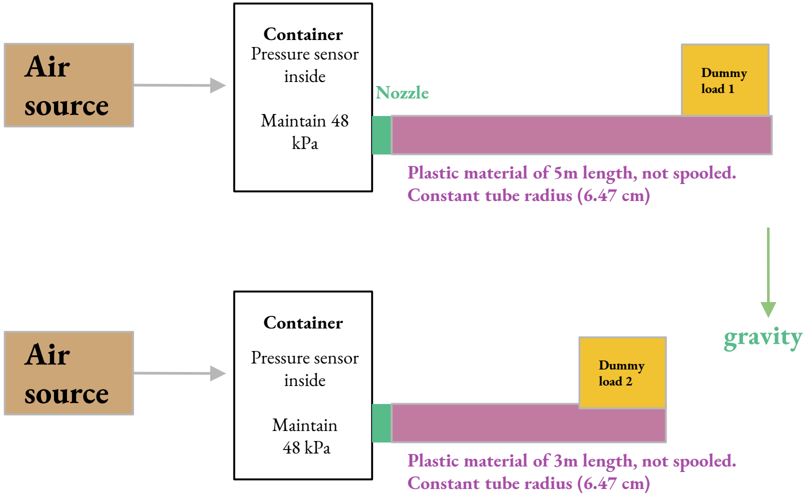




- **Test purpose:**
  - Increase the pressure inside the plastic tube until bursting
  - Determine the maximum pressure before bursting
  - The maximum pressure is directly related to the payload capacity
- **Test components:**
  - Air source (With hose)
  - Pressure sensor
  - Sealed plastic tube
- **Measured values:**
  - Pressure inside the plastic tubes to determine pressure before bursting
- **Expected values:**
  - Between 40.65 kPa and 58 kPa (backup slides)
- **Tolerated uncertainties:**
  - ±3 kPa
- **Key measurement issues:**
  - Sampling rate needs to be fast enough to
- **Safety concerns:**
  - Damaging the equipment (low probability)
  - People/other equipments close to the experiment
  - Leakages

Verification and Validation: Payload capabilities

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



- **Test purpose:**
  - Determine if the pressure and length combination can sustain the mass the model predicts
  - Vary the mass to check for a maximum
  - Repeat with different directions of tube extension (backup slides)
- **Test components:**
  - Air source (With hose)
  - Pressure sensor
  - Sealed plastic tube
  - Scale (to measure the dummy load)
  - Dummy load
- **Measured values:**
  - Maximum mass that can be sustained
- **Expected values:**
  - For 5m length: 0.33 kg mass of failure
  - For 3m length: 1.1 kg mass of failure

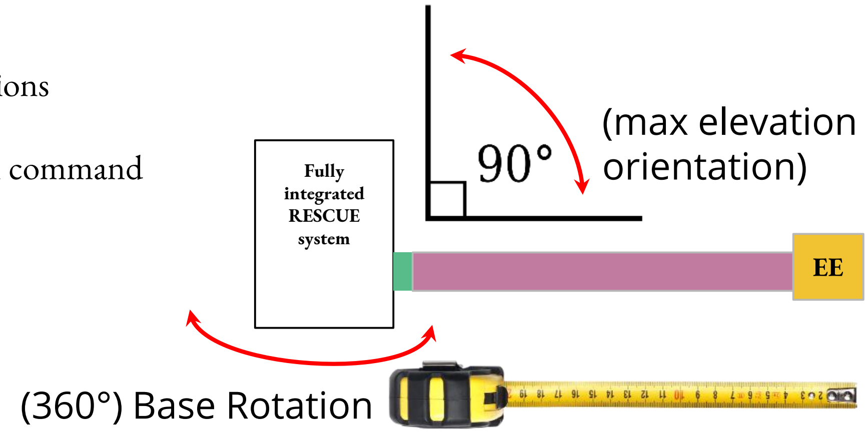
- **Tolerated uncertainties:**
  - ±100g
- **Key measurement issues:**
  - Maintaining constant pressure
  - Fabrication of imitation end effector
- **Safety concerns:**
  - Load falling on unprotected region
  - Presence of pressurized gas
  - Leakages

Verification and Validation: Extension range

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

- **Test purpose:**
  - Determine the accuracy of the range models.
- **Test components:**
  - Fully integrated RESCUE system
  - Measuring tape
- **Measured values:**
  - Range of extension
  - Range of extension in various directions
- **Expected values:**
  - Varies based on the extension length command

- **Tolerated uncertainties:**
  - ±0.1 meters
- **Key measurement issues:**
  - Fabrication of imitation end effector
- **Safety concerns:**
  - Arm collision with people or objects



Verification and Validation: Endurance

FR3.1: RESCUE shall withstand repeated deployments.

- **Test purpose:**
  - To ensure that RESCUE can deploy and retract successfully 5 times over the course of the 135 minutes competition time (one deployment every 27 minutes), deployments should take no longer than 40 seconds.
- **Test components:**
  - Fully integrated RESCUE system
  - Timer
- **Measured values:**
  - Number of complete, fully extended, deployments
  - Number of complete retractions
- **Expected values:**
  - 5 deployments
  - 5 retractions

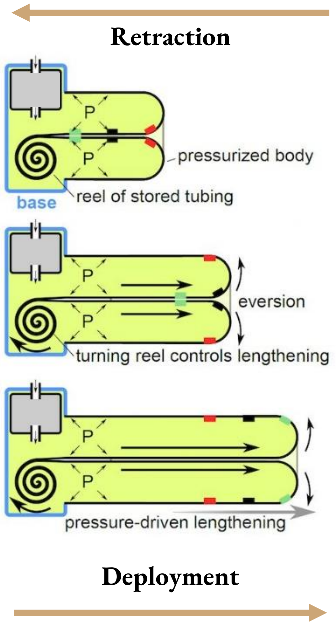
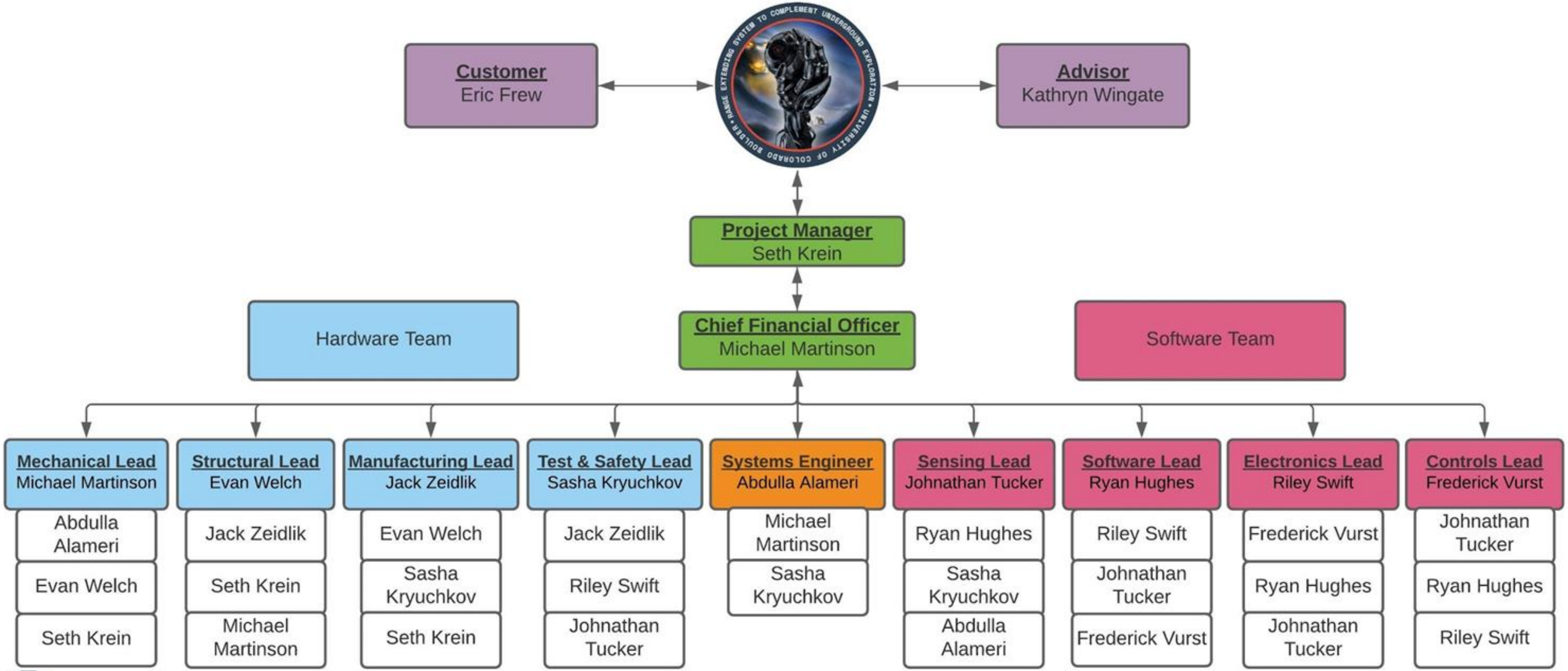


Figure 1: Deployment and retraction (Hawkes et al.)

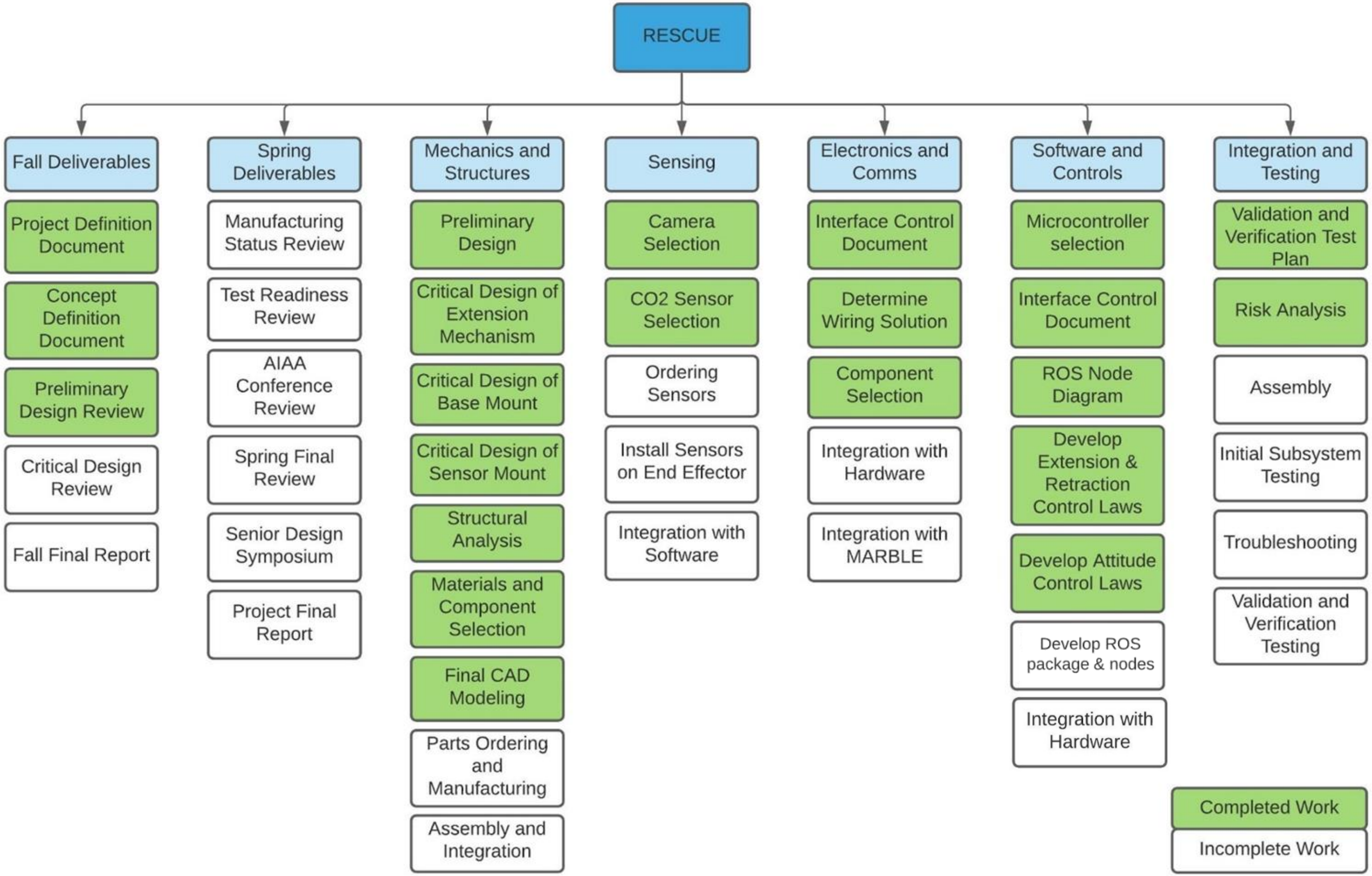
- **Tolerated uncertainties:**
  - ± 2 seconds
- **Key measurement issues:**
  - Human errors in timing
- **Safety concerns:**
  - Soft robotic arm reaching yield pressure
  - Compressed air plumbing malfunction

Project Planning

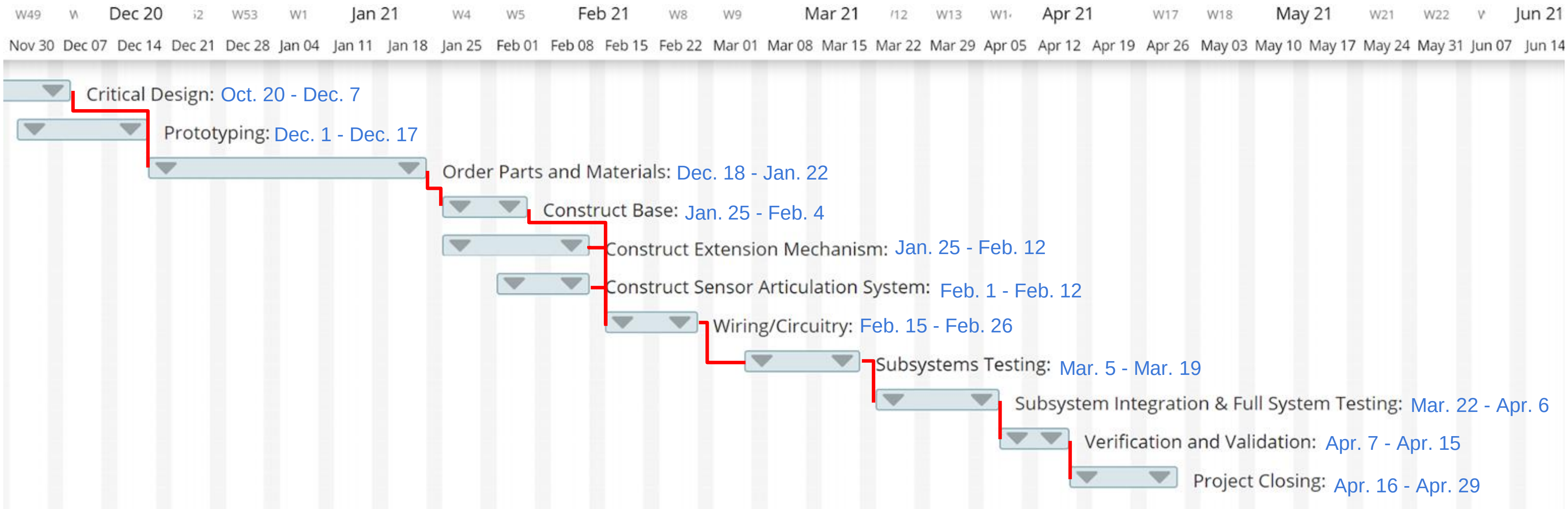
Project Planning: Organizational Chart



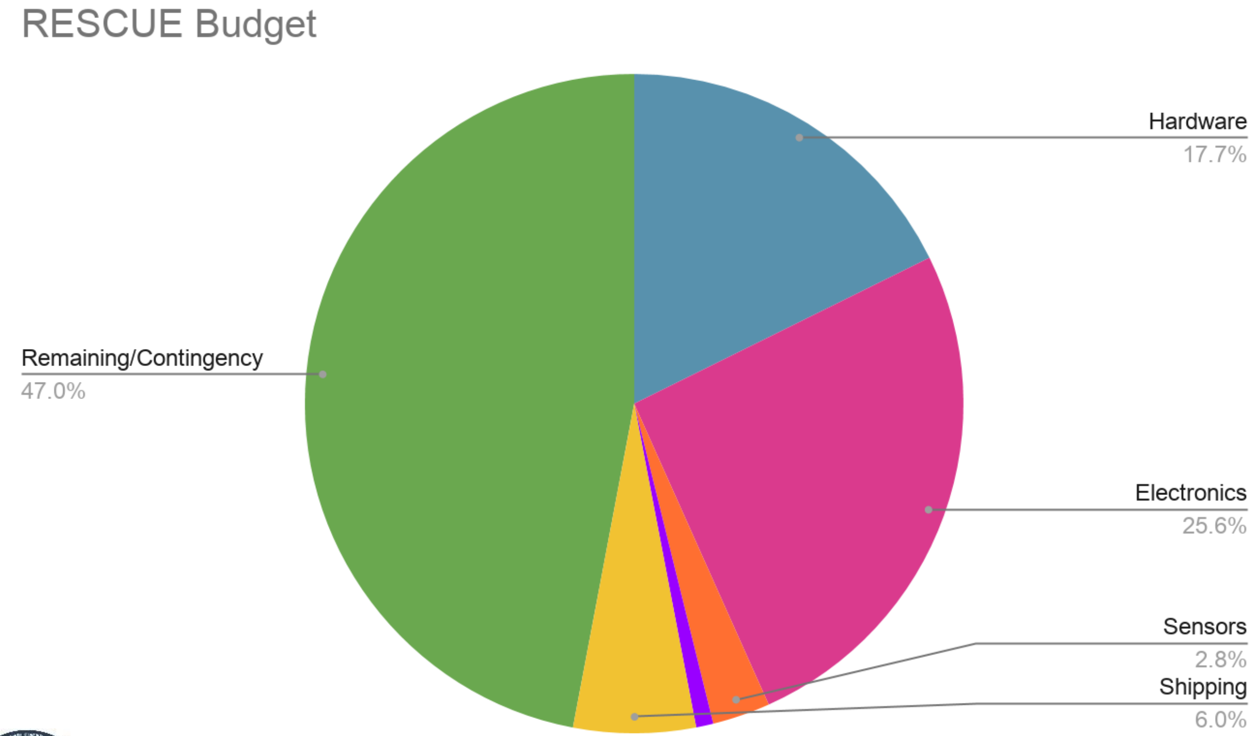
Project Planning: Work Breakdown Structure



Project Planning: Work Plan - Overview



Project Planning: Cost Plan



Hardware = $885

Electronics = $1,280

Sensors = $142

Software = $42

Shipping = $300

Remaining/Contingency = $2,351

Project Planning: Test Plan

1. **Full Extension: March 22 -March 24**
    - Ensuring system can reliably extend to commanded location at maximum distance with all subsystems functioning properly
1. **Variable Extension: March 25 - March 29**
    - Ensuring system can reliably extend to commanded location at various extension ranges with all subsystems functioning properly
1. **Nested Location Command: March 30 - April 1**
    - Ensuring system can successfully transition to a different location and extension distance after having been deployed.
1. **Repeated Use / Reliability: April 2 - April 6**
    - Ensuring system can reliably extend and retract multiple times to meet the endurance requirement (FR 3.1)

The team would like to acknowledge:

Professor Kathryn Wingate
Professor Frew
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Professor Trudy Schwartz
Professor Matt Rhode
Professor Nicholas Rainville
Professor Josh Mellin
Professor Zachary Sunberg
Professor Dennis Akos
Professor John Mah
Lara Buri :)

The PAB, and the TAs for the support during the design process. Without their valuable advice, this design would not be possible.

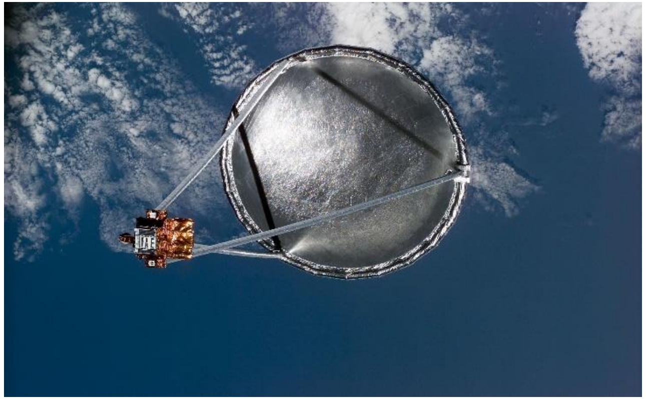
Questions?

Backup slides

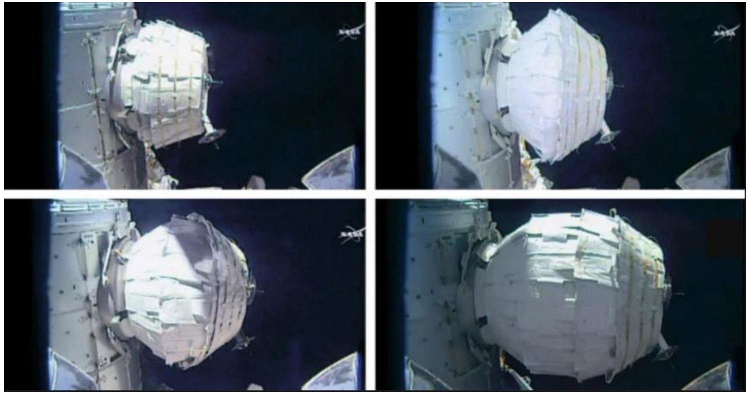
Backup Slides Directory Slide

FBD	Arm Structures Analysis	Thermodynamics Analysis	Verification and Validation	Project Planning
Off Ramps	CAD	Arm Control	End Effector Electronics	Requirements Satisfaction
Inflatable Arm Examples	Pressure System Design	Sensing Apparatus	Base Electronics	Risk Management

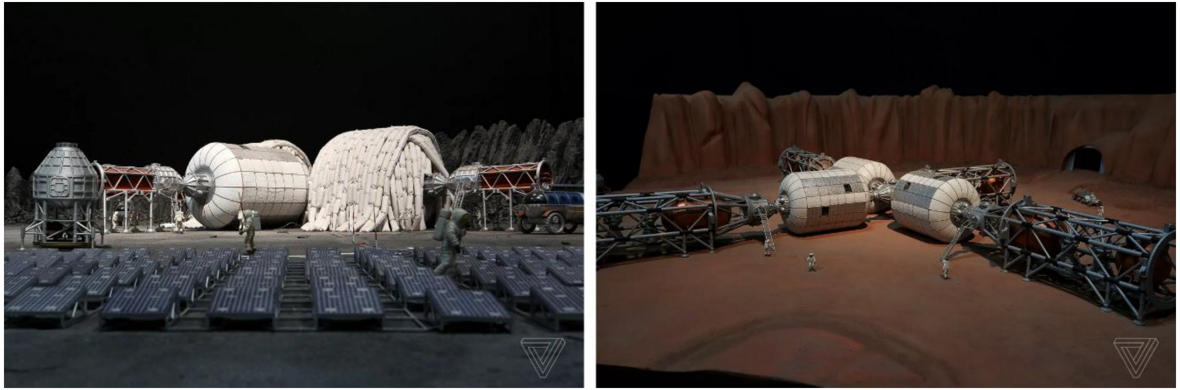
Design Solution: heritage and future



NASA's Inflatable Antenna Experiment (IAE)

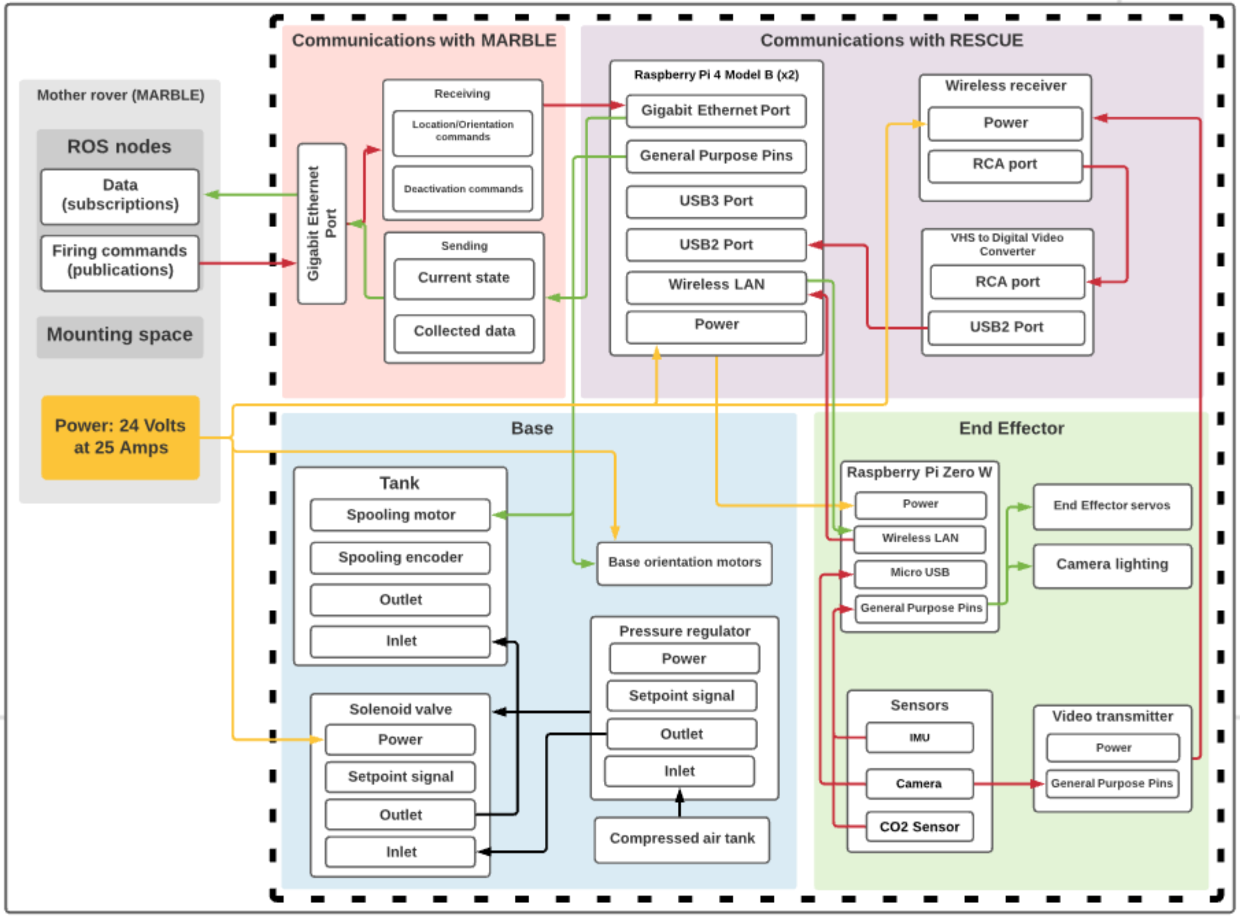


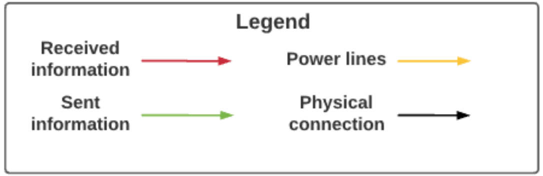
ISS inflatable habitat



Bigelow's next-generation inflatable space habitat for the Moon

Design Solution: Detailed FBD



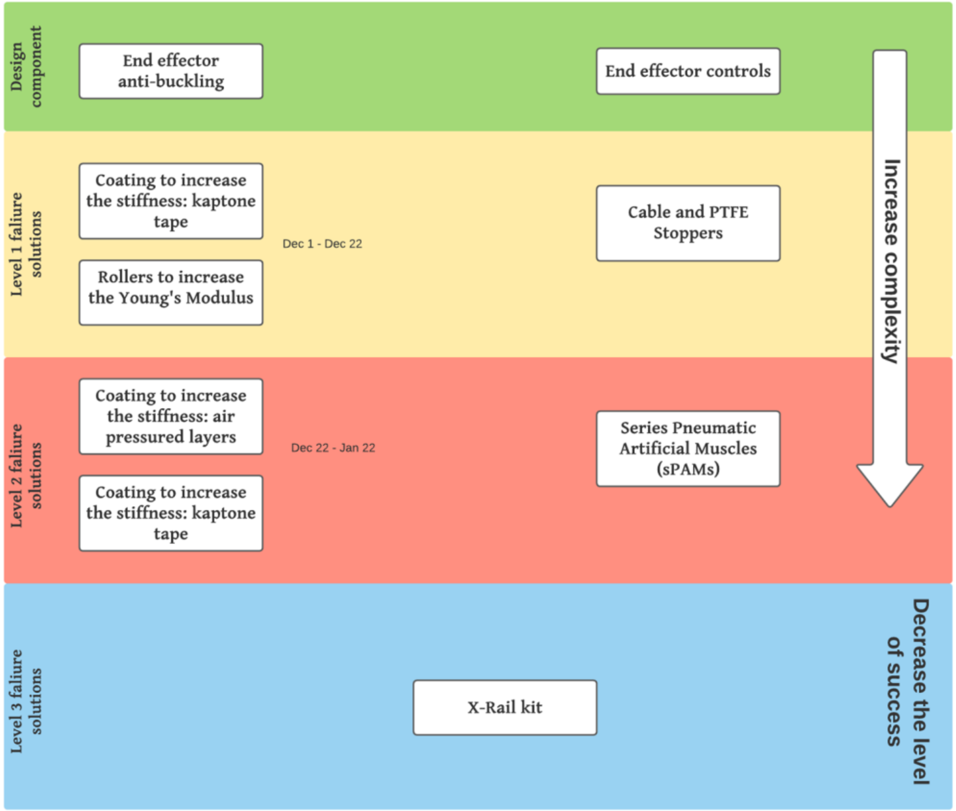


Back to Main Slides
Back to the Directory

Off Ramps

Offramps

All these solutions are related to the extension mechanism, ⅓ of the project! The base and the end effector are the same



