Critical Design Review

SIERRA NEVADA CORPORATION

University of Colorado Boulder

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Outline

- Project Overview
  - Purpose and Objectives
  - Design Solution
  - Critical Project Elements
- Design Requirements
  - Overview
  - Satisfaction
- Project Management
  - Risks
  - Verification and Validation
  - Project Planning

Section 1

Project Overview

Purpose and Objectives

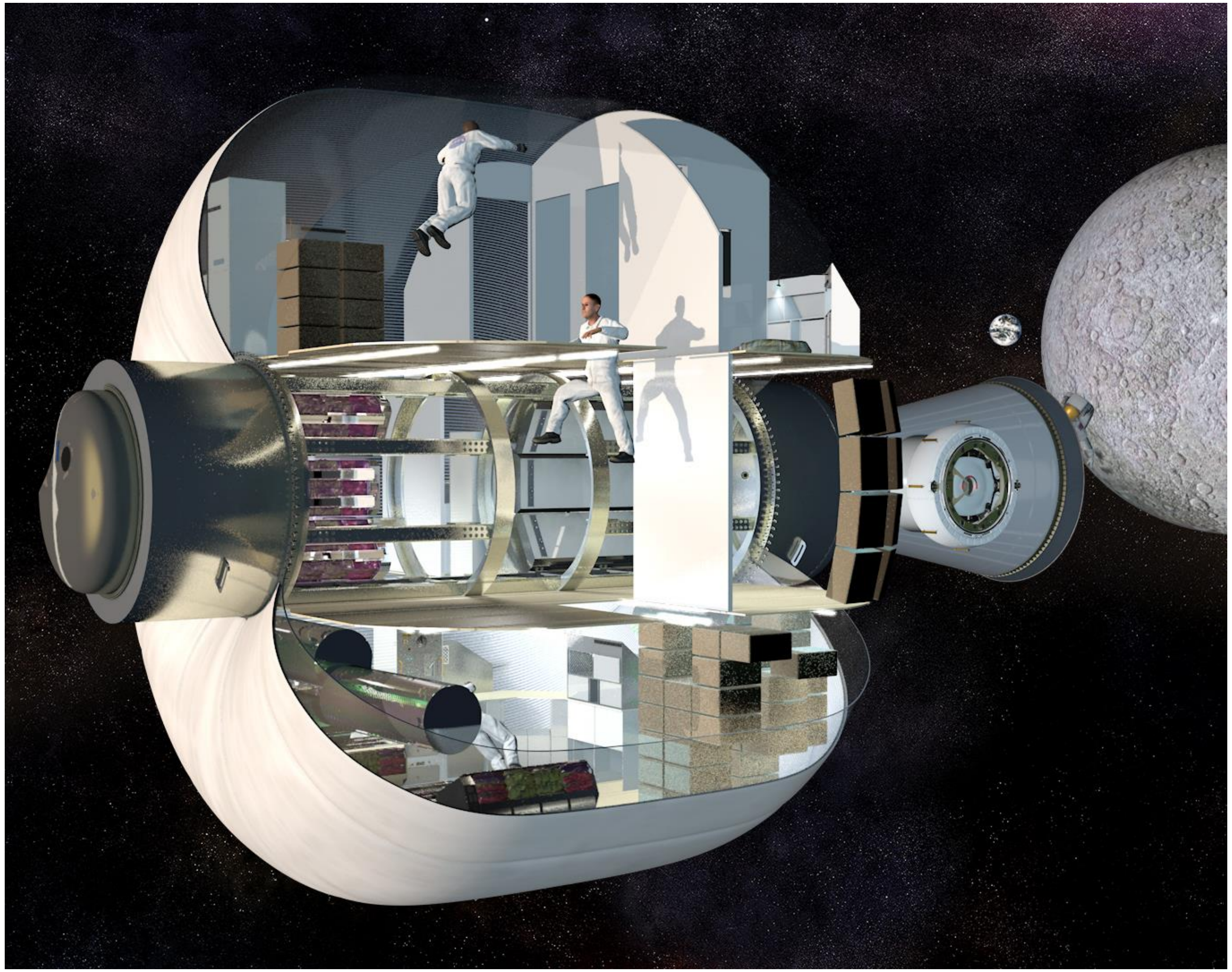
Design Solution

Critical Project Elements

Purpose and Objectives

Mission Context

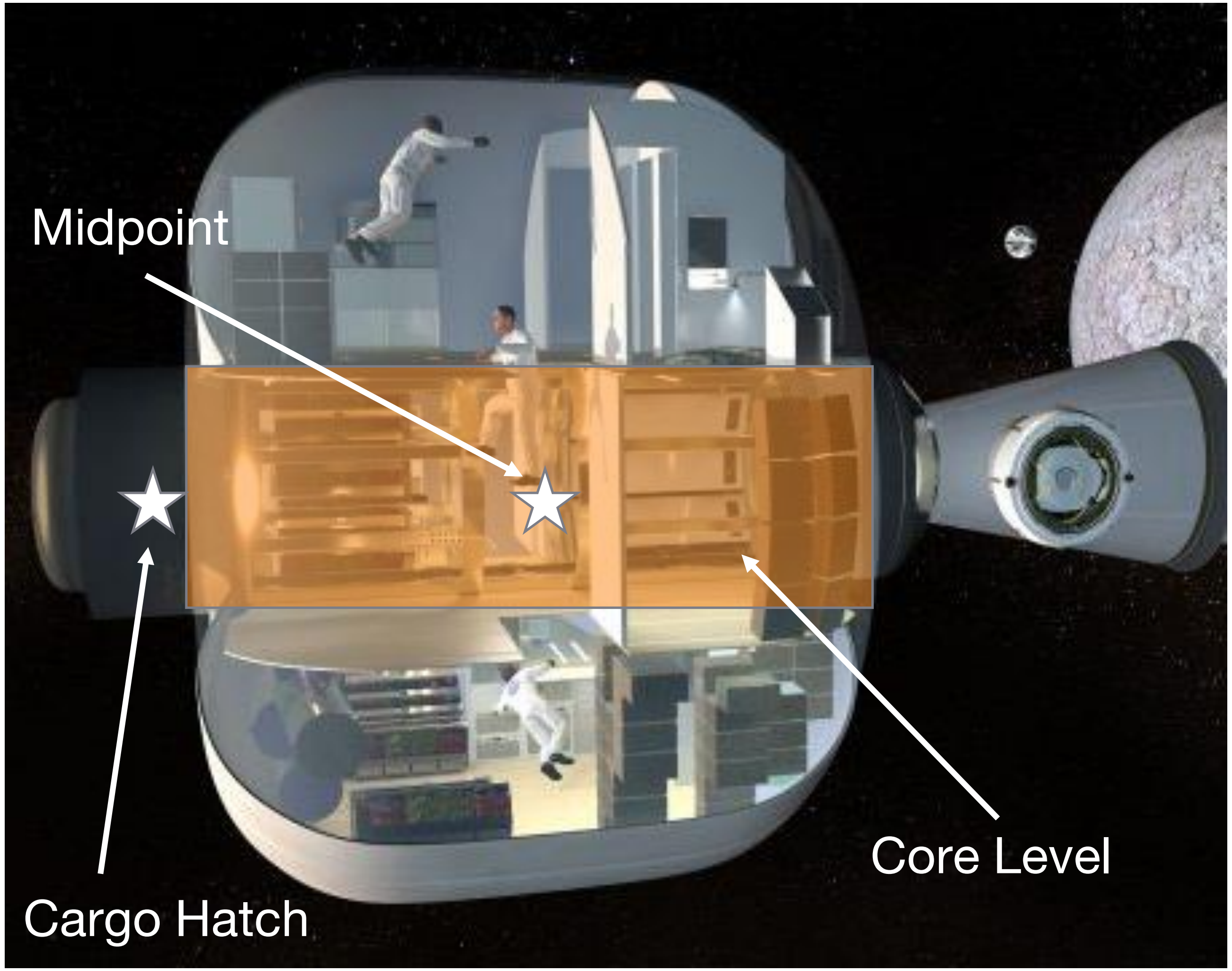
- SNC's inflatable LIFE™ Habitat is designed for deep space habitation
- Cargo will arrive **prior** to crew arrival
- **Need:** Use robotics to unload and transport cargo in the habitat without crew
- Derivative of NASA's need for a remote IVR system



RIVeR

Focus Area

- Simplified to one level of the habitat – Core
- Demonstrate transport from cargo hatch to midpoint
- **Assumptions:**
  - Bags are waiting at the opening of the cargo hatch (separate IVR system prior to our process)
  - The environment is pressure and temperature controlled



NASA Applicable Requirements

- Summary of the requirements given by NASA for an IVR system
- Simplified versions of these requirements were adapted for this project

ID	Requirement
L3-HAB-0196	The HAB shall provide the ability to access and service designated internal payloads and logistics without the need for crew intervention.
L3-HAB-0142	The HAB shall provide interfaces to enable internal robotic inspection, mobility, and dexterous manipulation.
L3-HAB-0145	The HAB shall provide a method for determining and communicating internal location information that is common to internal robotics and human operators (crew and ground).
L3-HAB-0312	The HAB shall use robotically compatible interfaces to allow the IVR system to access/retrieve/install internal logistics cargo.

Mission Statement

RIVeR will prove the feasibility of using Intra-Vehicular Robotics (IVR) to identify and distribute cargo bags within Sierra Nevada's LIFE™ Habitat to demonstrate task management in an uncrewed environment.

CONOPS

Stage 1: Capture

A) Identify a cargo bag and return location coordinates

B) Position arm to attach to bag

C) Engage magnetic end effector

D) Rotate to required pose

Stage 2: Translation

A) Begin motorized translation

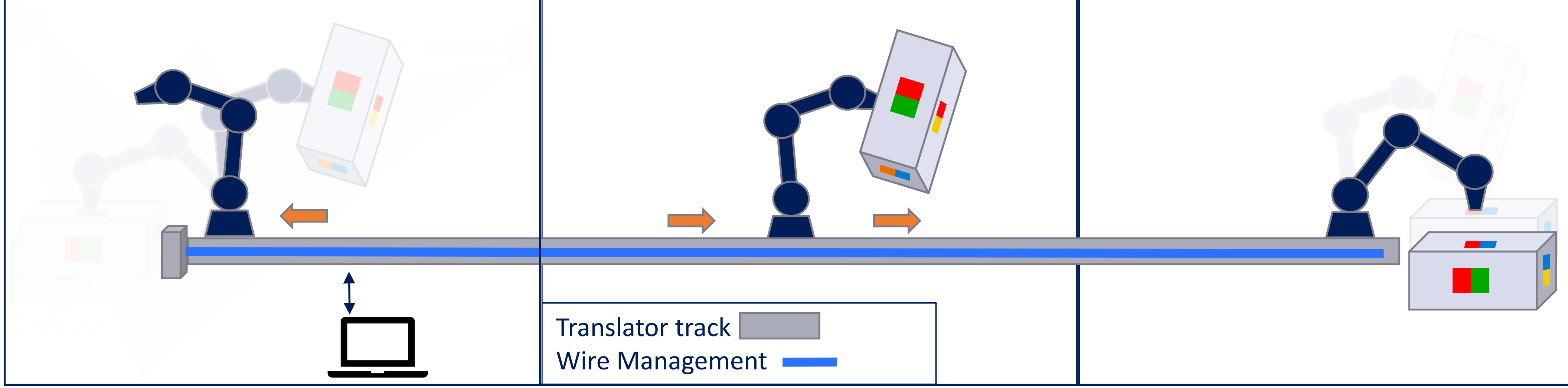
B) Stop translation at drop off location

Stage 3: Release

A) Rotate to drop off pose

B) Disengage end effector

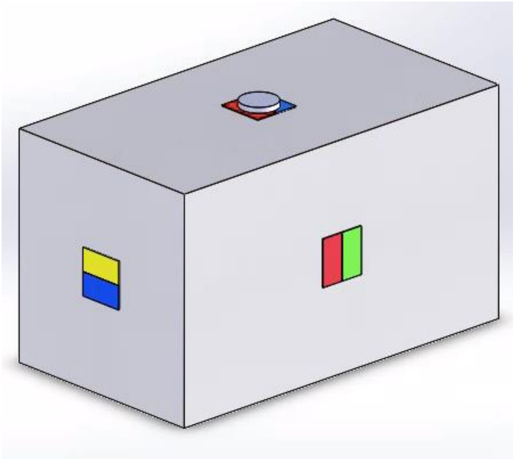
C) Return to origin and restart process



Design Solution

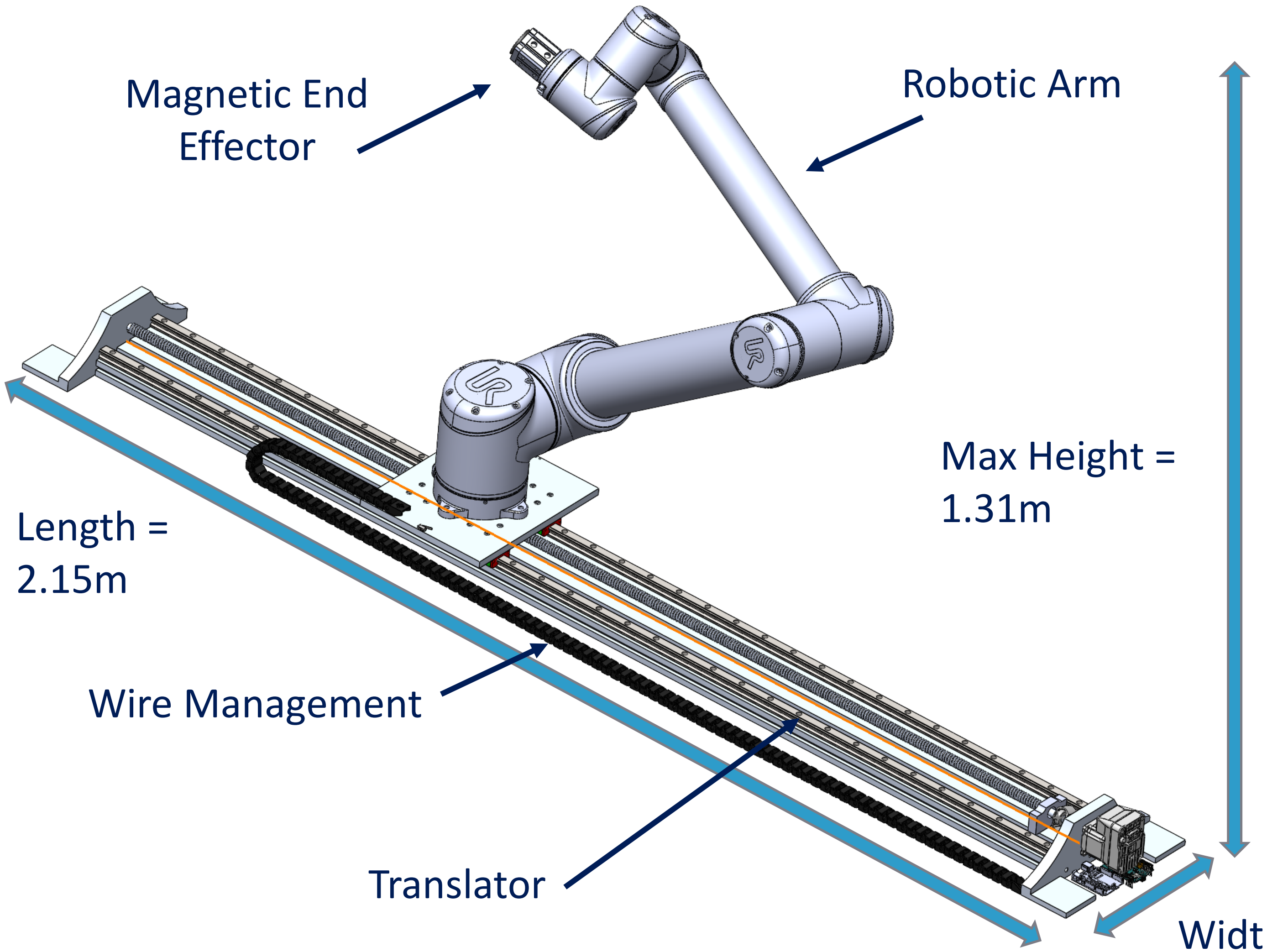
Design Overview

Image Recognition Sensor (x10)



Cargo Transfer Bag Model

Overall Mass	94 kg

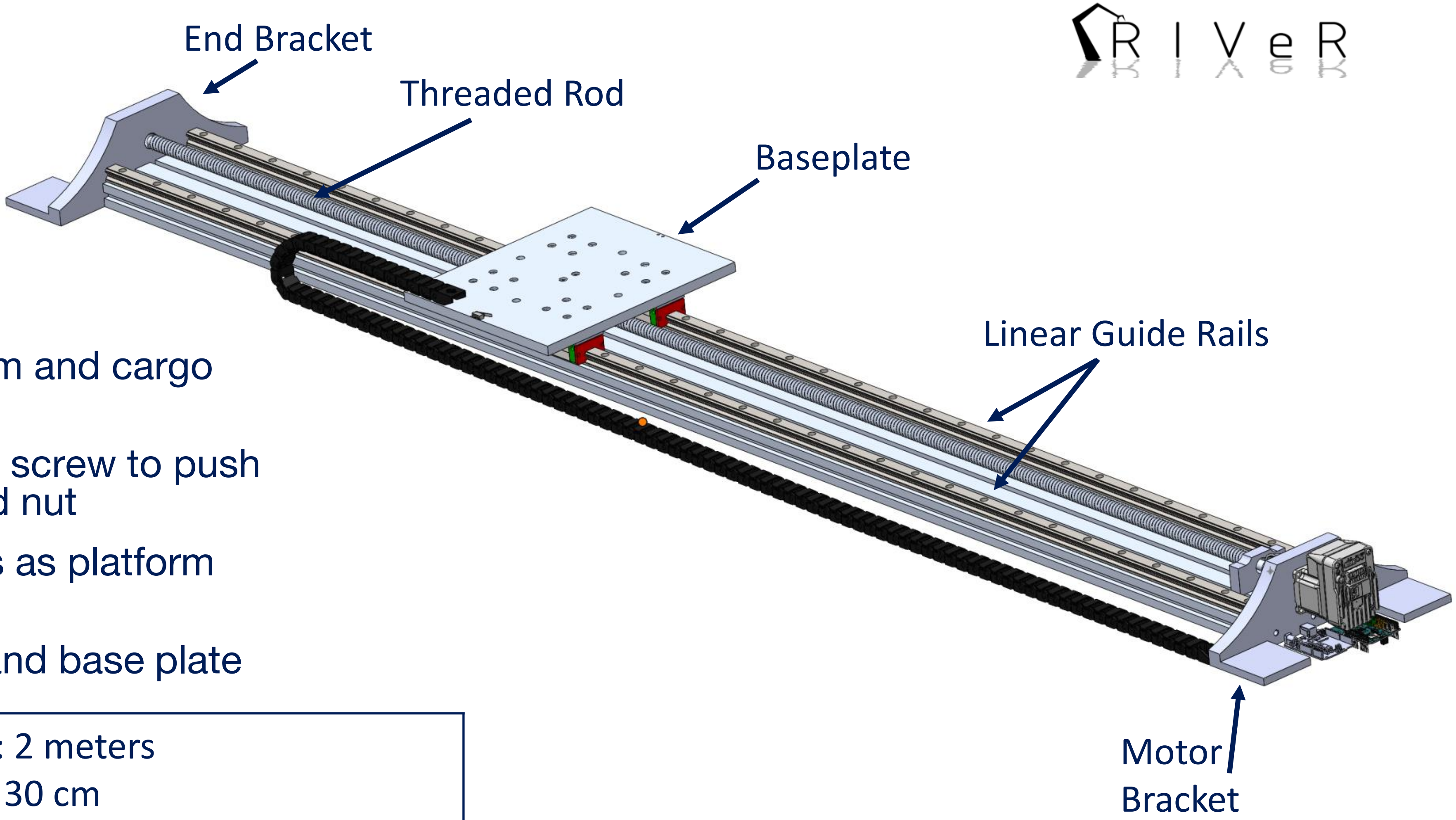


Robotic Arm

- UR10e from Universal Robots and acquired by SNC
- Command Input: Joint trajectory data generated by motion planner in ROS
- Includes force sensor
  - Force (x,y,z) up to 100N
  - Torque (x,y,z) up to 10Nm

Dimensions	Max Reach: 1.3m Footprint: 19cm
Mass	33.5 kg
Power Requirements	Arm: Max: 615W Avg: 350W Control Box: 24V 2A
Max Load	10 kg
Max Motor Speed	Joint size 2,3: 180 deg/sec Joint size 4: 120 deg/sec

Translator

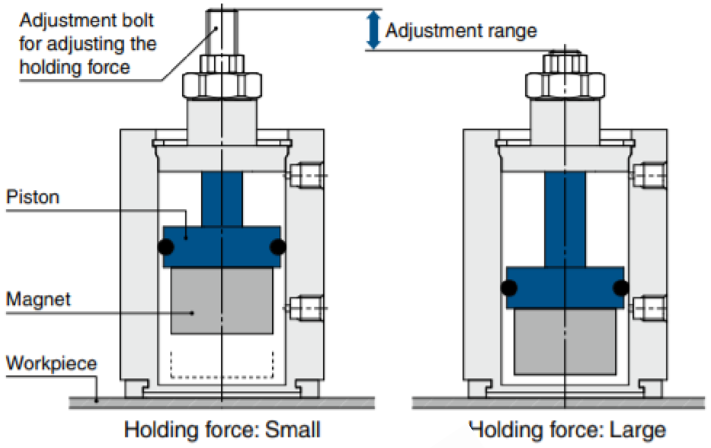


- Purpose: Move the robotic arm and cargo along the core
- A stepper motor rotates a ball screw to push baseplate attached to the lead nut
- Cable track neatly holds wires as platform moves
- Manufacturing end brackets and base plate

Dimensions	Length: 2 meters Width: 30 cm
Mass	60kg
Power Requirements	24V/3A/72W

End Effector Assembly

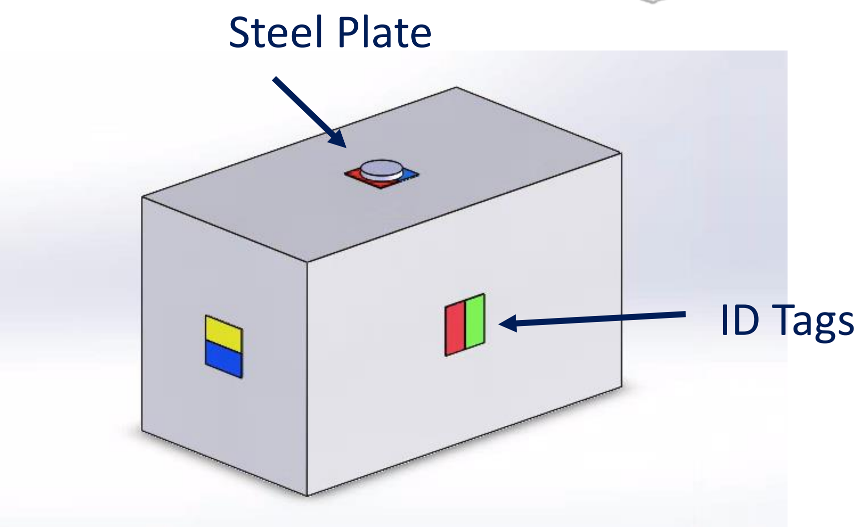
- SMC MHM-32 Magnetic Gripper
- Uses compressed air to actuate a magnetic piston
- All components procured from SMC



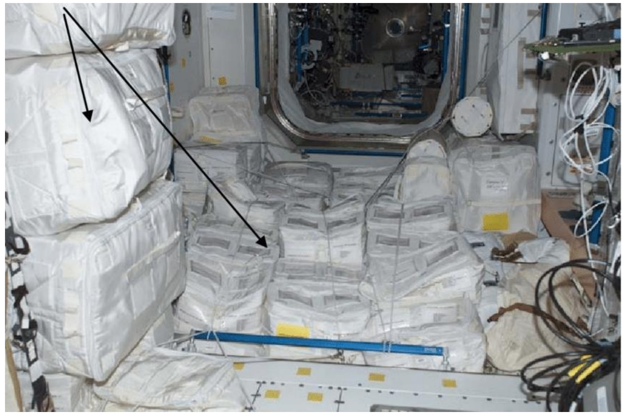
Dimensions	50mm x 50mm x 63mm
Mass	483 g
Power Requirements	1.92 W (for two Programmable Logic Controllers)
Holding Force	500 N
Operating Air Pressure	29-87 psi

Bag Design

- NASA's Cargo Transport Bag
  - In process of acquiring a real bag from NASA Hunch
- Steel plate for magnetic attachment
- Color ID tags for image recognition
- Initial testing with cardboard prototype
  - Gradually increase fidelity of bag model



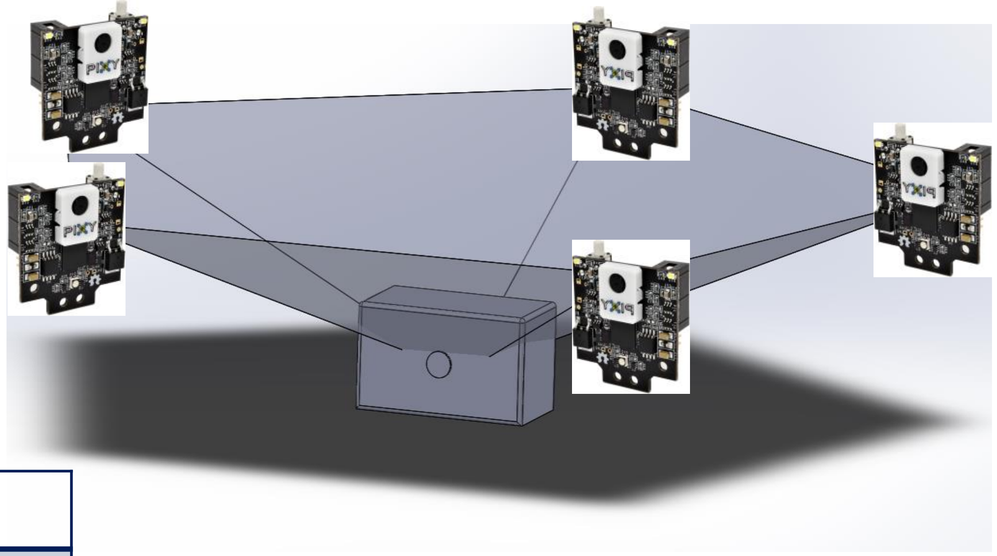
Bag Dimensions	41 cm x 23 cm x 24 cm
Mass	Max 1 kg
Material	PVC/Vinyl, Polyethylene, Polyurethane
Plate Dimensions	40 [mm] Diameter
Plate Material	409 Steel