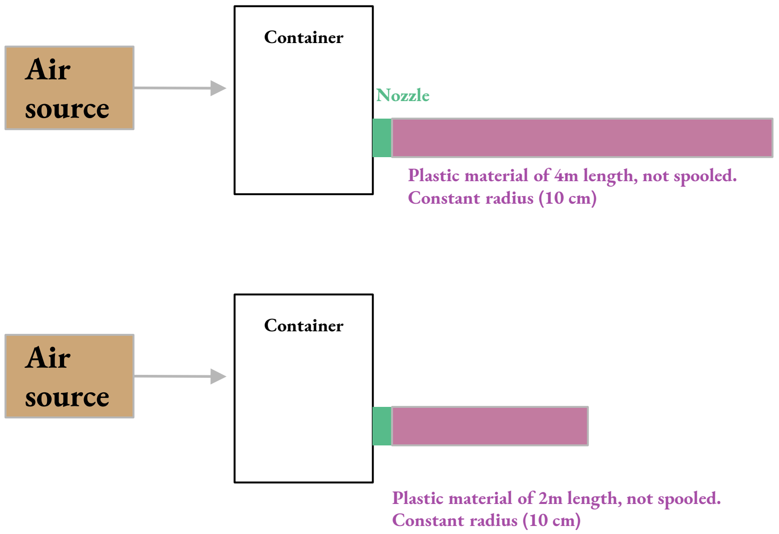
Prototyping period Dec 1 - Jan 22

Back to the Directory

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

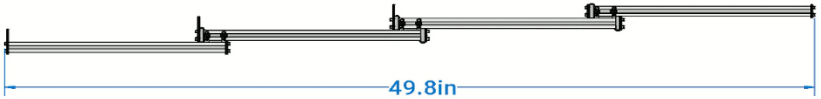


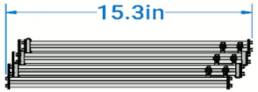
Extension Method Off Ramp 2: X Rail System

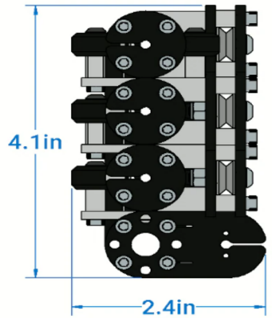
- Off the shelf option, all components commercially available
- Adding 2 x 12.45in. extension lengths would provide max ≈ 74in. **≈ 1.88m**
  - Required rails, extension line, cabling = 0.45kg
- 49.8in. k it supports ≈ 0.64 kg. In **horizontal** orientation.
  - Performance indication from ServoCity, **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

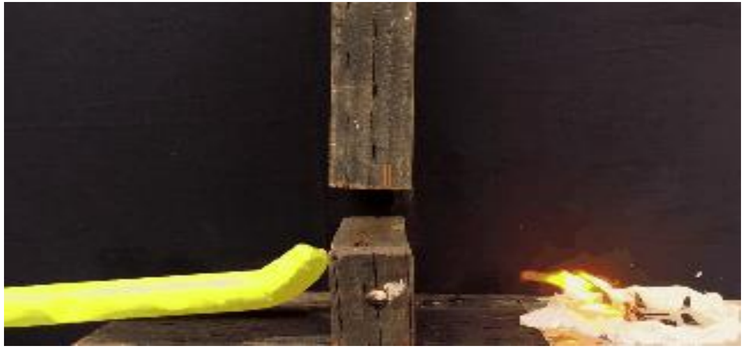


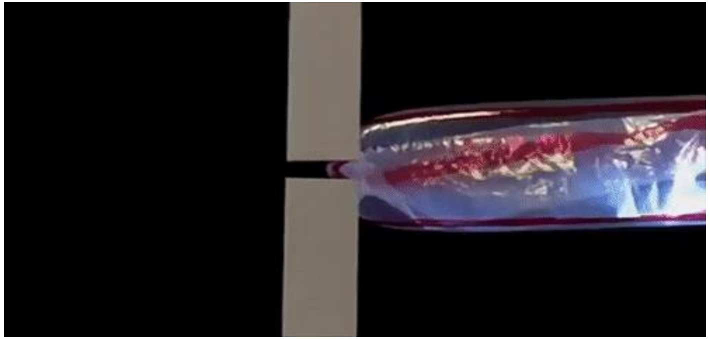




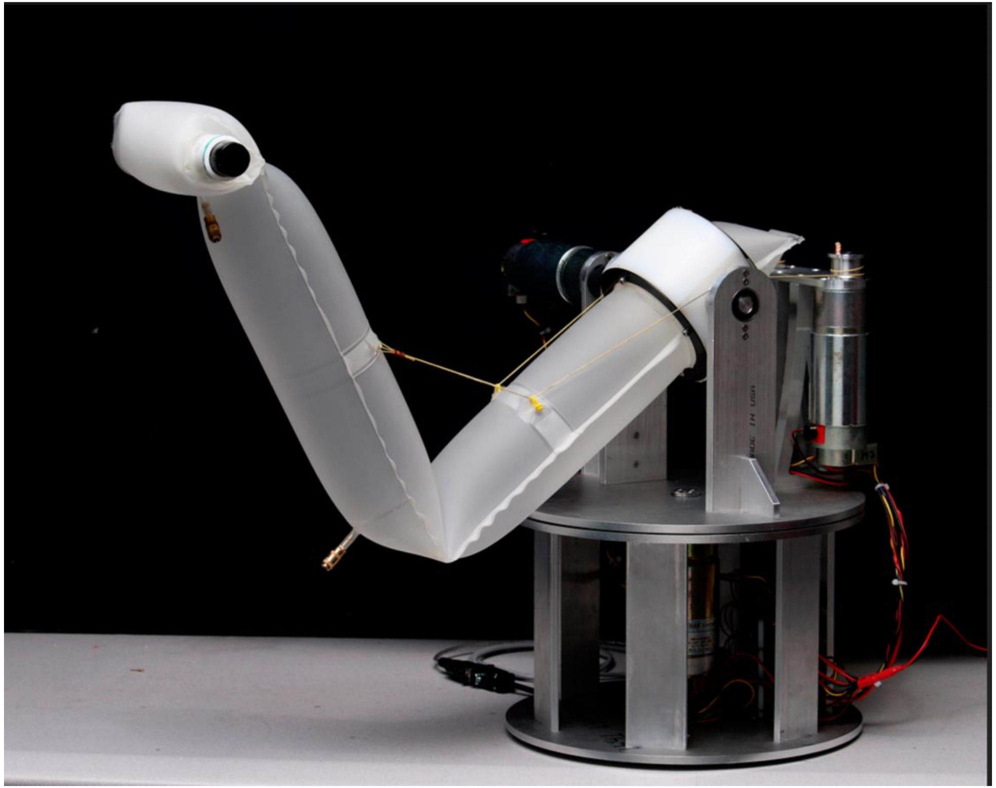
Back to the Directory

Inflatable Arm Examples



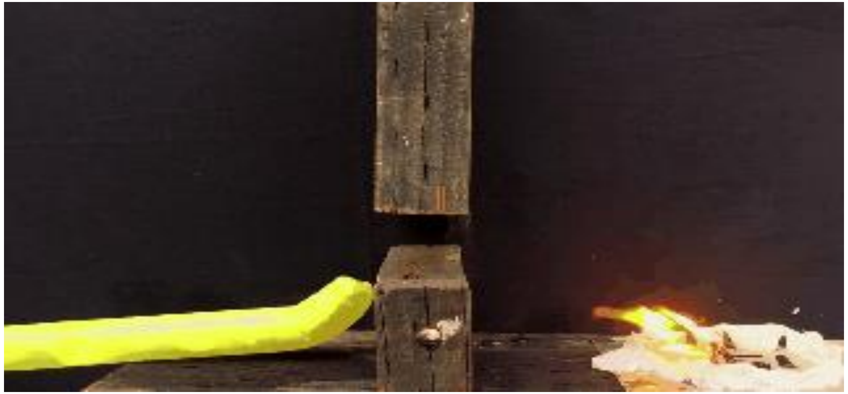


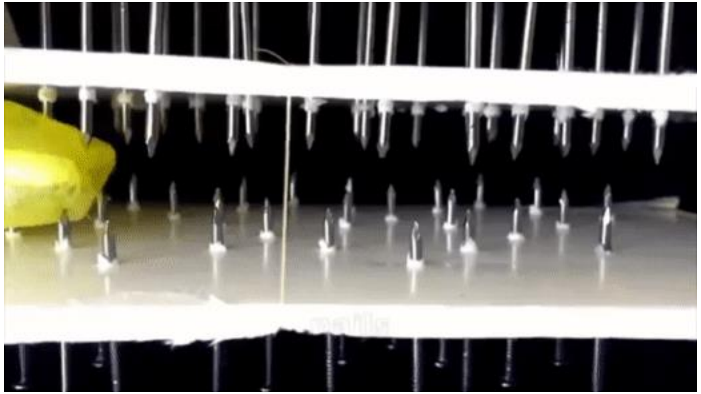
Base Design: typical design, even in Disney



Material failure

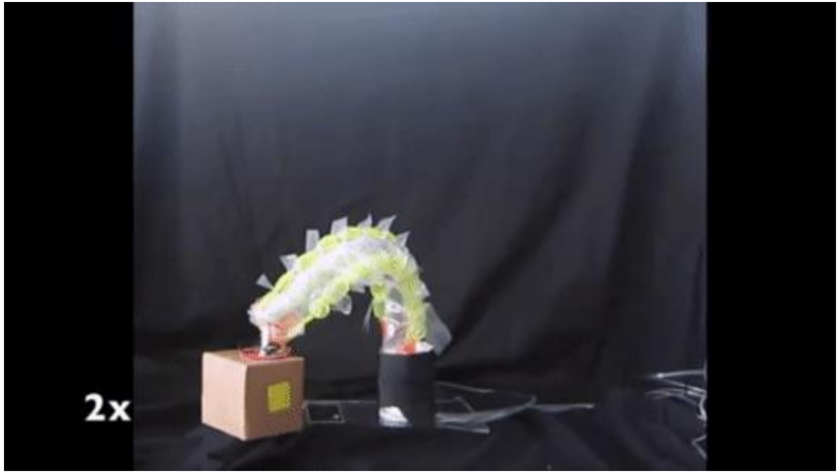
- We are not worried about obstacles because the trajectory is clear
- The concept works in a hazardous environment



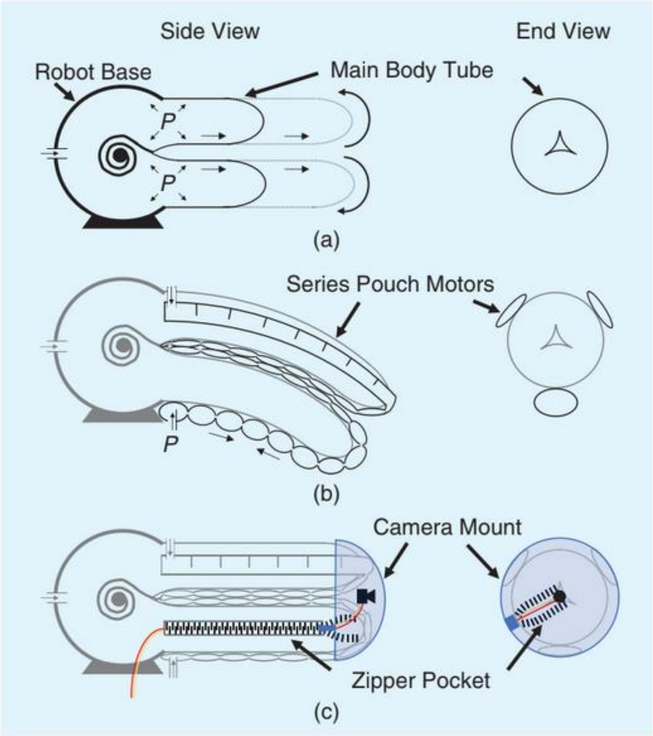


Structural rigidity

Structural rigidity

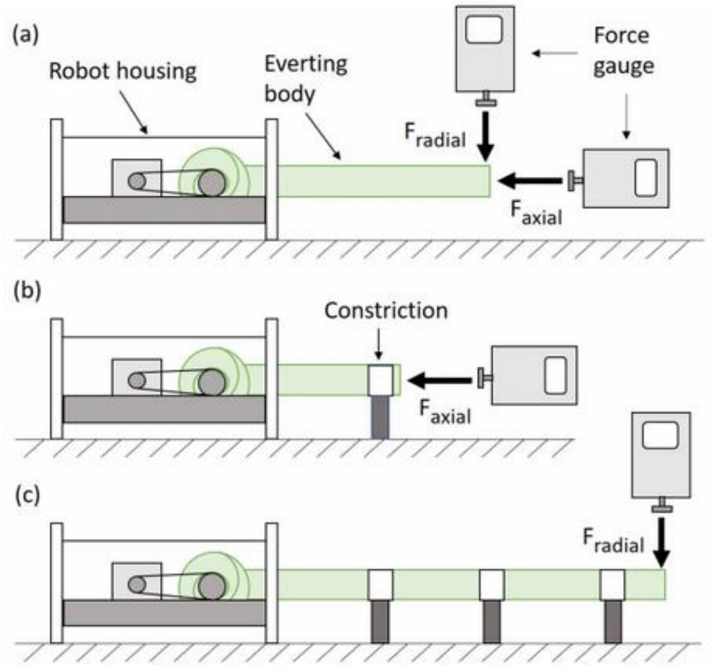


Schematic



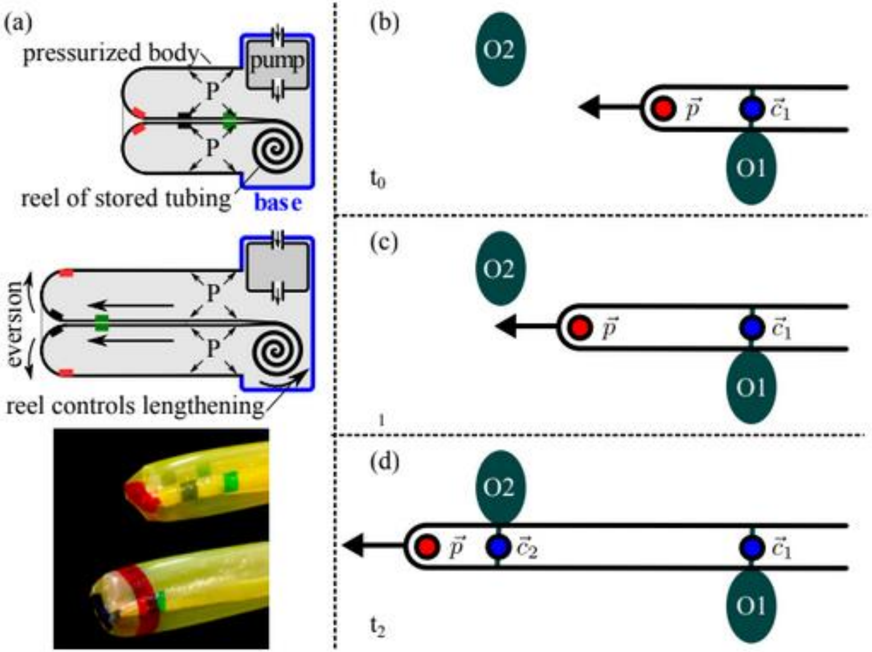
Side View
End View
Robot Base
Main Body Tube
P
P
(a)
Series Pouch Motors
P
(b)
Camera Mount
Zipper Pocket
(c)

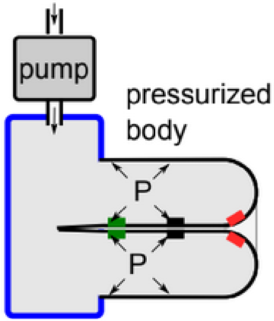
Schematic

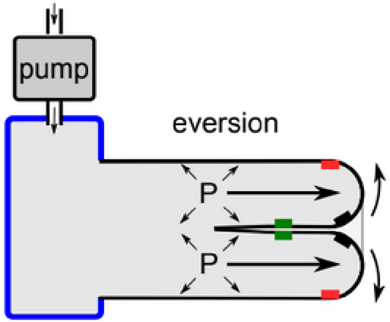


(a)
Robot housing
Everting body
Force gauge
F_{radial}
F_{axial}
(b)
Constriction
F_{axial}
(c)
F_{radial}

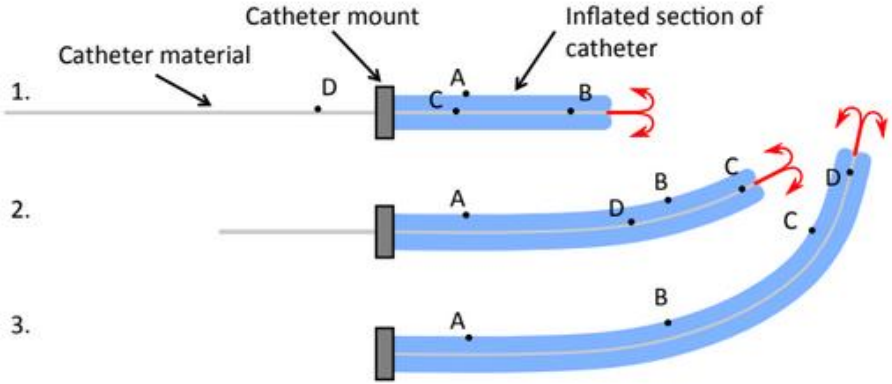
Schematic

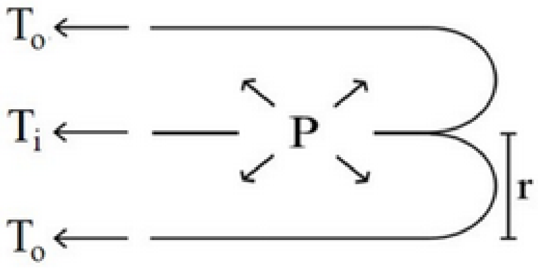

(a)
pressurized body
pump
P
P
reel of stored tubing
base
eversion
P
P
reel controls lengthening
(b)
O2
$\vec{p}$
$\vec{c}_1$
O1
t_0
(c)
O2
$\vec{p}$
$\vec{c}_1$
O1
(d)
O2
$\vec{p}$
$\vec{c}_2$
$\vec{c}_1$
O1
t_2


pump
pressurized body
P
P

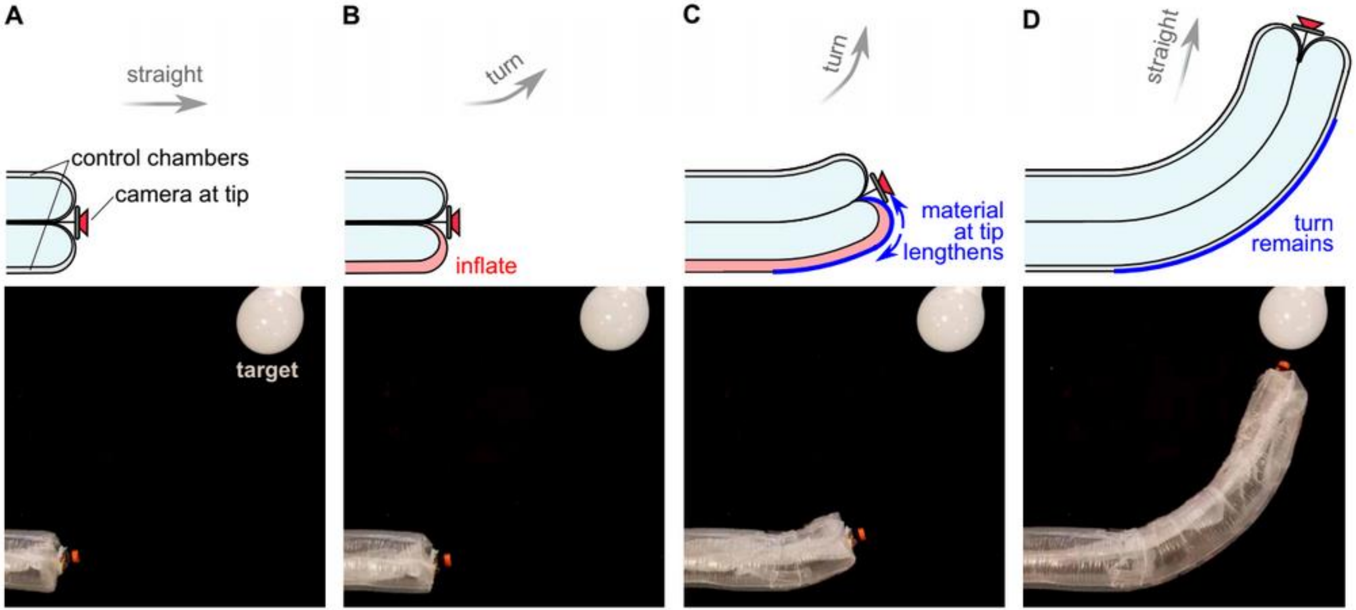

pump
eversion
P
P

Schematic


Catheter mount
Inflated section of catheter
Catheter material
1.
2.
3.
A
B
C
D


T_o
T_i
T_o
P
r

Schematic



A
B
C
D
straight
turn
turn
straight
control chambers
camera at tip
inflate
material
at tip
lengthens
turn
remains
target

Arm Structural Analysis

Backup Slide: Buckling Retraction Concern (anti buckling device)

- "Retraction of Soft Growing Robots Without Buckling"
  - Okamura et al. April 2020
- LDPE, inflated diameter 8.5 cm and thickness 74 μm.
- 100+ g anti-buckling device, requires additional motors
  - material/diameter discrepancies require experimental validation
- Additional workarounds

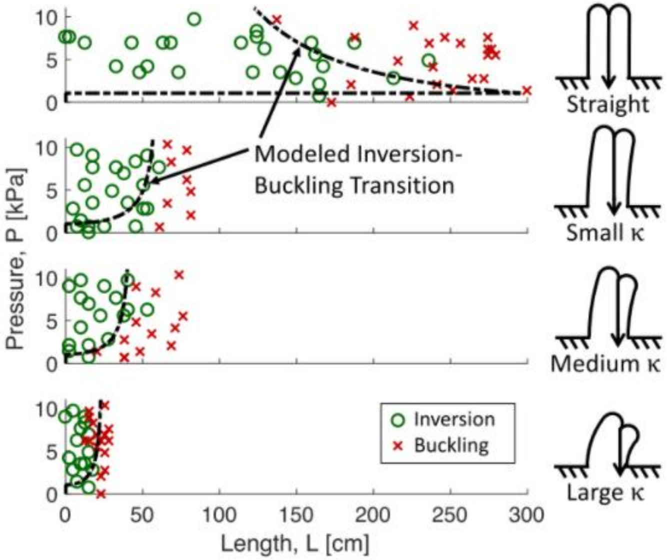


Figure 1: Retraction Buckling Results, Okamura et al.

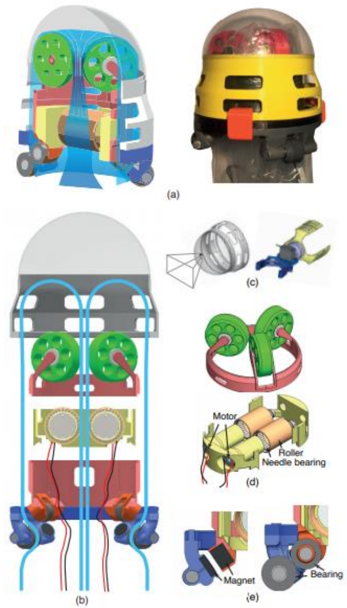


Figure 2: Advanced Anti-Buckling Device, Okamura et al.

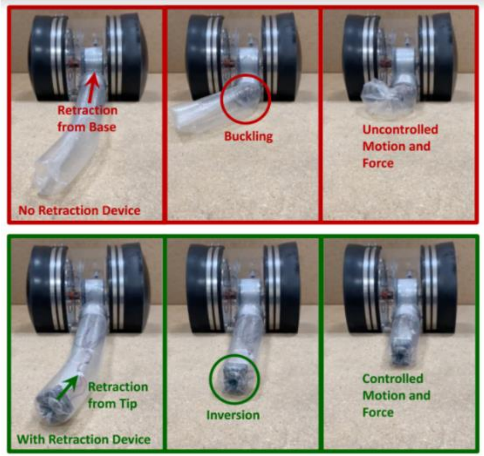


Figure 3: Retraction Buckling Concern, Okamura et al.

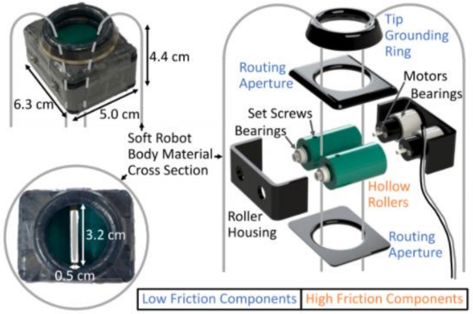
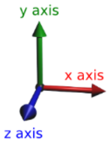


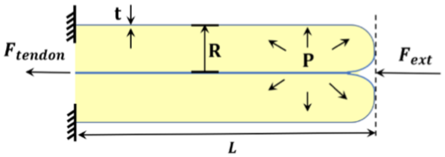
Figure 4: Simple Anti-Buckling Device, Okamura et al.

[Back to the Requirements Tree]

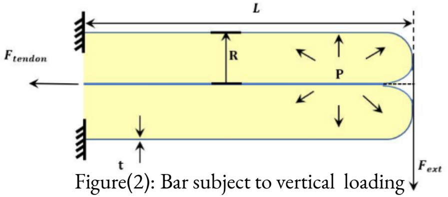
Structural Analysis (1)



FBD:



Figure(1): Bar subject to horizontal loading

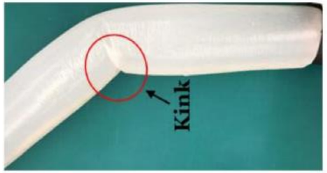


Figure(2): Bar subject to vertical loading

Assumptions:

- Isotropic material
- Constant cross sectional area
- Fixed support on one end (inflatable cantilever beam)
- Ftendon = 0 (The supporting structure does not pull on the material)
- Small strain.
- Modeling as thin walled pressure vessel as a cantilever beam

Figure(3): failure due to Buckling (horizontal loading)



Figure(4): failure due to bending (yielding) (vertical loading)

Solution

Longitudinal stress: $\sigma_L = PR/2t$.

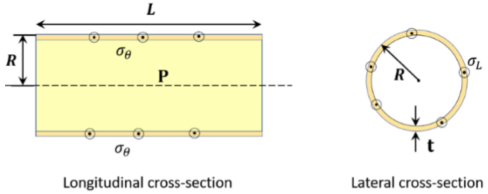
Circumferential (Hoop) stress: $\sigma_\theta = \frac{PR}{t}$.

From force balance, which results in the same exact expressions used in ASEN 3112, Spring 2019, Lecture 3.

Yield stress: σ_y

Assuming that Ftendon = 0, means that σ_L = 0, to avoid failure, we need the following condition to be true $\sigma_\theta \leq \sigma_y$,

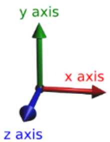
Thus, maximum pressure we could have is: $P \leq \frac{\sigma_y t}{R}$



Figure(6): cross sectional views.

Back to the Directory

Structural Analysis (2)



FBD:

Maximum vertical that could be applied before the collapse of the structure [1,2]: $$F_{collapse} = \frac{\pi R^3 P}{2L}.$$

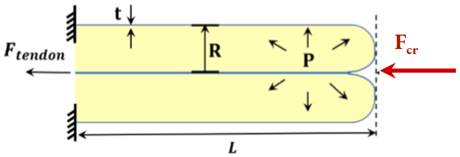
Maximum horizontal that could be applied before the collapse of the structure [1,2]: $$F_{cr} = \frac{(E + \frac{P}{S}) I \Omega^2}{1 + \Omega^2 \frac{I}{S} + \Omega^2 \frac{\left(E + \frac{P}{S}\right) I}{P + kGS}}$$

This expression is corrected to account for shear forces, where:

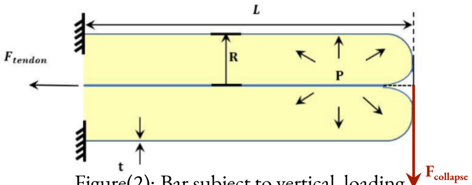
Ω = Mode shape of the buckled beam, given by $\Omega L = (2n - 1)\pi/2$
n = Coefficient that corresponds to the the buckling mode shape, which is **1** for the primary shape, the shape of interest here [3]
k = Correction shear factor, which is **0.5** for circular tubes
S = Cross sectional area of the structure
I = Second moment of area, about the central axis
E = Young's modulus
G = Shear modulus

Recall that maximum pressure we could have is: $P \leq \frac{\sigma_y t}{R}$

Thus for any given material with yield stress, we can get the maximum pressure we could use, and for any given material with a known material property we can understand critical loads, and hence understand mass that can be supported.

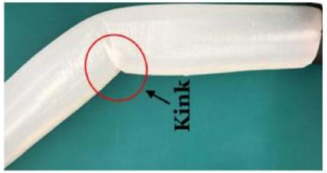


Figure(1): Bar subject to horizontal loading

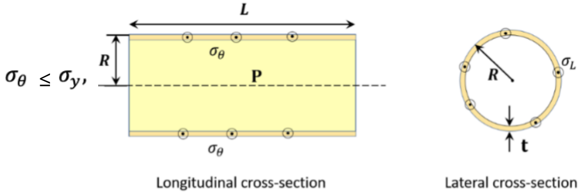


Figure(2): Bar subject to vertical loading

Figure(3): failure due to Buckling (horizontal loading)



Figure(4): failure due to bending (yielding) (vertical loading)

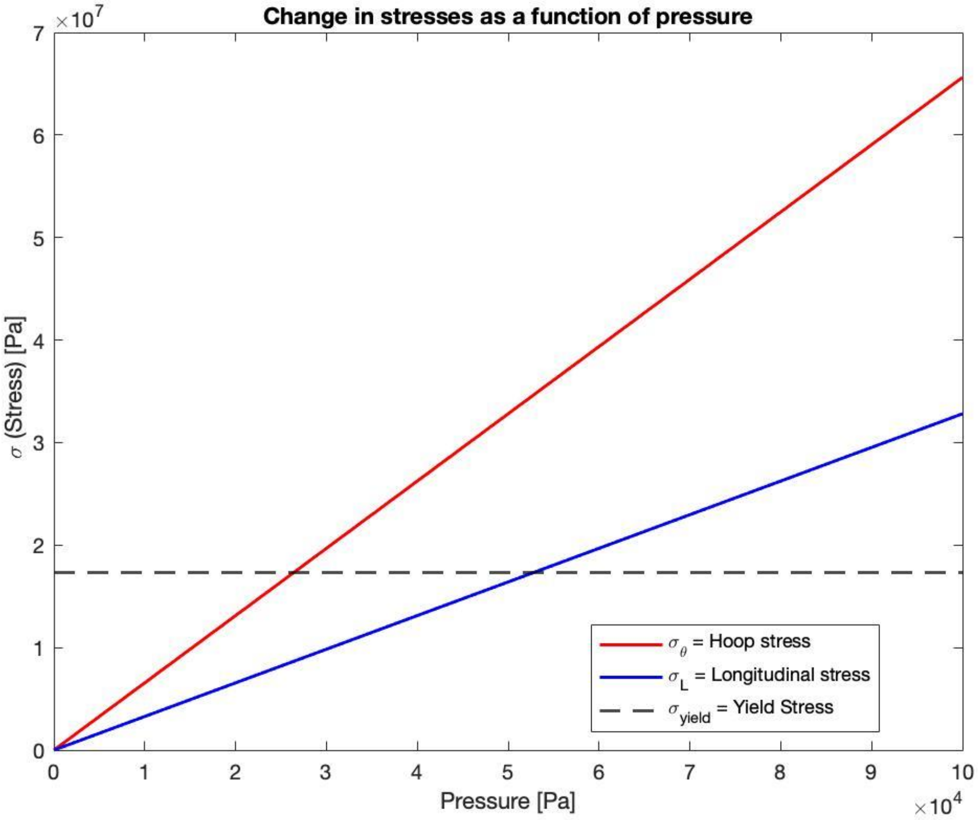


Figure(6): cross sectional views.

[1]: LEVY, R. L. COMER and SAMUEL, et al. "DEFLECTIONS OF AN INFLATED CIRCULAR-CYLINDRICAL CANTILEVER BEAM." *AIAA Journal*, 17 May 2012, arc.aiaa.org/doi/10.2514/3.1873.
[2]: Van, A. Le, and C. Wielgosz. "Erratum to: 'Bending and Buckling of Inflatable Beams: Some New Theoretical Results.'" Thin-Walled Structures, vol. 44, no. 7, 2006, pp. 822–823., doi:10.1016/j.tws.2006.08.001.
[3]: Godaba, Hareesh, et al. "Payload Capabilities and Operational Limits of Eversion Robots." Towards Autonomous Robotic Systems Lecture Notes in Computer Science, 2019, pp. 383–394., doi:10.1007/978-3-030-25332-5_33.

Back to the Directory

Stress as a function of pressure

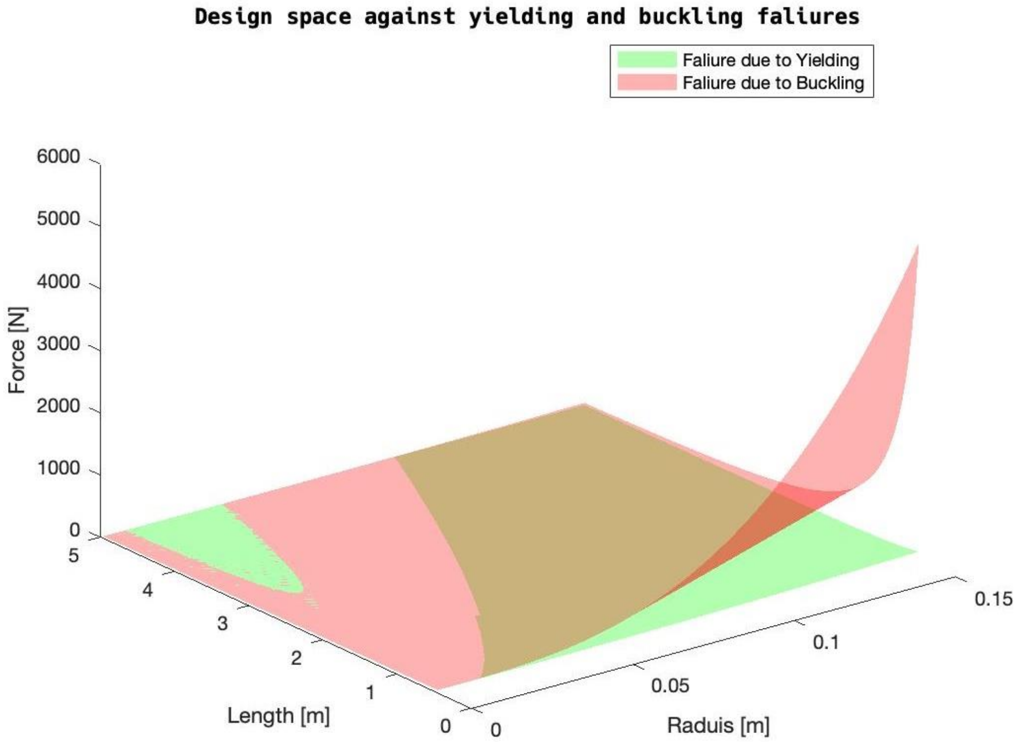


Back to the Directory

Operational envelope

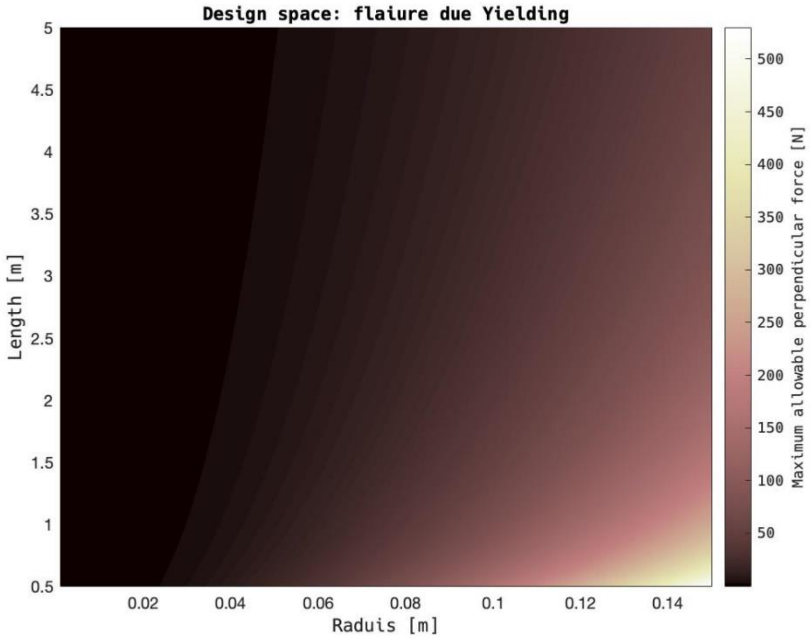
Material: low density polyethylene (LDPE)

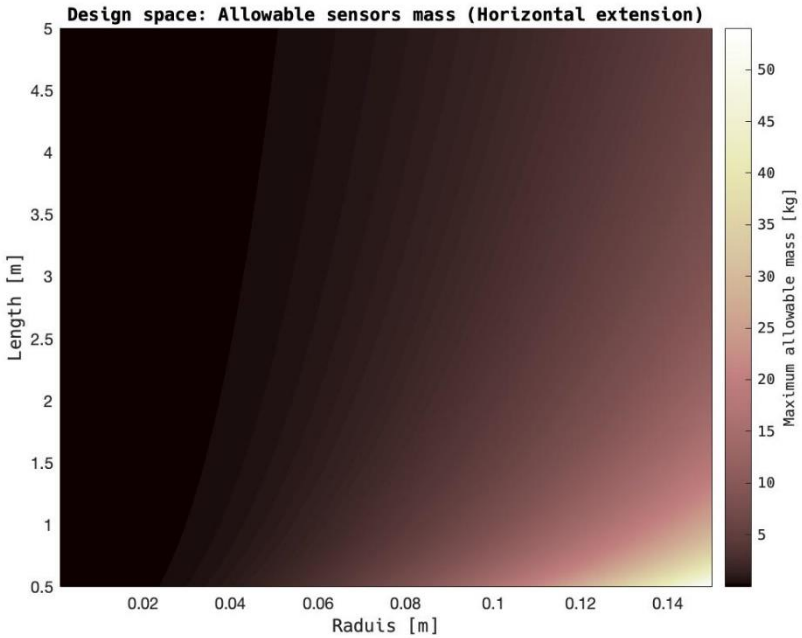
Property	Value [units]
Young's Modulus	110 [MPa]
Shear modulus	66 [MPa]
Yield Stress	40 [MPa]
Density	925 [kg/m^3]



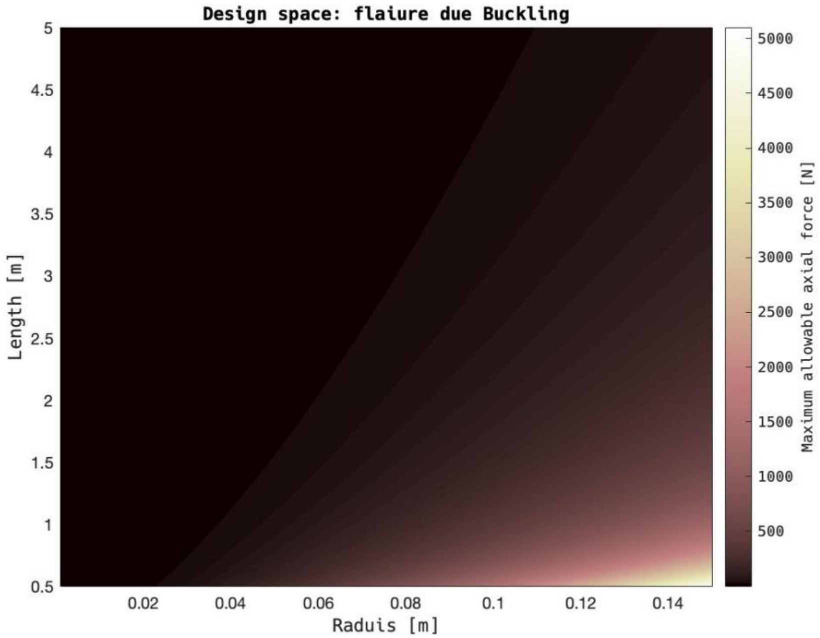
If the design parameters operate at a point where it touches the red or the green curves, the design will fail.

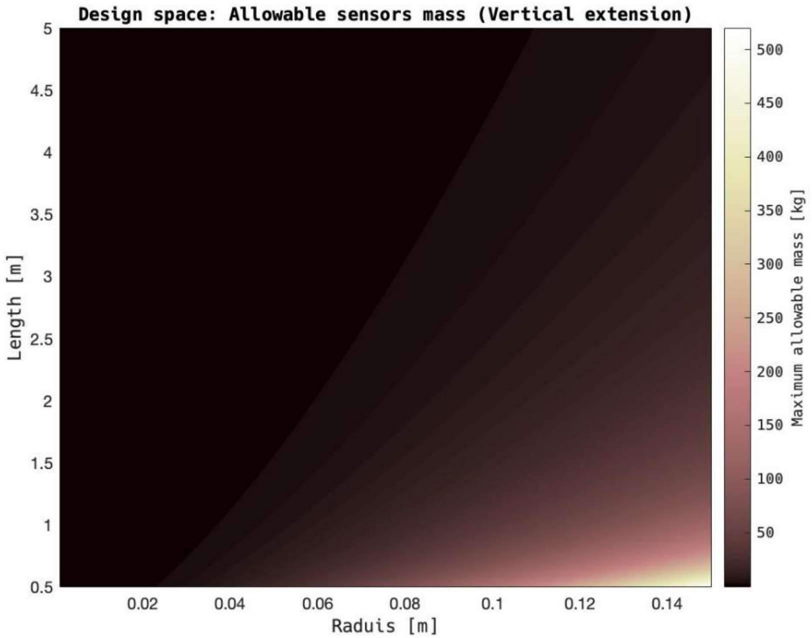
Operational envelope (Yielding)





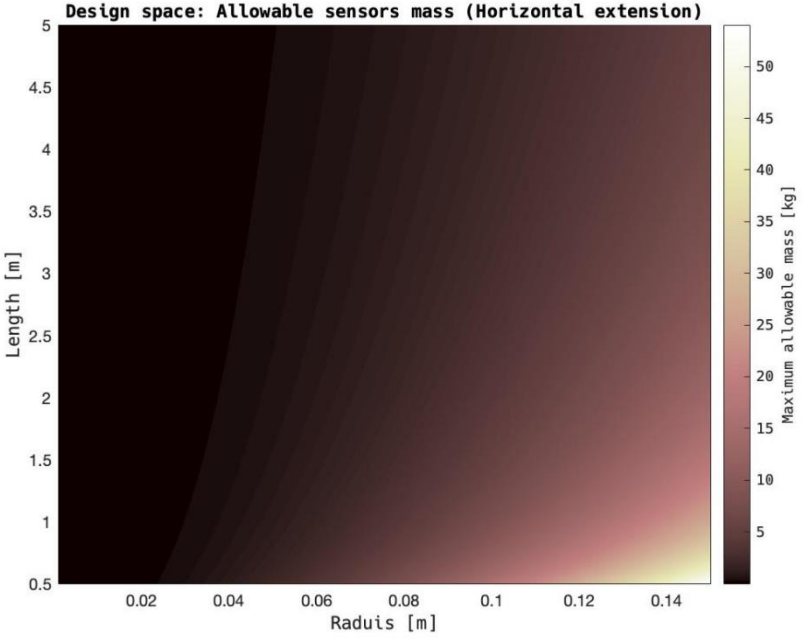
Operational envelope (Buckling)

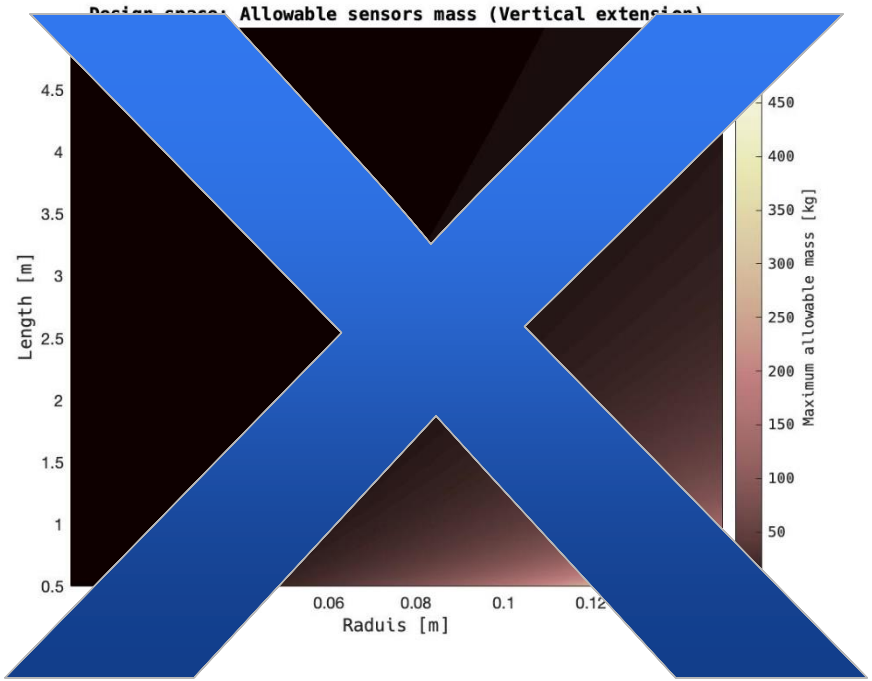




Back to the Directory

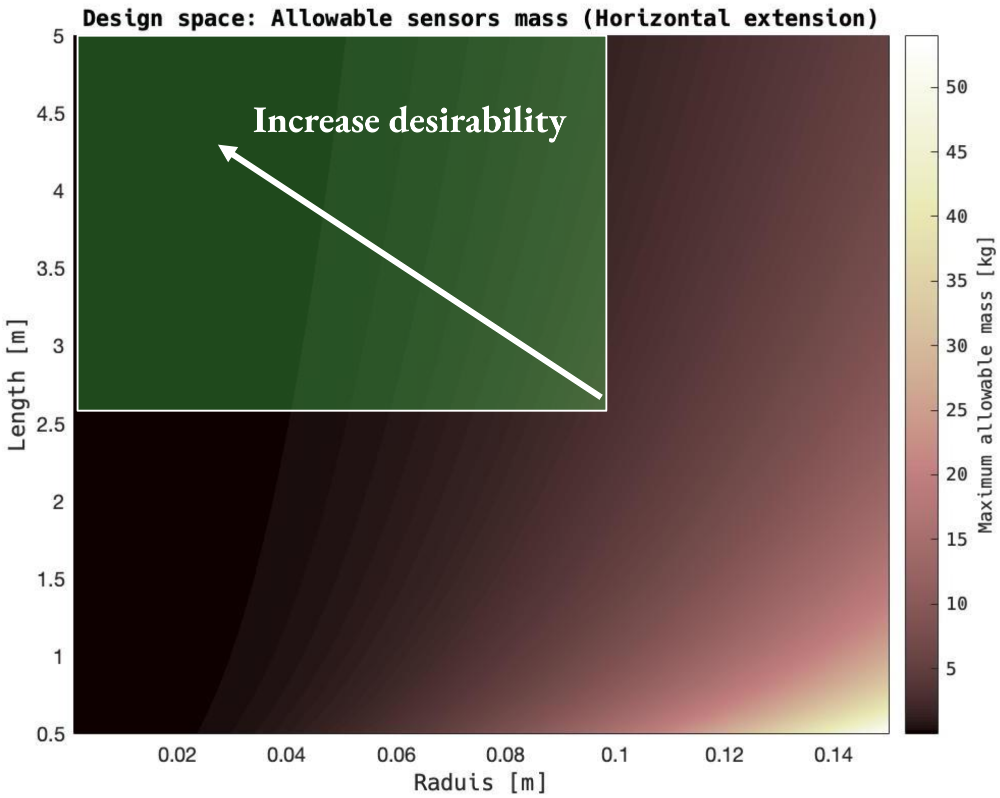
Operational envelope: Worst case scenario, horizontal extension



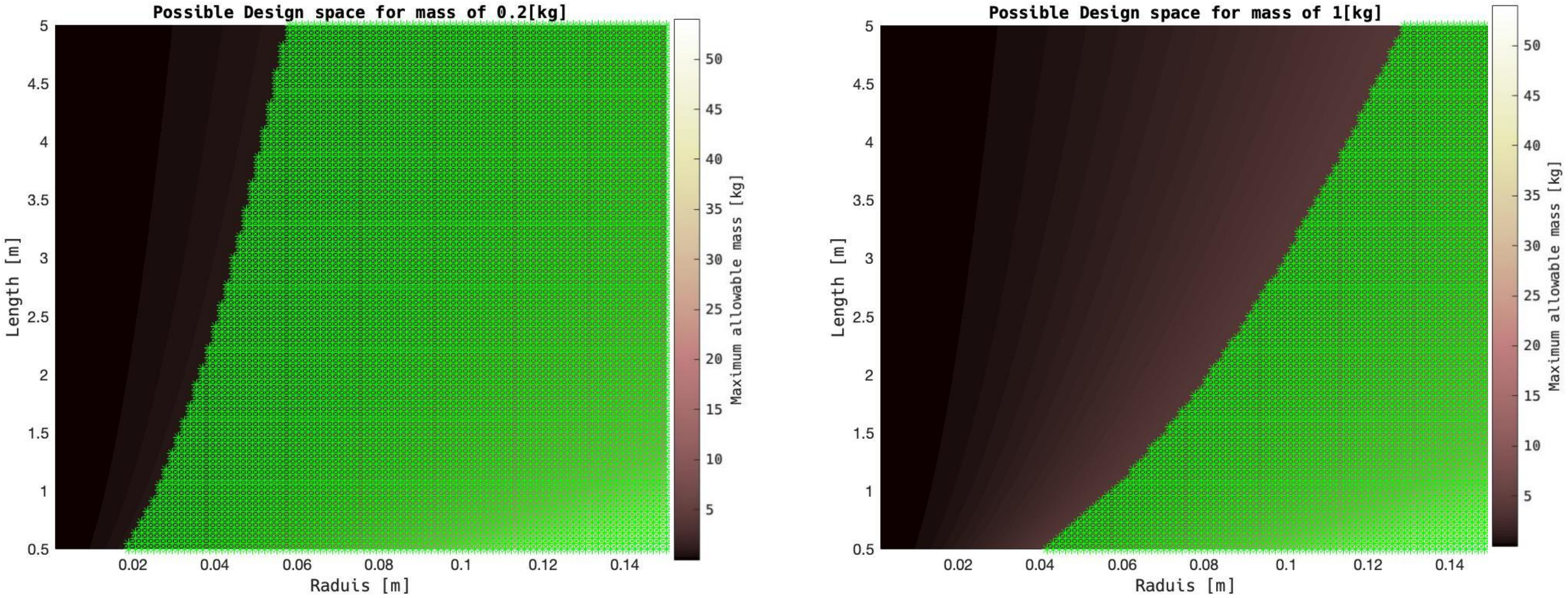


Back to the Directory

Operational envelope: Desirable regime, low mass, high range

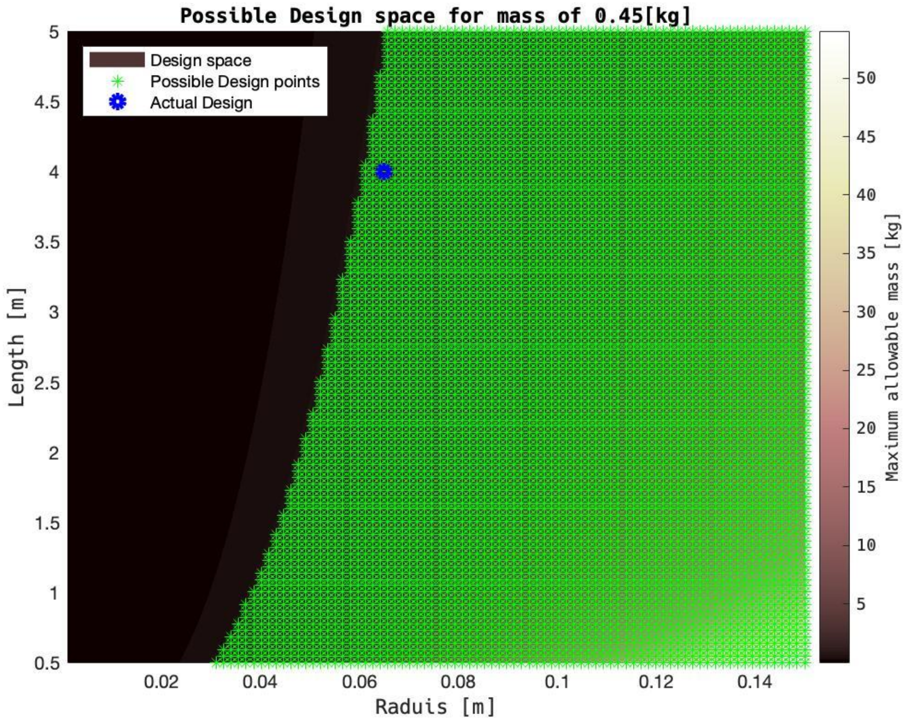


Operational envelope: Intuitive sense



We can ask the question of: if we have a given mass, what combinations of radius and range can we achieve?
As we increase the end effector mass, we need bigger tubes, same size tube if it can handle the mass it will not go far enough