CTB Stored on the ISS

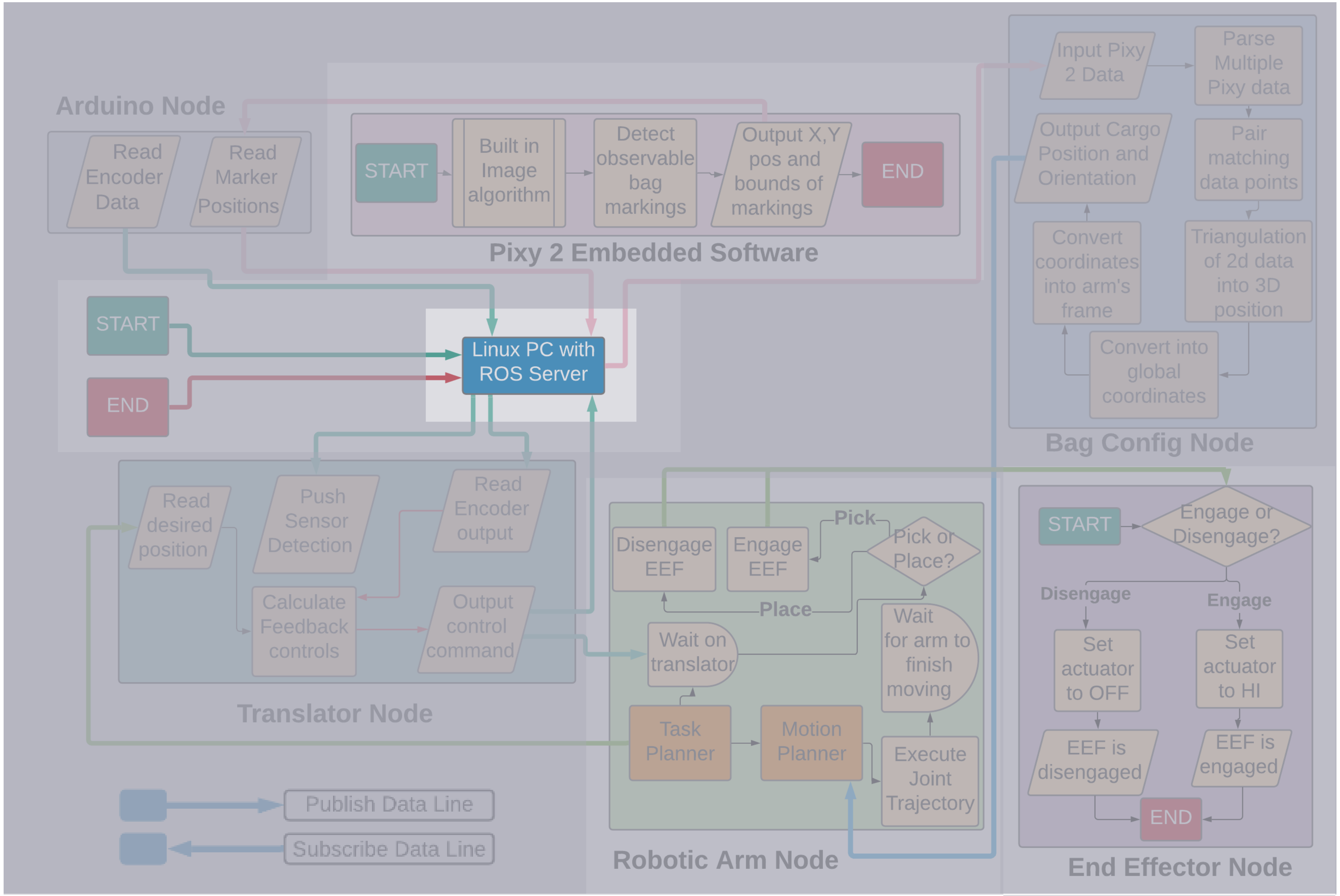
Sensing and Identification

- Object Recognizing Pixy2 Cameras
- Orientation Determination
  - 3+ bag faces & 2+ images of each face
  - 4+ cameras to determine all possible orientations
- Pentagonal-Pyramidal configuration
  - 4 for capture location
  - 5 for release location
- 1 Camera Facing Translator



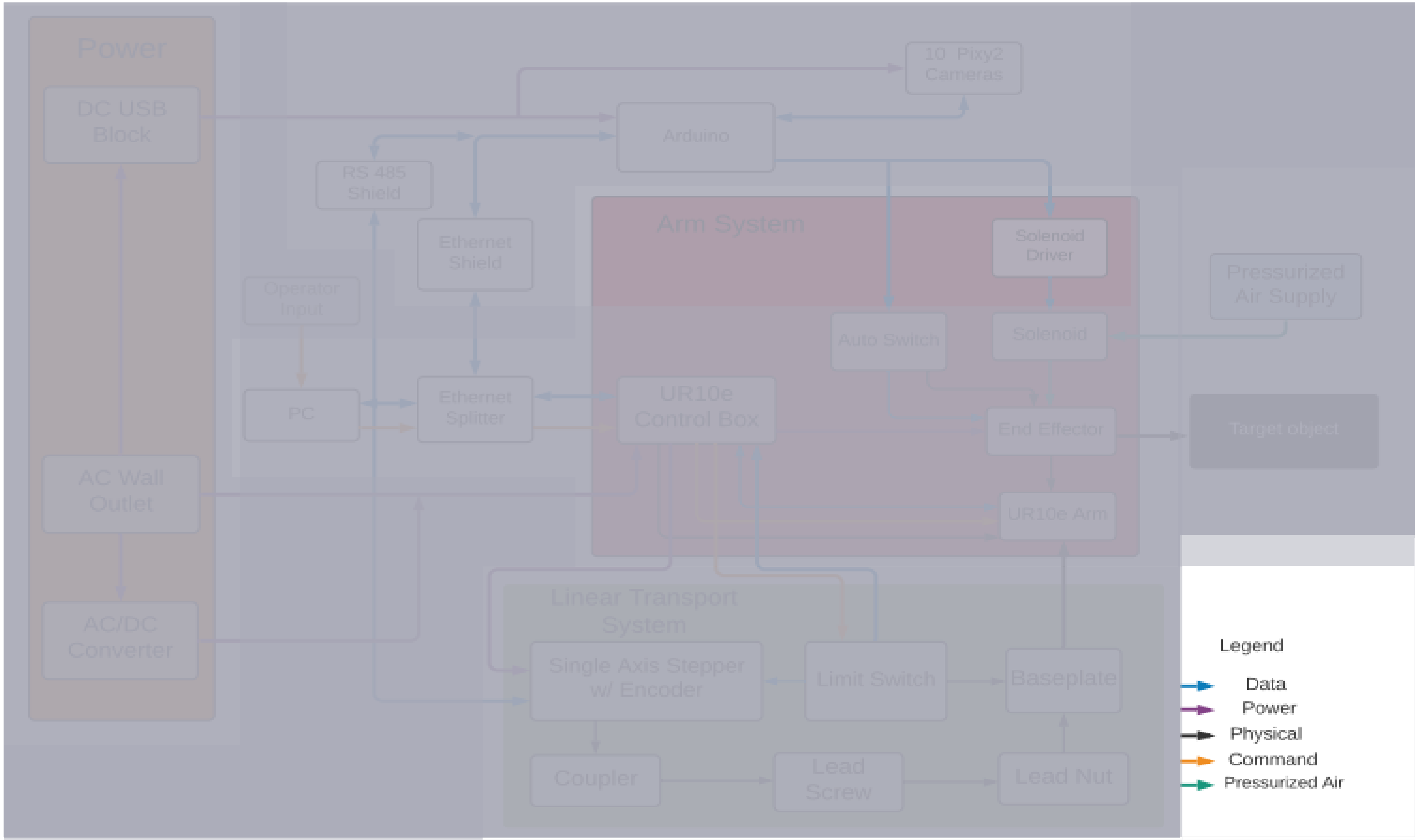
Dimensions	43mm x 39mm x 16mm
Mass	10g
Power Requirements	5V / 140mA / 3.5W
Quantity	10
Sample Rate	100 detections per frame at 60fps
Accuracy	≈ 3 – 10%

Software Flow Chart

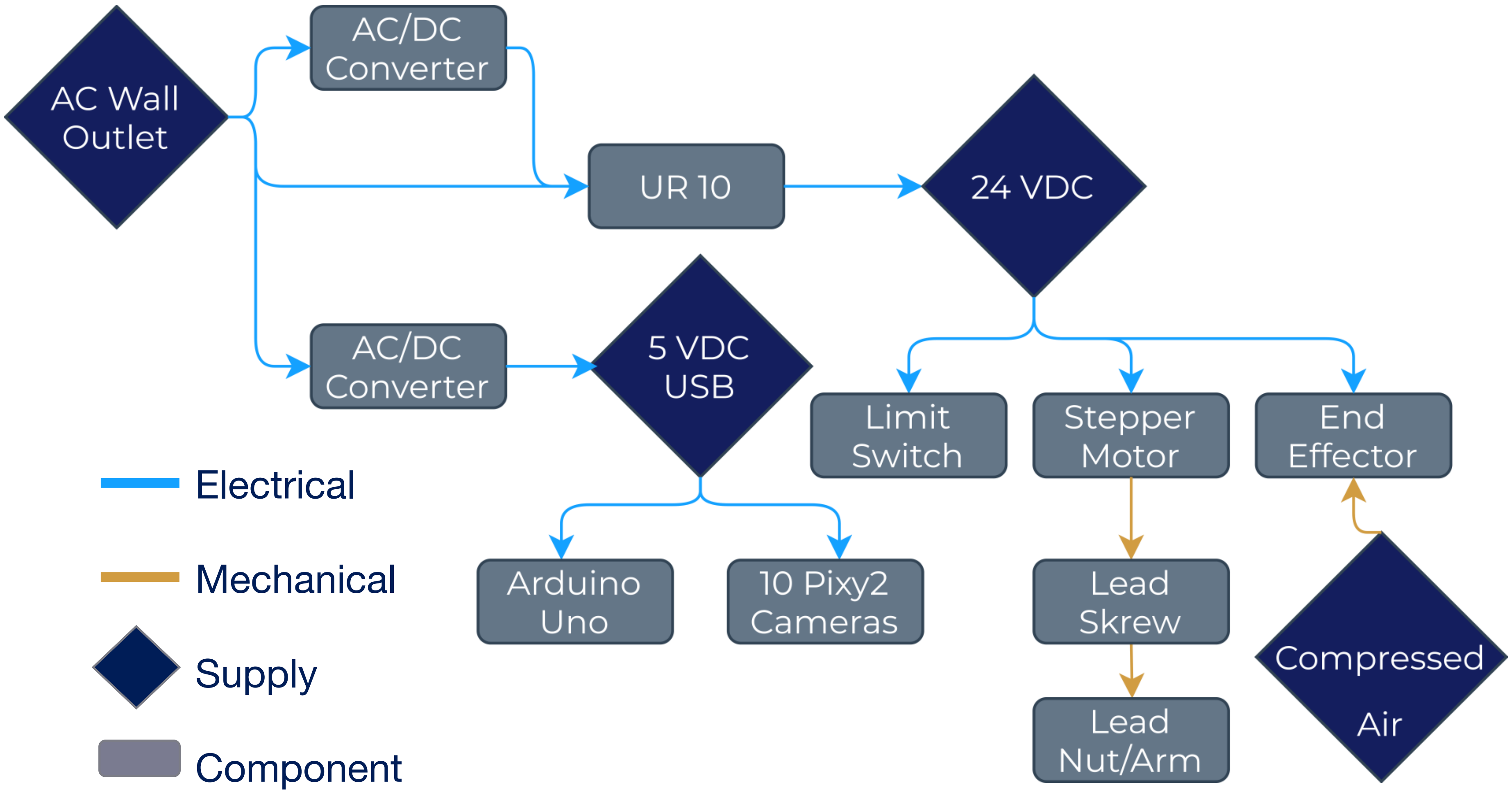


The Data Line Corresponds to the Color of the Node

FBD


Power
DC USB Block
AC Wall Outlet
AC/DC Converter
10 Pixy2 Cameras
Arduino
RS 485 Shield
Ethernet Shield
Operator Input
PC
Ethernet Splitter
Arm System
Solenoid Driver
Solenoid
Auto Switch
UR10e Control Box
End Effector
UR10e Arm
Pressurized Air Supply
Target object
Linear Transport System
Single Axis Stepper w/ Encoder
Limit Switch
Baseplate
Coupler
Lead Screw
Lead Nut
Legend
Data
Power
Physical
Command
Pressurized Air

Power Budget



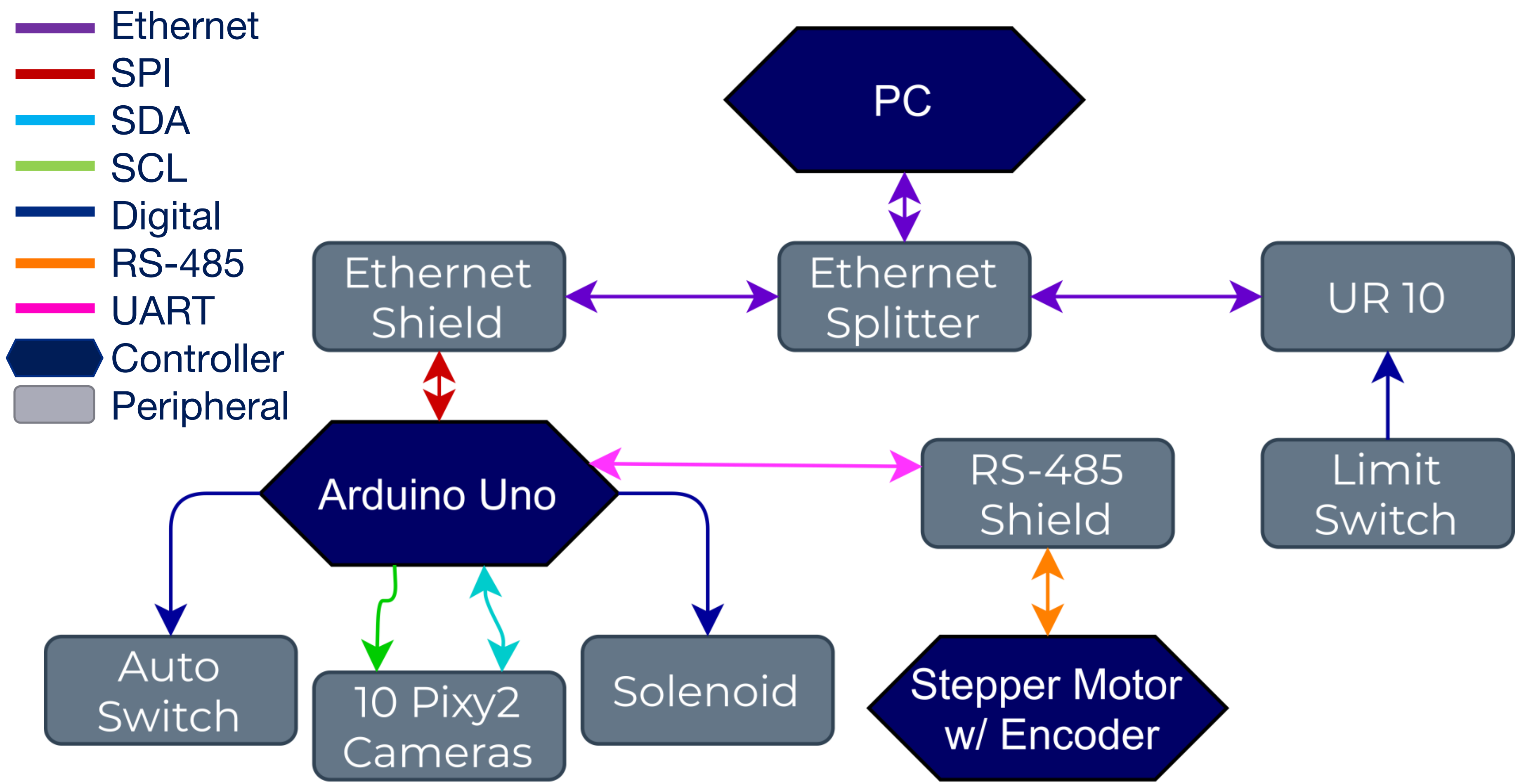
RIVeR

24 VDC	
Component	**Power**
UR 10	48 W
AC/DC	72 W
Limit Switch	-4.8 W
Stepper Motor	-72 W
End Effector	-20.72 W
Total	**22.48 W**

5 VDC - USB	
Component	**Power**
AC/DC	100W
Arduino	-.25 W
Pixy2s	-7 W
Total	**92.75 W**

Data Budget

RIVeR



Component	Data Rate
10 Pixy2 Cameras	1.15 Mbps
Stepper Motor	9.6 Kbps
Arduino Uno	2 Mbps
Ethernet Shield	100 Mbps
UR-10	100 Mbps
Ethernet Splitter	1000 Mbps
PC Requirement	**200 Mbps**

Critical Project Elements

Project Elements

Structural	Robotics	Actuators	Electronics	Software
Translator Track	Robotic Arm	Solenoid Valve (End effector)	Arduino	Image Processing
Base Plate (Arm)	End Effector	Motor (Translator)	Wire Management	Control System
			Imaging sensors	

Critical Element

Critical Element & CDR Focus

Critical Project Elements

CPE	Function	Analysis
Base Plate (Arm)	Integrates the robotic arm base with the translator	Base plate deformation/deflection
Motor (Translator)	Moves the robotic arm and base plate	Motor torque analysis
Image Processing (Software)	Manage data from each sensor and determine the orientation and position of cargo bags	Object position and orientation determination
Imaging Sensors	10 cameras to identify and locate the ID tags on cargo bags	Camera positioning, visual feasibility

Section 2

Design Requirements → Overview → Satisfaction

Satisfaction

Motor Torque Analysis

DR 1.1: The translation system shall be capable of translating the robotic arm, end effector, and cargo bag's combined mass.

- **Criteria:** T_s and T_m < $\mathbf{T_{rating}}$ **= 1.22 N*m** (given by motor datasheet)

$$F_{static} = F_m + F_{f,static} = 729.7N$$

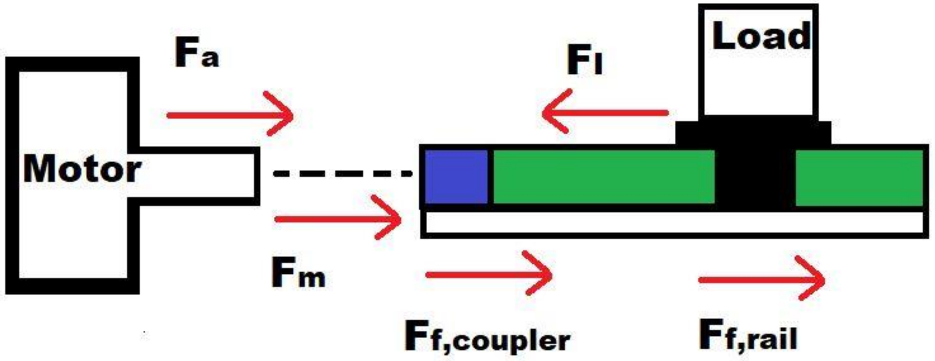
$$F_{sliding} = F_m + F_{f,kinetic} - F_I = 673.5N$$

$$T = \frac{F_a * l}{2\pi\eta}$$

$$T_{static} = \frac{F_{static} * l}{2\pi\eta} = 0.6452\,Nm$$

$$T_{sliding} = \frac{F_{sliding} * l}{2\pi\eta} = 0.5955\,Nm$$

F_m = Machining Force
F_f = Frictional Force
F_I = Inertial Force

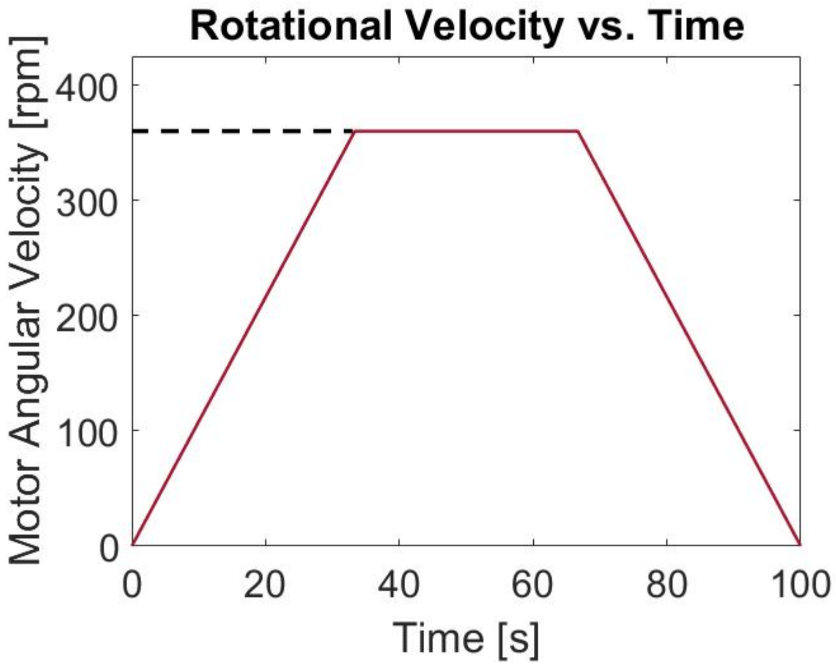


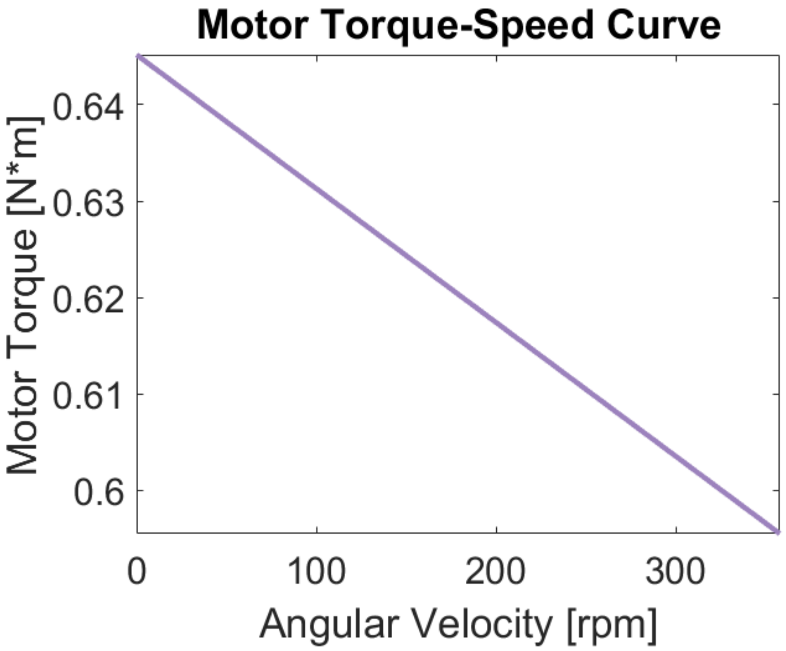
Design Req.	DR 1.1
$T_{max} < T_{rating}$	
Satisfied?	✓

Motor Torque – Rotation Velocity

- **DR 1.1:** The translation system shall be capable of translating the robotic arm, end effector, and cargo bag's combined mass.
  - **Criteria:** $\omega_{max} < \boldsymbol{\omega_{rating}}$ **= 2160 rpm** at 24 V (given by motor data sheet)

$$\boxed{\omega_{max} = PPS(\frac{60s}{1\,min})/n = 357.6rpm}$$

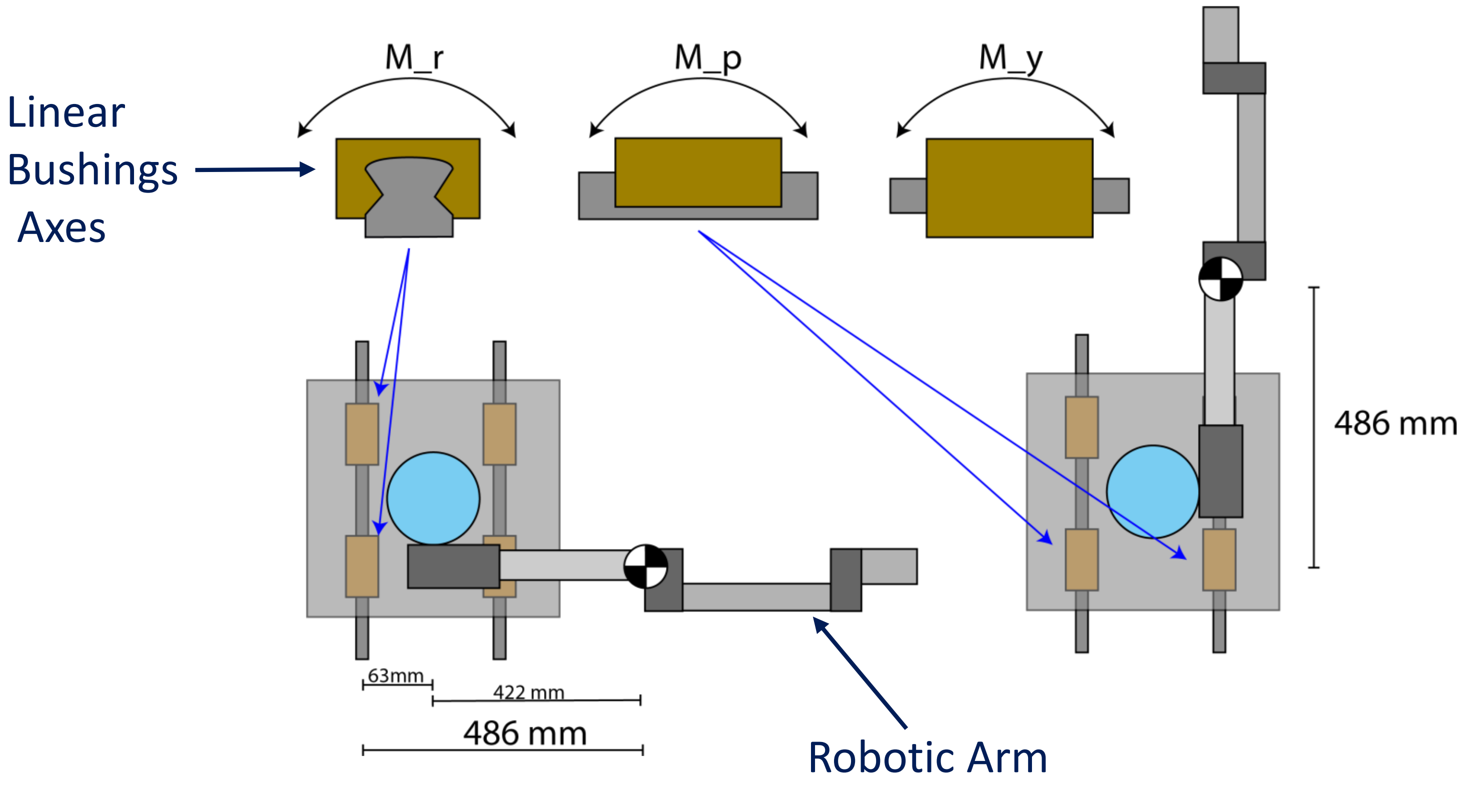




Design Req.	DR 1.1
$\omega_{max} < \omega_{rating}$	
Satisfied?	✓

Linear Bushing Compatibility

RIVeR



Variable	Linear Bushing Rating	Maximum Value per Bushing
M_r	270 Nm	163.6 Nm
M_p	200 Nm	162.4 Nm
M_y	200 Nm	82.5 Nm
Dynamic Load	17.75 KN	140 N
Static Load	27.76 KN	167.75 N