Operational envelope: Our actual mass,



<u>Our design has a tube radius of 6.5cm, and could go up to 4m or higher!</u>

Back to the Directory

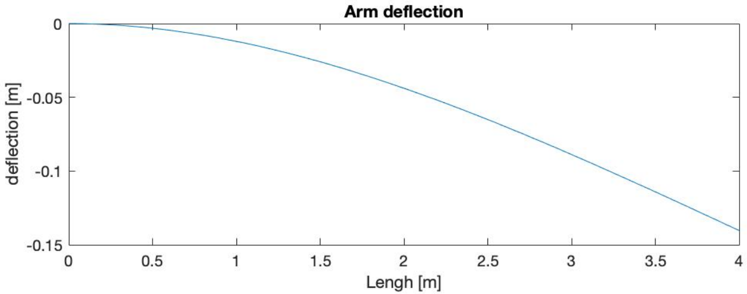
Tip displacement and deflection

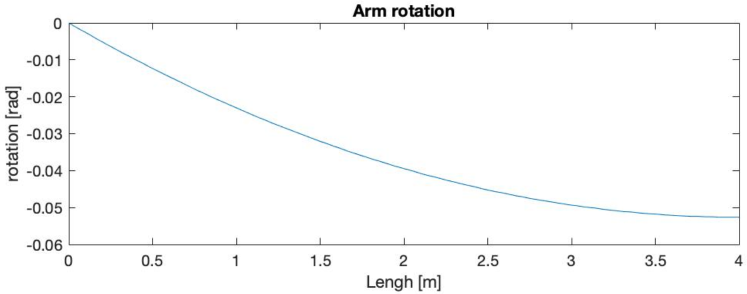
$$V(x) = \frac{F}{(E+P/S_o)I_o}\left(\frac{\ell_o x^2}{2} - \frac{x^3}{6}\right) + \frac{Fx}{P+kG\,S_o},$$

$$\theta(x) = \frac{F}{(E+P/S_o)I_o}\left(\ell_o x - \frac{x^2}{2}\right),$$

Model developed using virtual work methods [1], V(x) is the deflection and **θ**(x) is the rotation

x = location along the tip $[0:l_0]$
k = Correction shear factor, which is **0.5** for circular tubes
S_0 = Cross sectional area of the structure
I_0 = Second moment of area, about the central axis
E = Young's modulus
G = Shear modulus
l_0 = Length of the tube
F = Applied vertical force at the tip



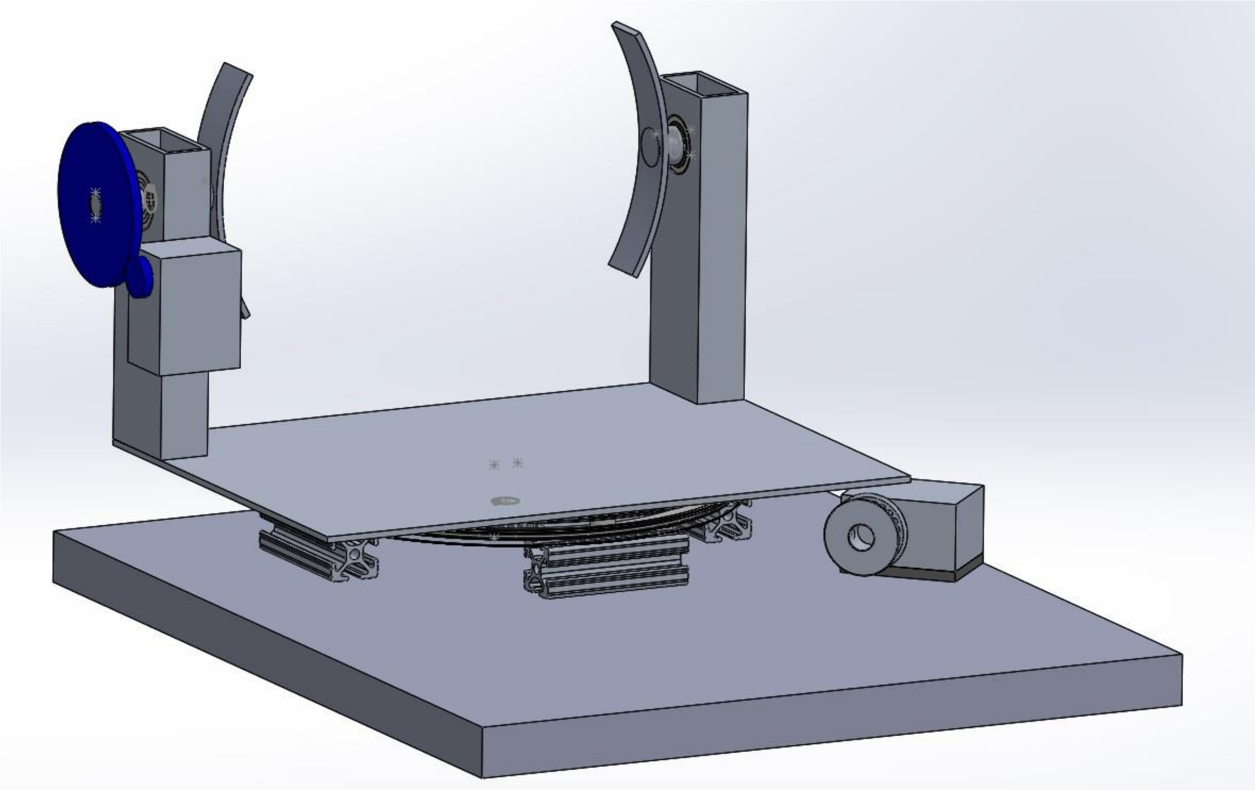


[1]: Van, A. Le, and C. Wielgosz. "Erratum to: 'Bending and Buckling of Inflatable Beams: Some New Theoretical Results.'" Thin-Walled Structures, vol. 44, no. 7, 2006, pp. 822–823., doi:10.1016/j.tws.2006.08.001.

CAD
Parts

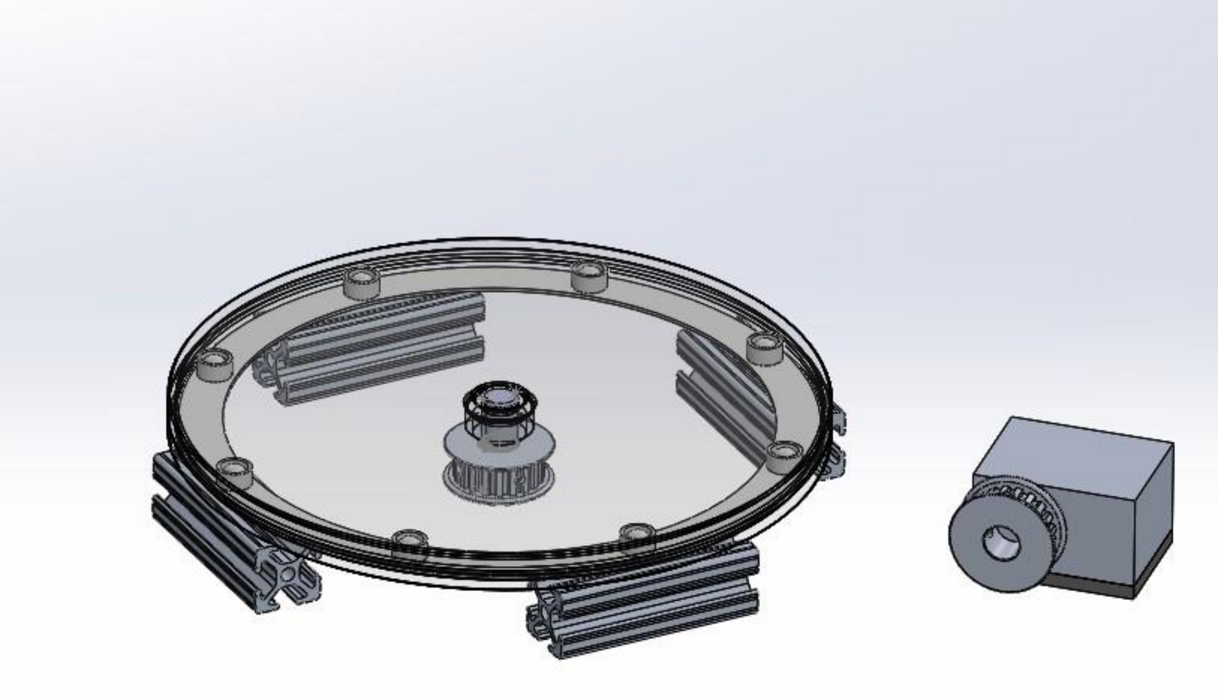
Base Design

- Full base system using premade bearings for rotation
- Support plate 31.75 cm x 22.86 cm
- Height from base is 22.78 cm
- Utilize same motor for base and pivot mechanism



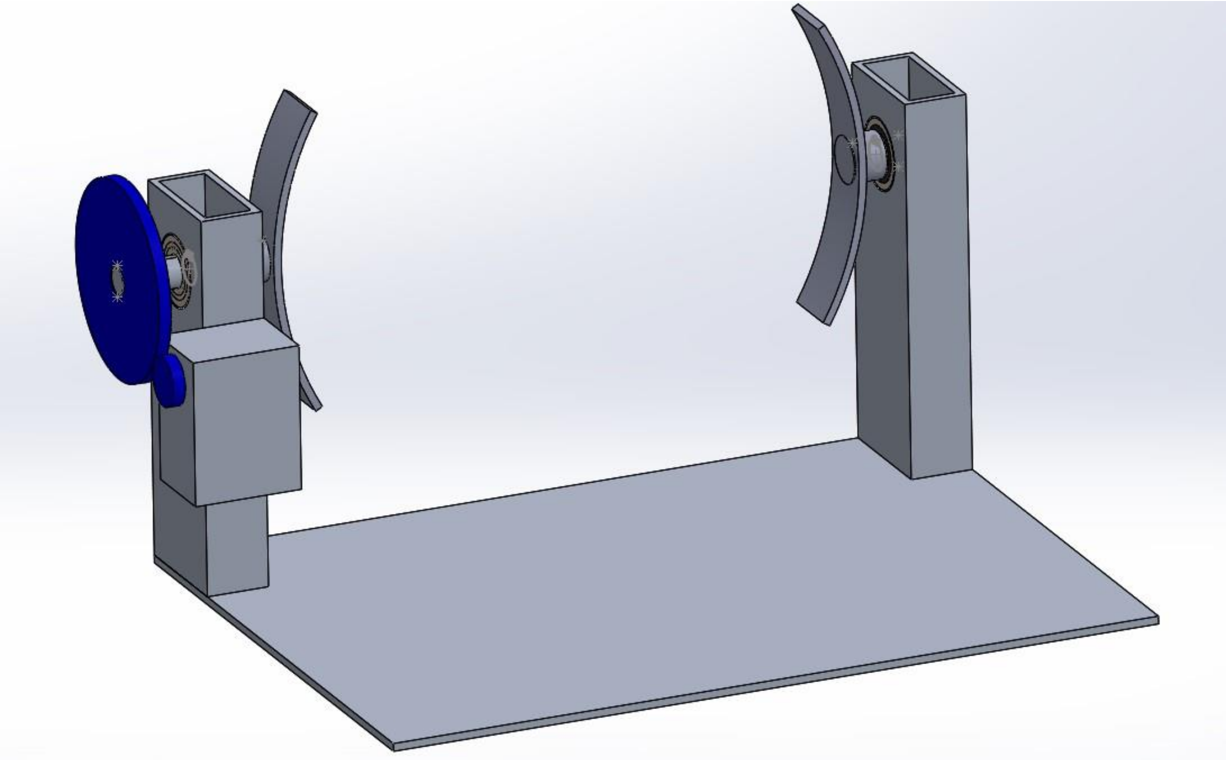
Base Rotation 360 Mechanism

- 22.86 cm diameter turntable
- Table raised by 2.54cm off of the base
- Timing belt connection between motor and turntable
- Required 105 kgcm of torque
- 1:1 gear ratio



Base Pitch 90 Mechanism

- Require 356.14 kg·cm of torque
- 4:1 gears to connect motor
- Custom made gears to achieve ratio
- Attached to container with epoxy
- 3D print connectors to container



Backup Slide: Material Spooling System

- 203.2 mm OD, 38.1 mm “nozzle” for material flow
- Parallax 900-00360-ND servo
- 7.94 mm diameter keyed rotary shaft
- 3.175 mm width timing belt

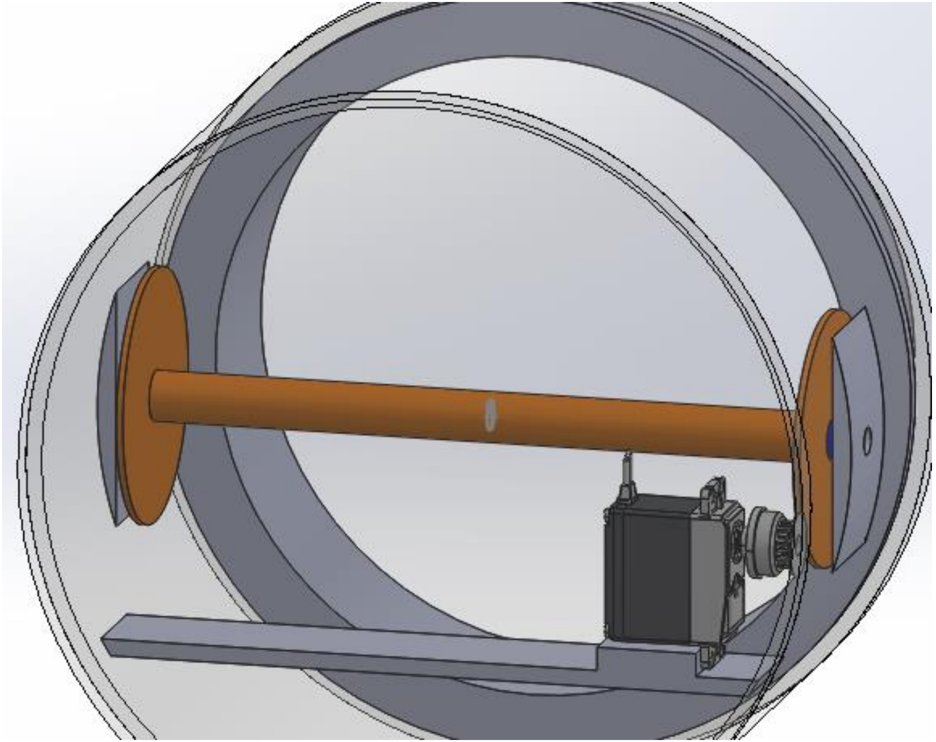


Figure 1: Spooling assembly cad

Pressure System Design

Air tank

- 68 ci / 4500 psi HPA compressed air tank
- Max output pressure 800 psi (31 MPa)
- 4.5 in diameter x 10 ½ in + 1.82 in regulator
- Capacity ~= 68 in^3

Fully extended volume - 4009 in^3

Provides almost 13 full deployments to *4 meters*

https://www.ansgear.com/Ninja_SL2_68_4500_Tank_Black_Blue_p/ninjatanksl2-68blkbluv2ul.htm

Air tank

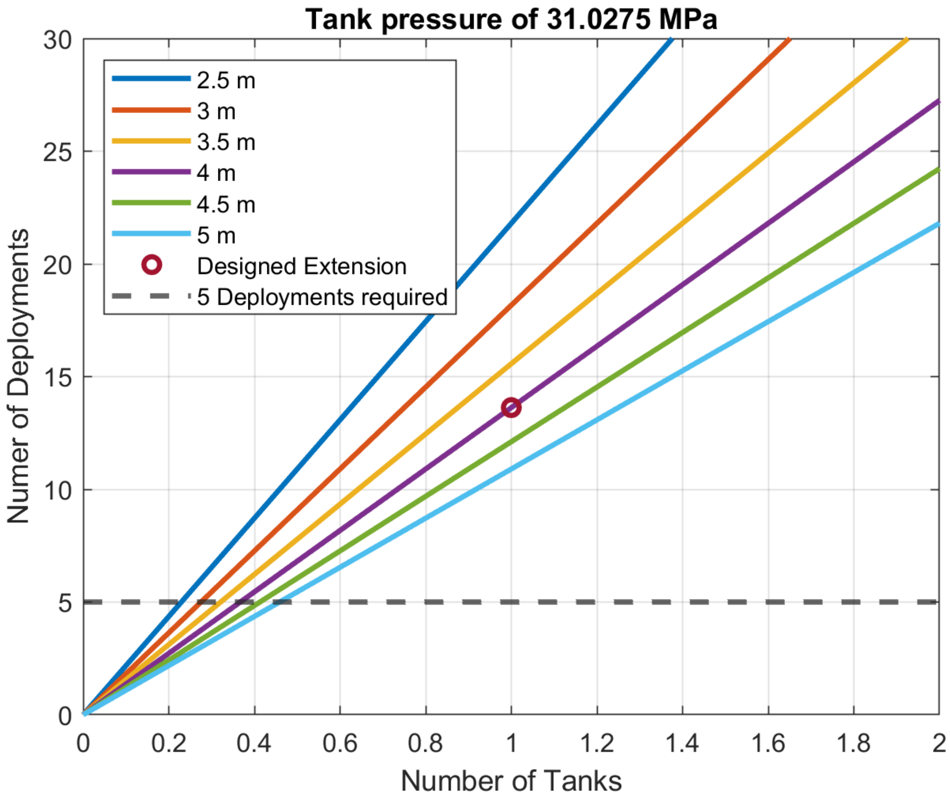
- 48 ci / 3000 psi HPA compressed air tank
- Max output pressure 800 psi (31 MPa)
- 3.5 in diameter x 10 ¾ in
- Capacity ~= 86.5 in^3

Fully extended volume - 11600 in^3

https://www.amazon.com/HK-Army-Aluminum-HPA-Tank/dp/B07MR6QCSR/ref=sr_1_5?crid=16K01738Z95AI&dchild=1&keywords=paintball+air+tank&qid=1605894660&sprefix=oaintball+air+tank%2Caps%2C176&sr=8-5

Air tank

$$V_{arm} = \frac{P_{tank} * V_{tank}}{P_{arm}}$$



- 1.1E-3 m^3 at 31 MPa
- Required *maximum* volume 0.0657 m^3 at 48.3 kPa

Back to FR 3.1 Back to the Directory

Pressure Regulator

- Max Inlet pressure 3600 psi (24.8 MPa)
- Inlet range 0-25 psi (0.17 MPa)
- ¼” FNPT
- 0.06 C_V vs 0.018 needed

https://www.swagelok.com/en/catalog/Product/Detail?part=KPR1DRC412A2000 0

$$C_V = \frac{1}{100} Q \sqrt{(\frac{SG}{\Delta P})}$$

- C_V = Coefficient of Flow
- Q = Flow in gallons/minute
- SG = Specific Gravity
- ΔP = Pressure Difference

Solenoid Valve

- ⅛” FNPT
- 12 VDC
- Power consumption 4.5 W
- 6.9 CFM ~= 3256 cm^3/s
- Pressure range 0 to 120 psi (0.82 MPa)

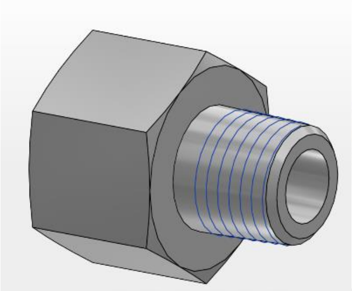
https://www.zoro.com/aro-solenoid-air-control-valve-18-in-12vdc-power-consumption-45-w-p211ss-012-d/i/G2681366/

Hose

- 1 ft to 1.5 ft (30.5-45.7 cm) long
- ⅛" NPT Male connections on both sides
- Working Pressure 4500 psi (31.0 MPa)

https://atdtools.com/8202

Connection Adaptors

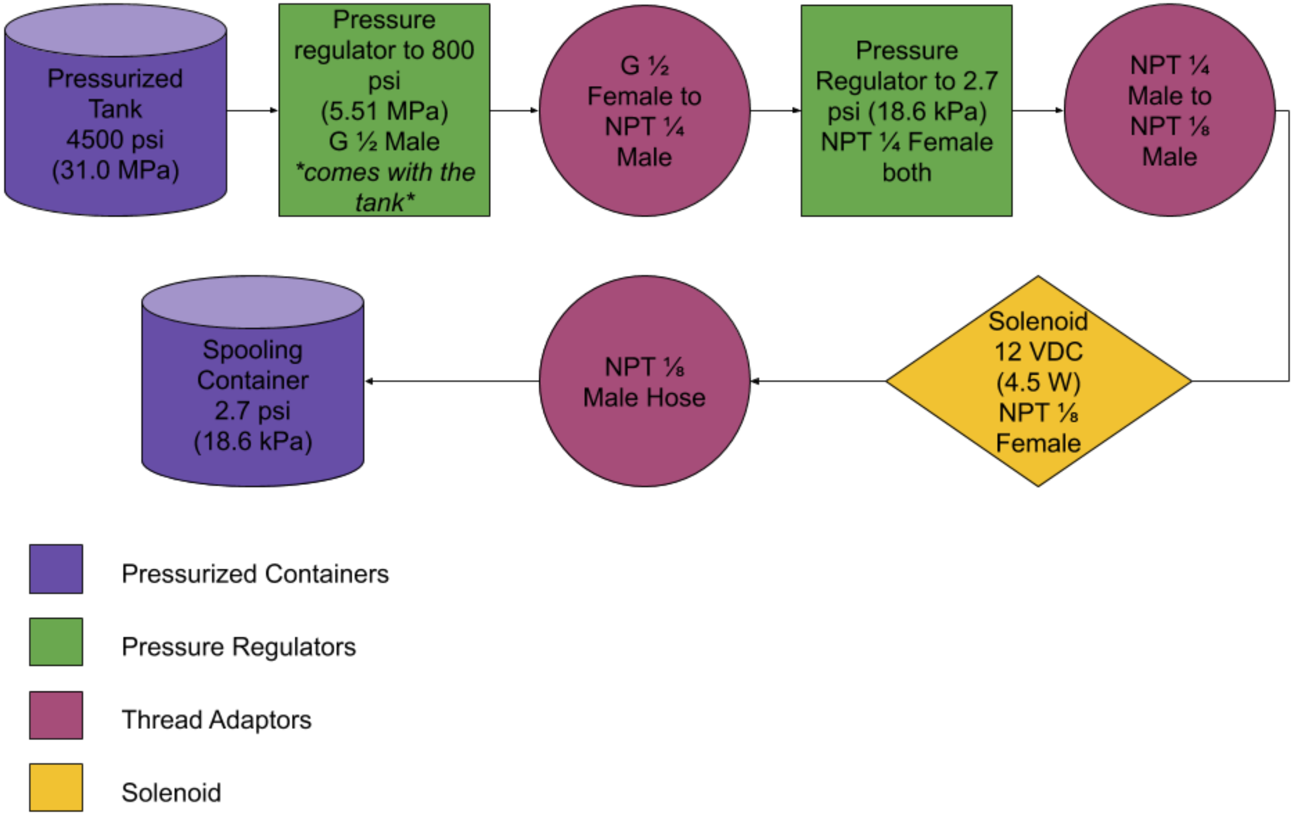



Adaptors:

- G ½ to NPT ¼ Adaptor
- NPT adaptors of different sizes

https://serto.partcommunity.com/3d-cad-models/?catalog=serto&part=TAD.5124.224
https://www.stainlesssteelfittings.com/Female_Pipe_Coupling_stainless_5000_p/ss-5000.htm?gclid=Cj0KCQiAkuP9BRCkARIsAKGLE8VXz--WeTlaKy4kso1Dt-85XvlPqIjWjacgg3GTjDSOk3PoLKd3_NgaAqwqEALw_wcB

Pressure System Diagram



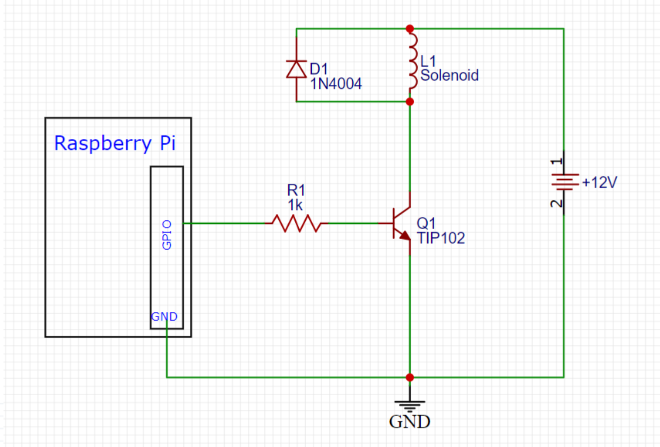
Pressure control

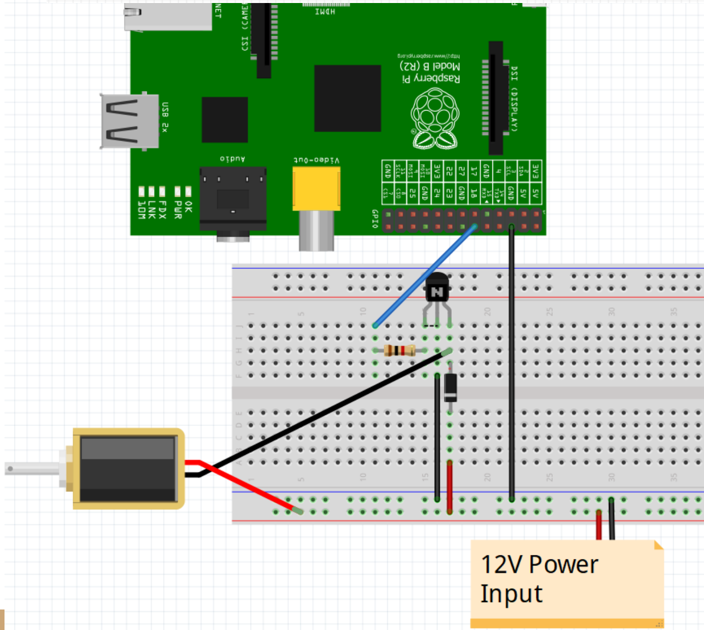
1. Pressure from compressor to regulator at 800 psi
2. Pressure regulator to solenoid at 2.7 psi
3. Solenoid on/off controlled by Raspberry Pi

Transistor: Functions as the switch to open and close solenoid

Diode: Protects the RasPi from discharge in the circuit that occurs when the solenoid turns off

Resistor: Regulates output from RasPi to transistor





Back to the Directory   Back to FR 3.1

Check Valve

- Maximum pressure 145 psi (1 MPa)
- Minimum opening pressure 7 psi (48.3 kPa)
- C_V = 0.93