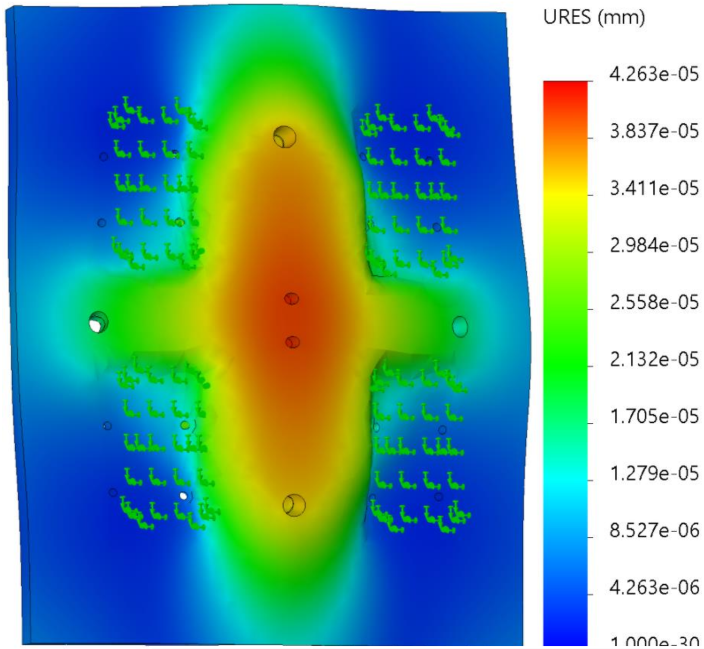
Max Arm Motor Torque = 330 Nm
Per Bushing = 82.5 Nm
Total Moment = Motor Torque + Gravity
*Stepper Motor Torque included on M_r
1.23 FOS for Linear Stage

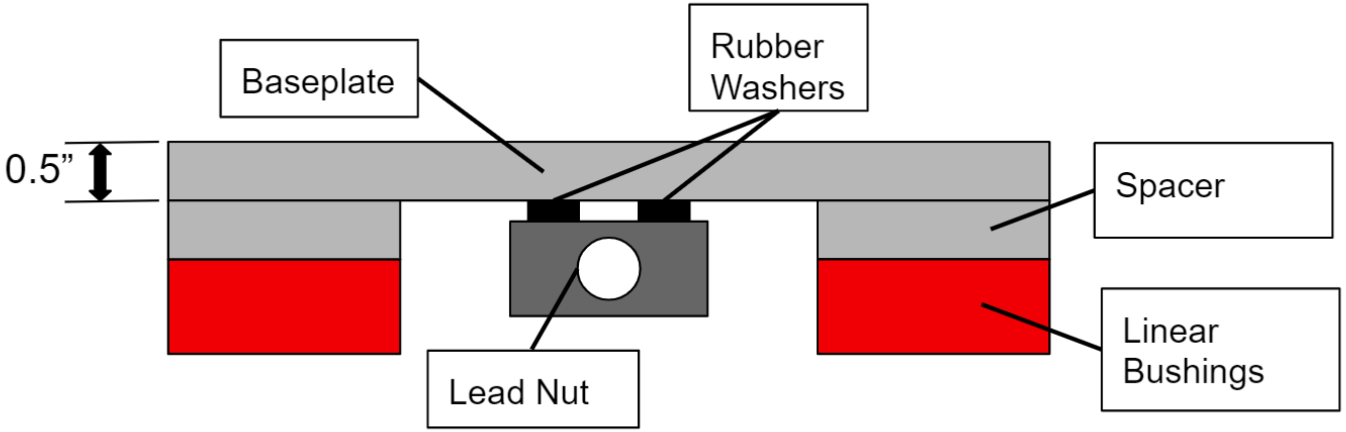
DR.8.1	The system shall not deflect from any torques caused by motors.	Satisfied ✓

Baseplate Deflection

- Baseplate Material: Aluminum 6061
  - Youngs Modulus: 69 GPa
  - Yield Strength: 55.1 GPa
- Expected stress .165 MPa < 55.1 GPa
  - Von Mises Model holds for elastic material

Model	Maximum Deflection
Von Mises Designed Baseplate	4.236×10^-5 mm
Von Mises Original Baseplate	2.944×10^-5 mm
Calculated Beam Deflection for Designed Baseplate	1.89×10^-8 mm





DR.8.2	The rail system shall not experience any deflection that misaligns the threads.	Satisfied ✓

Sensory Modeling

RIVeR

2D Display Model	
Input: Defined 3D Workspace	Output: Simulated 2D discretized data

↓

Triangulation Model/State Estimation	
Input: 2D data points grouped by camera	Output: 3D triangulated data

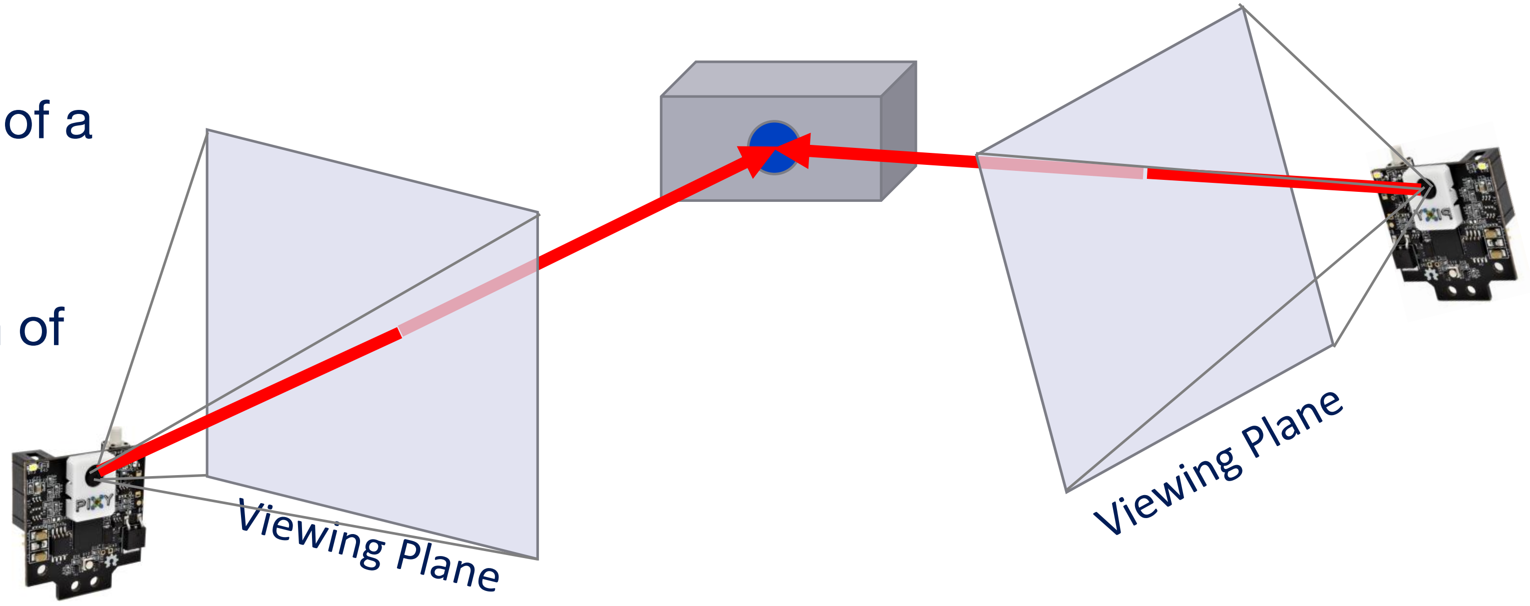
↓

Orientation Determination Model	
Input: 3D triangulated data	Output: 3D orientation of the bag

RIVeR

Object Position Determination

- Must determine the bag position to pick it up with the robotic arm
- Sensors return (x, y) coordinate of a detected object
  - In the Sensor Frame
- Can reconstruct the 3D position of an object, based on:
  - Measurements
  - Sensor Positions
  - Sensor Orientations



DR.3.1	The system shall identify a cargo bag with its orientation and position.
DR.3.2	The system shall be able to determine if the cargo has reached the target location
DR.3.3	The operating system shall be able to determine if the cargo is irretrievable.
DR.3.4	The system shall give feedback if the transportation has failed and cease operations.

Object Position Determination

- Define the Estimation Cost Function
  - Nonlinear Least Squares of the Measurement Residuals

$$J(T) = \sum_{k=1}^{T} (y(k) - \hat{y}(k))^T (y(k) - \hat{y}(k))$$

$$y(k) = \begin{bmatrix} x_{S1} \\ y_{S1} \\ x_{S2} \\ y_{S2} \\ \vdots \end{bmatrix} =$$ True Sensor Measurements

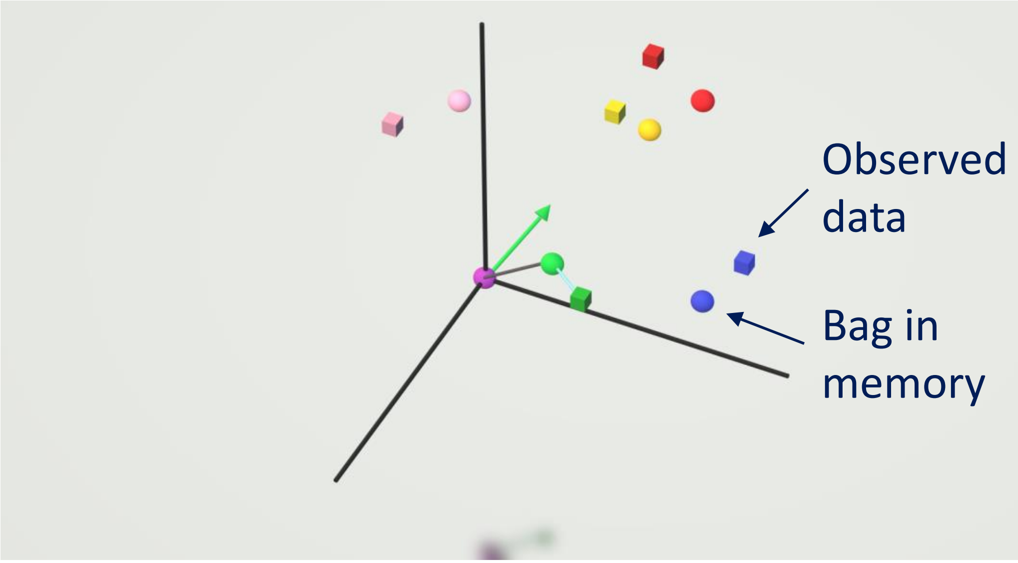
$$\hat{y}(k) = \mathcal{H}_i(\mathbf{x}) =$$ Non-Linear Measurement Function (Based on the geometry)

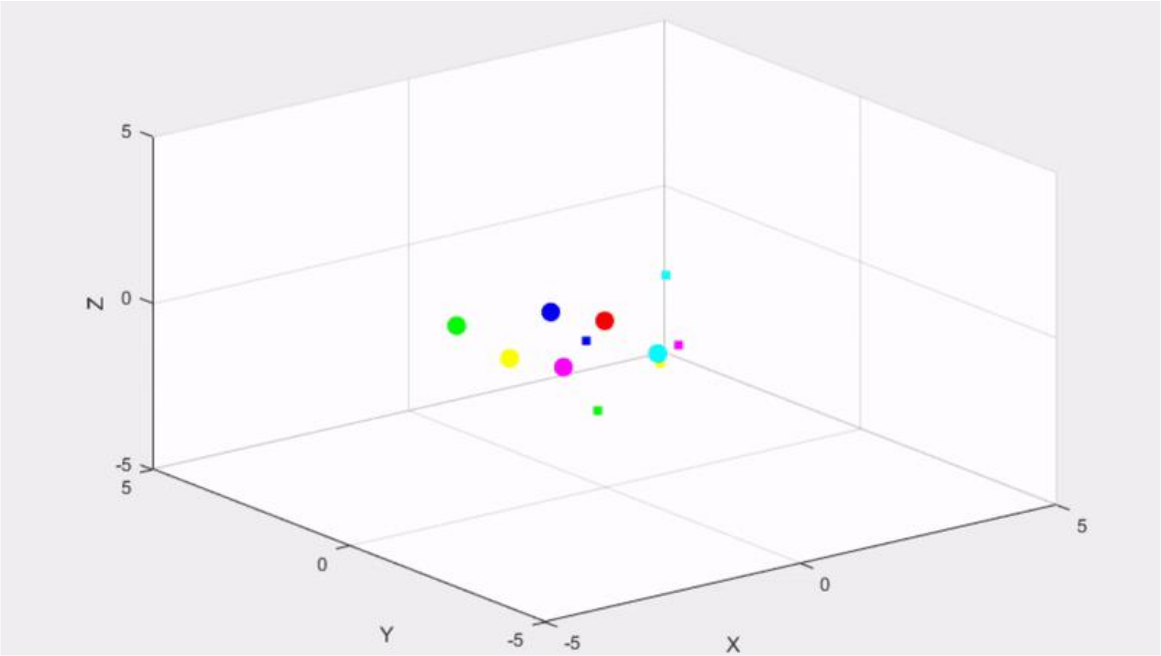
- Our goal is to find the $\mathbf{x}$ that minimizes $J(T)$ using gradient descent

Object Orientation Determination

Goal: Determine the orientation of the bag based on observed markers.

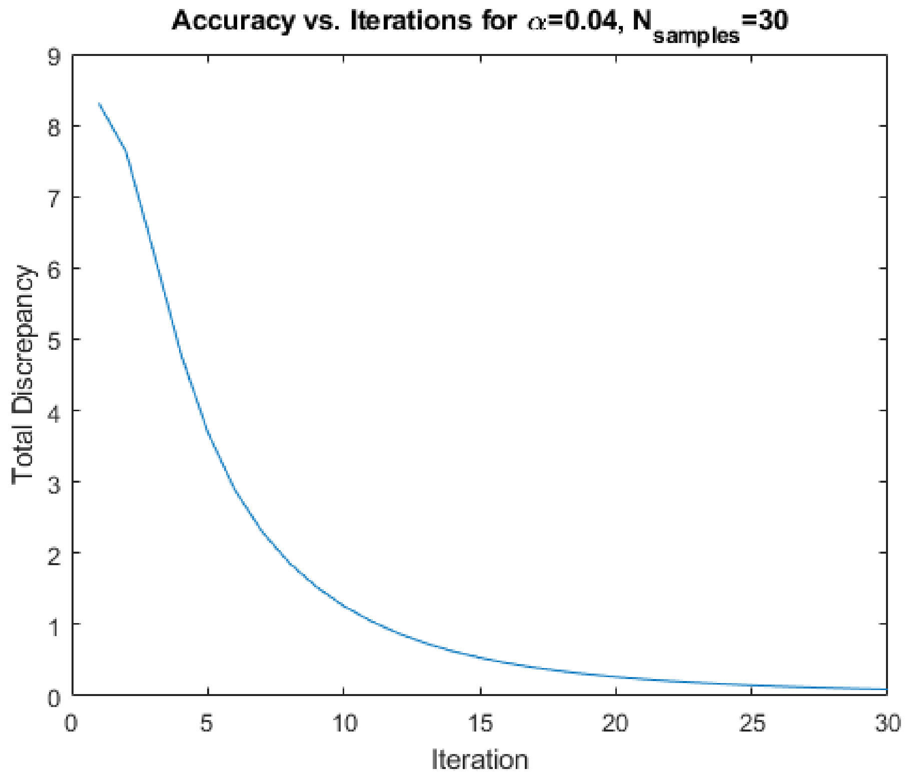
- Rotates a predefined set of markers to best represent the input data

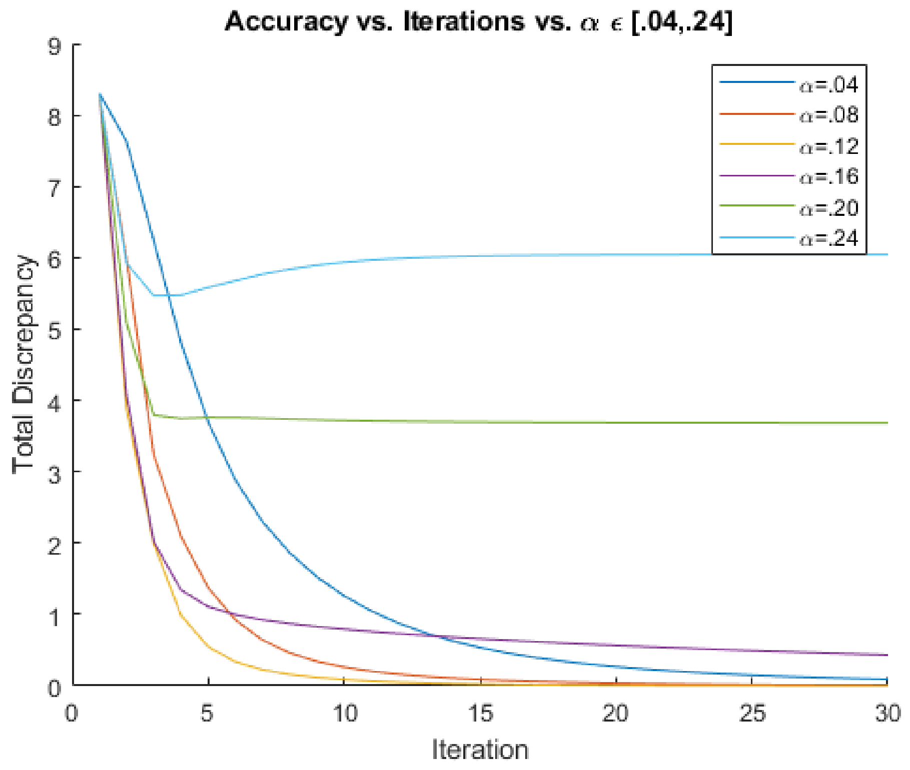




Object Orientation Determination

- Performs gradient descent to minimize the summed cartesian distance discrepancy
- "α" (gradient gain) affects rate of convergence and stability
- Converges to non-zero minimum value





Sensor Suite

- Position Determination Algorithm
- Orientation Determination Algorithm

DR.3.1	The system shall identify a cargo bag with its orientation and position.	✓
DR.3.2	The system shall be able to determine if the cargo has reached the target location	✓
DR.3.3	The operating system shall be able to determine if the cargo is irretrievable.	✓
DR.3.4	The system shall give feedback if the transportation has failed and cease operations.	✓

Section 3

- **Project Management**
- Risks
- Verification and Validation
- Project Planning

Risk

Risk Matrix

Risks

ARM-1	Arm is commanded to a position that damages it
ARM-2	Arm cannot make contact with bag
TR-1	Stripping of lead screw
TR-2	Linear stage tipping over
SOFT-1	Cargo bag cannot be identified
END-1	Pressure actuator failure
END-2	Improper alignment/bag dropping

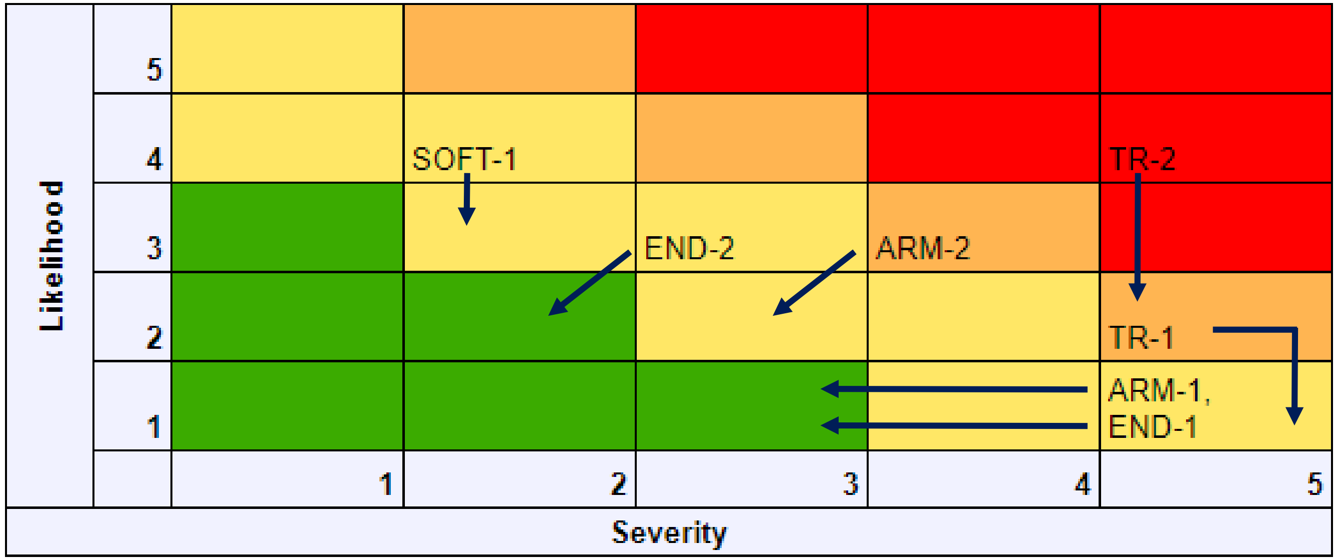
Likelihood					
5					
4		SOFT-1			TR-2
3			END-2	ARM-2	
2					TR-1
1					ARM-1, END-1
	1	2	3	4	5
	Severity				

Mitigation

RIVeR

Risks

ARM-1	Arm has built in safety features
ARM-2	Manual control directs arm
TR-1	Alleviate force with linear bushings
TR-2	Weighted end brackets
SOFT-1	Arm can be controlled manually to find the cargo bag
END-1	Replacement Parts
END-2	Arm can be manually driven



Verification and Validation

Testing Plan I

Test Name	Definition/ Purpose	Driving Requirements	Completion Date	Location and Equipment
Robotic Arm: Functionality Test	Test UR10e Motion Planning and Pose Determination.	FR.1 FR.2 FR.4	February 5th	Senior Projects Room Wall Power Supply
End-Effector: Static Load Test	Test Capture Mechanism and End-Effector Controls with Bags.	FR.1 FR.2 FR.5 FR.6	February 5th	Senior Projects Room Air Supply Wall Power Supply
Translator: Calibration and Arduino Test	Test Motor Accuracy, Sensor Functionality, and Translator Controls.	FR.1 FR.7 FR.8	February 19th	Senior Projects Room Wall Power Supply
Pixy Camera: Bag Identification Test	Test Camera Triangulation Method and Accuracy for Bag Retrieval.	FR.1 FR.3 FR.4	March 12th	Senior Projects Room Wall Power Supply
Robotic Arm: ROS Test	Utilize ROS to Integrate the Translator and Arm for Dynamics Test and Failure Detection.	FR.3	March 19th	Senior Projects Room Wall Power Supply

Testing Plan II

Test Name	Definition/ Purpose	Driving Requirements	Completion Date	Location and Equipment
Cargo Bag: Varied Bag Fidelity for Capture	Test Capture/Identification of Cargo Bags of Varied Fidelity	FR.1 FR.2 FR.3	April 9th	Senior Projects Room Air Supply Wall Power Supply
Full System Software Test	Test Control Software of the UR10, Translator, and Camera System with Single PC Control.	FR.1 FR.2 FR.3 FR.4 FR.5 FR.6 FR.7 FR.8	April 9th	Senior Projects Room Air Supply Wall Power Supply
Full System Functionality Test	Test UR10, End-Effector, Translator, and Camera System for a Full Cycle of Operations.	FR.1 FR.2 FR.3 FR.4 FR.5 FR.6 FR.7 FR.8	April 9th	Senior Project Room Air Supply Wall Power Supply
Full Systems Test	Test Software and Hardware of the Assembled System for a Full Cycle of Operations.	FR.1 FR.2 FR.3 FR.4 FR.5 FR.6 FR.7 FR.8	April 16th	Senior Projects Room Air Supply Wall Power Supply

Testing Tasks

Translator

- Calibrate stop sensors
- Test precision and repeatablity of baseplate positioning
- Test accuracy at different speeds ~0.3 mm/s
- Repeat Process with baseplate loading

End Effector

- Test static force for bag separation to occur
- Test magnetic distance for bag separation to occur
- Test various orientations

Pixy Camera

- "Visually" capture target using triangulation (0-3 meters)
- Compare color vs pixel accuracy
- Test effects caused by shadows and non ideal lighting conditions

Robotic Arm

- Manually position arm to preassigned locations using ROS Software
- Simulate movement with attached cargo bag
- Validate range of motion