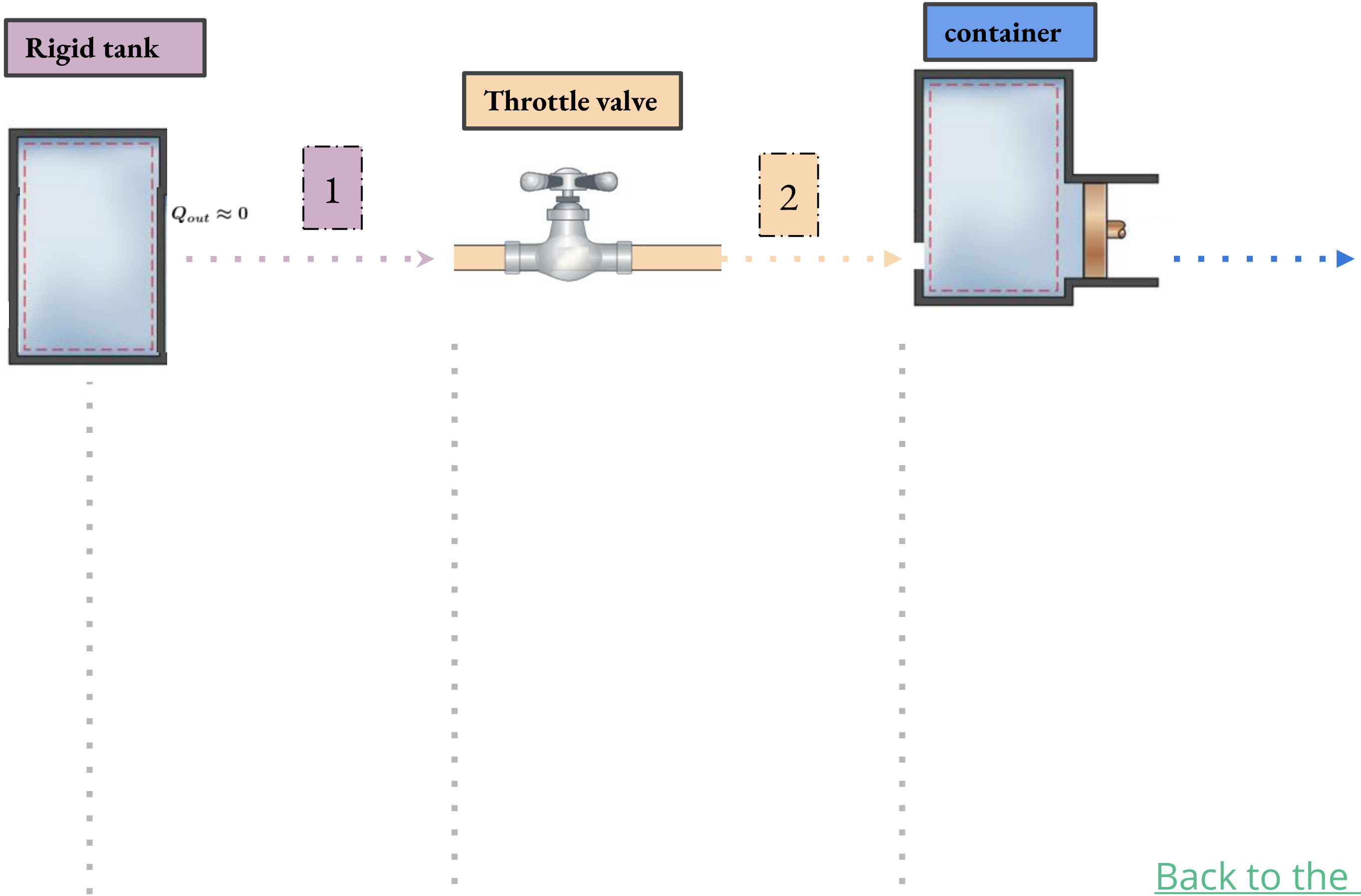
https://www.mcmaster.com/1096T3/

$$C_V = \frac{1}{100} Q \sqrt{(\frac{SG}{\Delta P})}$$

- C_V = Coefficient of Flow
- Q = Flow in gallons/minute
- SG = Specific Gravity
- ΔP = Pressure Difference

Thermodynamics Analysis

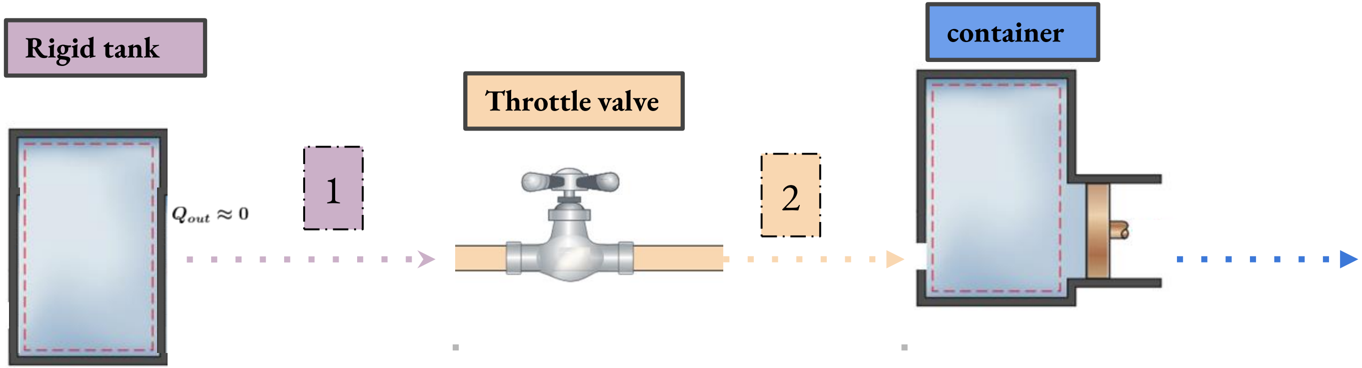
Thermodynamics analysis: $\dot{Q}_{in} + \dot{W}_{in} + \sum_{in} \dot{m}_{in}\left(h_{in} + \frac{V_{in}^2}{2} + gz_{in}\right) = \dot{Q}_{out} + \dot{W}_{out} + \sum_{out} \dot{m}_{out}\left(h_{out} + \frac{V_{out}^2}{2} + gz_{out}\right)$ } Conservation of energy



Thermodynamics analysis:

$$\dot{Q}_{in} + \dot{W}_{in} + \sum_{in} \dot{m}_{in}\left(h_{in} + \frac{V_{in}^2}{2} + gz_{in}\right) = \dot{Q}_{out} + \dot{W}_{out} + \sum_{out} \dot{m}_{out}\left(h_{out} + \frac{V_{out}^2}{2} + gz_{out}\right)$$

Conservation of energy



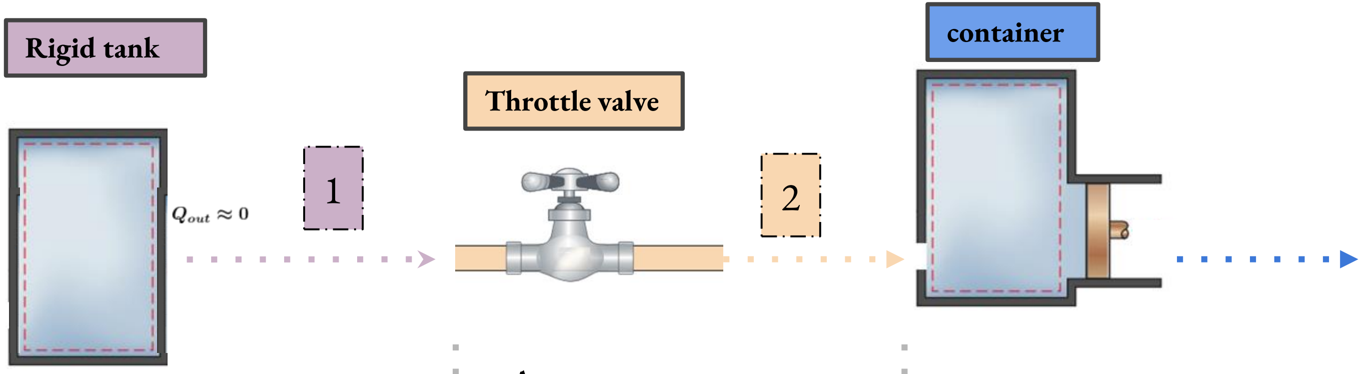
Assume

- Isentropic process
- Ideal gas
- Steady flow

Thermodynamics analysis:

$$\dot{Q}_{in} + \dot{W}_{in} + \sum_{in} \dot{m}_{in}\left(h_{in} + \frac{V_{in}^2}{2} + gz_{in}\right) = \dot{Q}_{out} + \dot{W}_{out} + \sum_{out} \dot{m}_{out}\left(h_{out} + \frac{V_{out}^2}{2} + gz_{out}\right)$$

} Conservation of energy



Rigid tank

Assume
- Isentropic process
- Ideal gas
- Steady flow

Throttle valve

Assume
- Isentropic process
- Ideal gas
- Steady flow

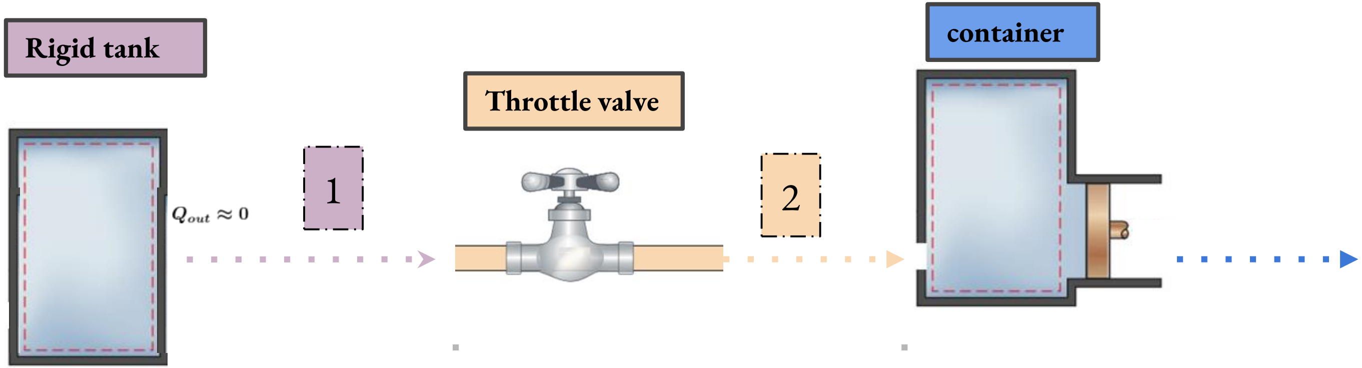
$$h_1 = h_2$$

Back to the Directory

Thermodynamics analysis:

$$\dot{Q}_{in}+\dot{W}_{in}+\sum_{in}\dot{m}_{in}\left(h_{in}+\frac{V_{in}^{2}}{2}+gz_{in}\right)=\dot{Q}_{out}+\dot{W}_{out}+\sum_{out}\dot{m}_{out}\left(h_{out}+\frac{V_{out}^{2}}{2}+gz_{out}\right)$$

} Conservation of energy



Rigid tank

Assume
- Isentropic process
- Ideal gas
- Steady flow

Throttle valve

Assume
- Isentropic process
- Ideal gas
- Steady flow

$$h_1 = h_2$$

Container

Assume
- Isentropic process
- Ideal gas
- Steady flow
- Isobaric process

$$\dot{W}_{out} = m_{in}h_{in}$$

$$\dot{W}_{out} = \dot{W}_{Boundary,Isobaric} = \frac{P_3(V_3 - V_2))}{\Delta t}$$

$$\frac{P_3(V_3 - V_2))}{\Delta t} = m_{in}h_{in}$$

$$\Delta V_{2\to3} = \pi r^2 Range$$

$$\frac{P_3(\pi r^2 Range))}{\Delta t} = \dot{m}_2 Cp \frac{P_1}{\rho R}$$

$$\dot{m}_2 = \frac{P_3(\pi r^2 Range)\rho R}{P_1 \Delta t Cp}$$

Note: All P1 should be P2

Directory

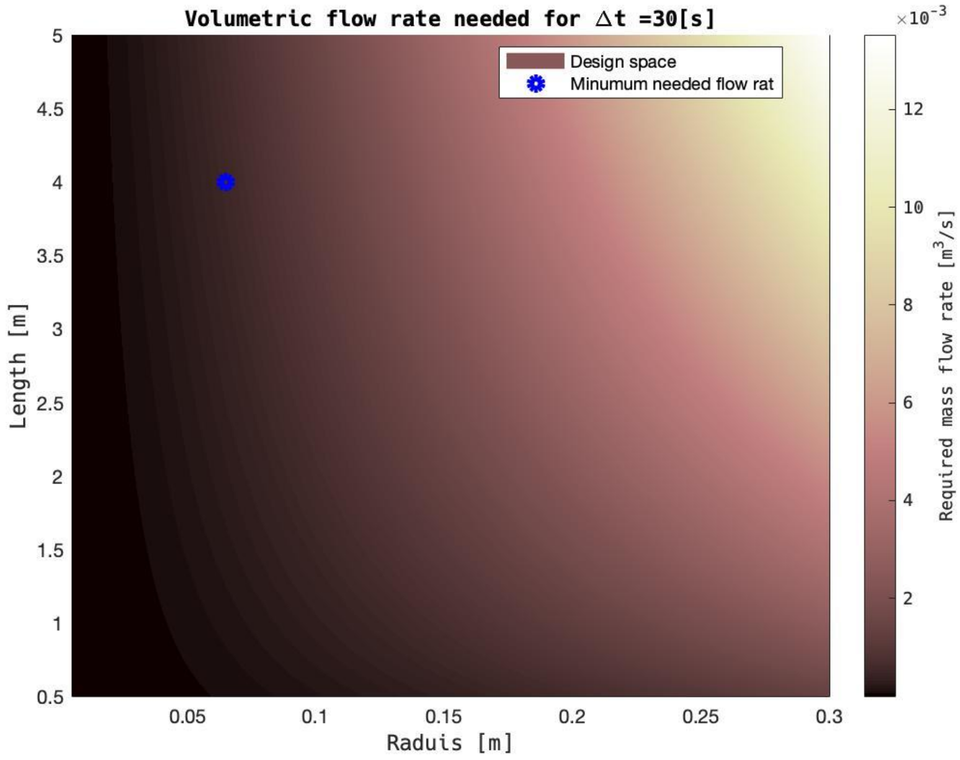
Thermodynamics analysis

$$\dot{m}_2 = \frac{P_3(\pi r^2 Range)\rho R}{P_1 \Delta t C p}$$

$$\dot{V} = \frac{\dot{m}}{\rho}$$

- Δt = specified by the requirements to be 60 seconds
- ρ = 1.225 [kg/m^3]
- R = 287 [J/Kg-K]
- Cp = 1000 [J/Kg-K]
- P3 = Pressure before yielding
- P1 = Pressure in tank

Note: All P1 should be P2



Intuitively, if we want to go further with a bigger tube, we would need to pump more air, nothing surprising!
<u>Need a mass flow rate of 0.00051 m^3/s or more</u>

Back to the Directory

Thermodynamics analysis: Vacuuming

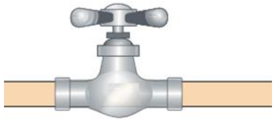
- Vacuum pumps were considered for more control of retraction
- Take up a lot of space
- Take a lot of power
- Generally slow

Thermodynamics analysis:

$$\dot{Q}_{in} + \dot{W}_{in} + \sum_{in} \dot{m}_{in}\left(h_{in} + \frac{V_{in}^{2}}{2} + gz_{in}\right) = \dot{Q}_{out} + \dot{W}_{out} + \sum_{out} \dot{m}_{out}\left(h_{out} + \frac{V_{out}^{2}}{2} + gz_{out}\right)$$

Conservation of energy

Throttle valve



Assume

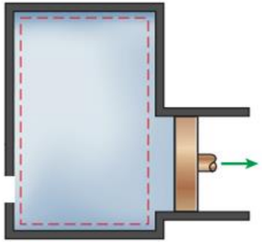
- Isentropic process
- Ideal gas
- Steady flow

$$\cancel{\dot{Q}_{in}} + \cancel{\dot{W}_{in}} + \sum_{in} \dot{m}_{in}\left(h_{in} + \cancel{\frac{V_{in}^{2}}{2}} + \cancel{gz_{in}}\right) = \cancel{\dot{Q}_{out}} + \cancel{\dot{W}_{out}} + \sum_{out} \dot{m}_{out}\left(h_{out} + \cancel{\frac{V_{out}^{2}}{2}} + \cancel{gz_{out}}\right)$$

Thermodynamics analysis:

$$\dot{Q}_{in} + \dot{W}_{in} + \sum_{in} \dot{m}_{in}\left(h_{in} + \frac{V_{in}^{2}}{2} + gz_{in}\right) = \dot{Q}_{out} + \dot{W}_{out} + \sum_{out} \dot{m}_{out}\left(h_{out} + \frac{V_{out}^{2}}{2} + gz_{out}\right)$$

Conservation of energy

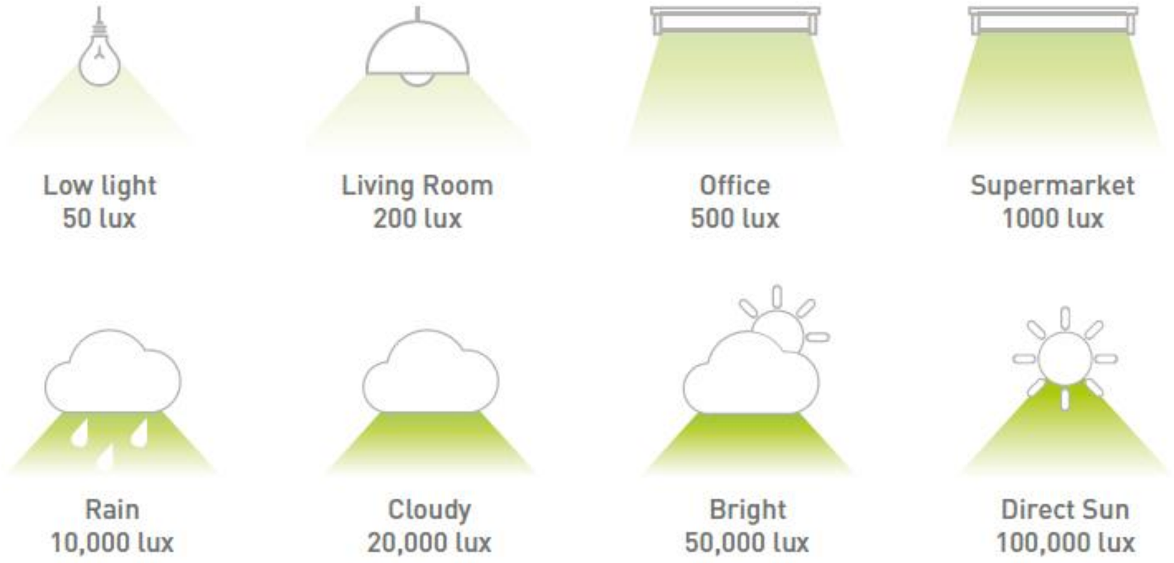


Assume

- **Isentropic process**
- **Ideal gas**
- **Steady flow**
- **Isobaric process**

$$\cancel{\dot{Q}_{in}} + \cancel{\dot{W}_{in}} + \sum_{in} \dot{m}_{in}\left(h_{in} + \cancel{\frac{V_{in}^{2}}{2}} + \cancel{gz_{in}}\right) = \cancel{\dot{Q}_{out}} + \dot{W}_{out} + \sum_{out} \cancel{\dot{m}_{out}}\left(h_{out} + \frac{V_{out}^{2}}{2} + gz_{out}\right)$$

Lux levels


Low light
50 lux
Living Room
200 lux
Office
500 lux
Supermarket
1000 lux
Rain
10,000 lux
Cloudy
20,000 lux
Bright
50,000 lux
Direct Sun
100,000 lux

Arm Control

Vine Robot Eversion and Inversion Control

The controls for eversion(deployment) and inversion(retraction) will take place in two systems synchronously:

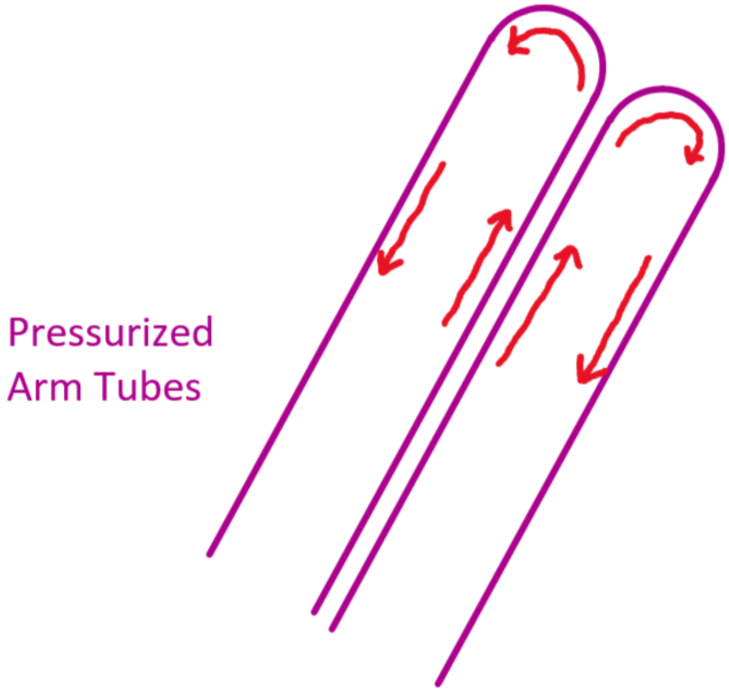
- Pressure Control (Eversion)
  - The compressed air will travel through two regulators that will control the pressure.
  - A solenoid will open when a command is received from the Raspberry Pi during eversion.
  - When the desired length is reached the solenoid will close.

- Pressure Control (Inversion)
  - As the tube inverts pressure inside will increase.
  - When the pressure increases to 3 psi a solenoid will open to let air escape.

- Motor Control
  - The motor needs to rotate at a rate that matches the pressure entering into the tube.
  - The following PI control law will be used by ROS MoveIT to control the unspooling of the material.

$$u = k_p(\omega_d - \omega) + k_i \int (\omega_d - \omega)$$

Spool Encoder/Extension Kinematics



When material is spooled out from base:

- Inner material is increased by some length
- Material on tip is displaced by same length
  - Moves to outer edge, becomes ‘outer material’
- Outer material increases by same length as inner material

However:

- Inner and outer material must both increase in length
  - Split the length of spooled-out material evenly
  - Thus,

Sensing Apparatus

Sensing Apparatus: RunCam Split3 Micro Transmitter

Frequency Table

200mW Lock

Channel	CH1	CH2	CH3	CH4	CH5	CH6	CH7	CH8
1 Band A	5865	5845	5825	5805	5785	5765	5745	5725
2 Band B	5733	5752	5771	5790	5809	5828	5847	5866
3 Band E	5705	5685	5665	5645	5885	5905	5925	5945
4 Airwave	5740	5760	5780	5800	5820	5840	5860	5880
5 Race Band	5658	5695	5732	5769	5806	5843	5880	5917
6 Low Race	5362	5399	5436	5473	5510	5547	5584	5621

Sensing Apparatus: RunCam Split3 Micro Transmitter

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]:

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

$$SNR = 39.2841$$

Back to the Directory

Power Budget

	Part Name	Devices per Board	Supply Current per Device (A)	Supply Current per Board (A)	Supply Voltage	Power Subtotal (W)
WRIST						
CO2	Sensirion SCD30	1	0.019	0.019	3.3	0.0627
AHRS	3-Space™ Embedded LX	1	0.022	0.022	3.3	0.0726
Camera	RunCam Split 3	1	0.65	0.65	5	3.25
Camera Transmitter	RunCam TX200U	1	0.4	0.4	3.3	1.32
Raspi zero	Raspberry Pi Zero WH	1	2	2	5	10
Lights	Bright Pi- Lights	1	0.016	0.016	3.3	0.0528
Wrist Servos	TowerPro SG90 9G Micro Servo Motor	2	0.22	0.44	6	2.64
BASE						
Microcontroller	Raspberri Pi 4 Model B	2	3	6	5	30
Wireless Reciever	Wolfwhoop WR832 RC832	1	0.22	0.22	12	2.64
Soleniod Valve	Maximatic 2 Way Valves	1			12	4.5
CONTAINER						
Material Spool Servo	Paralax Feedback 360	1	1.2	1.2	6	7.2
Tension motors	HSR-2645CRH Servo	3	1.2	3.6	6	21.6
Base Pivot Servo	DYNAMIXEL XM540-W150-T	1	4.4	4.4	12	52.8
					Power Total (W)	136.1381
					Margin	50%
					Input Power Needed (W)	272.2762

Back to the Directory

Verification and Validation

Verification and Validation: Burst Pressure
Why the pressure is different?

Two methods of checking the Burst pressure:

- Method 1: ASEN 3112
  - **FOS on the container: 3**
  - P = 40.65 kPa
  - Function of Yield stress, not provided by commercial sellers

$$P \leq \frac{\sigma_y t}{R}$$

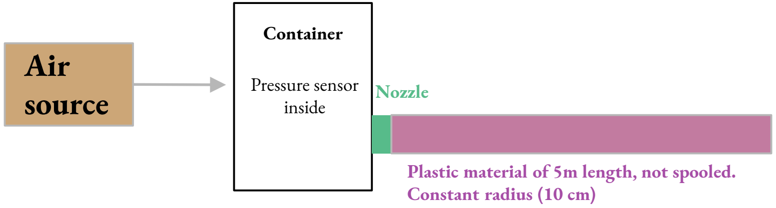
- Method 2: Burst formula for tubes to account for resin grades
  - **FOS on the container: 1.48**
  - P = 58 kPa

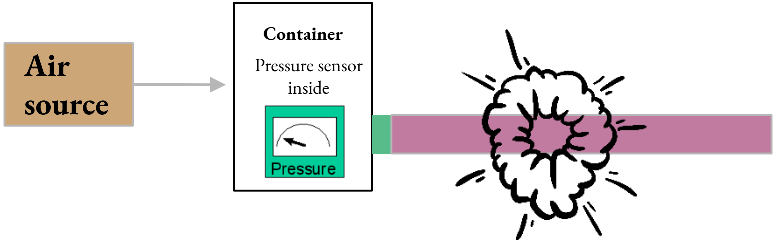
$$P = \frac{T(x^2-y^2)}{y^2\left(1+\frac{x^2}{y^2}\right)}$$

where

P = burst pressure
T = tensile strength
OD = outside diameter of the tubing
ID = inside diameter of the tubing

$x = \frac{OD}{2}$ $y = \frac{ID}{2}$

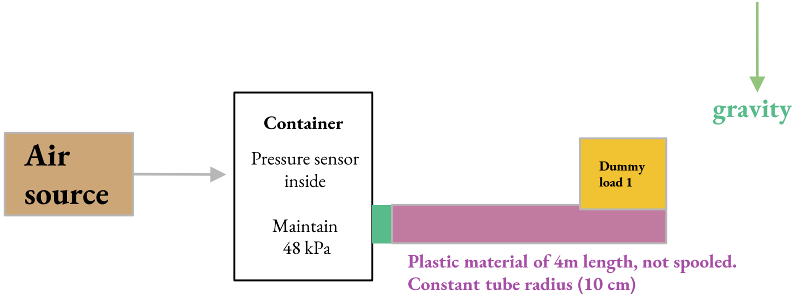




Back to the Directory

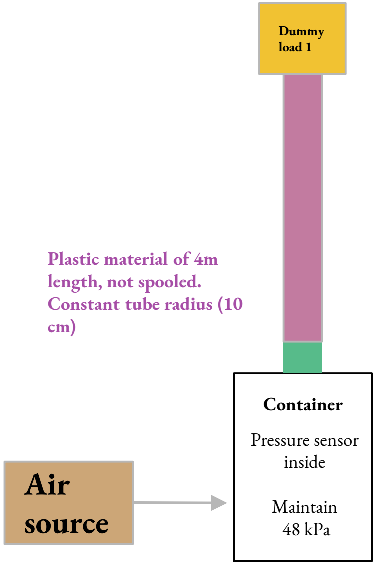
Verification and Validation: Payload capabilities directional change

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



- **Test purpose:**
  - Determine if the pressure and length combination can sustain the mass the model predicts
  - Varry the mass to check
  - Extend the tube a long horizontal and vertical direction
- **Test components:**
  - Air source (With hose)
  - Pressure sensor
  - Sealed plastic bag
  - Scale (to measure the dummy load)
  - Dummy load
- **Measured values:**
  - Maximum mass that can be sustained
- **Expected values:**
  - For 5m length: 0.33 kg mass of failure
  - For 3m length: 1.1 kg mass of failure

- **Tolerated uncertainties:**
  - ± .1 meters and ± 50 grams
- **Key measurement issues:**
  - Maintaining constant pressure
  - Fabrication of imitation end effector
- **Safety concerns:**
  - Load falling on unprotected region
  - Presence of pressurized gas
  - Leakages



Verification and Validation: Artifact Sensing

TDR 1.1.1 & 1.1.3: Camera and lighting.