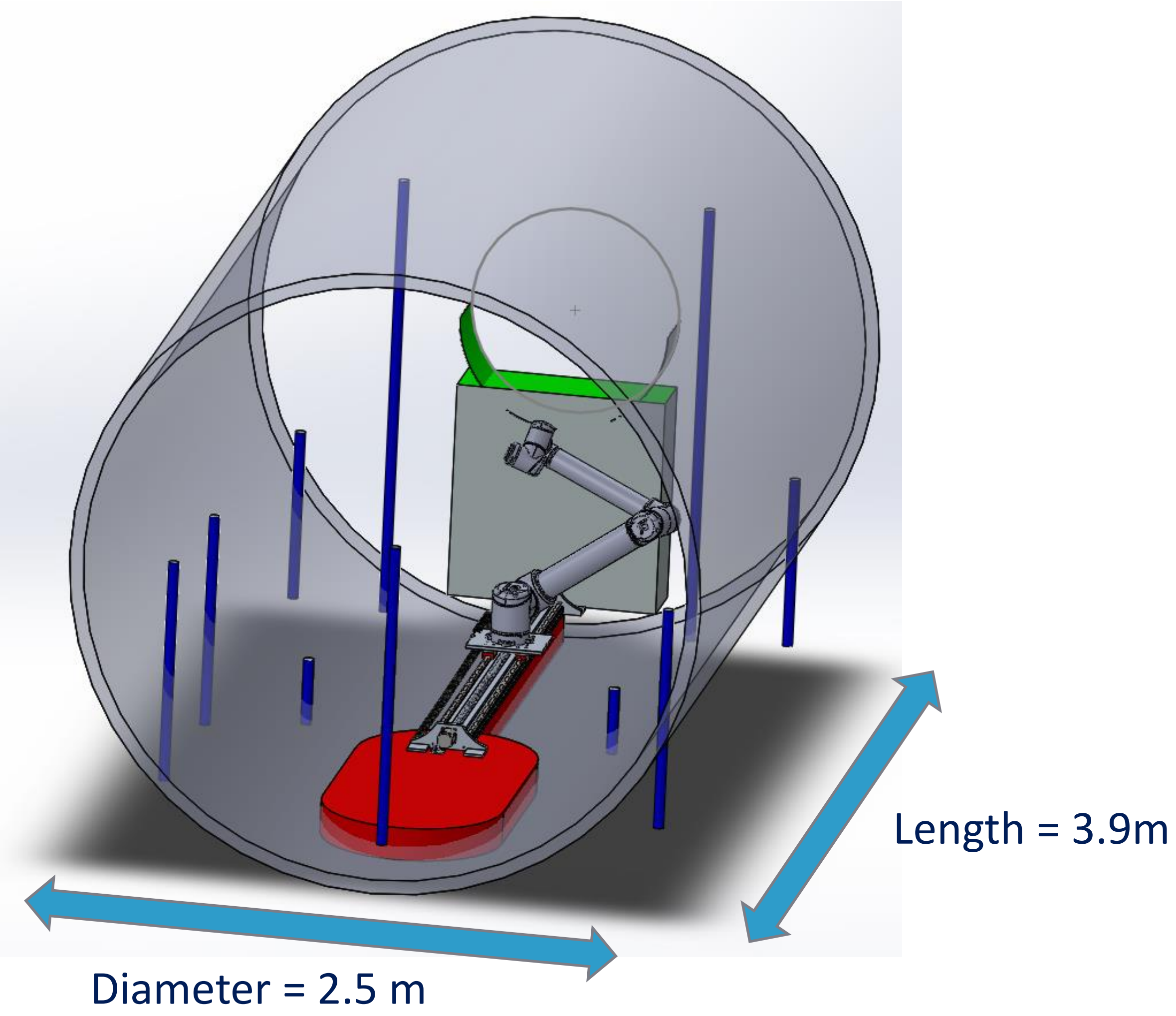
Electronics

- Measure and evaluate voltage signals from components

Full Functionality Test

- Complete each stage of CONOPS with single PC control
- Record Power Supply, Air Pressure, and Translational Speed.
- Test Control Software of UR10
- Test Translator Positioning
- Test Camera System

Testing Set Up



Capture Area: 0.2 square meters

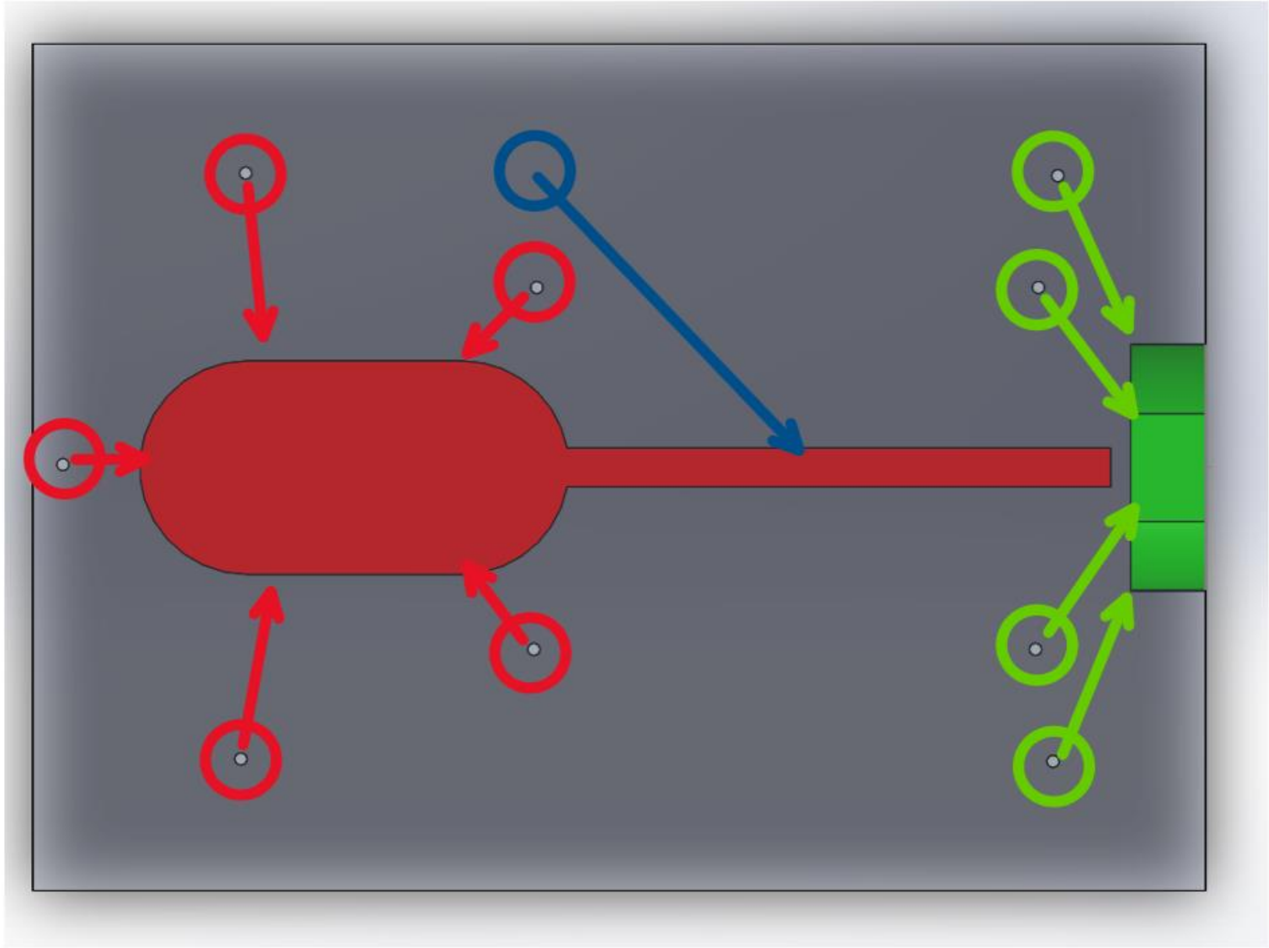
Release Area: 0.915 square meters

Camera Stands

Cameras mounted using square, telescoping rods

Origin at center of hatch

Camera Set Up: Top Down



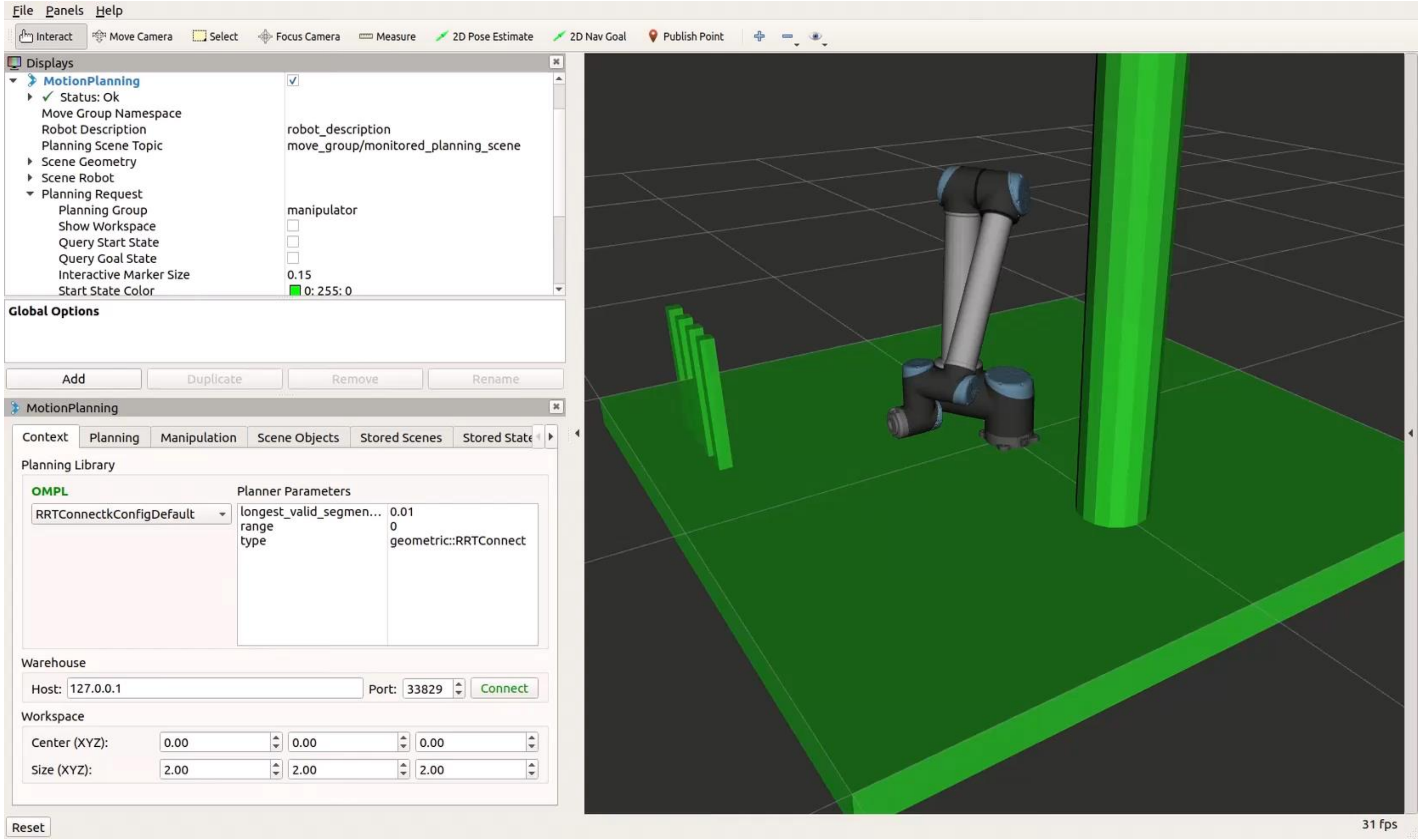
Location	Cameras	Symbol
Facing Capture Zone	4	green circle
Facing Release Zone	5	red circle
Facing Translator Path	1	blue circle

Camera configuration centered about the middle of the Capture/Release Zones

- Each camera is 1.228 meters from this point

Translator camera is an average of 1.865 meters from the translator.

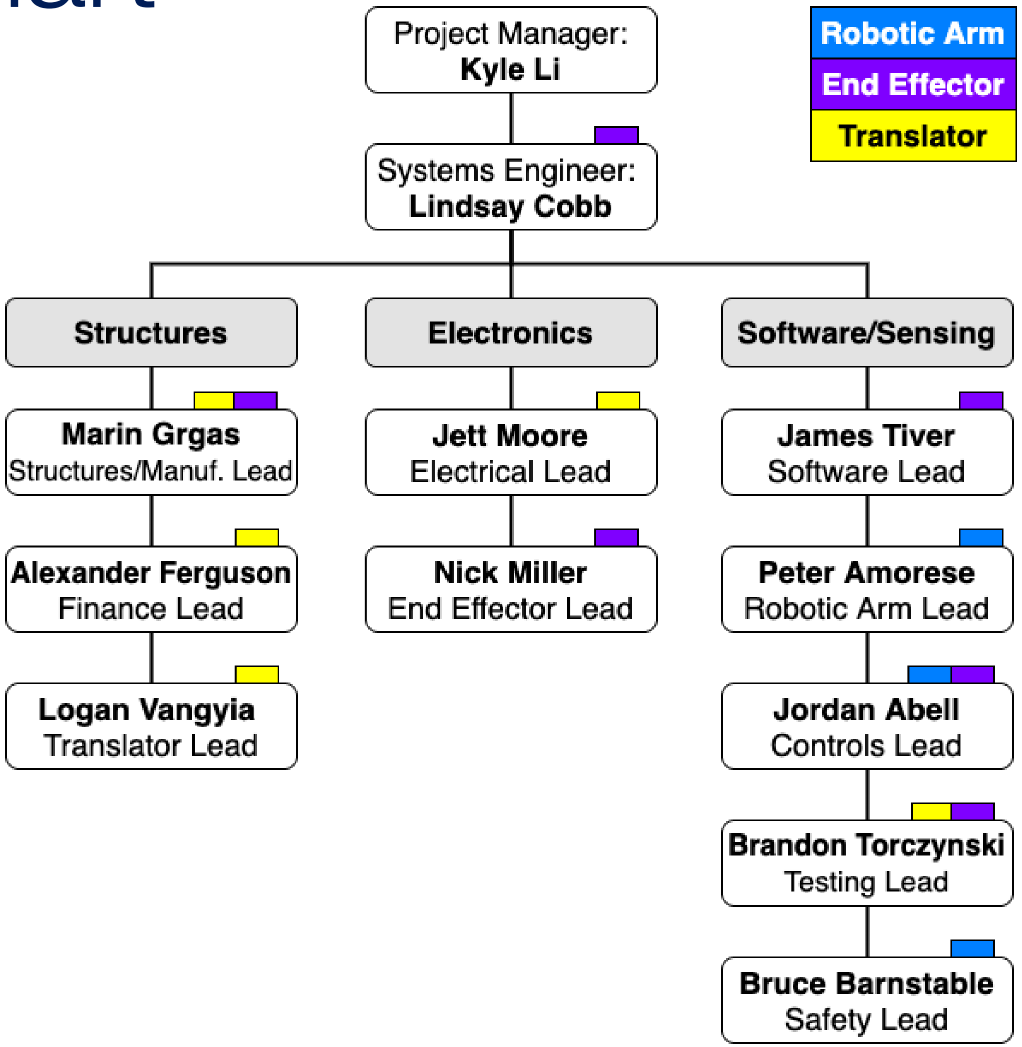
RViz Demonstration



Project Planning

Org Chart

RIVeR

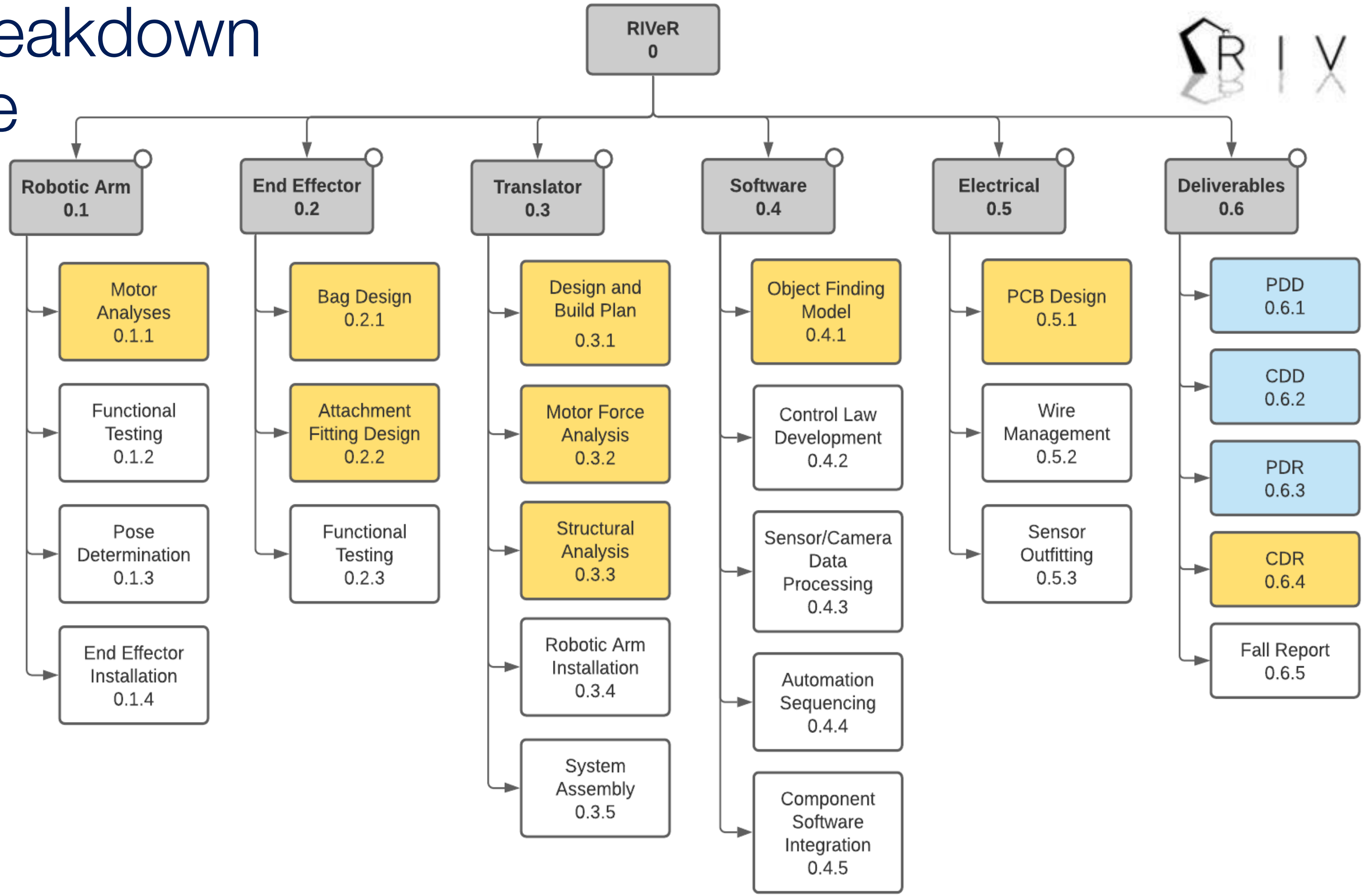


Software:
Sensor integration, communication and controls, software

Electronics:
Circuit design, power budget

Structures:
Analysis of all structural forces. Design interfaces and attachments for arm/end effector. Owns master CAD assembly of entire system

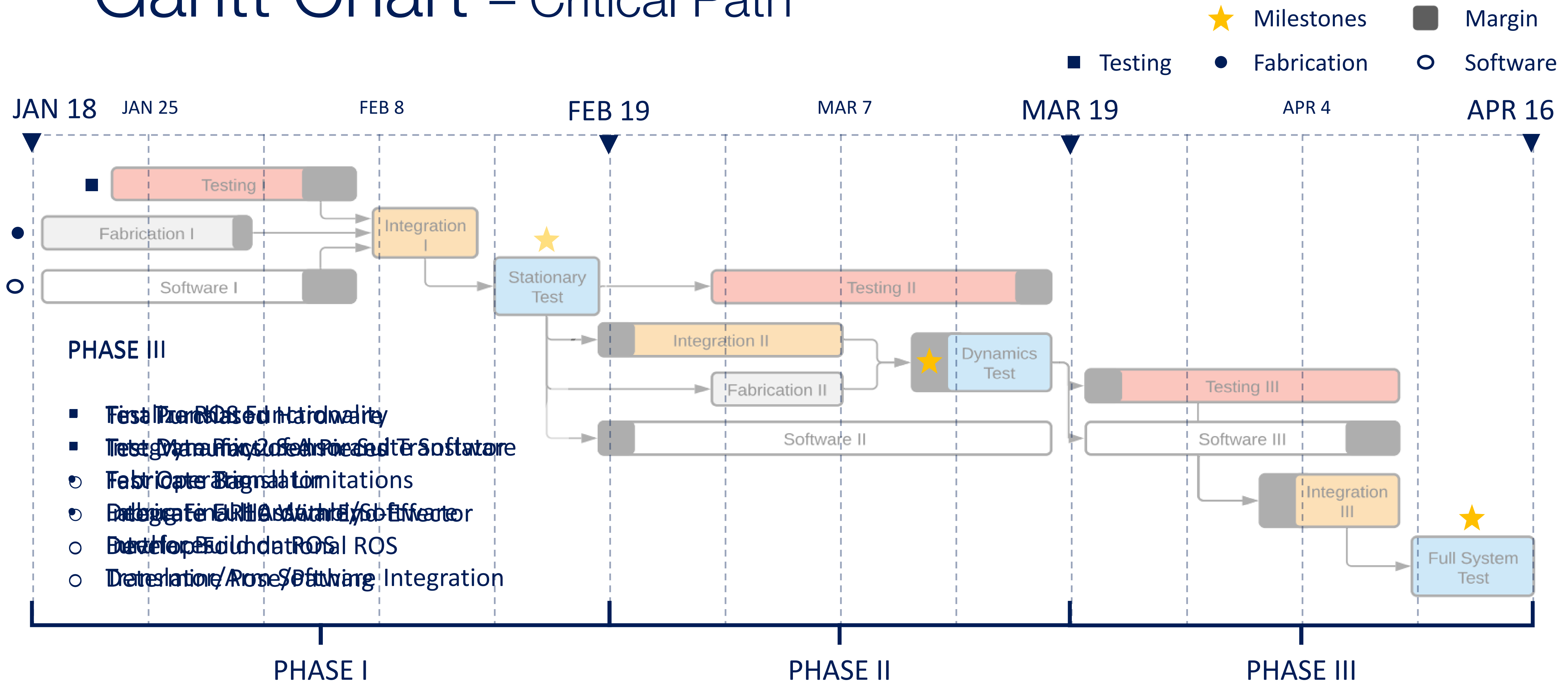
Work Breakdown Structure



Legend

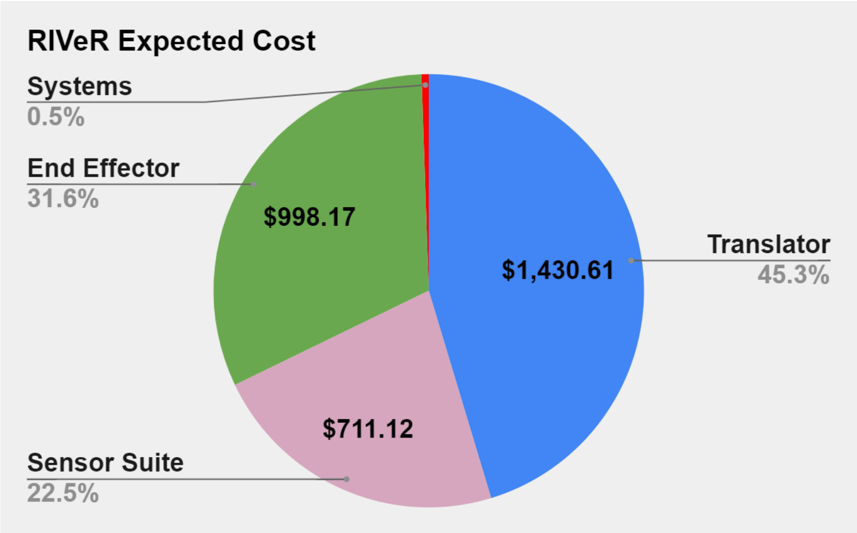
- Completed
- In Progress
- Future Work

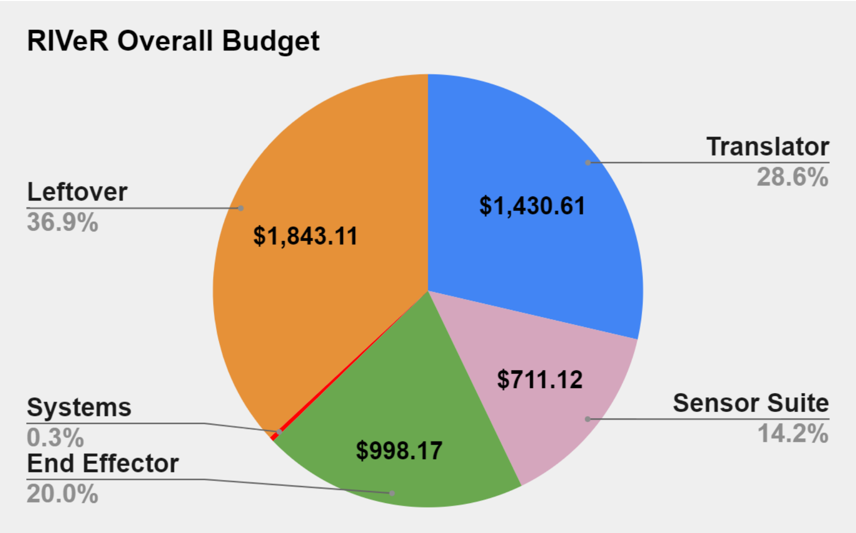
Gantt Chart – Critical Path



Cost Plan

Subsystem	Expected Cost	Allocated Amount	Budget Margin
Translator	$1,430.61	$2200	**$769.39**
End Effector	$998.17	$1600	**$601.83**
Sensor	$711.12	$1100	**$388.88**
Systems / Electrical	$16.99	$100	**$83.01**
RIVeR Total	**$3,156.89**	**$5000**	**$1843.11**





Special Thanks

Sierra Nevada Corportation and Loren McDaniel

Dr. Neogi

CU Boulder Aerospace Department

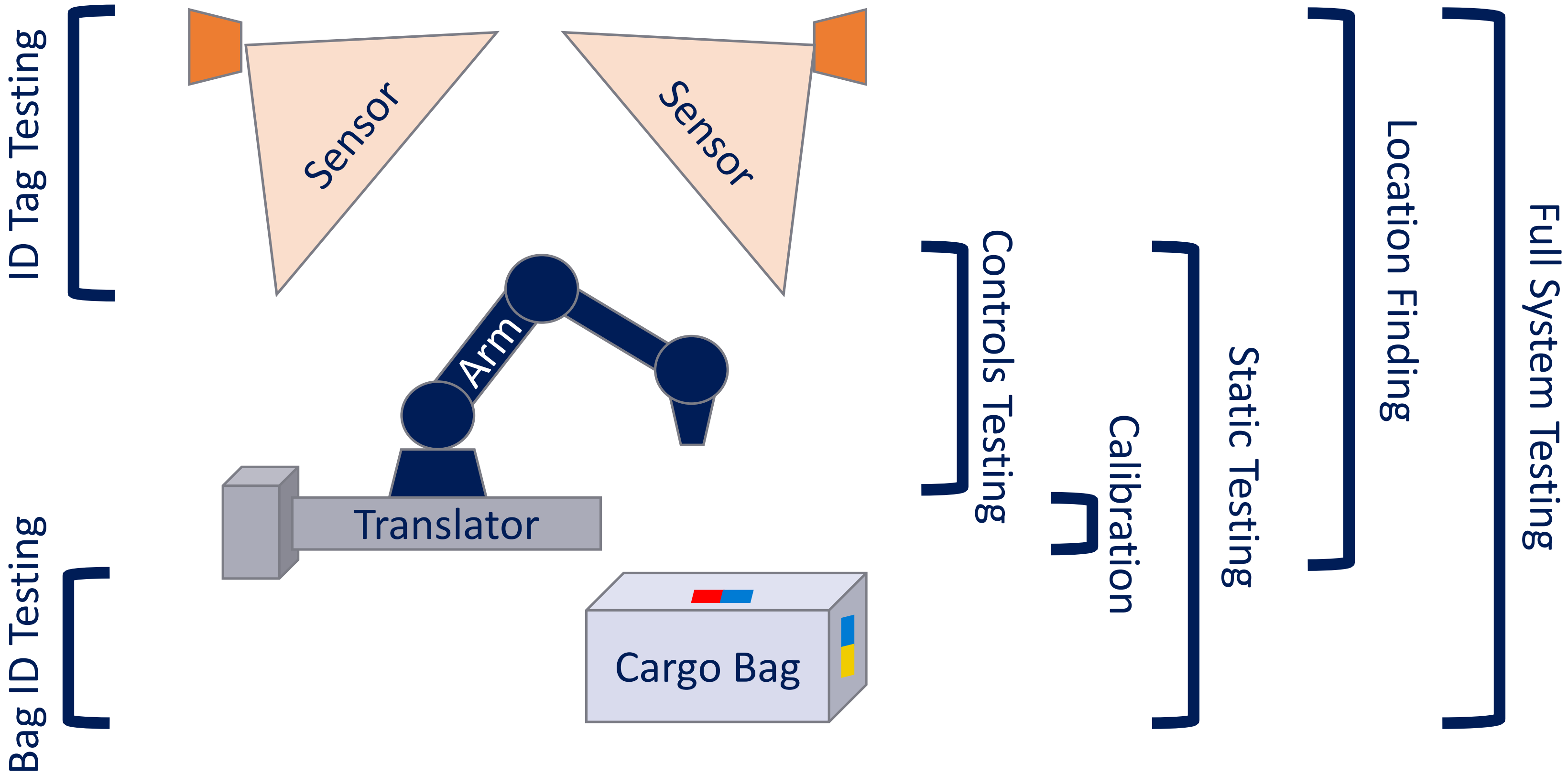
PAB

Back Up

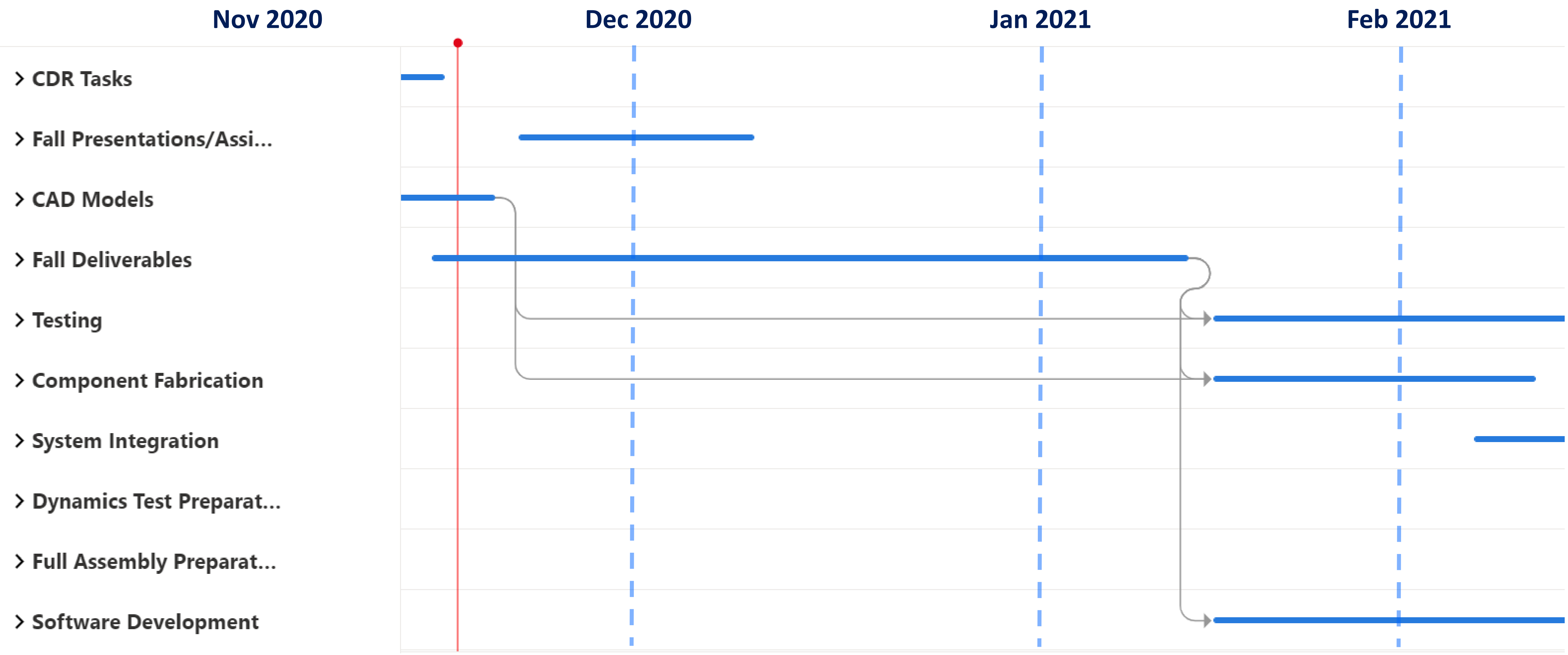
Roadmap

Fall Semester

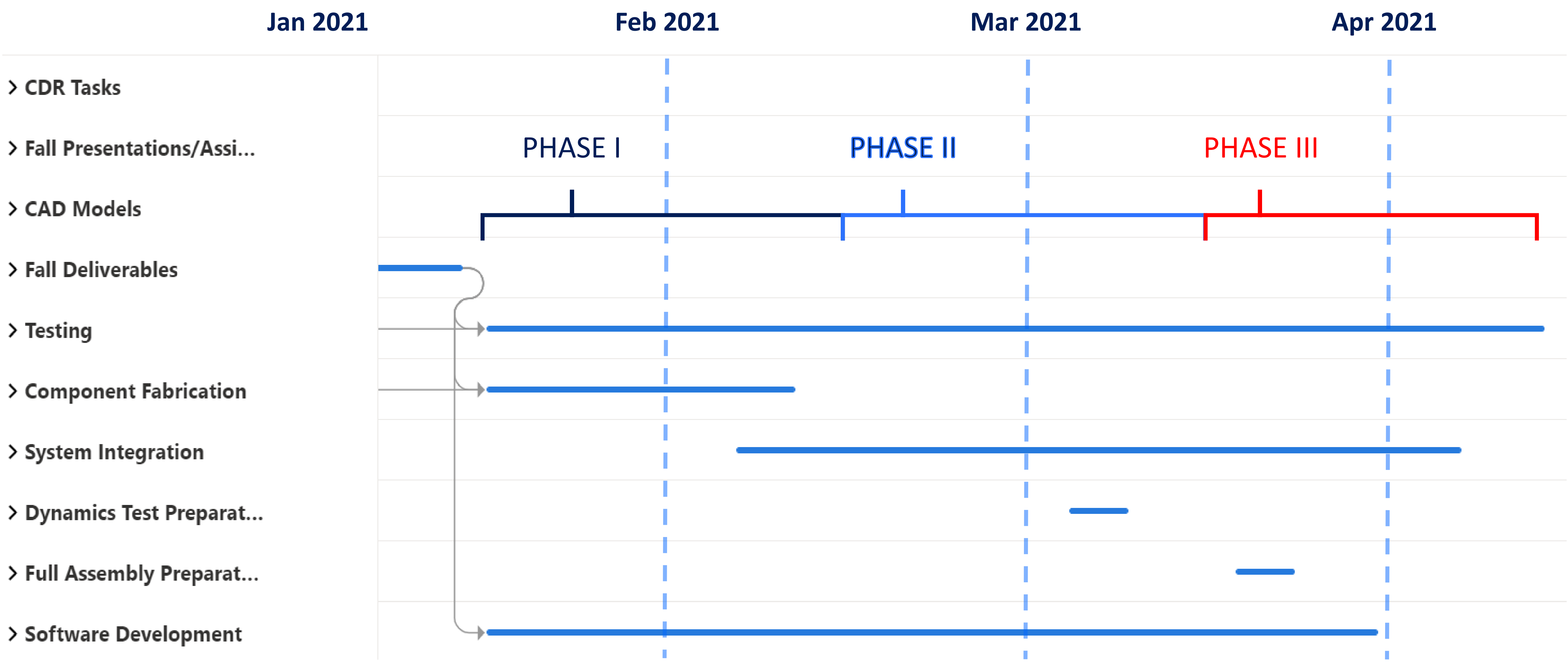
Spring Semester



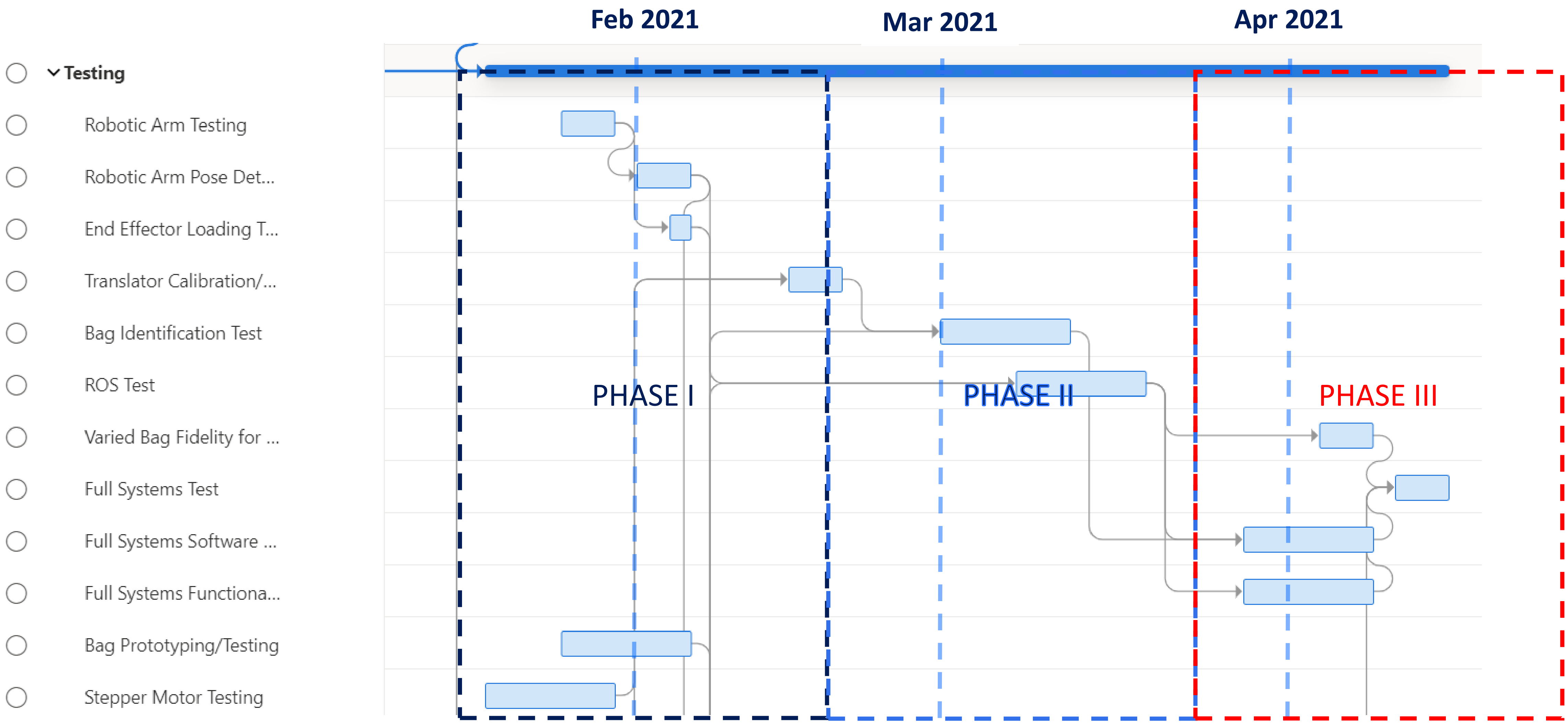
Gantt Chart – Overview I Fall



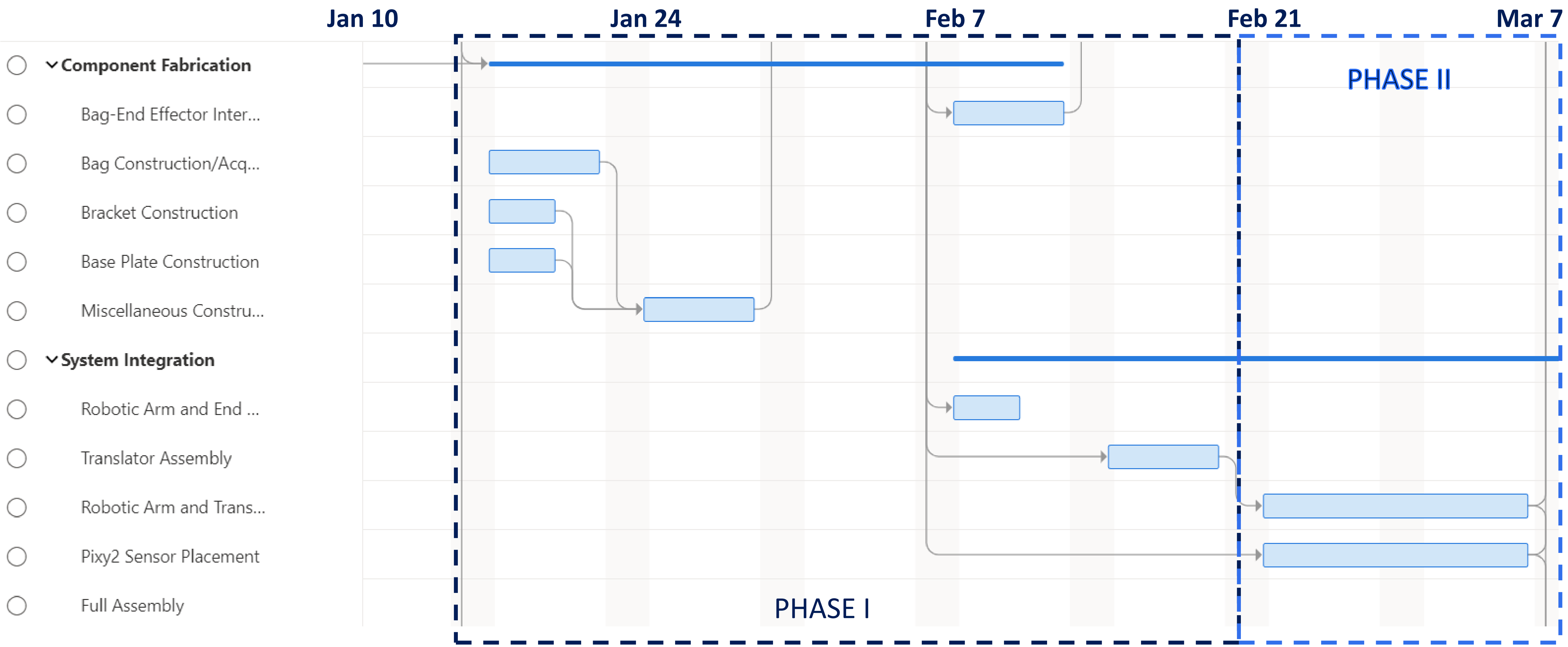
Gantt Chart – Overview II Spring



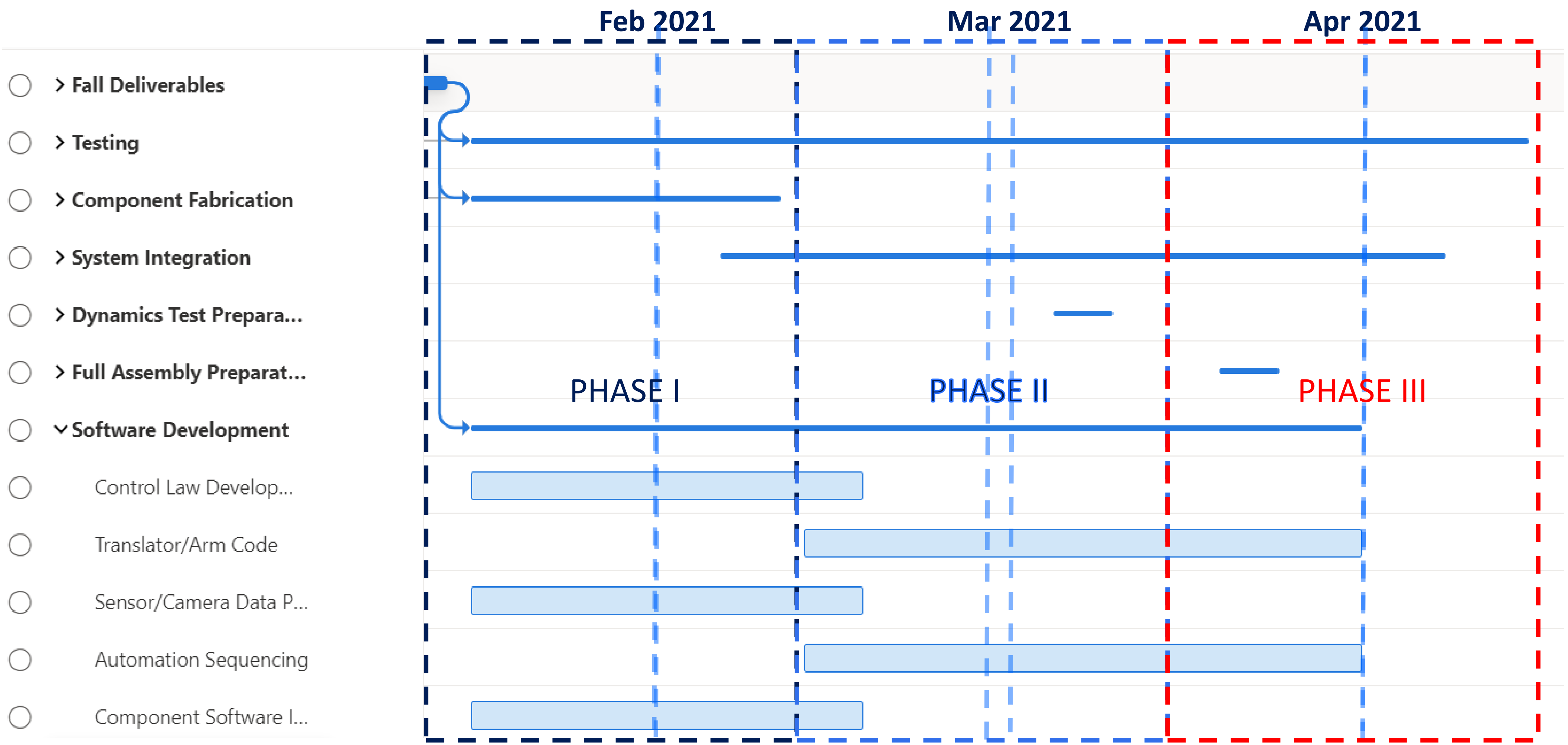
Gantt Chart – Testing



Gantt Chart – Component Fabrication and System Integration



Gantt Chart – Software



Translator

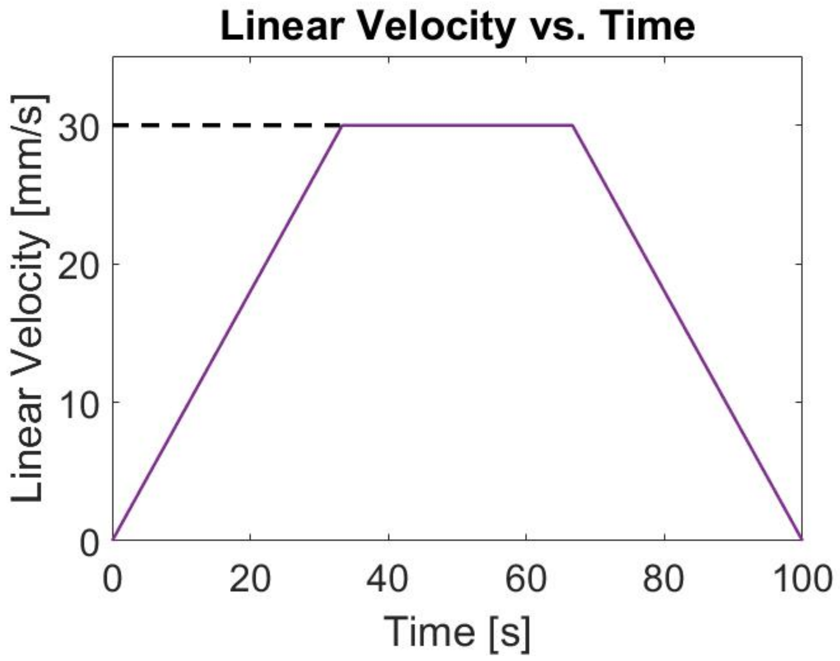
Design Requirements that pertain to the Translator Subsystem

DR 1.1	The translation system shall be capable of translating the robotic arm, end effector, and cargo bag's combined mass.
DR 8.1	The system shall not deflect from any torques caused by motors.
DR.8.2	The rail system shall not experience any deflection that misaligns the threads.

Motor Analysis

- Key Values:
  - Load mass [m] = 38 kg
  - Holding Torque rating [T_{rating}] = 1.22 N*m
  - Screw efficiency [η] = 90 ± 5 %
  - Lead screw [l] = 5 ± 0.03 mm
  - Max microstep velocity [PPS] = 305,175 steps/s
  - Max microstep acceleration [α] = 6.104×10^{6} steps/s^2
  - Microstep size [step] = 7.031×10^{-3} °/step
  - Static friction [μ_s] = 1.96
  - Kinetic friction [μ_k] = 1.87

Motor Analysis



$$V_{max} = PPS * l * step/360^\circ = 29.8mm/s$$

Axial Force $F_a = F_m + F_f - F_l$

$$F_{static} = F_m + F_{f,static} = F_m + mg * \mu_s = 729.7N$$

$$F_{sliding} = F_m + F_{f,kinetic} - F_l = F_m + m(g\mu_k - a) = 673.5N$$

Motor Analysis - Tolerances

- Assumption:
  - Screw Efficiency: Ball screw efficiency typically between 85% and 95% $\eta = 90 \pm 5\%$
- From translator data sheet:
  - Lead screw: $l = 5 \pm 0.03mm$

Motor Analysis - Tolerances

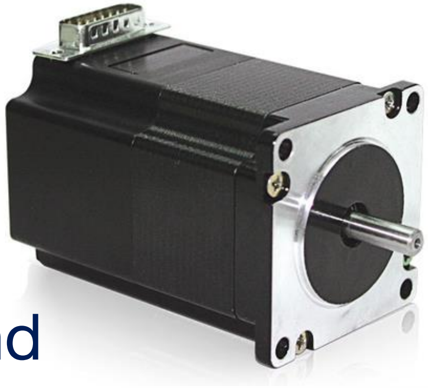
- Error Propagation:
  - Acceleration: $\frac{\delta a}{|a|} = \sqrt{(\frac{\delta\alpha}{\alpha})^2 + (\frac{\delta n}{n})^2 + (\frac{\delta I}{I})^2)} = 0.6\% = 0.0036 m/s^2$
  - Sliding Force: $\frac{\delta F_{a,m}}{|F_{a,m}|} = \sqrt{(\frac{\delta a}{a})^2 + (\frac{\delta m}{m})^2 + (\frac{\delta\mu_k}{\mu_k})^2} = 0.6\% =$ 4.041 N
  - Moving Torque: $\frac{\delta T_{a,m}}{|T_{a,m}|} = \sqrt{(\frac{\delta F_{a,m}}{F_{a,m}})^2 + (\frac{\delta I}{I})^2 + (\frac{\delta\eta}{\eta})^2} = 5.62\% =$ 0.0335 Nm
  - Static Torque: $\frac{\delta T_{a,s}}{|T_{a,s}|} = \sqrt{(\frac{\delta F_{a,s}}{F_{a,s}})^2 + (\frac{\delta I}{I})^2 + (\frac{\delta\eta}{\eta})^2} = 5.59\% =$ 0.0361 Nm
  - Linear Velocity: $\frac{\delta V_{max}}{|V_{max}|} = \sqrt{(\frac{\delta stepsize}{stepsize})^2 + (\frac{\delta I}{I})^2 + (\frac{\delta PPS}{PPS})^2} = 0.6\% = 0.178 mm/s$

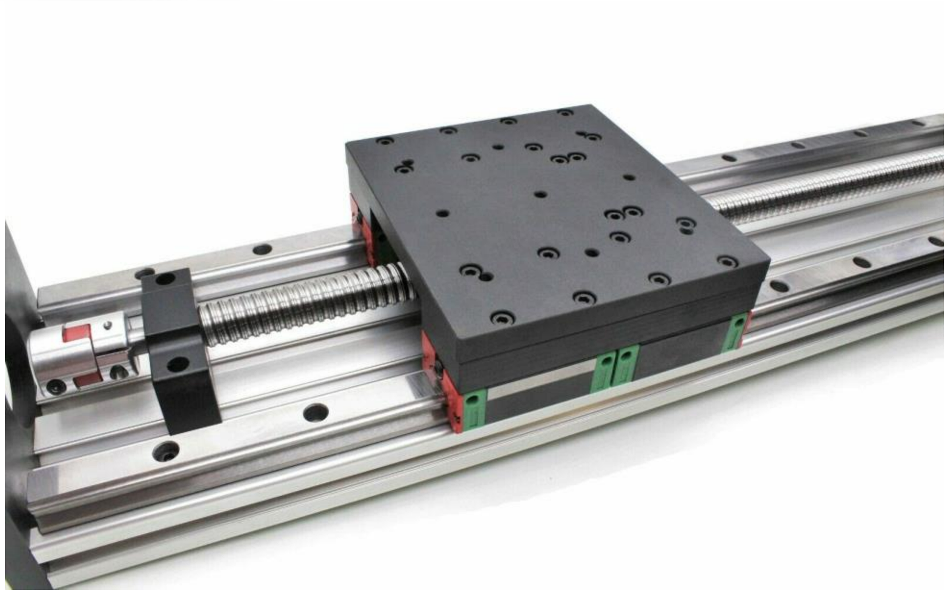
Motor Analysis – Limit Tolerance

- Some variables for Torque analysis have unknown tolerances
  - Solution: find limit values for these variables to prove feasibility through the Torque rating of the motor (**T_{rating} = 1.22 N*m**)
    - Screw Efficiency: $\eta_{lim} = \frac{F_{sliding} * l}{2\pi T_{rating}}$ = 43.9 %
    - Kinetic friction: $\mu_{k,lim} = \frac{F_{rating}/m - a}{g} - 1$ = 2.651
    - Static Friction: $\mu_{s,lim} = \frac{F_{rating}}{m * g} - 1$ = 2.711
    - Load Mass: $m_{lim} = \frac{F_{rating}}{a + g(1+\mu_k)}$ = 48.12 kg
    - Machining Force: $F_m = F_{rating} - F_{static}$ = 652.0 N