- **Test purpose:**
  - Ensure that sensor suite will be able to pick up signatures of artifacts for identification by the MARBLE team
- **Test components:**
  - Camera
  - CO_2 sensor
  - YOLOV3 image recognition software
- **Measured values:**
  - Video quality
  - Accurate reading of CO_2 concentration
- **Expected values:**
  - Video output at 1920x1080 pixels, 30-60 FPS
  - Video output discernible to the human eye and/or YOLOV3
  - Correct identification of CO_2 concentration over 2000 ppm
- **Tolerated uncertainties:**
  - Video resolution as low as 640x480 pixels
    - Key criteria is human/YOLOV3 recognition
  - CO_2 measurement accuracy within ± 30 ppm
- **Key measurement issues:**
  - Configuring YOLOV3 software
  - Determining actual CO_2 concentration
- **Safety concerns:**
  - Decreased oxygen concentration in CO_2 vessel
  - Possible use of pressurized gas

Verification and Validation: Arm Orientation

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

- **Test purpose:**
  - Ensure that RESCUE is able to re-position to possible desired orientations
- **Test components:**
  - Fully functional arm
    - Sensor suite optional
  - Base rotation mechanism
- **Measured values:**
  - Arm orientation
  - Sensor orientation
- **Expected values:**
  - Arm re-orientation corresponding to input to base rotation mechanism

- **Tolerated uncertainties:**
  - +/- 3 degrees
- **Key measurement issues:**
  - Accurately measuring independent of IMU
- **Safety concerns:**
  - N/A

Verification and Validation: Environmental Hazard

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

- **Test purpose:**
  - To ensure that RESCUE is completely robust to possible environmental impacts.
- **Test components:**
  - Fully integrated RESCUE system
- **Measured values:**
  - Attainable base yaw and pitch rotation range
  - Attainable ende effector pan and tilt rotation range
  - Sensor package functionality
- **Expected values:**
  - 360° and 90° base yaw and pitch rotation
  - 45° and 45° end effector pan and tilt
  - All sensors fully operational
- **Tolerated uncertainties:**
  - ±1 degree cumulative uncertainty in servos
- **Key measurement issues:**
  - Replicating environmental impacts without directly damaging equipment
- **Safety concerns:**
  - Environmental impacts causing hazards such as water on electronics

Verification and Validation: Endurance

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

- **Test purpose:**
  - To ensure that RESCUE does not use more power than is available.
- **Test components:**
  - Fully integrated RESCUE system
- **Measured values:**
  - Voltages and currents across all sensors, servos and hardware both during active state and standby state
- **Expected values:**
  - 12V inputs to receiver, wrist and solenoid valve
  - 5.5V inputs to Raspberry Pi
  - All sensors fully operational with a total input of 24V at 25A

- **Tolerated uncertainties:**
  - ± 5 W
- **Key measurement issues:**
  - Measuring over all connections,
- **Safety concerns:**
  - Faulty connections with high current input

Verification and Validation: System Position and Orientation

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

- **Test purpose:**
  - To ensure that RESCUE is able to accurately determine and report it's position and orientation.
- **Test components:**
  - Fully integrated RESCUE system
- **Measured values:**
  - Location of end effector relative to base
  - Range of motion of camera orientation
  - AHRS accuracy
- **Expected values:**
  - Multiple tests, each with a different input command, to known locations will be sent to the arm. These locations will be chosen to best test the full range of motion the arm. The physical end location will be compared to the reported end location from the servos and AHRS data.
  - Multiple tests will be run by sending physically measurable input commands to the wrist and visually inspect its rotation

- **Tolerated uncertainties:**
  - ±0.5 degree
- **Key measurement issues:**
  - Replicating movements precisely

Verification and Validation: Mission Time

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

TDR5.2.1 and TDR5.2.2: Time from firing command to active state, and command processing while active/operational (respectively)

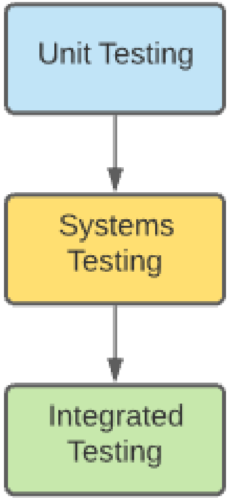
- Simulated commands sent to RESCUE system
  - System will send response when transitioned to active state or response processed
- Measure time from command to response
  - Software-based timer

TDR5.2.3: Time from operational to standby configuration

- Measure time from deactivation command to fully stowed configuration
- Compare with modeled and maximum allowed retraction time

Verification and Validation: Software Systems

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



Unit Testing:

- Test instruments individually
- Ensure that each instrument is functional
    - Outputs correct data and/or activates correctly

Systems Testing:

- Test subsystems separately
    - Camera + lighting, communication between microcontrollers
- Ensure that subsystems operate as planned

Integrated Testing:

- Test all subsystems together
    - Go through full proces, start to finish
        - Based on mock firing command
- Directly indicates functionality of RESCUE software

ROS Verification and Validation

Automated Unit Testing with ROS

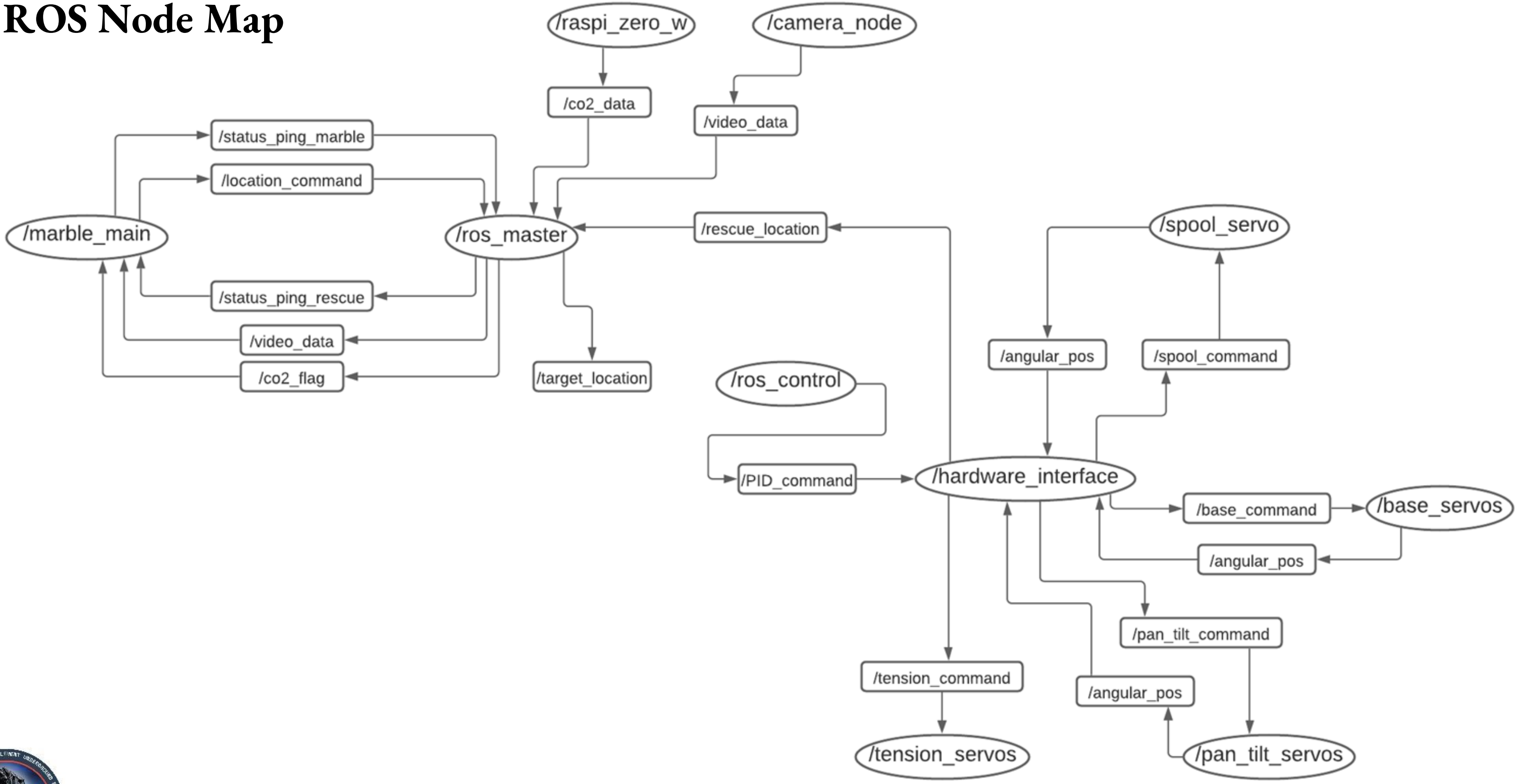
- Simplifies maintenance
- Ensures working code through incremental changes
- Prevents bug regressions
- Conducive to collaborative programming
- 3 levels of testing:
    1. Library unit test (**gtest**)
        - Test code sans ROS
        - Pre- and post- conditions, underlying functions
    2. ROS node unit test (**rostest + gtest**)
        - Test external API of individual nodes
            - Published topics, subscribed topics, services
    3. ROS nodes integration / regression test (**rostest + gtest**)
        - Test that nodes work together as expected

```
[==========] Running 3 tests from 1 test case.
[----------] Global test environment set-up.
[----------] 3 tests from MapServer
[ RUN      ] MapServer.loadValidPNG
[       OK ] MapServer.loadValidPNG
[ RUN      ] MapServer.loadValidBMP
[       OK ] MapServer.loadValidBMP
[ RUN      ] MapServer.loadInvalidFile
[       OK ] MapServer.loadInvalidFile
[----------] Global test environment tear-down
[==========] 3 tests from 1 test case ran.
[  PASSED  ] 3 tests.
```

Console output from a sample execution of **gtest**, or Google Test

(https://wiki.ros.org/gtest)

ROS Node Map

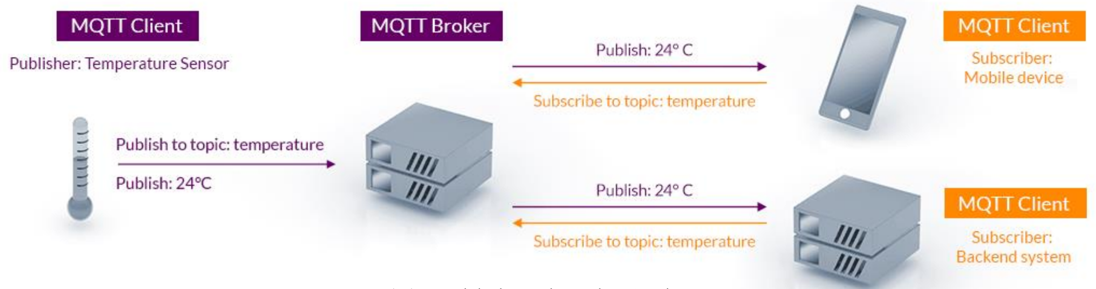


[Back to the Directory]

Wireless Communication: MQTT

Message Queueing Telemetry Transport

- Standard messaging protocol for the Internet of Things
- Extremely lightweight and efficient
  - Small code footprint, minimal network bandwidth
  - Ideal for small microcontrollers
- Bidirectional messaging
- Support for unreliable networks
- Follows a publish/subscribe architecture
- Supported by ROS **mqtt_bridge** package
  - Create **mqtt_bridge_node** to bridge between ROS and MQTT in bidirectional



MQTT Publish/Subscribe Architecture

https://mqtt.org/
https://wiki.ros.org/mqtt_bridge

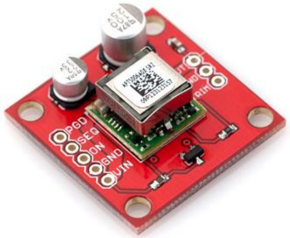
End Effector Electronics

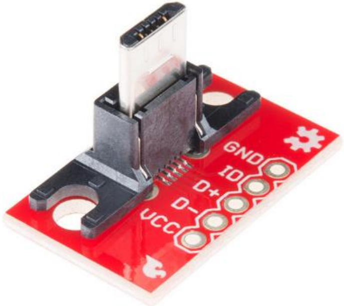
End Effector Electronics: General Flow

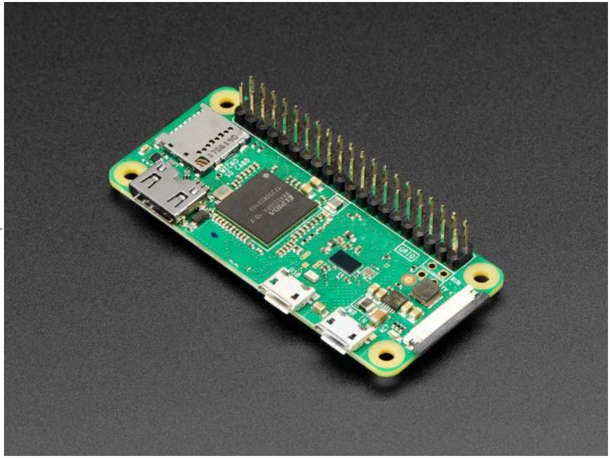
1. From the base the end effector will receive 12V at 1.5A
2. Power and Ground will split
    a. 12V to the camera at 270 mA
    b. 5.1V to the Raspberry Pi Zero W, Servos, and Camera at 120, 440, and 150 mA respectively
3. Raspberry Pi powers and receives data from all sensors via I2C protocol.

End Effector Electronics: From Base Power to RasPi

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

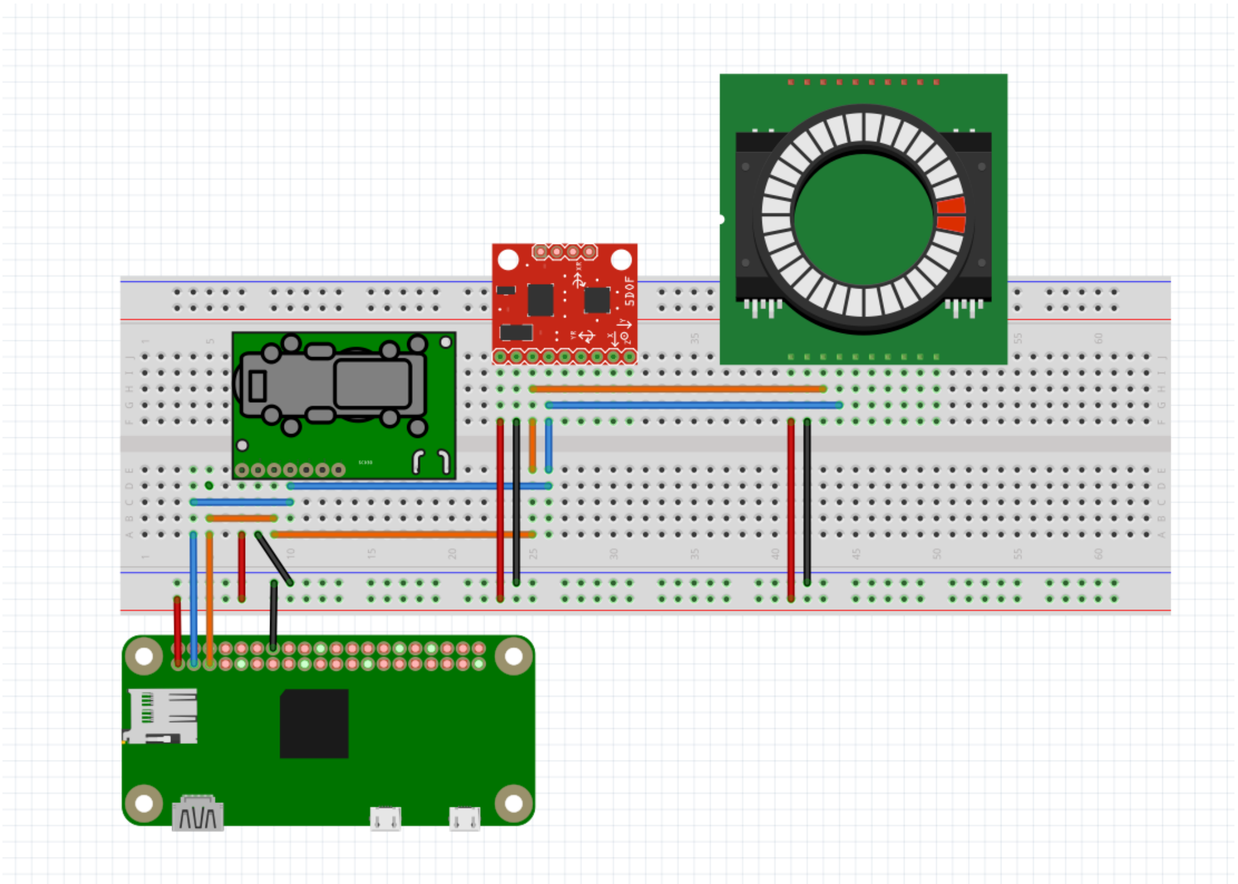






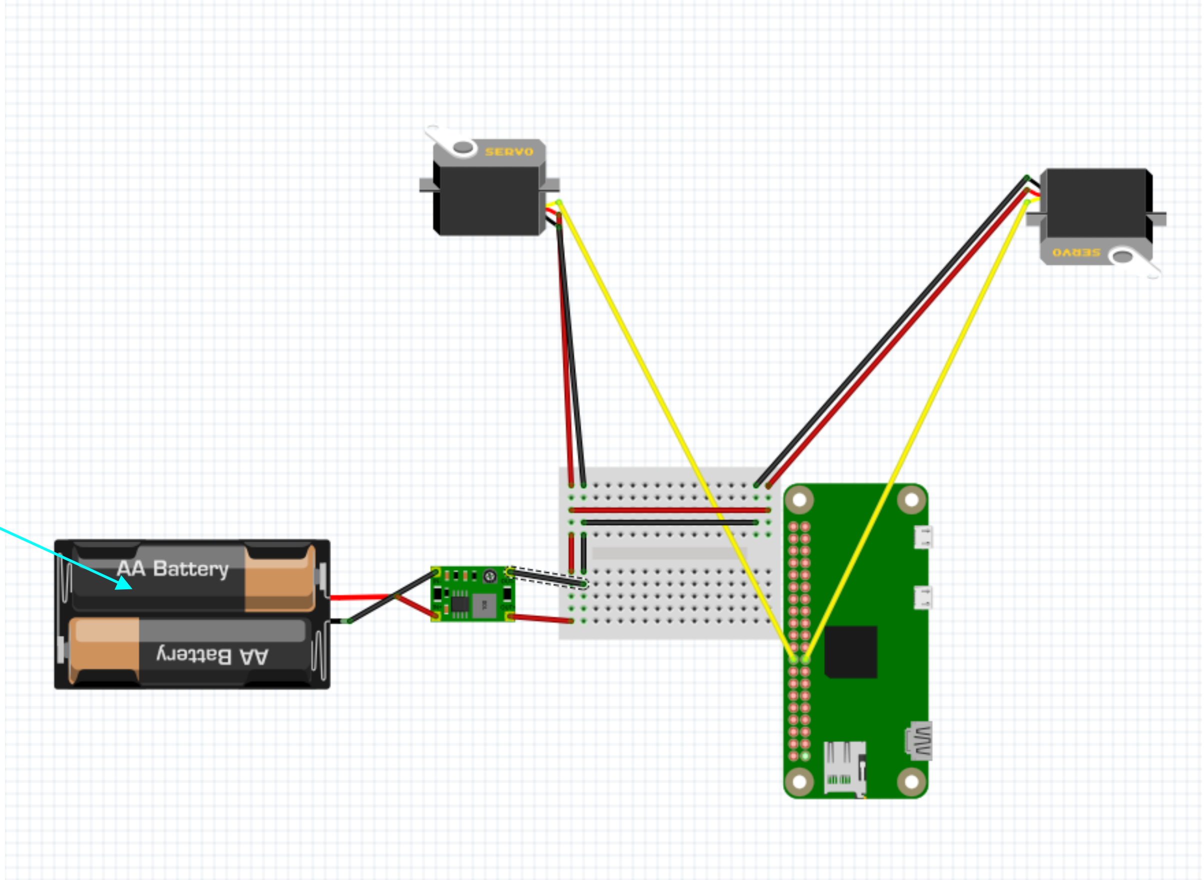
Using a USB MicroB breakout the power will be transferred to the RasPi Zero W

End Effector Electronics: Sensor Diagram



End Effector Electronics: Servo Diagram

Power From
Base



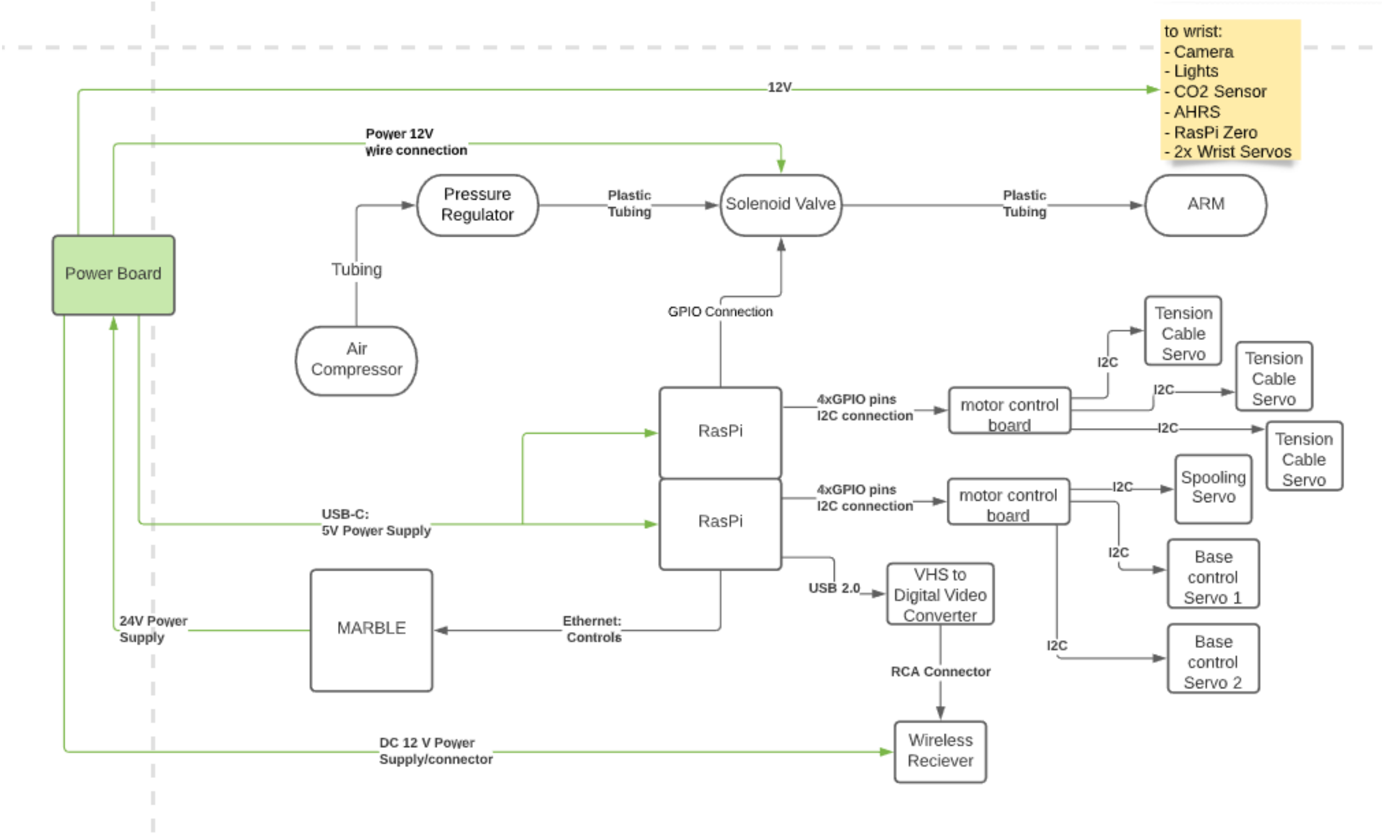
Base Electronics: General Flow

Base Electronics: General Flow

1. From MARBLE, the base will receive 24V at 25A
2. Power and Ground will split
    a. 12V to the solenoid, receiver and wrist
    b. 5.1V to each of the Raspberry Pi 4s at 3A
3. Raspberry Pi's power and receive data from the two base servos, the spool servo and the tension servos. They also send commands to the solenoid valve, wrist and receiver. And sends and receives data from MARBLE via ethernet.

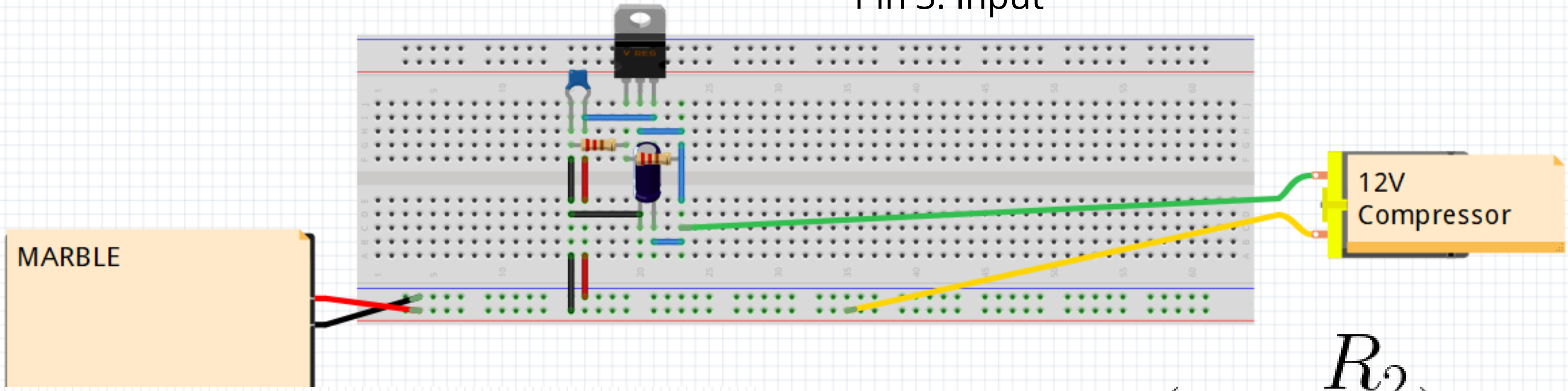
Back to the Directory

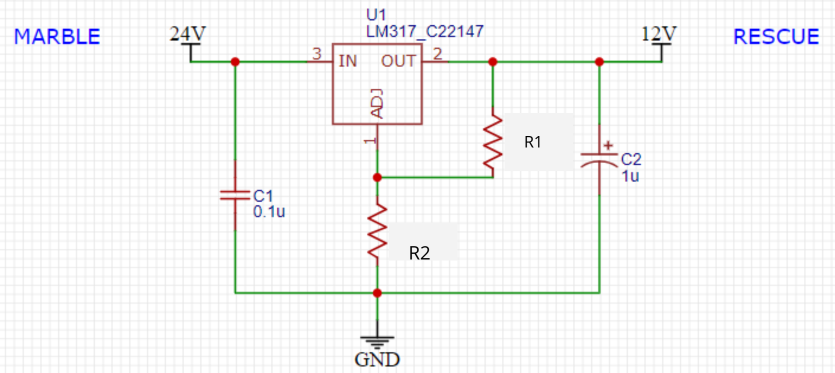
Base Electronics: Connections (to be updated)



Base Electronics: Power Board

LM317: Pin 1: Adjust
Pin 2: Output
Pin 3: Input





$$V_{out} = 1.25(1 + \frac{R_2}{R_1})$$

C1 = 0.1 μF to filter high frequency
C2 = 1 μF to stabilize output

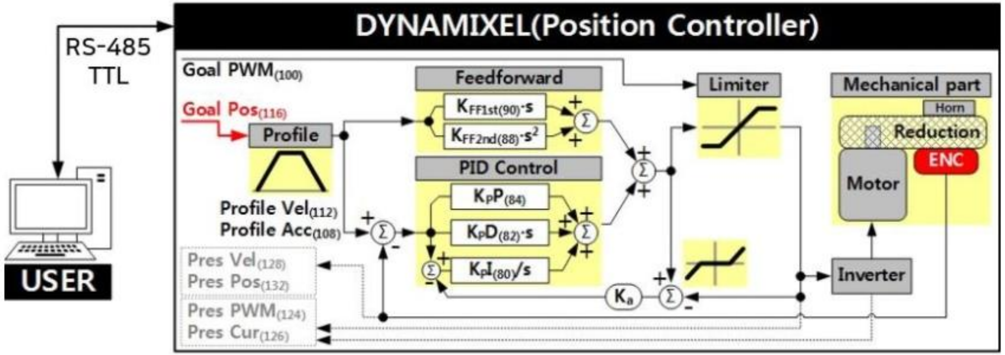
Resistors for output voltages of 12V and 5V will be determined by the above equations and Pilot lab availability.

Back to the Directory

Base Rotation Control: Pitch and Yaw

Servo Used: DYNAMIXEL XM540-W150-T

- Contactless absolute encoder
- Onboard master control unit
- PID Control loop for position and velocity control

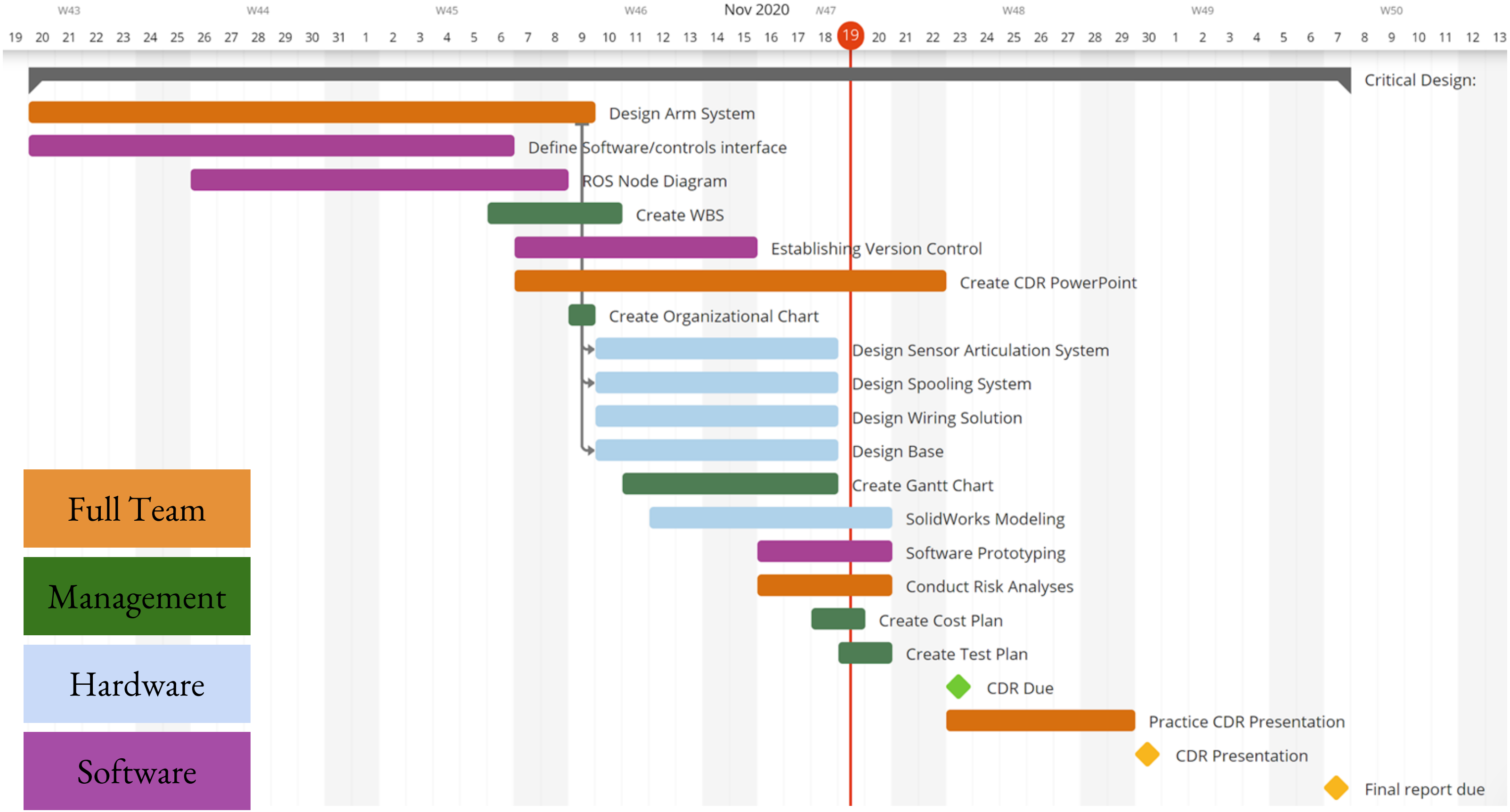


Raspberry Pi DYNAMIXEL Servo Controllerboard:

- Hat for the RasPi that allows for control of DYNAMIXEL Servos
- Open Source ROS node available to allow for seamless integration into MoveIT

Project Planning

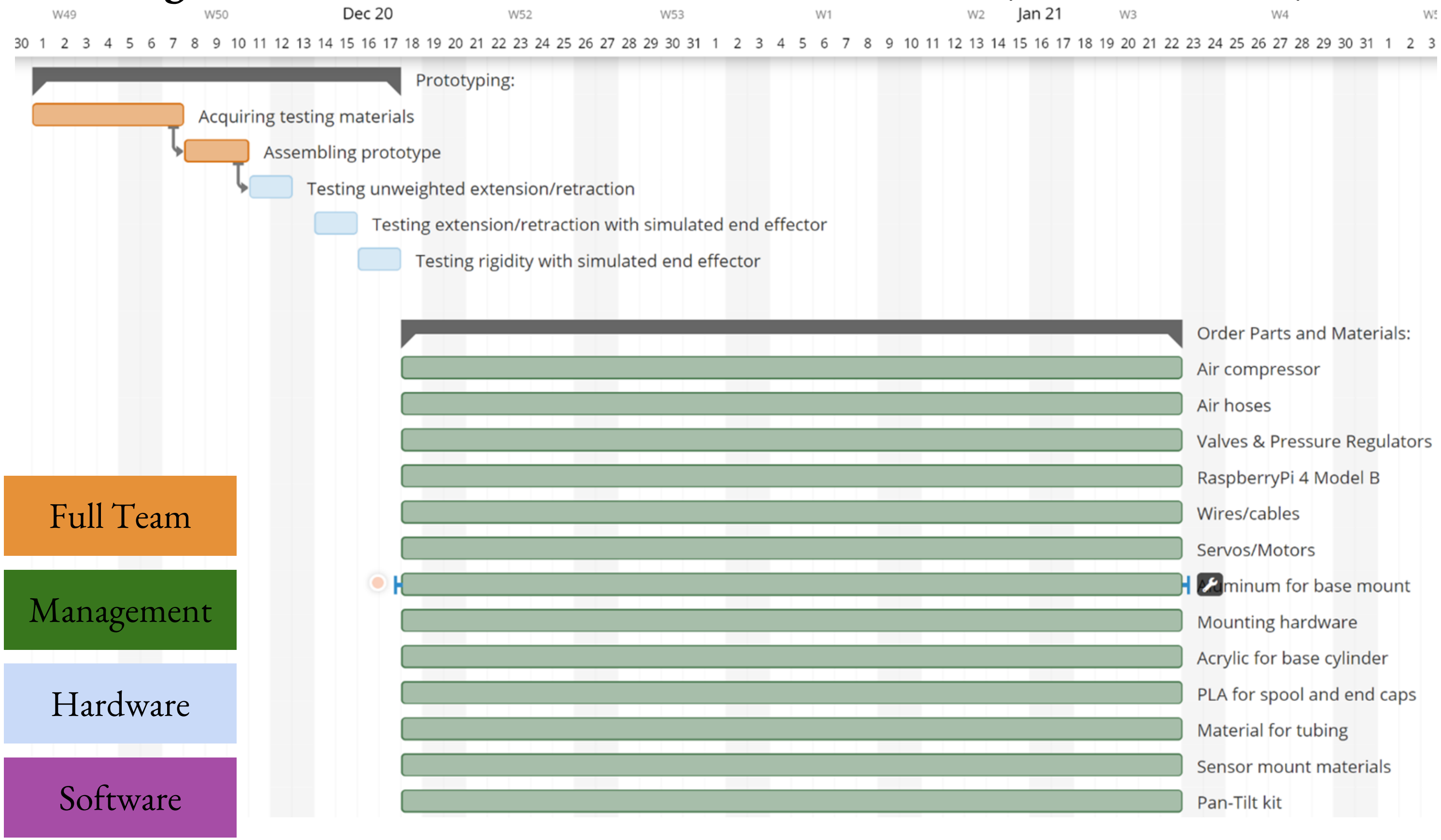
Project Planning: Work Plan - Critical Design Process (Oct. 20 - Dec. 7)



Back to Work Plan Overview

Back to the Directory

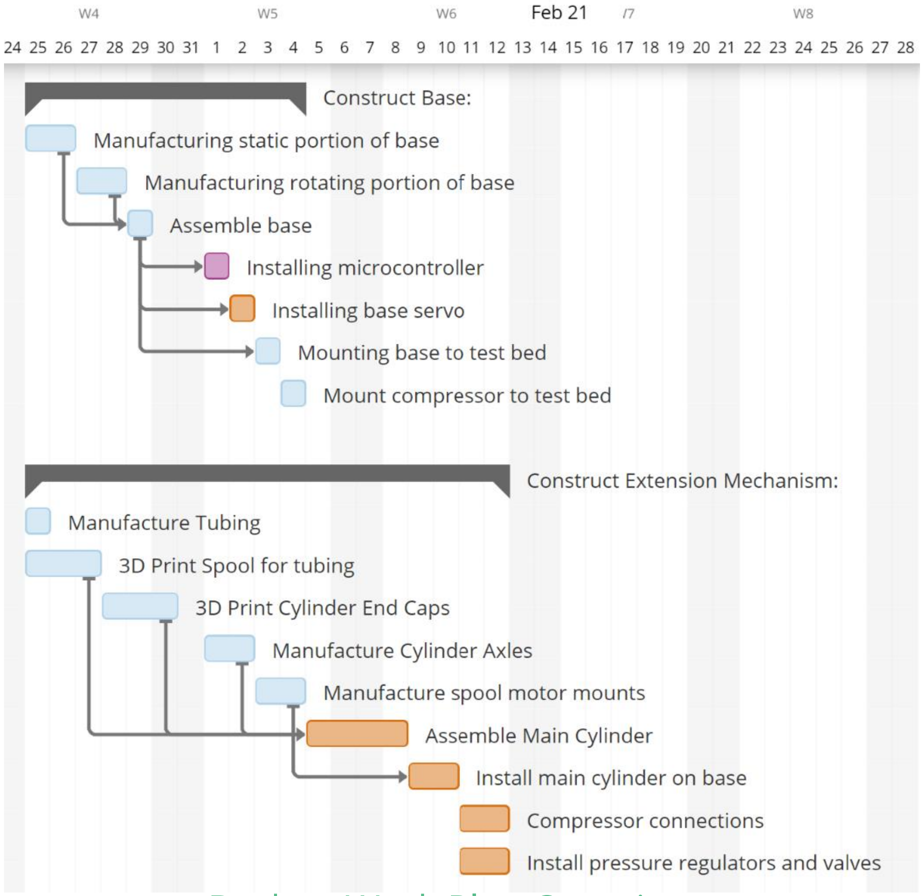
Project Planning: Work Plan - Post CDR & Winter Break (Dec. 1 - Jan 22)



Back to Work Plan Overview

Back to the Directory

Project Planning: Work Plan - Manufacturing Initiation (Jan.23 - Feb. 13)



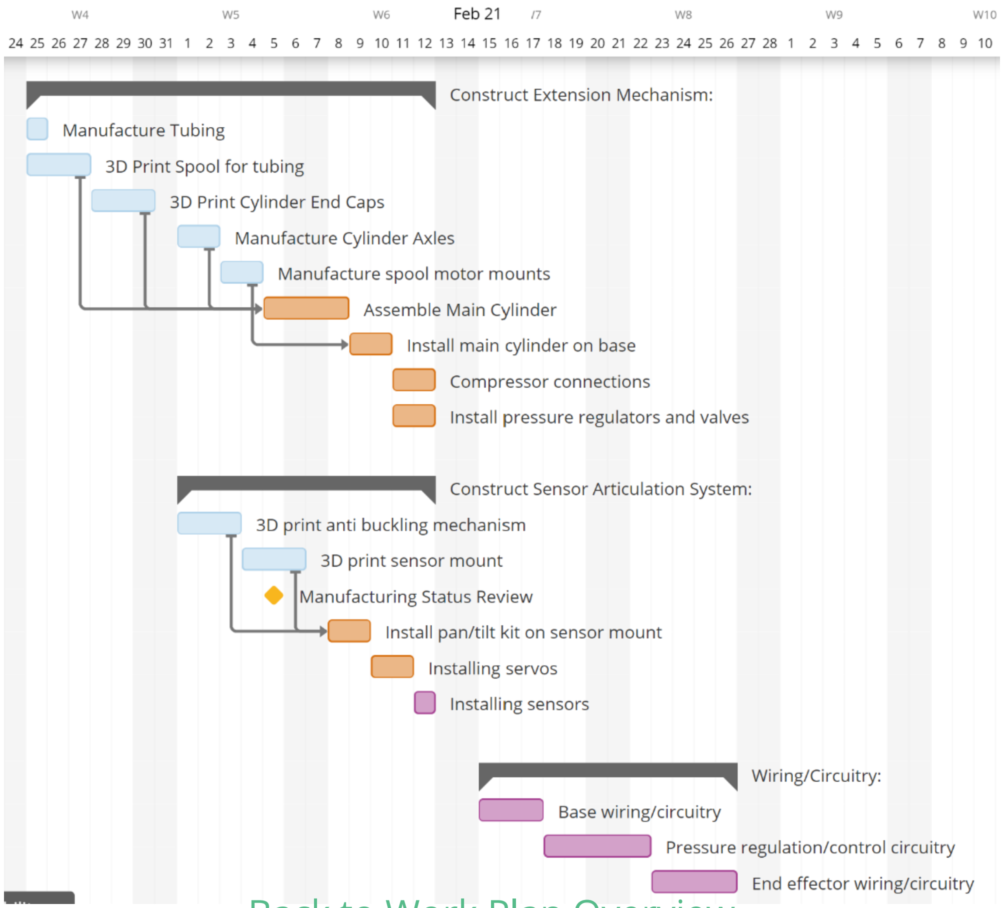
Full Team

Hardware

Software

Back to Work Plan Overview

Project Planning: Work Plan - Manufacturing Cont. (Jan. 23 - Feb. 26)



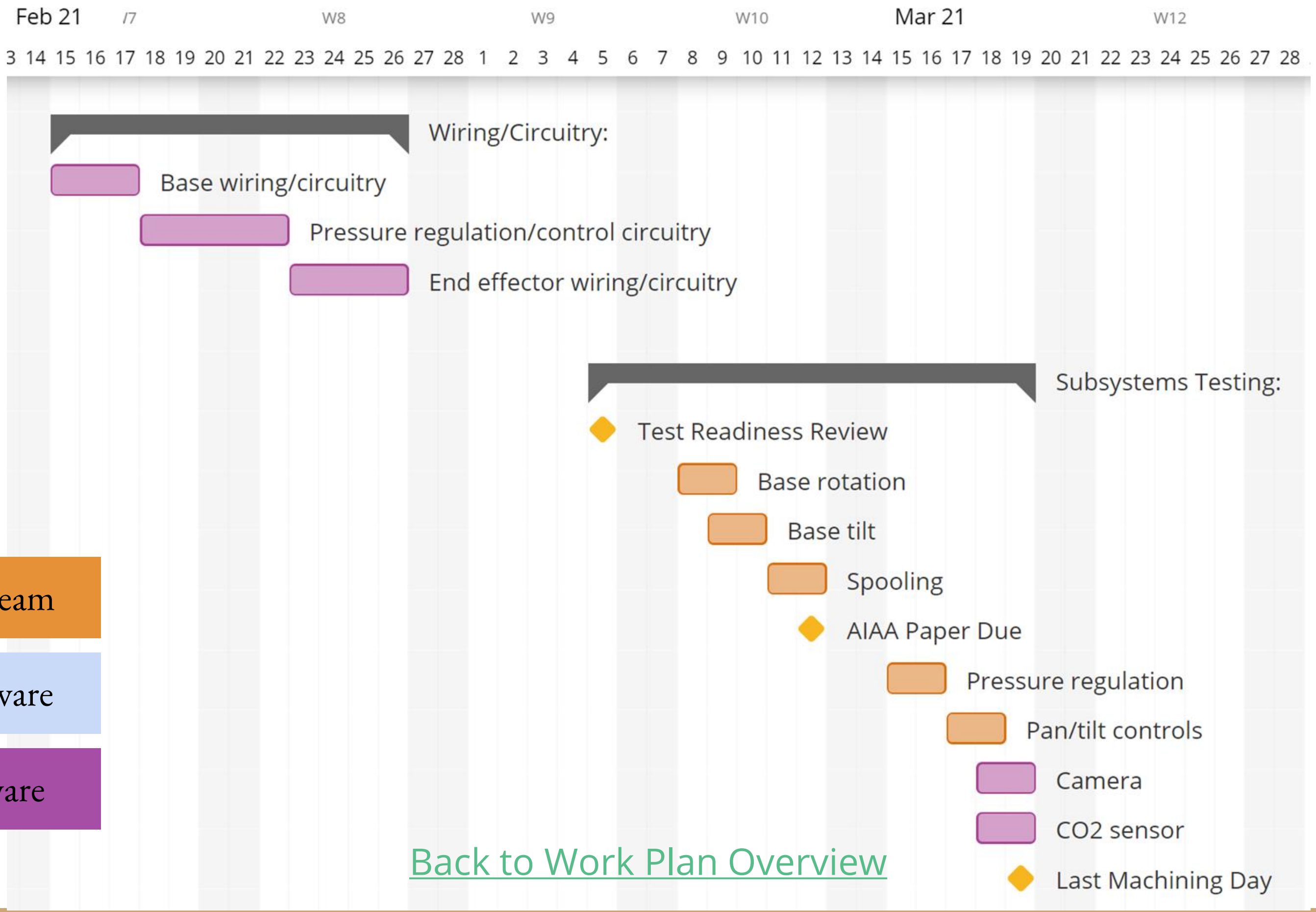
Full Team

Hardware

Software

Back to Work Plan Overview

Project Planning: Work Plan - Subsystems Testing (Mar. 5 - Mar. 19)



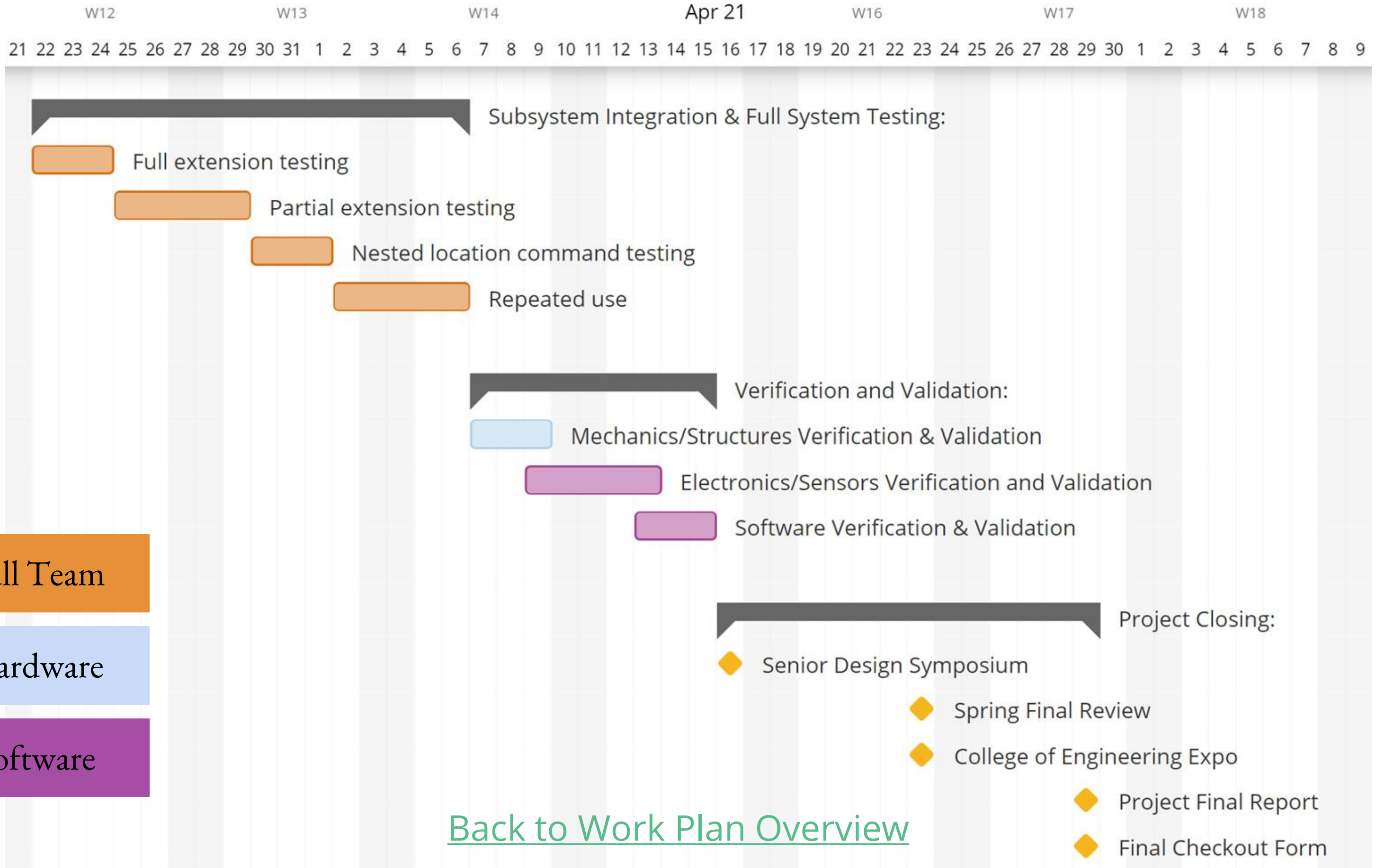
Full Team

Hardware

Software

Back to Work Plan Overview

Project Planning: Work Plan - Full System Testing, V & V, and Closing (Mar. 22 - Apr. 29)



Full Team

Hardware

Software

Back to Work Plan Overview

Requirements Satisfaction

Back to the Requirements Tree
Back to the Directory

Requirements satisfaction: Plastic Spool Extension

FRs	TDRs	Requirement	Functional Category
FR 2.1		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

Spooling Mechanism:

- Inner Spool Radius = 1.5cm
- Outer Spool Radius (includes thickness of all the layers of plastic tube) = 7.6 cm
- Average diameter = roughly 5 cm
- To reach 4 meters in 30 seconds (27 cm/s unspooling rate), we need an average spin rate of 103 RPM

Servo Choice: Parallax 900-00360

- 120 RPM
- Continuous rotation, incremental rates based on input voltage

Requirement	Design	Satisfaction	FOS
RESCUE will be able to reach 1-5 meters from MARBLE		✓	

Back to the Requirements Tree
Back to the Directory

Requirements satisfaction: Extension Mechanism, Electrical Power

FRs	TDRs	Requirement	Functional Category
FR 2.1		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

- **Spooling Mechanism:**
  - Inner Spool Radius = 2.5cm
  - 65 RPM for 17/cm extension
  - Assume 13.6 rad/s^2 (0.5 to 65 RPM)
  - 0.04 kg-cm required torque
  - HSR-2645CRH Servo continuous rotation servo
  - 72 RPM, 12 kg-cm at 7.4V
- **Twisting Issue:**
  - Taidacent 3 Wire 5A Slip ring

- **Wire Selection:**
  - Power/Ground For 1.15 A, Assuming 1.5 A for margin
  - 20 AWG, stranded conductor, bonded zip cord
  - ≈80g total for 15.15m

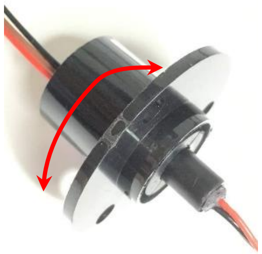


Figure 1: 5A, 22mm Slip Ring

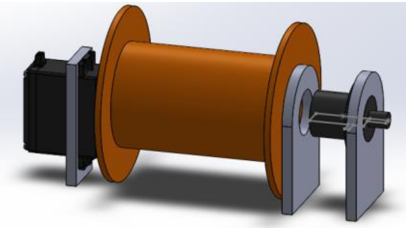


Figure 2: Base Power Wire Motorized Spool

Figure 3: Bonded Zip Wire, 20AWG

Requirement	Design	Satisfaction	FOS
RESCUE will be able to reach 1-5 meters from MARBLE		✓	

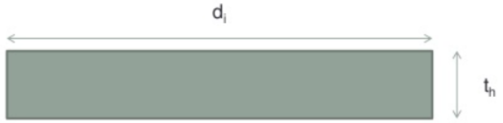
Back to the Requirements Tree

Back to the Directory

Requirements satisfaction: Extension Mechanism, Material Spool Container Cont.