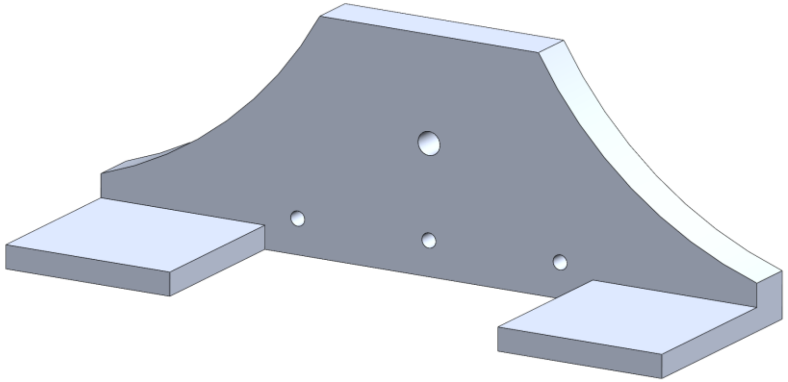
Procured Components

- Stepper Motor
  - Silverpak 23 C
  - Ethernet Connection
  - Built in driver/controller and Encoder
- Linear Stage
  - ACT-PG-150-BS-20-5-N34
- Coupler
- Limit Switch
  - WS0850101F050SA

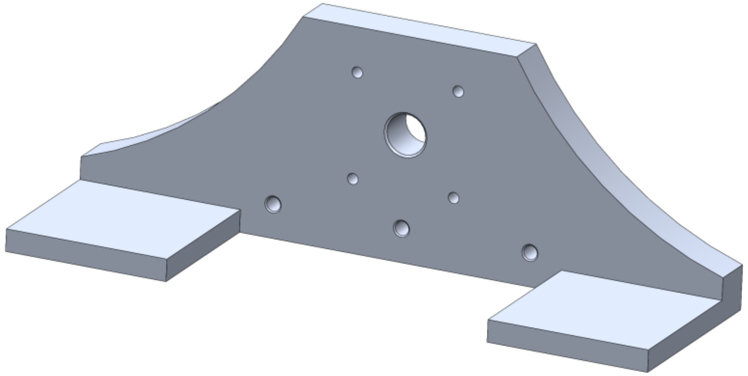




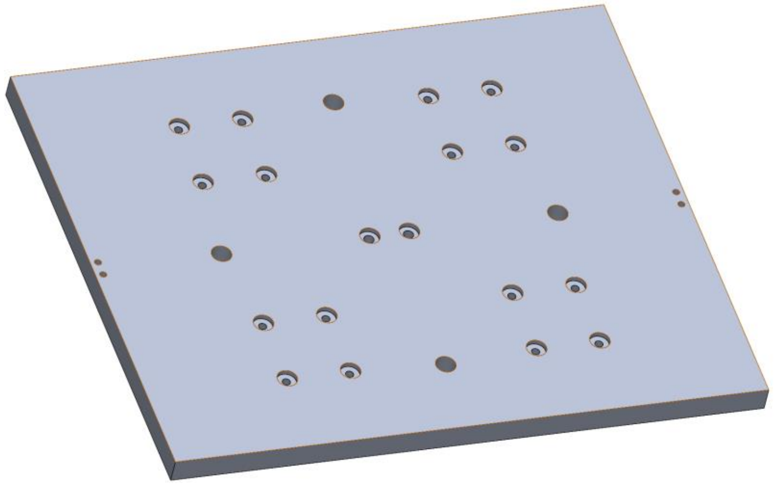
Manufactured Parts



End Bracket

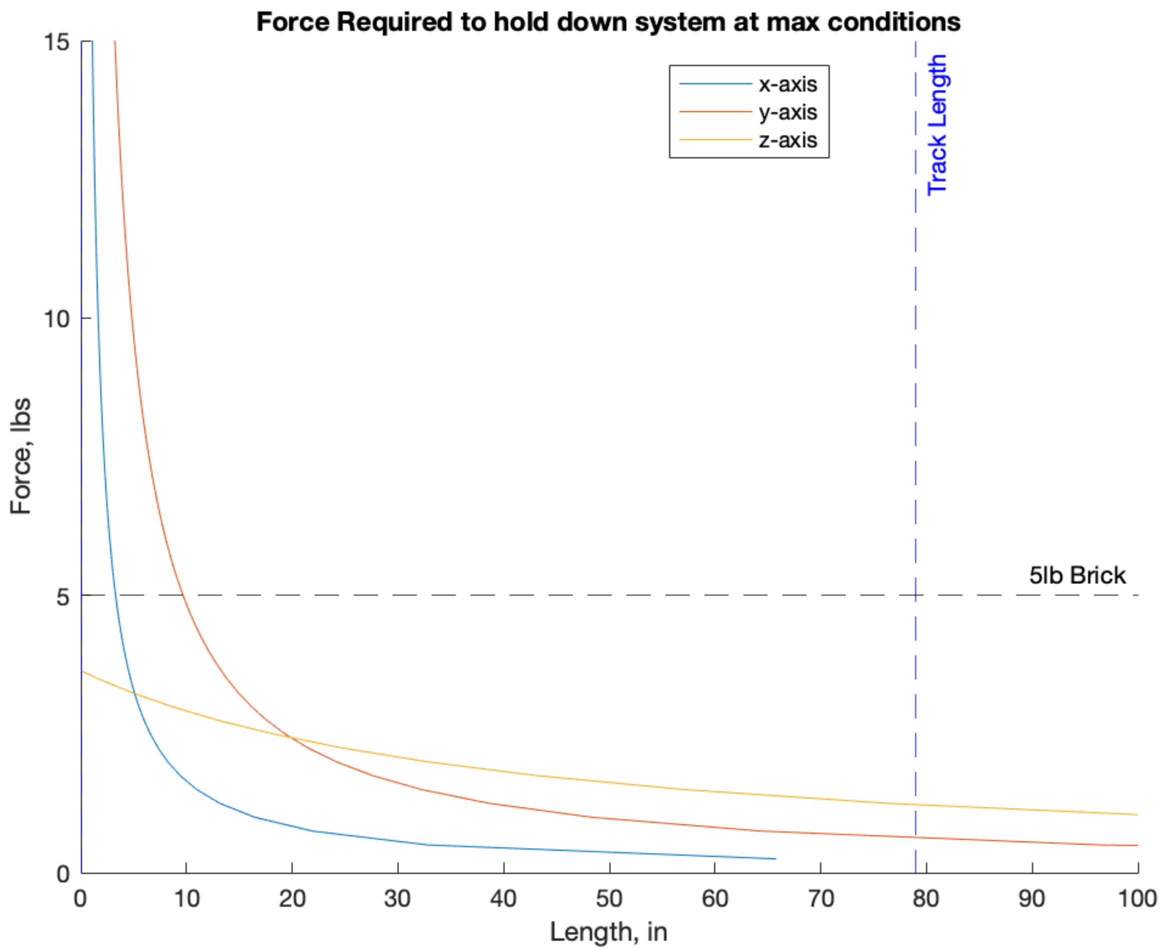


Motor Bracket

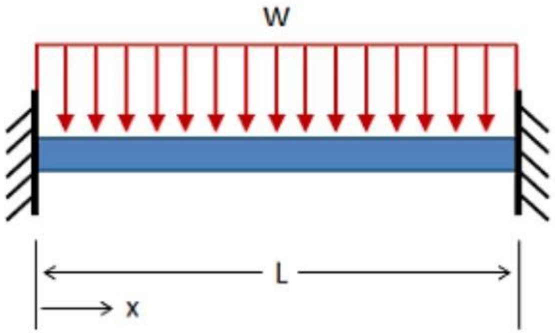


Base Plate

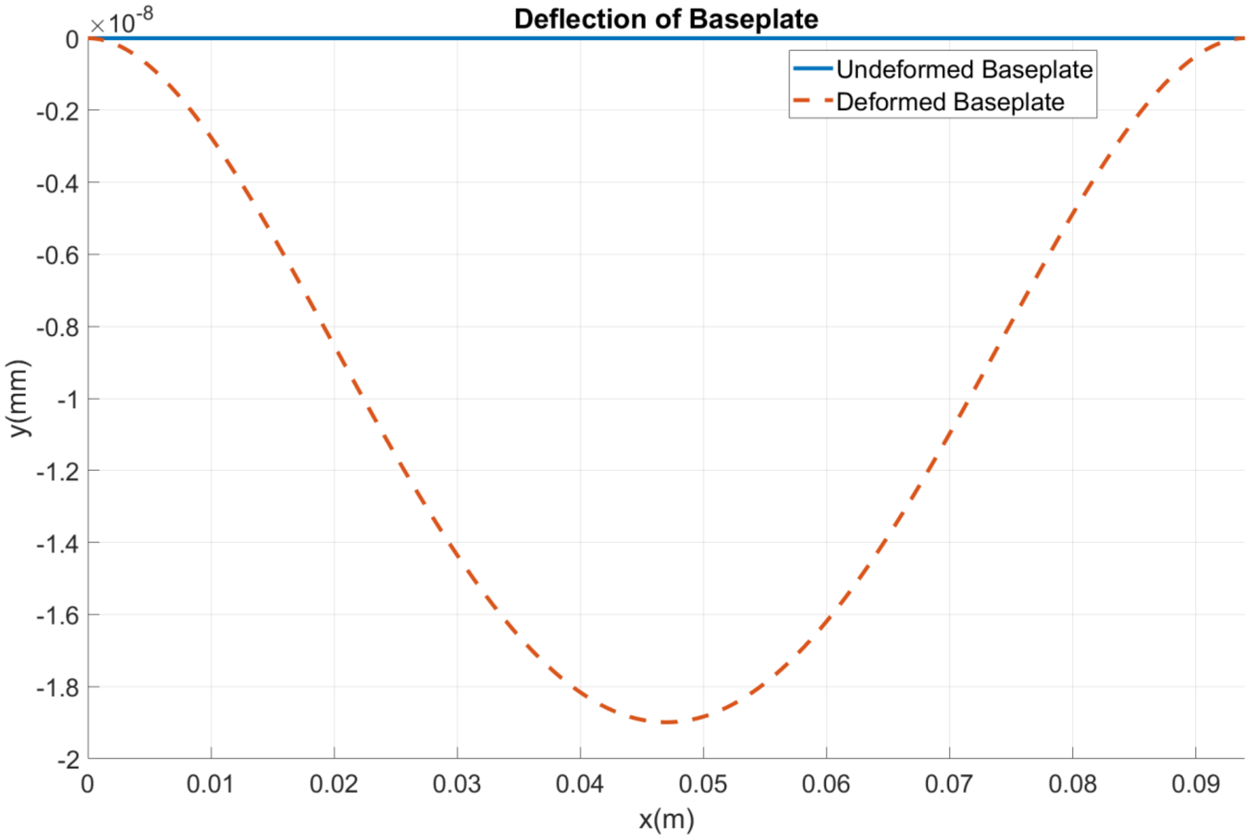
Feasibility of Mounting



Baseplate Beam Calculation



$$\delta = -\frac{wx^2}{24EI}(L-x)^2$$



- E = 69 GPa
  - 6061 Aluminum
- I = (b•d^3)/12 = 5.12e-8 m^2
  - b= 300 mm (Distance along rail)
  - D= 1.27 mm (Thickness of plate)
- L = 94 mm (Distance Between Bearings)
- w= 330 N (Weight of Arm/ End Effectors)

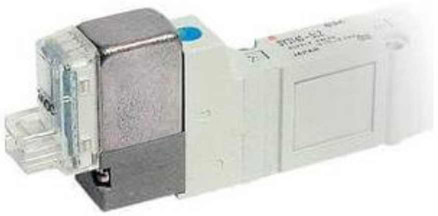
Torque Analysis Assumptions

- Gravitational moment distributed among farthest bearings.
- Max robotic motor torque 330 Nm evenly distributed amongst bearings.
  - Won't be running on max torque.
- Over estimate proves stage viability

Additional Components (End Effector)

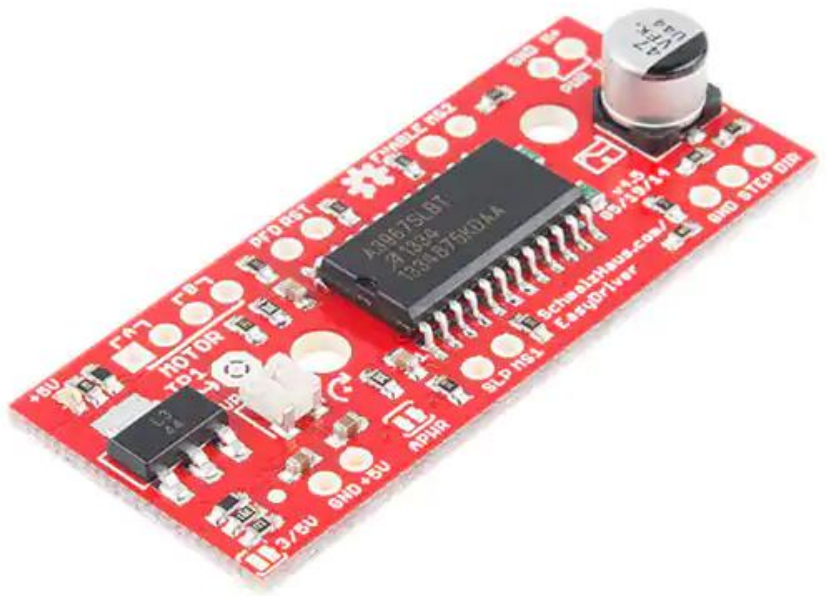
Components	Power Required
Manual Dump Valve, ¼ NPT	--
Filter/Regulator Combo, ¼ NPT	--
Electronic Dump Valve, 24v DC, ¼ NPT	0.35 W
0-160 psi gauge	--
Single Solenoid Valve	0.35 W
Speed Controller	--
¼" Tube to 10-32 straight connector	--
¼" Tube to ¼ NPT Elbow connector	--
1/4" Polyurethane Tubing, Black, 20 meters	--



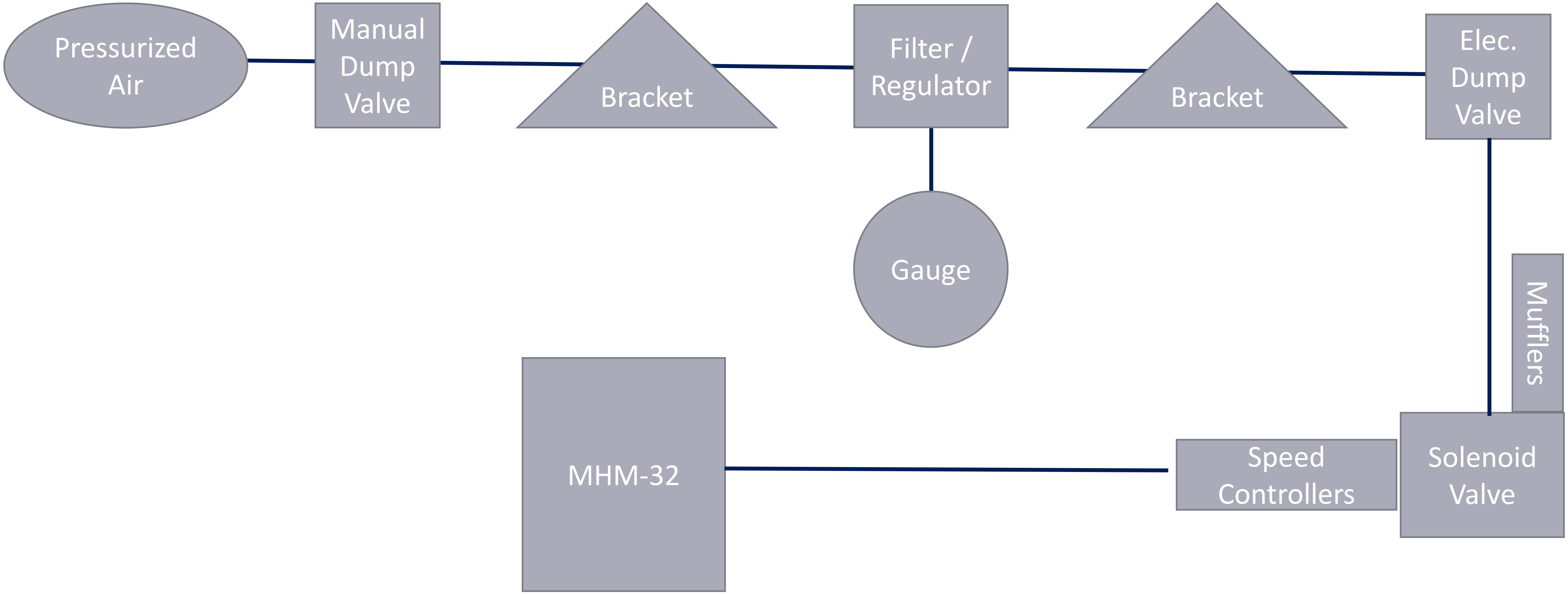



Solenoid Driver

- ROB-12779
  - Arduino Compatible
- Will use digital Logic from Arduino
- Enable line to Solenoid
- Powered from 24 V
  - Included with End Effector in power budget



Assembly Diagram (End Effector)



Robotic Arm

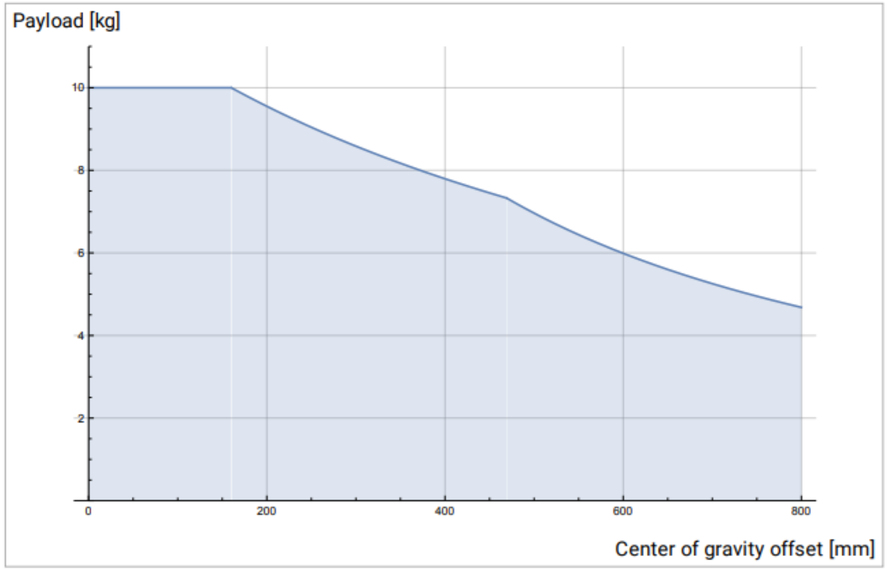
DR #	Req(s)
DR 1.2	Arm shall be able to maintain security of bags with a force of 10N
DR 6.1	Secure cargo for the duration of transit from the origin to the end of the track system.

- Show previous analysis for torque stall

Motor Torque-Speed Analysis

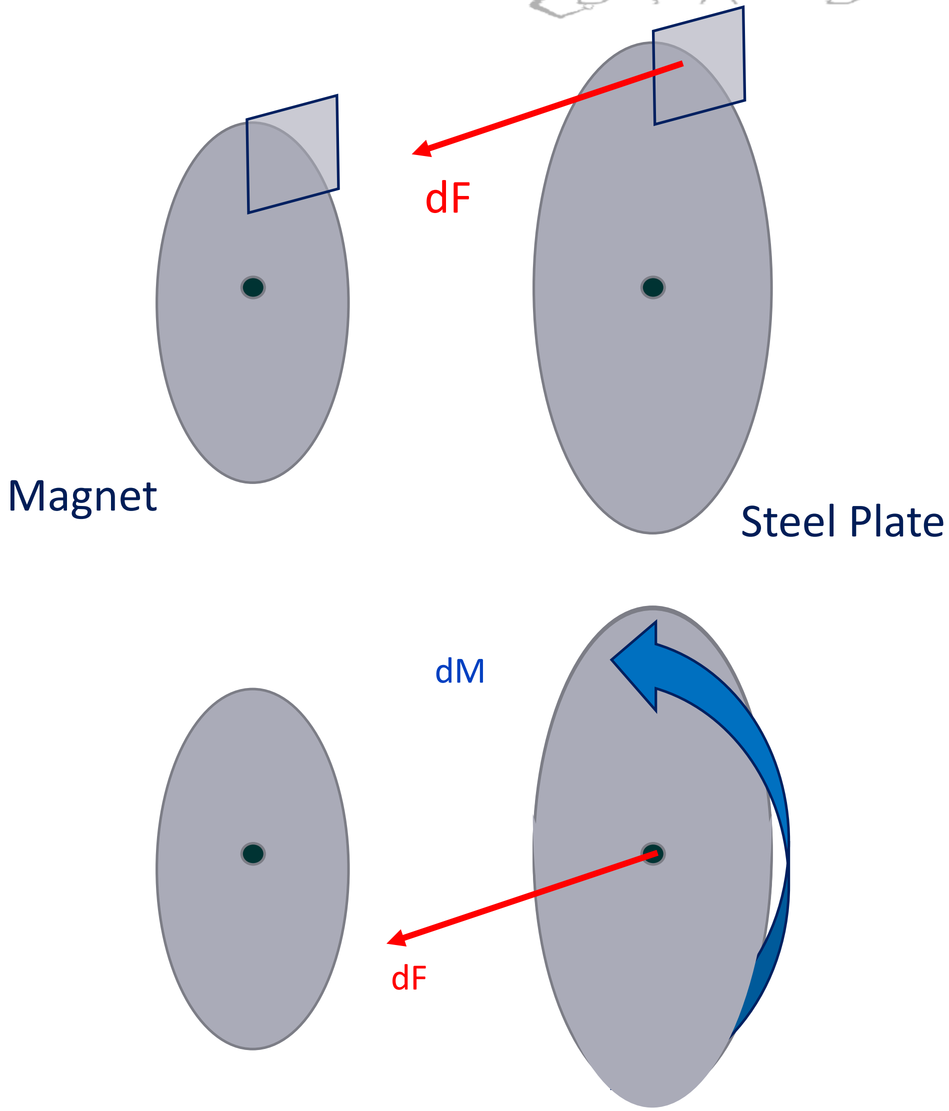
- Max speed is limited by manufacturer
  - Joint size 2,3: 180 deg/sec
  - Joint size 4: 120 deg/sec
- Motors are rated such that max speed is viable through the continuous torque range
- Max payload is dependent on the *center of gravity of offset*
  - *C.O.G. Offset:* Distance b/t payload c.o.g. and center of tool flange
  - With the given 1 kg payload the c.o.g offset can be up to .8 m, well within our parameters

Axis movement	Working range	Maximum speed
Base	± 360°	± 120°/s
Shoulder	± 360°	± 120°/s
Elbow	± 360°	± 180°/s
Wrist 1	± 360°	± 180°/s
Wrist 2	± 360°	± 180°/s
Wrist 3	± 360°	± 180°/s

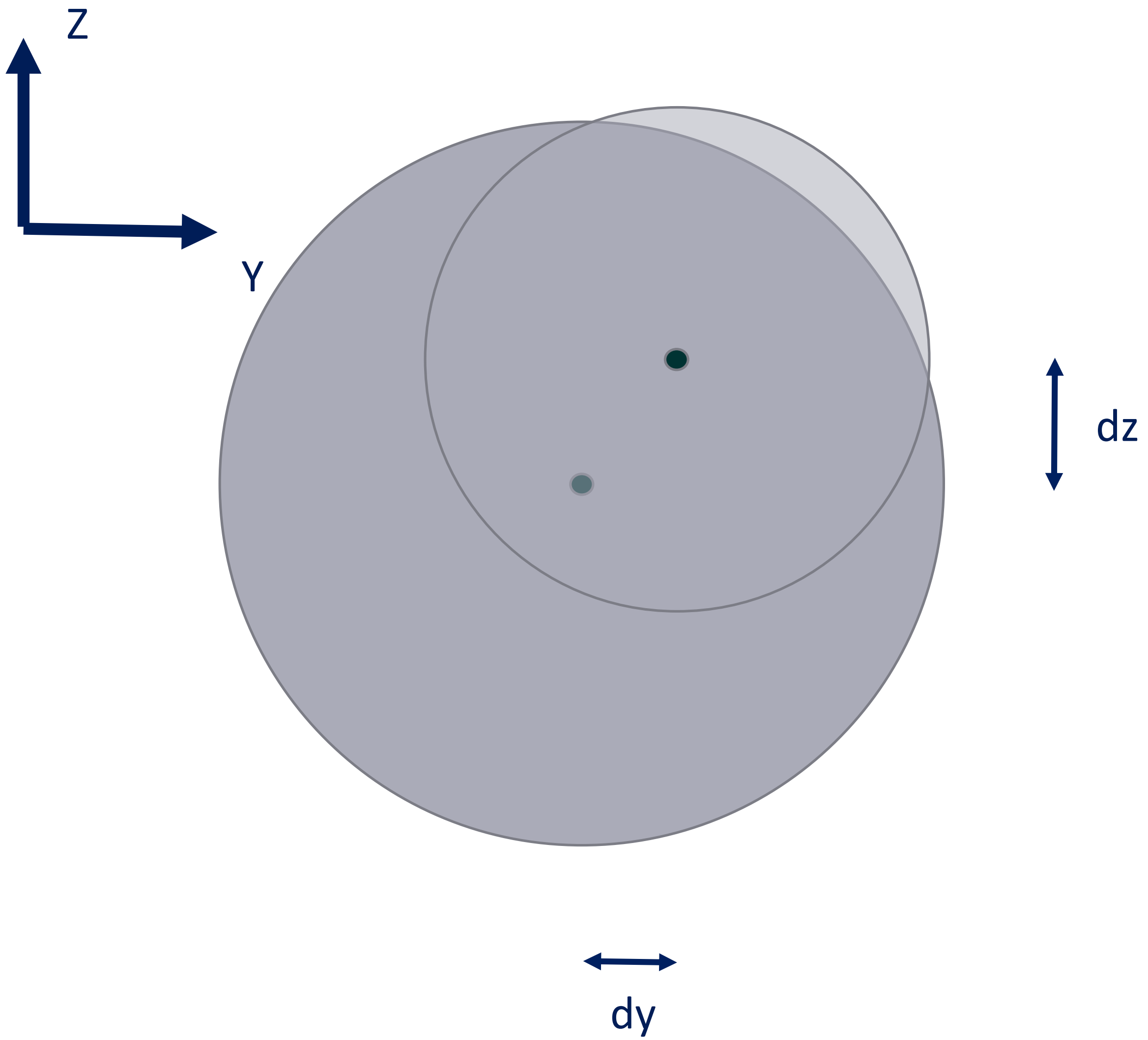


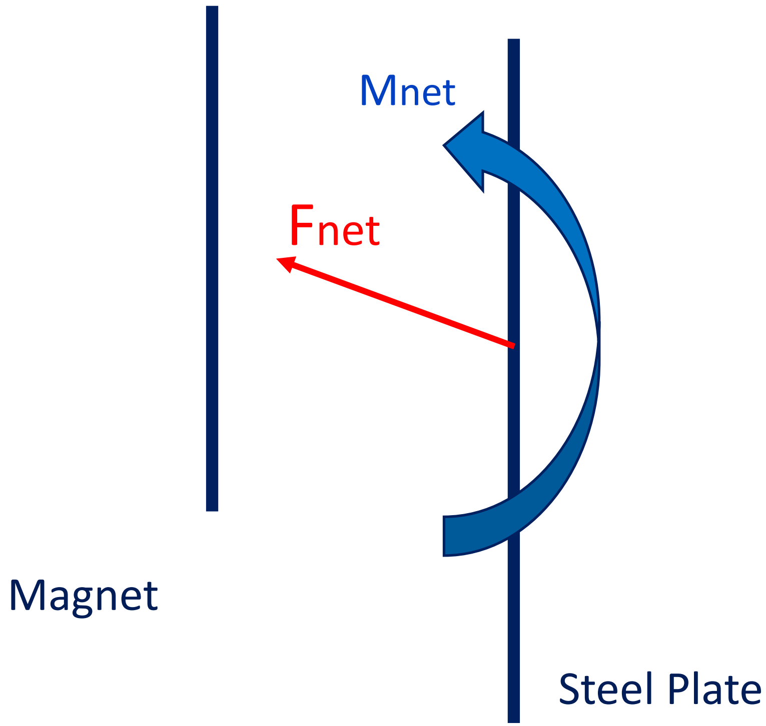
End Effector Magnetic Force Analysis

- Discretize magnet and steel plate
- Compute the force between each gridpoint of the magnet to each gridpoint of the steel plate
- Make an equivalent Force-Moment representation to get a net Force and net moment



End Effector Reaction Force Analysis

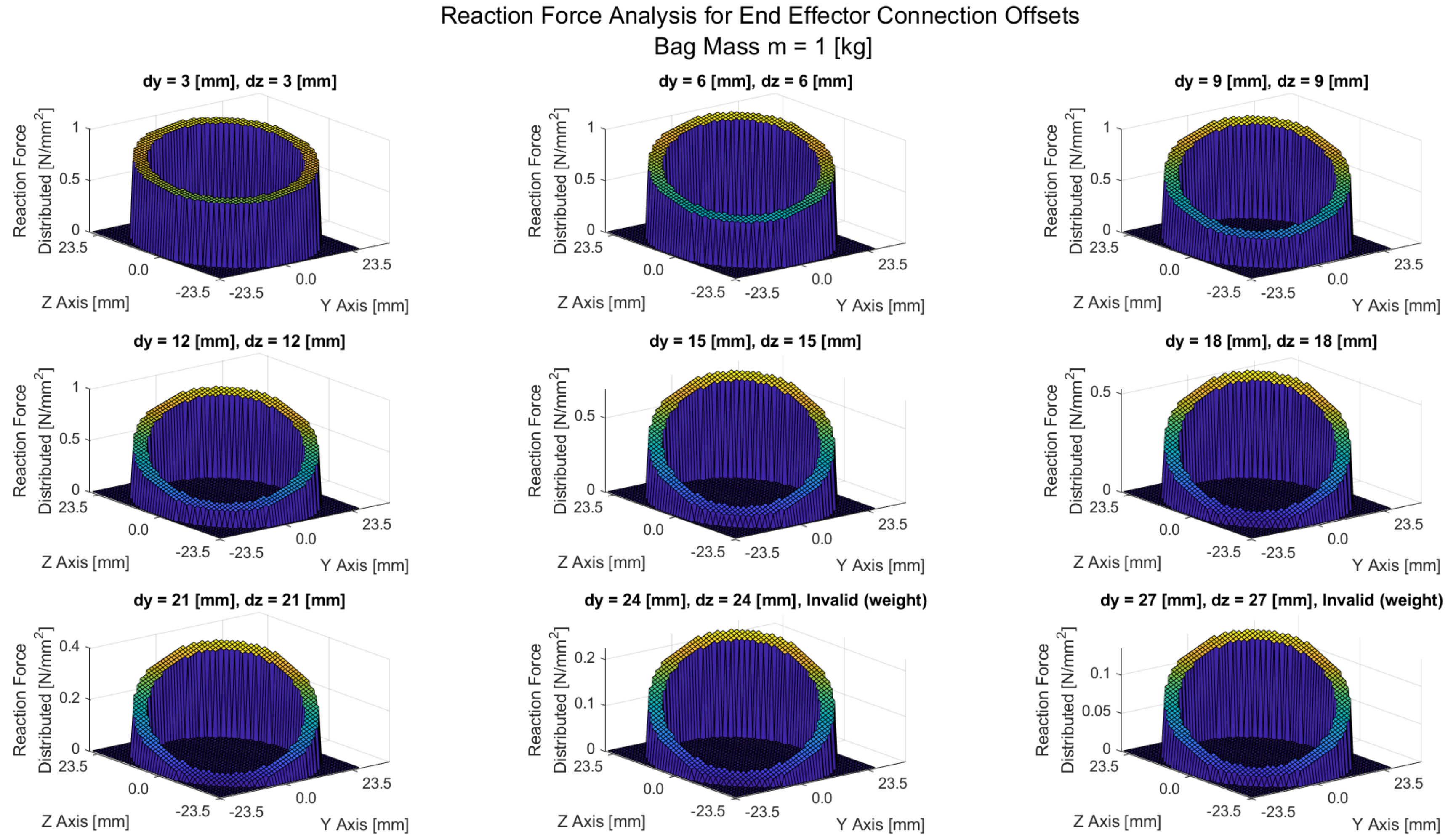




End Effector Reaction Force Analysis

- Reaction Force Form: $p(y,z) = az + by + c$
- Force Balance: $$\iint_{\text{Pad}} p(y,z)\,dydz = F_x$$
  - Solve for c
- Centroids: $$\bar{z} = \frac{\int\int zp(y,z)dydz}{\int\int p(y,z)dydz}$$ $$\bar{y} = \frac{\int\int yp(y,z)dydz}{\int\int p(y,z)dydz}$$
- Moment Balance: $$\bar{y}\iint_{\text{Pad}} p(y,z)\,dydz = M_z$$ $$\bar{z}\iint_{\text{Pad}} p(y,z)\,dydz = M_y$$
  - Solve for a and b

End Effector Reaction Force



DR #	Req(s)
DR 1.2	Arm shall be able to maintain security of bags with a force of 10N
DR 6.1	Secure cargo for the duration of transit from the origin to the end of the track system.

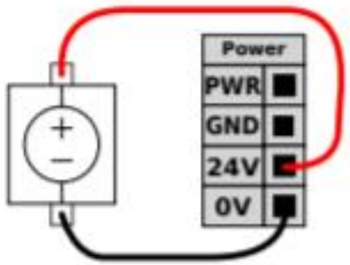
Steel Plate: d = 40 [mm]
$\mu = 0.1$

Robotic Arm Tech Specs

- Communication:
  - 500 Hz Control frequency
  - Modbus TCP
  - PROFINET
  - Ethernet/IP
  - USB 2.0, USB 3.0
- Operating Temperature Range 0-50°C

Extra Power to UR-10

If more current is needed, an external power supply can be connected as shown below.



- 24V 3A Power Supply Attached
  - Adds to 2 A included
- Total Power From 24V Rail
  - 5 A
  - 120 W
- Includes free wire adapter

USB Power

- Arduino
  - Includes 1 Meter USB 2.0
  - .05 A 5 VDC
- Pixy 2 Cameras
  - Micro USB
  - 1 Meter Included
  - .14 A 5 VDC
- USB Power Supply
  - 2.4 A per port for multiple devices

Power Budget Cont.

24VDC Rail				
Part	**Current [A]**	**Voltage[VDC]**	**Number of Parts**	**Power[W]**
Power Supply	3	24	1	72
UR-10	2	24	1	48
Stepper Motor	-3	24	1	-72
Limit Switch	-0.1	24	2	-4.8
MHM 25	-0.8233333333			-20.72
Total	1.076666667			22.48

5 VDC Rail				
Part	**Current [A]**	**Voltage[VDC]**	**Number of Parts**	**Power[W]**
USB Power Supply	20	5	1	100
Arduino	-0.05	5	1	-0.25
Pixy2	-0.14	5	10	-7
Total				92.75

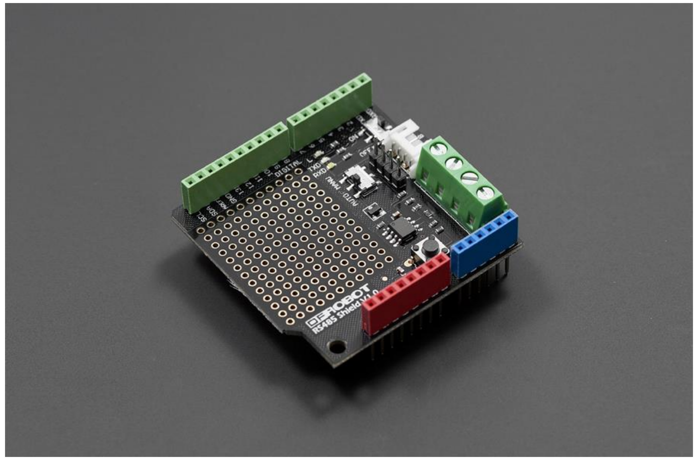
MHM 25 Breakdown				
Part	**Current [A]**	**Voltage[VDC]**	**Number of Parts**	**Power[W]**
D-M9PWV	-0.04	24	2	-1.92
Solenoid Driver	-0.75	24	1	-18
Solenoid	-0.01458333333	24		-0.35
Solenoid SY	-0.01875	24		-0.45
Total	-0.8233333333			-20.72

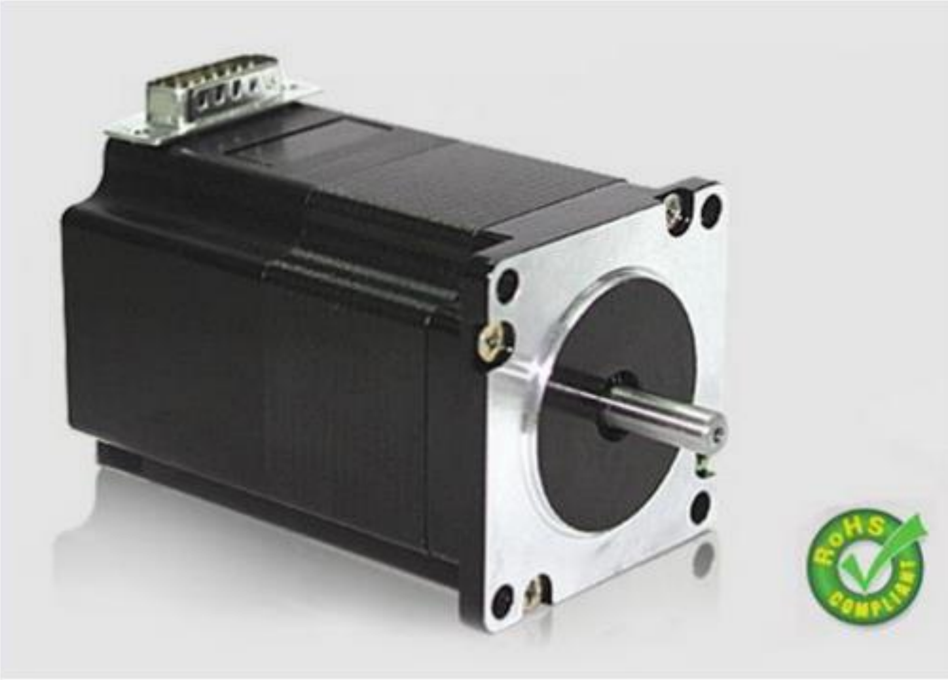
Voltage Rails	Parts
24 V	MHM 25, Stepper, Limit Switch
12 V	
5 V	Pixy 2, Arduino
30 V	

Stepper Motor

Silverpak 23C and 23CE
INTEGRATED STEP MOTOR, DRIVER AND CONTROLLER(CE)
(23CE With optional encoder feedback – closed loop)

- RS-485
  - Differential signal
- Arduino used as PLC
  - Serial commands converted from UART to RS-485
  - Receives corrected encoder data
- RS-485 Shield



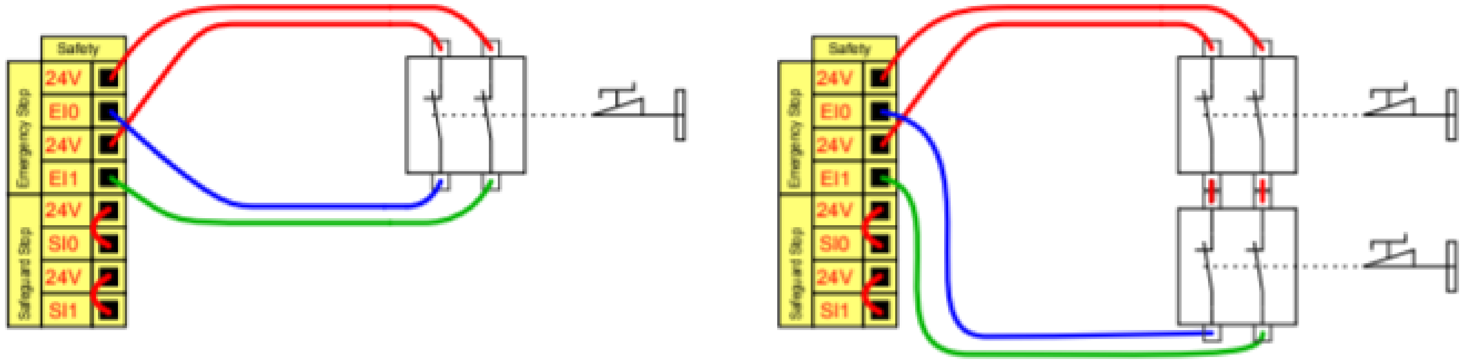


Limit Switch

- 2 Limit Switches
- Connected to emergency stop
- 2 Pin outs
- 24V limit switch selected.

4.3.2.2 Connecting emergency stop buttons

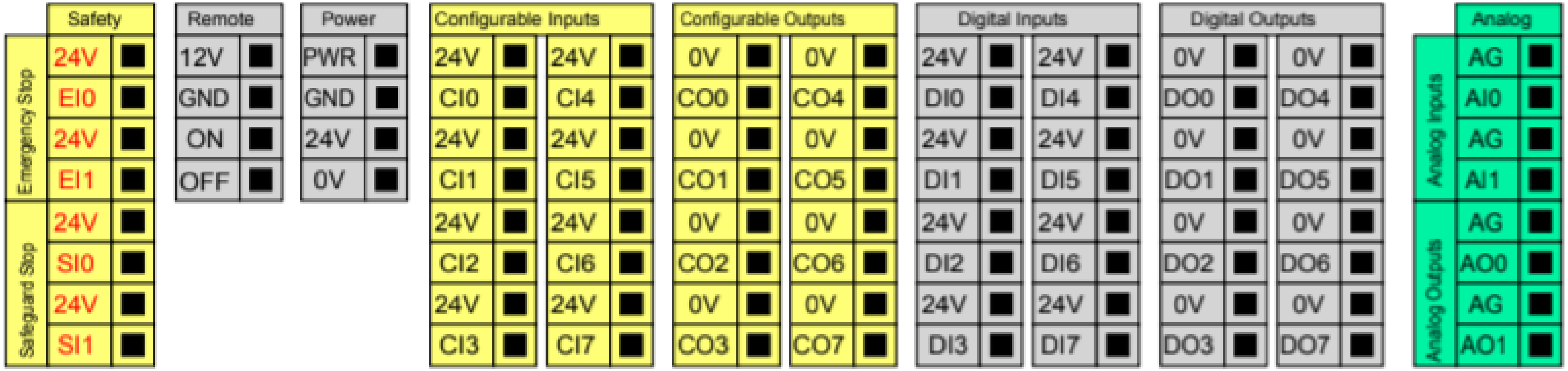
In most applications it is required to use one or more extra emergency stop buttons. The illustration below show how one or more emergency stop buttons.



Wiring

- 75 ft needed
  - 180 ft accounted for
- 24 Gauge Wire Selected
- 30 T2 connectors to split I2C and power lines

UR-10 Electronics Interface

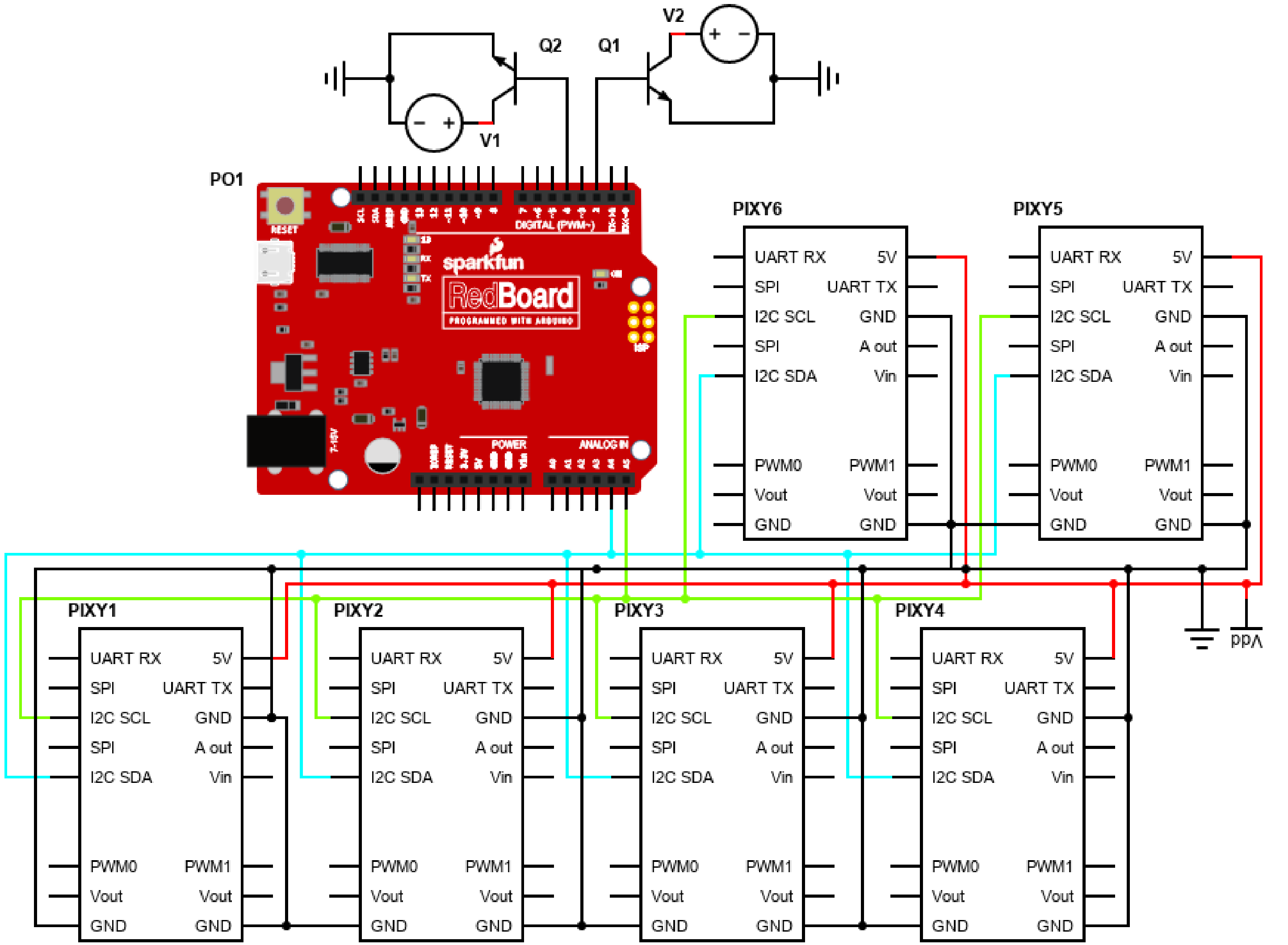


Arduino Uno Pin Out

Pin	Function	Device
RX0 (Pin 1)	UART RX	RS-485 Shield
TX0 (Pin 2)	UART TX	RS-485 Shield
Digital 3	Logic High/Low	Solenoid Driver
Digital 4	Logic High/Low	Auto Switch
Digital 10	SS	Ethernet Shield
Digital 11	MOSI	Ethernet Shield
Digital 12	MISO	Ethernet Shield
Digital 13	SCK	Ethernet Shield
Analog 4	SDA	Pixy2 Cameras
Analog 5	SCL	Pixy2 Cameras

Arduino Pin Out

- SDA
- SCL
- Power
- Ground



Sensor State Estimation

$$T = \begin{bmatrix} tan(\gamma) & 0 & 0 \\ 0 & tan(\theta) & 0 \\ 0 & 0 & 1 \end{bmatrix} \qquad \Delta = \begin{bmatrix} \frac{2}{\Delta x} & 0 \\ 0 & \frac{2}{\Delta y} \\ 0 & 0 \end{bmatrix} \qquad \vec{i} = \begin{bmatrix} 1 \\ 1 \\ -1 \end{bmatrix}$$

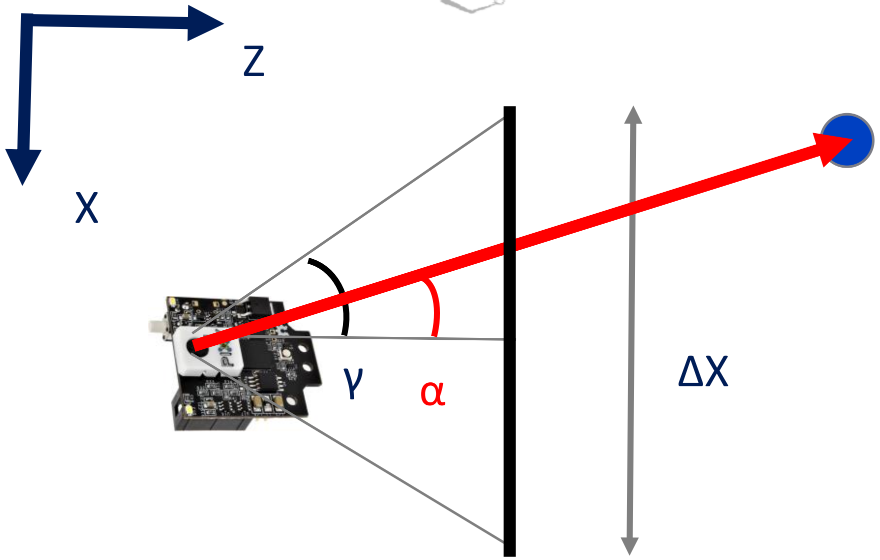
$$C = \begin{bmatrix} \hat{x}_C & \hat{y}_C & \hat{z}_C \end{bmatrix} =$$ Core Coordinate Frame Definition Matrix

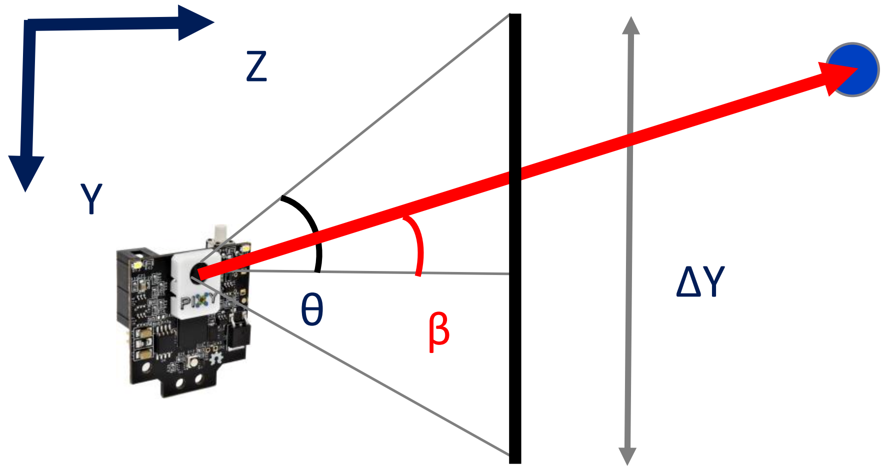
$$S = \begin{bmatrix} \hat{x}_s & \hat{y}_s & \hat{z}_s \end{bmatrix} =$$ Sensor Coordinate Frame Definition Matrix

$$\vec{s} = \begin{bmatrix} x_s & y_s & z_s \end{bmatrix} =$$ Sensor Position Vector