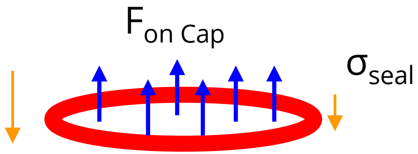
FRs	TDRs	Requirement	Functional Category
FR 2.1		RESCUE shall have the ability to physically reach a location along an unobstructed linear path that is at least 1 meter but not more than 5 meters away from RESCUE's stowing position on the MARBLE Clearpath Husky.	Physical Reach

- **End Caps:**
  - 9.375 in (23.8 cm) OD, 9 in (22.9 cm) ID Tube
- **Pressurization:**
  - 21 psi (144.8 kPa) - (7 psi (48.3 kPa) with a 3 FOS)
  - Cast Acrylic - 10,000 psi (64.8 MPa) yield tensile strength
  - t_h minimum = 0.77 cm
  - McMaster Cast Acrylic: 0.9525 cm., 10,000 psi (68.9 MPa) yield strength
  - 63.6 in^2 (410 cm^2) "Seal Area", 535 lbf (2.4 kN) force from pressure
  - $\sigma_{seal} \approx$ 250 psi (1724 kPa)
  - Glenmarc G5000 Epoxy: 7600 psi (52.4 MPa) tensile strength



- t_h = thickness of head
- d_i = inner dia of vessel shell
- p_i = design pressure, N/mm^2
- σ = allowable tensile stress, N/mm^2
- C = corrosion allowance

$$th = 0.7\,di\sqrt{\frac{Pi}{\sigma}} + C$$



Back to the Requirements Tree

Back to the Directory

Requirements satisfaction: Tension Line Extension

FRs	TDRs	Requirement	Functional Category
FR 2.1		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

Spooling Mechanism:

- Needs to spin to accommodate 4m/30s, or 13.3 cm/s
- HSR 2645CRH Servo: Variable rotation speeds
  - 7.4V = 72 RPM
  - 6.0V = 58 RPM
  - 4.8V = 46 RPM
- During testing, we can fine tune the servo rotation speed
- Spool average diameter = 3.5cm
  - This translates to roughly 72 RPM

Requirement	Design	Satisfaction	FOS
RESCUE will be able to reach 1-5 meters from MARBLE	4m	✓	N/A

Back to the Requirements Tree
Back to the Directory

Requirements satisfaction: Endurance

FRs	TDRs	Requirement	Functional Category
FR3.2		RESCUE shall withstand the environment of the DARPA subterranean challenge which is to be restricted to possible dust/mist and restricted temperatures.	Endurance: Environmental Hazard
	TDR3.2.1	RESCUE's mechanical and electrical components shall be able to function in a musty and/or dusty environment. mechanical and electrical components shall be able to function in a musty and/or dusty environment.	Endurance: Environmental Hazard
	TDR3.2.2	RESCUE shall accomplish all other design requirements in an nominal thermal environment of 50-65°F	Endurance: Environmental Hazard

Requirement	Design	Satisfaction	FOS
RESCUE is able to withstand the environment		✓	

Back to the Requirements Tree
Back to the Directory

Requirements satisfaction: Endurance

FRs	TDRs	Requirement	Functional Category
FR3.3		RESCUE shall have enough electrical power to maintain standby, active, and operational states fitting the MARBLE team's mission performance expectations.	Endurance: Power
	TDR3.3.1	RESCUE shall have enough electrical power to maintain a standby state for at least 135 minutes.	Endurance: Power
	TDR3.3.2	RESCUE shall have enough electrical power to maintain an operational state for at least 30 minutes.	Endurance: Power

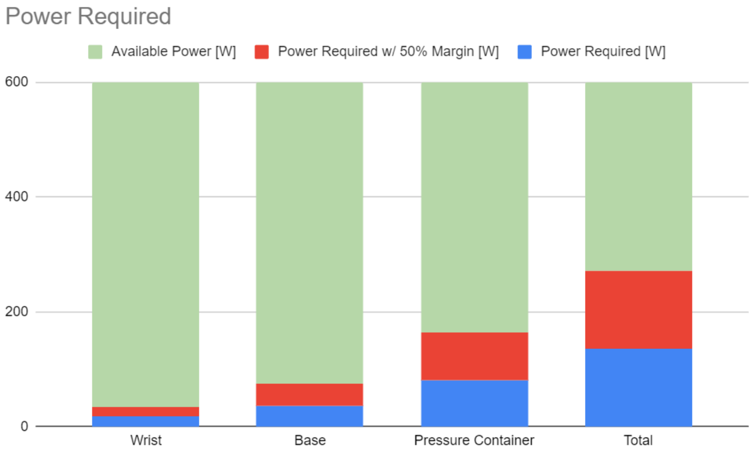
- **Components:**
  - All of the required electronics
- **Capability:**
  - MARBLE provides 24V at 25A for 600W available power
  - RESCUE requires 272.3W (including a %50 margin)

Requirement	Design	Satisfaction	FOS
RESCUE has enough power to operate for entire mission.	Voltage regulators and efficient electronics	✓	N/A

Back to the Requirements Tree
Back to the Directory

Requirements satisfaction: Endurance

FRs	TDRs	Requirement	Functional Category
FR3.3		RESCUE shall have enough electrical power to maintain standby, active, and operational states fitting the MARBLE team's mission performance expectations.	Endurance: Power
	TDR3.3.1	RESCUE shall have enough electrical power to maintain a standby state for at least 135 minutes.	Endurance: Power



Minimum of 135 minutes standby use

Total active power with a %50 margin is 272.3W at 135 minutes is 612.7Wh

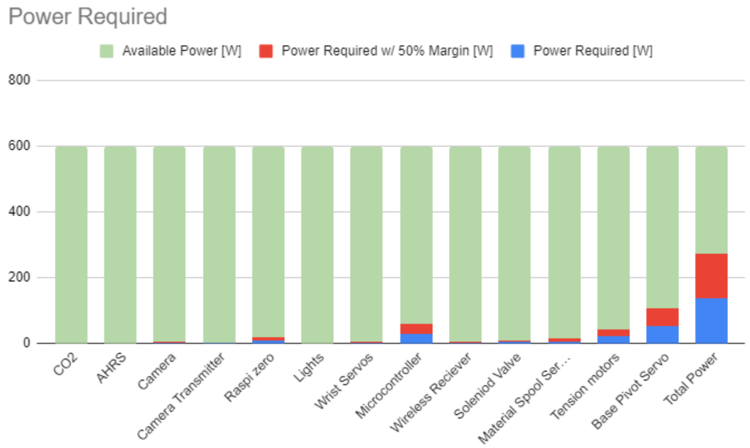
The standby power state will be <u><612.7Wh</u>

Requirement	Design	Satisfaction	FOS
RESCUE has enough power to operate for entire mission.	Less power is required in standby	✓	N/A

Back to the Requirements Tree
Back to the Directory

Requirements satisfaction: Endurance

FRs	TDRs	Requirement	Functional Category
FR3.3		RESCUE shall have enough electrical power to maintain standby, active, and operational states fitting the MARBLE team's mission performance expectations.	Endurance: Power
	TDR3.3.2	RESCUE shall have enough electrical power to maintain an operational state for at least 30 minutes.	Endurance: Power



Total active power with a %50 margin is 272.3W

Minimum of 30 minutes active use

136.2Wh required

Requirement	Design	Satisfaction	FOS
RESCUE has enough power to operate for entire mission.	System is not in active mode the whole time.	✓	N/A

Back to the Requirements Tree
Back to the Directory

Requirements satisfaction: IMU and Encoders

FRs	TDRs	Requirement	Functional Category
FR 4.1		RESCUE shall determine and report its location and orientation relative to the ground robot	System Position and Orientation
	TDR 4.1.1	RESCUE shall be able to determine its position relative to the ClearPath Husky within 1 meter accuracy of its ground truth location at all times	System Position and Orientation
	TDR 4.1.2	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

- **Components:**
  - IMU to determine orientation
  - Motor encoders to determine position

Requirement	Design	Satisfaction	FOS
RESCUE determines and reports it's local frame	IMU and base servos w/ encoders	✓	N/A

Back to the Requirements Tree
Back to the Directory

Requirements satisfaction: Encoders

FRs	TDRs	Requirement	Functional Category
FR 4.1		RESCUE shall determine and report its location and orientation relative to the ground robot	System Position and Orientation
	TDR 4.1.1	RESCUE shall be able to determine its position relative to the ClearPath Husky within 1 meter accuracy of its ground truth location at all times	System Position and Orientation

Incremental motor encoder much like the one encased in the spooling motor. https://ecatalog.dynapar.com/ecatalog/incremental-encoders/en/F15

Incremental Motor Encoder

- Returns rotational position of spooling motor
- Values are given relative to reference state
- Basic kinematics to convert to linear position:

$$\Delta L = \frac{1}{2}s = \frac{1}{2}r\theta$$

ΔL represents change in arm length,
s represents linear position,
r represents radius of the spool,
θ represents angular position

Encoder Precision

- Feedback signal frequency of 910 Hz
  - f = 910 signals/second
- Spline outer diameter of 5.96 mm
  - c = 1.872 cm
- Maximum RPM (with feedback) of 120 RPM
  - ω = 2 rotations/second
- Calculate maximum distance per signal:
  - $c \cdot \omega \cdot f \cong$ .00412 cm/signal
  - Accuracy of $4.12 \cdot 10^{-3}$ m

Requirement	Design	Satisfaction	FOS
≤ 1m precision	$4.12 \cdot 10^{-3}$ m precision	✓	N/A

Back to the Requirements Tree

Back to the Directory

"900-00360 Datasheet by Parallax Inc." *DigiKey Electronics*, Parallax Inc., 12 Sept. 2017, www.digikey.com/htmldatasheets/production/2483575/0/0/1/900-00360.html.

Requirements satisfaction: IMU

FRs	TDRs	Requirement	Functional Category
FR 4.1		RESCUE shall determine and report its location and orientation relative to the ground robot	System Position and Orientation
	TDR 4.1.2	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

Orientation range	360° about all axes
Orientation accuracy	±1.5° for dynamic conditions & all orientations
Orientation resolution	<0.08°
Orientation repeatability	0.085° for all orientations
Accelerometer scale	±2g / ±4g / ±8g / ±16g selectable
Accelerometer resolution	16 bit
Accelerometer noise density	90µg/√Hz
Accelerometer sensitivity	0.000061g/digit-0.000488g/digit
Accelerometer temperature sensitivity	±0.01%/°C

Requirement	Design	Satisfaction	FOS
RESCUE shall determine and report it's orientation wrt MARBLE	Inclusion of an IMU	✓	N/A

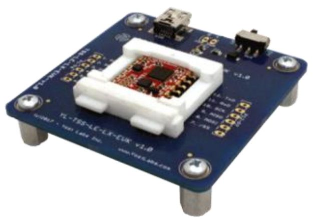


Figure 1: YOST Labs 3-Space™ Embedded LX Evaluation Kit

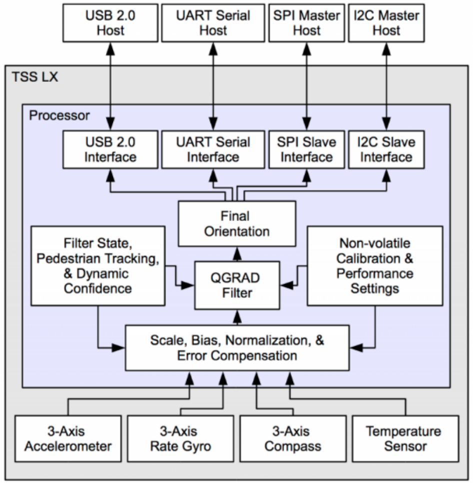


Figure 2: The filtration capabilities to correct for errors

Back to the Requirements Tree
Back to the Directory

Requirements satisfaction: Deployment Constraints

FRs	TDRs	Requirement	Functional Category
FR 5.1		When in its standby configuration, RESCUE shall be compatible with the MARBLE team's Clearpath Husky.	Deployment: Interference constraints
	TDR 5.1.1	When in its standby configuration, RESCUE shall not exceed a volume of 38 centimeters wide by 45 centimeters long by 30 centimeters tall.	Deployment: Interference constraints
	TDR 5.1.2	RESCUE shall not exceed a total mass of 10 kilograms	Deployment: Interference constraints
	TDR 5.1.3	If RESCUE is directly connected to the Husky, power drawn from the Husky robot shall be less than or equal to 24-30 Volts at 25 Amps.	Deployment: Interference constraints
	TDR 5.1.4	When RESCUE is deploying, in its active state, or in its operational state, the sensing apparatus shall not apply a force or moment that can unintentionally alter the position and/or orientation of or damage the MARBLE Clearpath Husky	Deployment: Interference constraints

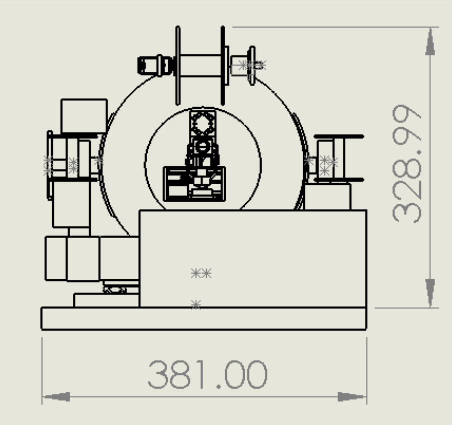
Requirement	Design	Satisfaction	FOS
RESCUE shall not interfere with MARBLE operation	Part selection and design based on volume, power, and mass constraints	✓	N/A

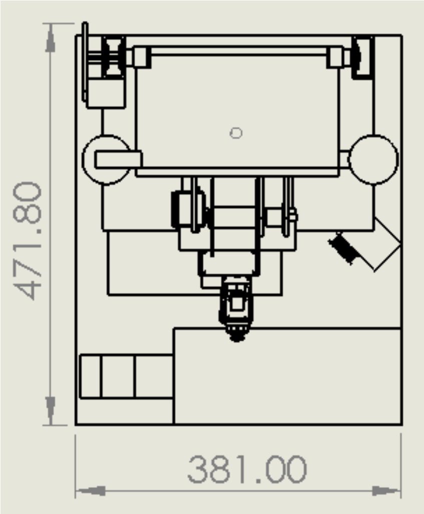
Back to the Requirements Tree
Back to the Directory

Requirements satisfaction: Volume Constraints

FRs	TDRs	Requirement	Functional Category
FR 5.1		When in its standby configuration, RESCUE shall be compatible with the MARBLE team's Clearpath Husky.	Deployment: Interference constraints
	TDR 5.1.1	When in its standby configuration, RESCUE shall not exceed a volume of 38 centimeters wide by 45 centimeters long by 30 centimeters tall.	Deployment: Interference constraints

Width: less than 38 cm
Length: 47.2 cm > 45 cm (out of the back side)
Height: 32.9 cm > 30 cm





Requirement	Design	Satisfaction	FOS
In standby RESCUE is compatible with MARBLE	Reconfiguration of components to ensure capability and volume requirements are met	X	N/A

Back to the Requirements Tree
Back to the Directory

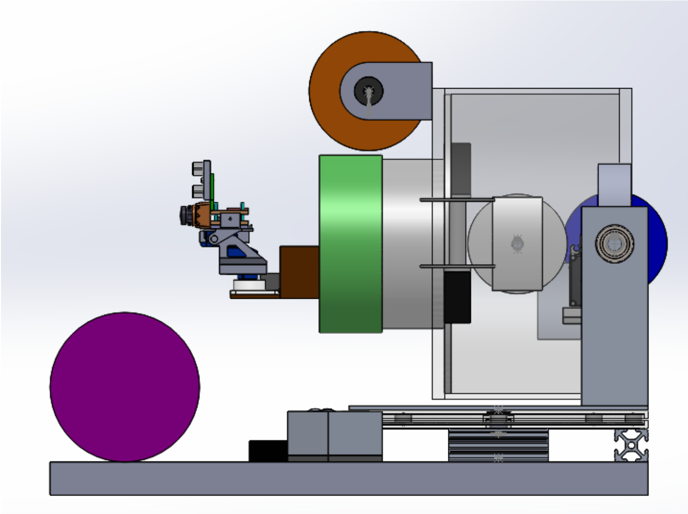
Requirements Satisfaction: Physical Reach

Hemispherical 4m physical reach

- Small obstructed section directly in front of the tube
- For straight horizontal extension, the end cap would
  Intersect the purple pressurized tank

Solution: 9 degree incline

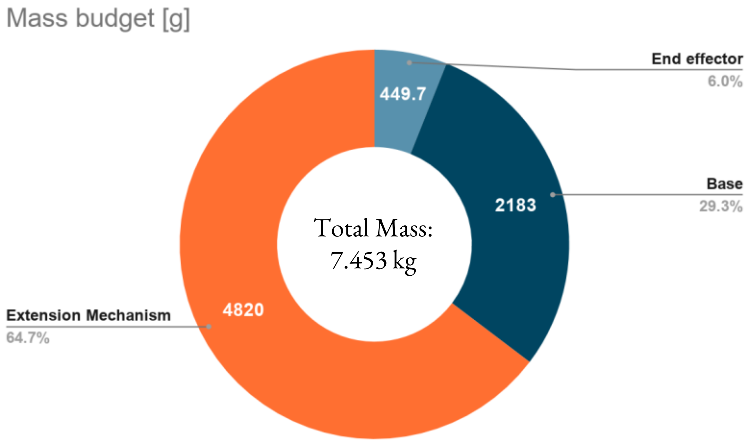
- 9.1 degree incline in this quadrant will put the tube over the pressure tank



Requirements satisfaction: Mass Constraints

FRs	TDRs	Requirement	Functional Category
FR 5.1		When in its standby configuration, RESCUE shall be compatible with the MARBLE team's Clearpath Husky.	Deployment: Interference constraints
	TDR 5.1.2	RESCUE shall not exceed a total mass of 10 kilograms	Deployment: Interference constraints

- Mass budget totals to 7.453 kg
- Allows margin for adjustments and additional components

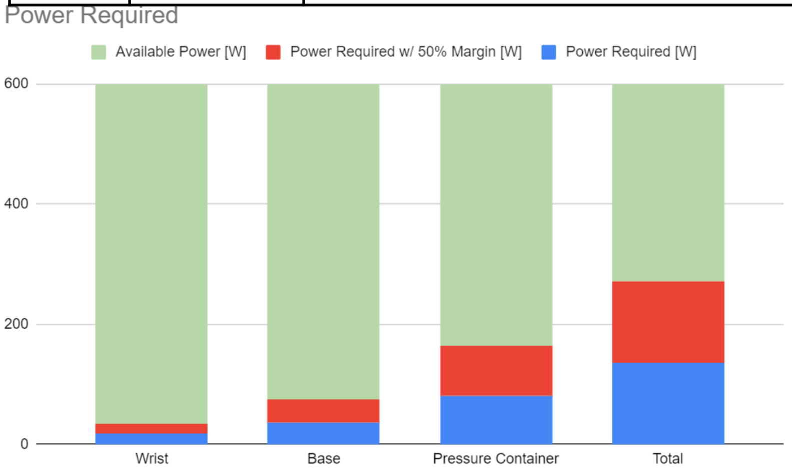


Requirement	Design	Satisfaction	FOS
10 kg or less	7.453 kg	✓	1.34

Back to the Requirements Tree
Back to the Directory

Requirements satisfaction: Power constraints

FRs	TDRs	Requirement	Functional Category
FR 5.1		When in its standby configuration, RESCUE shall be compatible with the MARBLE team's Clearpath Husky.	Deployment: Interference constraints
	TDR 5.1.3	If RESCUE is directly connected to the Husky, power drawn from the Husky robot shall be less than or equal to 24-30 Volts at 25 Amps.	Deployment: Interference constraints



- 600W Available from MARBLE
- Including a 50% margin, RESCUE uses 272.3 W

Requirement	Design	Satisfaction	FOS
RESCUE has enough power to operate for entire mission.	RESCUE uses less than the available power	✓	N/A

Back to the Requirements Tree
Back to the Directory

Requirements satisfaction: Interference Constraints

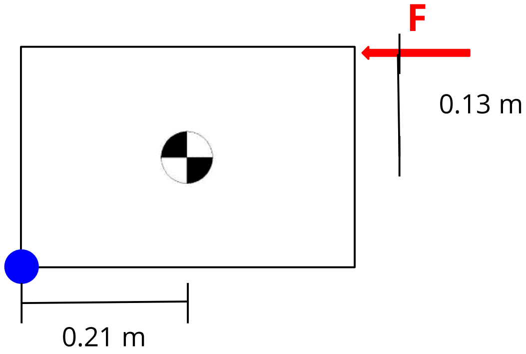
FRs	TDRs	Requirement	Functional Category
FR 5.1		When in its standby configuration, RESCUE shall be compatible with the MARBLE team's Clearpath Husky.	Deployment: Interference constraints
	TDR 5.1.4	When RESCUE is deploying, in its active state, or in its operational state, the sensing apparatus shall not apply a force or moment that can unintentionally alter the position and/or orientation of or damage the MARBLE Clearpath Husky	Deployment: Interference constraints

Counterclockwise Moment = Clockwise Moment

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

$$F_{needed\ to\ tip} = 792.346\ N$$

$$F_{full\ extension} = 39.24\ N$$



Requirement	Design	Satisfaction	FOS
In standby RESCUE is compatible with MARBLE	RESCUE will not be capable of tipping MARBLE	✓	20.19

Back to the Requirements Tree

Back to the Directory

Requirements satisfaction: Deployment time

FRs	TDRs	Requirement	Functional Category
FR 5.2		RESCUE's deployment operations shall be rapid enough to incur a minimal time cost to MARBLE's total mission time.	Deployment: Time
	TDR 5.2.1	Upon receiving a command from the MARBLE team when RESCUE is in an active or operational state, RESCUE shall respond as soon as the command is received (within 2 seconds).	Deployment: Time
	TDR 5.2.2	Upon receiving a deactivation command from the MARBLE team, the system shall return from its operational/active configuration to its standby configuration within 120 seconds.	Deployment: Time

Requirement	Design	Satisfaction	FOS
RESCUE's deployment time is minimal.	Servos and electronics were chosen to ensure rapid deployment	✓	N/A

Back to the Requirements Tree
Back to the Directory

Requirements satisfaction: Deployment time

FRs	TDRs	Requirement	Functional Category
FR 5.2		RESCUE's deployment operations shall be rapid enough to incur a minimal time cost to MARBLE's total mission time.	Deployment: Time
	TDR 5.2.1	Upon receiving a command from the MARBLE team when RESCUE is in an active or operational state, RESCUE shall respond as soon as the command is received (within 2 seconds).	Deployment: Time

- **Components:**
  - Gigabit ethernet connection.
- **Purpose:**
  - To ensure rapid communication with MARBLE.
- **Capability:**
  - Less than 1 ms ping between MARBLE and RESCUE

Requirement	Design	Satisfaction	FOS
RESCUE's deployment time is minimal.	Gigabit ethernet connection between RESCUE and MARBLE	✓	N/A

Back to the Requirements Tree
Back to the Directory

Requirements satisfaction: Deployment time

FRs	TDRs	Requirement	Functional Category
FR 5.2		RESCUE's deployment operations shall be rapid enough to incur a minimal time cost to MARBLE's total mission time.	Deployment: Time
	TDR 5.2.2	Upon receiving an deactivation command from the MARBLE team while, the system shall return from its operational/active configuration to its standby configuration within 120 seconds.	Deployment: Time

- **Components:**
  - Rapid movement servos on the spool and base.
- **Purpose:**
  - To ensure RESCUE is able to augment MARBLE's mission rather than be a detriment.
- **Capability:**
  - Rotation rates up to 120 RPM

Requirement	Design	Satisfaction	FOS
RESCUE's deployment time is minimal.	Servos were chosen to ensure rapid deployment	✓	N/A

Back to the Requirements Tree
Back to the Directory

Requirements satisfaction: FR6.1

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

Requirement	Design	Satisfaction	FOS
RESCUE shall be able to communicate with MARBLE without interference	Use of ROS nodes, gigabit ethernet, and different wireless channels for comms	✓	N/A

Back to the Requirements Tree
Back to the Directory

Requirements satisfaction: FR6.1

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

ROS Framework

- Nodes subscribe and publish to 'topics'
  - e.g. **location_command**, **image_data**, **servo_control**
- Standardized message formats and extensive packages
- ROS package will be designed to accommodate all expected message types
  - Specifically firing commands

Requirement	Design	Satisfaction	FOS
RESCUE shall be able to receive firing commands from MARBLE	RESCUE node will be subscribed to MARBLE ROS location_command topic	✓	N/A

Back to the Requirements Tree
Back to the Directory

Requirements satisfaction: FR6.1

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

Software architecture

- Checks to ensure that transmission is complete before redeployment
- Written in C++
  - Low-level, compiler optimization, asynchronous execution capabilities
  - Extensive compatibility & documentation within ROS

Requirement	Design	Satisfaction	FOS
RESCUE shall be able to communicate sensing data with MARBLE within 60s	Use of C++ to create ROS nodes and topics that will publish sensor data	✓	N/A

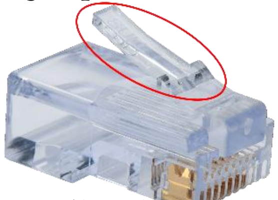
Back to the Requirements Tree
Back to the Directory

Requirements satisfaction: FR6.1

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 6.1.3	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

Gigabit Ethernet attachment

- 400 Mbit/s available
- Built-in locking clip to ensure a secure connection



libertycable.com

Off-ramp: USB 3.0 Type A

- Higher data rate capability
- Less secure connection
  - No locking clip
  - Requires adapters

Requirement	Design	Satisfaction	FOS
RESCUE shall be able to transmit data to MARBLE via wired connection	Use of a Gigabit Ethernet cable	✓	N/A

Back to the Requirements Tree
Back to the Directory

Requirements satisfaction: FR6.1

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 6.1.4	RESCUE shall deliver frequent status reports to the MARBLE robot regarding deployment status and data collection	Communications

Status reports designed into ROS package

- **status_ping_marble** and **status_ping_rescue** topics
  - Former is published by MARBLE for RESCUE to subscribe to
  - Latter is published by RESCUE for MARBLE to subscribe to
- Status report frequency will be determined by testing
  - Likely sent for every 'event' in system procedure

Requirement	Design	Satisfaction	FOS
RESCUE shall report status on deployment and data collection	Establish a ROS topic that will be publish with RESCUE status	✓	N/A

[Back to the Requirements Tree](#)
[Back to the Directory](#)

Risk Management

Risk management: Less Significant Risks (Pre-Mitigation)

Risk	Subsystem(s) at Risk	Original Severity	Original Probability	Original Risk Level	Mitigation Strategy
Wiring Disconnections	Sensors, Software	Intolerable	Very Unlikely	Medium 5	Fasteners and tape designed to secure the electrical cables.
Pressure Tube Disconnections	Structures, Hardware	Intolerable	Very Unlikely	Medium 5	Use of nuts that secure connections and include silicone o-rings to prevent leakage.
Tank Failure	Structures, Hardware	Intolerable	Very Unlikely	Medium 5	Use of epoxy to seal the tank and rigorous testing to ensure all seals are maintained.
System Leaking	Structures, Hardware	Intolerable	Very Unlikely	Medium 5	Rigorous testing to ensure all seals can withstand repeated pressurization, extension and retraction.

Risk management: Less Significant Risks (Pre-Mitigation)

Risk	Subsystem(s) at Risk	Original Severity	Original Probability	Original Risk Level	Mitigation Strategy
Spool & Pressure Desynchronization	Hardware	Tolerable	Unlikely	Medium 4	Verify valve will expel any extra pressure.

Risk management: Risk Matrix Ranking

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

Risk management: Less Significant Risks (Post-Mitigation)

Risk	Subsystem(s) at Risk	New Severity	New Probability	New Risk Level
Wiring Disconnections	Sensors, Software	Undesirable	Very Unlikely	Medium 3
Pressure Tube Disconnections	Structures, Hardware	Undesirable	Very Unlikely	Medium 3
Tank Failure	Structures, Hardware	Undesirable	Very Unlikely	Medium 3
System Leaking	Structures, Hardware	Undesirable	Very Unlikely	Medium 3

Risk management: Less Significant Risks (Post-Mitigation)

Risk	Subsystem(s) at Risk	New Severity	New Probability	New Risk Level
Spool & Pressure Desynchronization	Hardware	Acceptable	Unlikely	Low 2