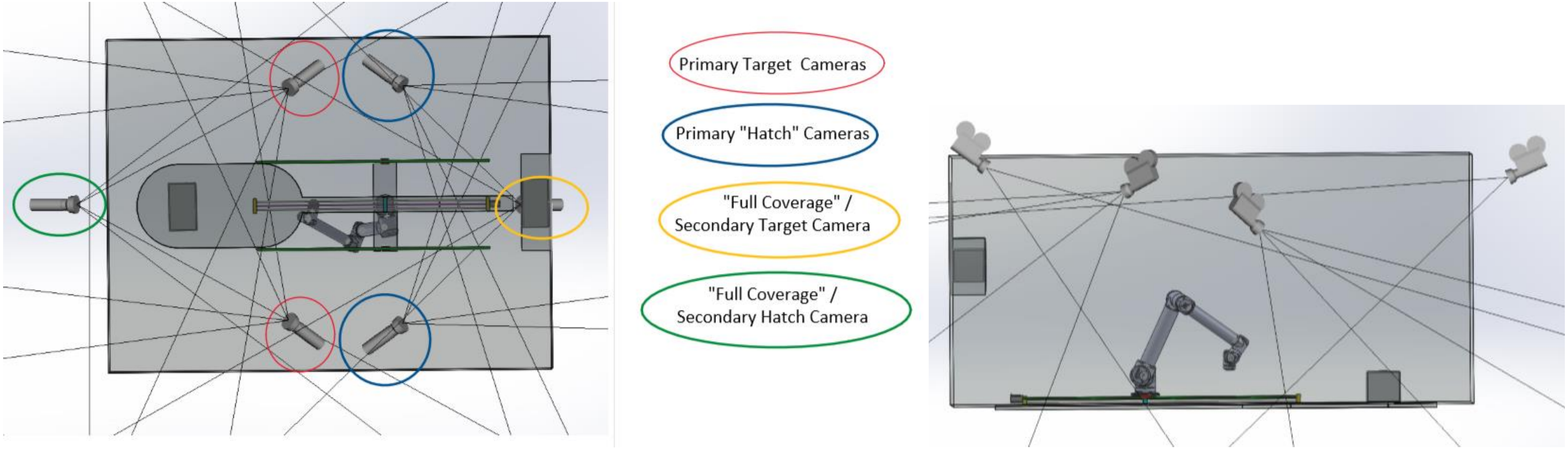
$$a = \hat{z}_s C^T(\mathbf{x} - \vec{s}) =$$ Proportionality Constant

$$\hat{y}(k) = (\Delta^T\Delta)^{-1}\Delta^T(\frac{1}{a}T^{-1}S^TC^T(\mathbf{x} - \vec{s}) + \vec{i})$$





Pixy2 Placement: 6-Cam System



Pixy Locations

				Camera 4					
X (meters)	+0.50	+0.56	+0.56	+0.50	+2.23	3.21	3.8	3.19	2.22
Y	-0.55	+0.52	+0.52	-0.55	-1.16	-0.54	-0.22	-0.54	-1.16
Z	-0.98	-0.60	+0.60	0.98	0.61	0.98	0	0.99	-0.6

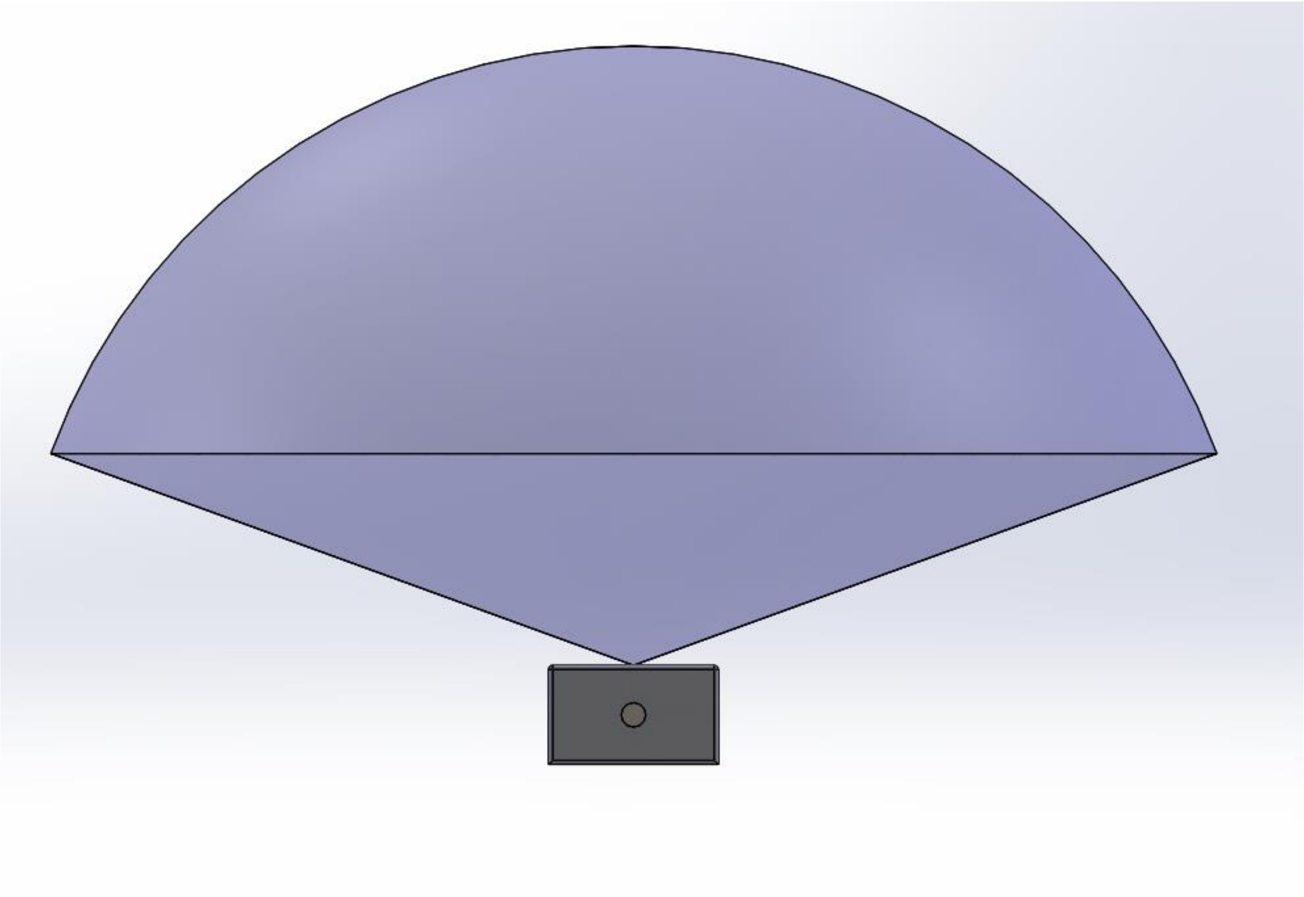
0.25 m into the center of the hatch

Pixy Locations – Center of Hatch

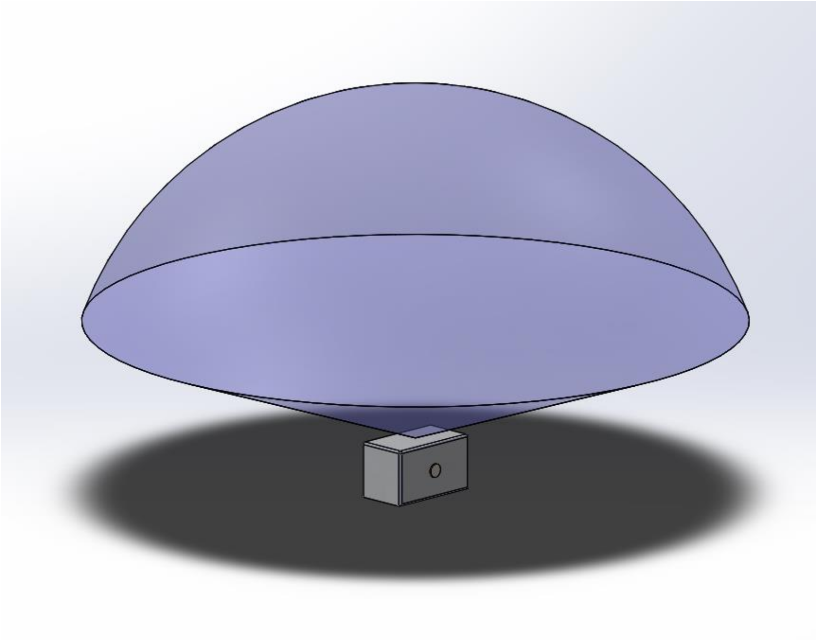
				Camera 4					
X (meters)	+0.25	+0.31	+0.31	+0.25	+1.975	2.96	3.55	2.94	1.975
Y	-0.55	+0.52	+0.52	-0.55	-1.16	-0.54	-0.22	-0.54	-1.16
Z	-0.98	-0.60	+0.60	0.98	0.61	0.98	0	0.99	-0.6

X is normal to hatch-plane
Y is vertical up down in hatch-plane
Z is horizontal left-right in hatch-plane

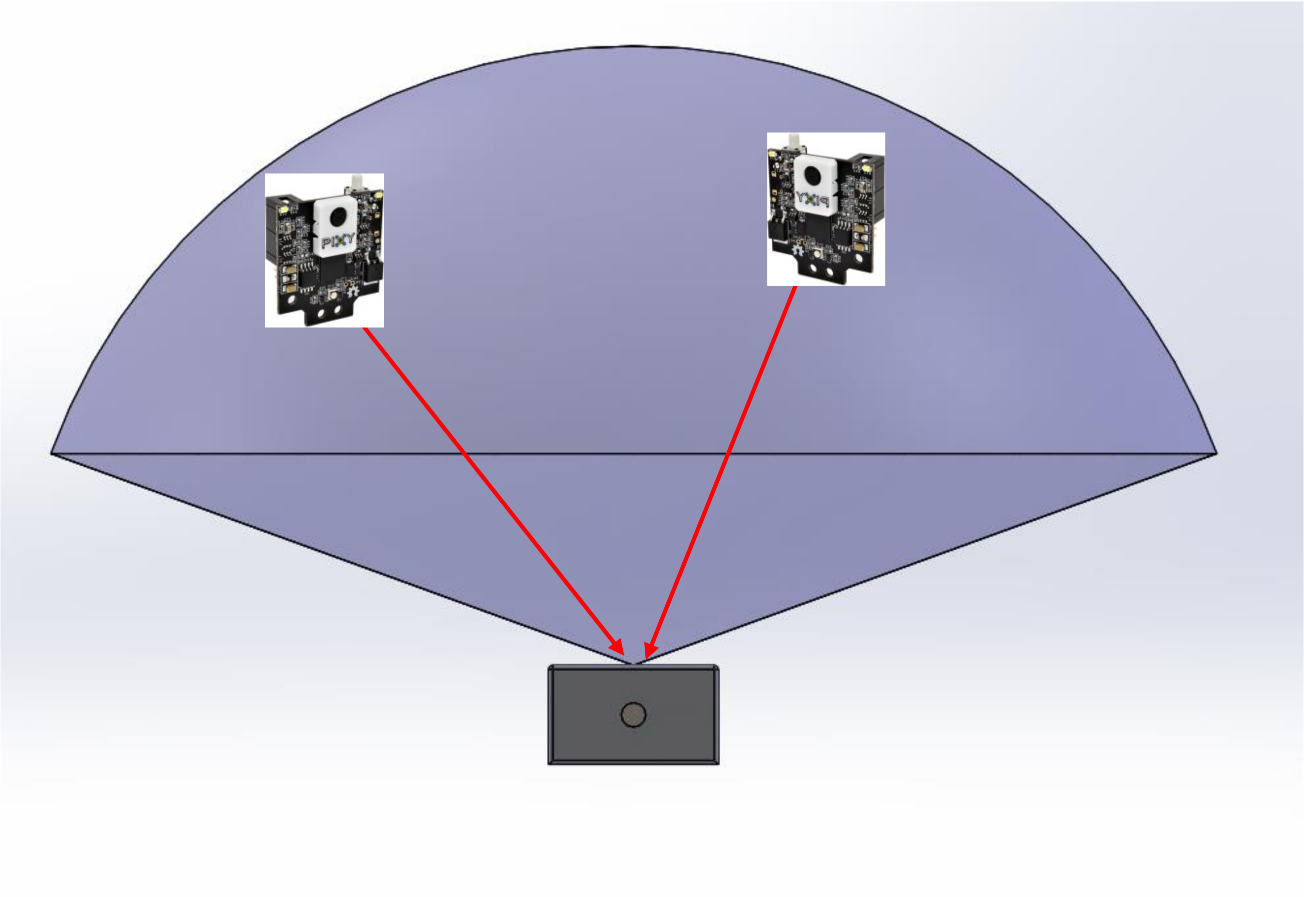
Viewing Regions



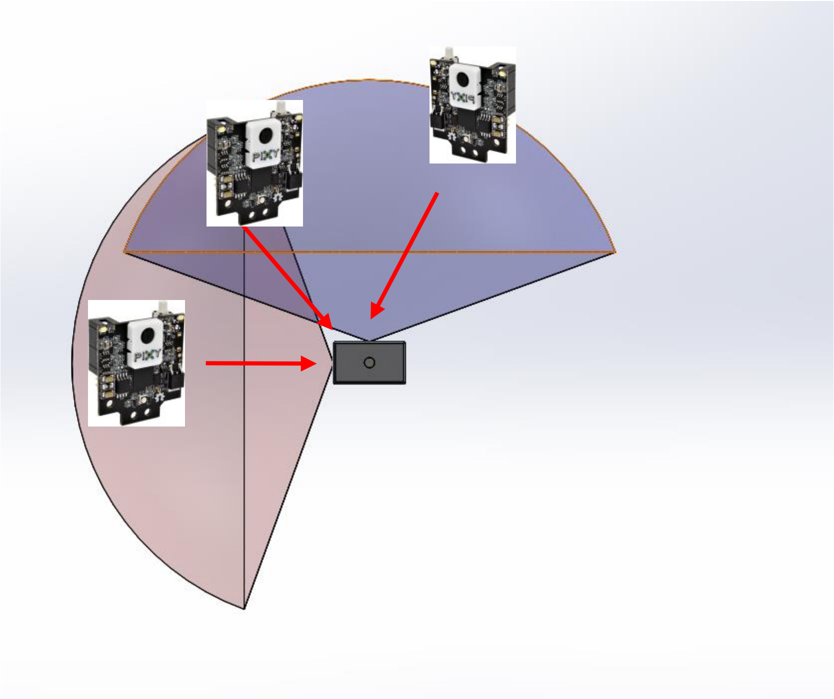
- Dependent on viewing distance and maximum incident angle
- Regions repeat every 90 degrees



Camera Angles



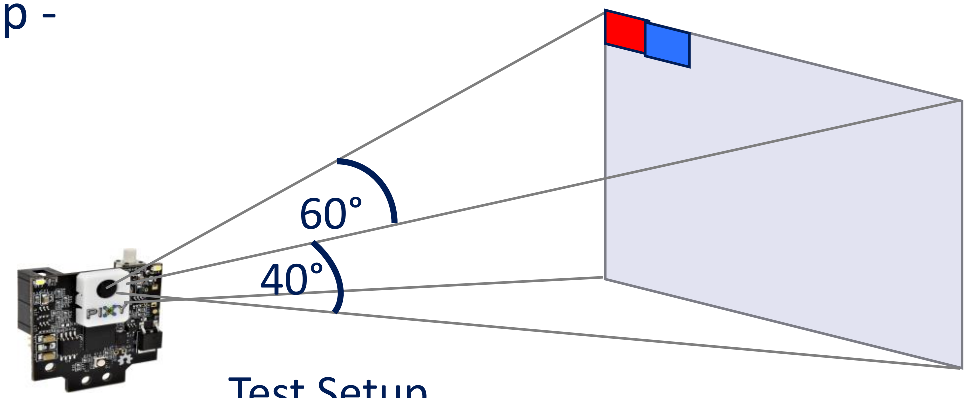
- 2 Cameras in the same region will see the same face
- Angle between 2 Cameras must be less than 90 degrees



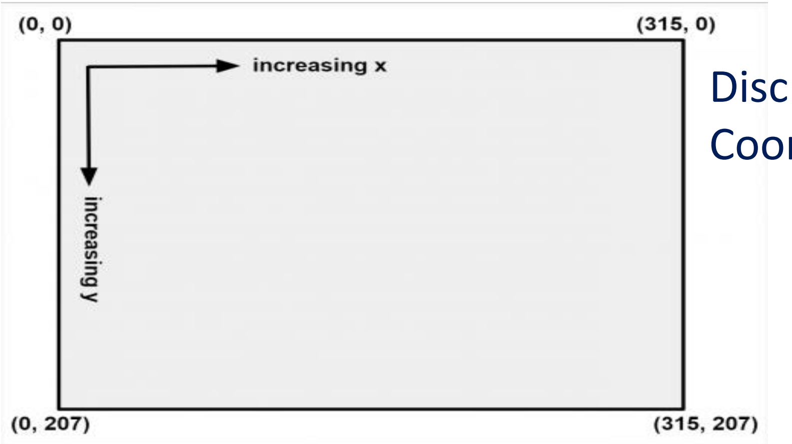
Sensor Suite

DR.3.1	The system shall identify a cargo bag with its orientation and position.	
DR.3.2	The system shall be able to determine if the cargo has reached the target location	
DR.3.3	The operating system shall be able to determine if the cargo is irretrievable.	
DR.3.4	The system shall give feedback if the transportation has failed and cease operations.	
DR.6.1	The end-effector shall secure cargo for the duration of all translation and rotation required for a task.	

- Satisfaction of the above dependent upon Pixy 2 uncertainty
- Setup -

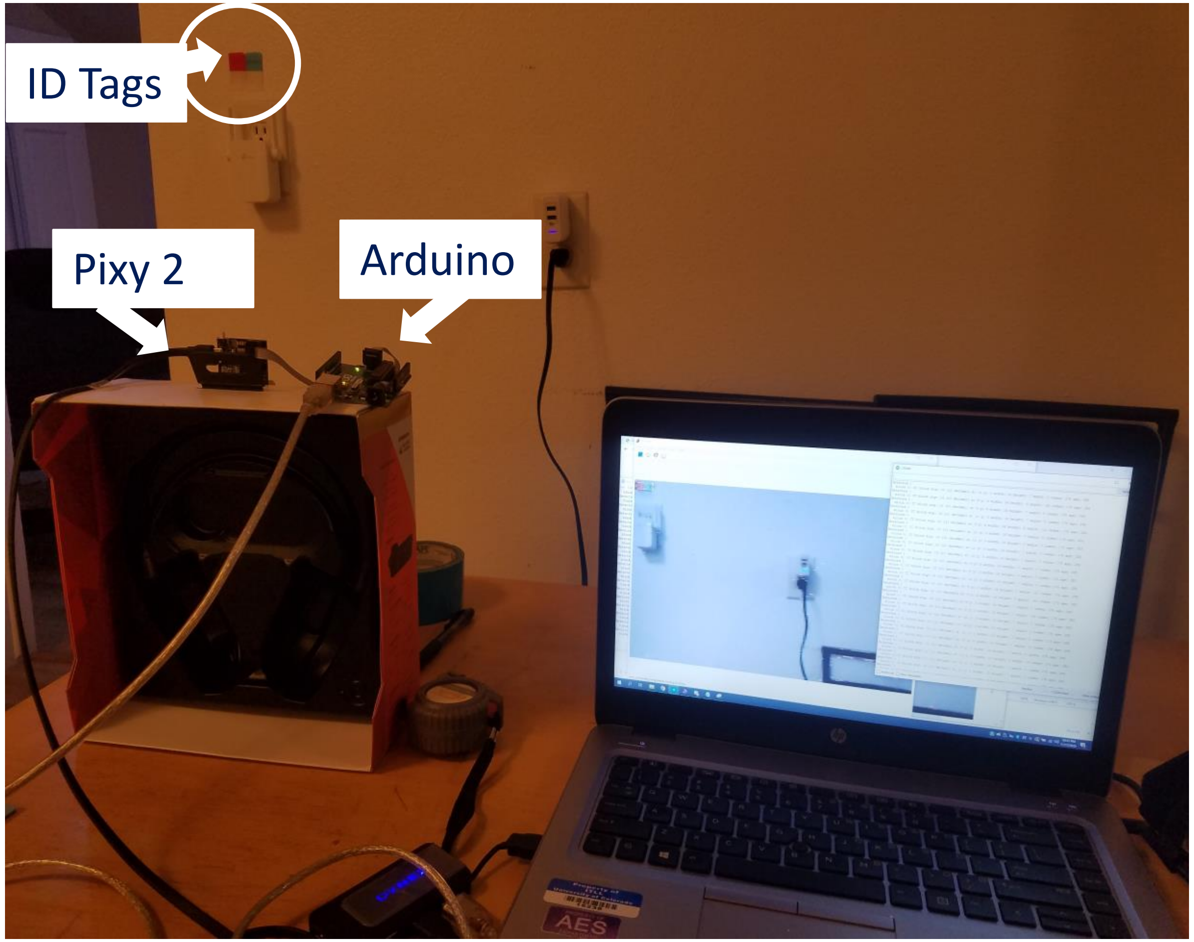


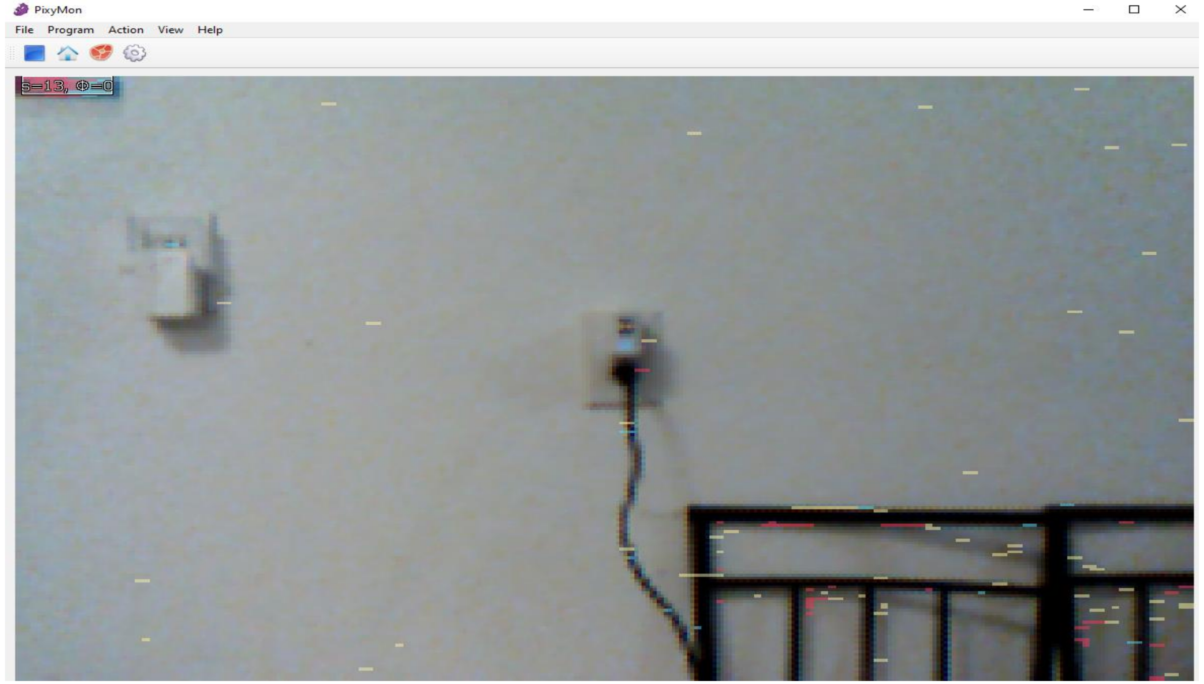
Test Setup



Discretized Pixel Coordinates

Test Setup





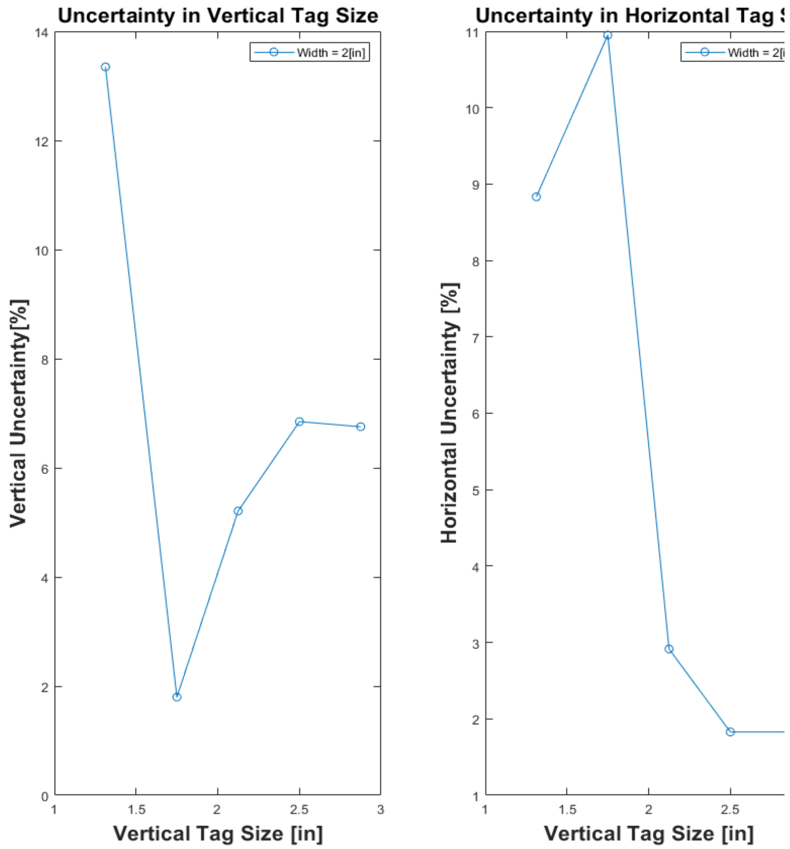

```
Detected 1
  block 0: CC block sig: 12 (10 decimal) x: 15 y: 5 width: 26 height: 6 angle: -4 index: 218 age: 255
Detected 1
  block 0: CC block sig: 12 (10 decimal) x: 16 y: 4 width: 28 height: 5 angle: -11 index: 218 age: 255
Detected 1
  block 0: CC block sig: 12 (10 decimal) x: 15 y: 4 width: 26 height: 5 angle: 0 index: 218 age: 255
Detected 1
  block 0: CC block sig: 12 (10 decimal) x: 15 y: 4 width: 26 height: 5 angle: 0 index: 218 age: 255
Detected 1
  block 0: CC block sig: 12 (10 decimal) x: 15 y: 5 width: 26 height: 6 angle: -11 index: 218 age: 255
Detected 1
  block 0: CC block sig: 12 (10 decimal) x: 14 y: 4 width: 28 height: 5 angle: 4 index: 218 age: 255
```

Uncertainty Results

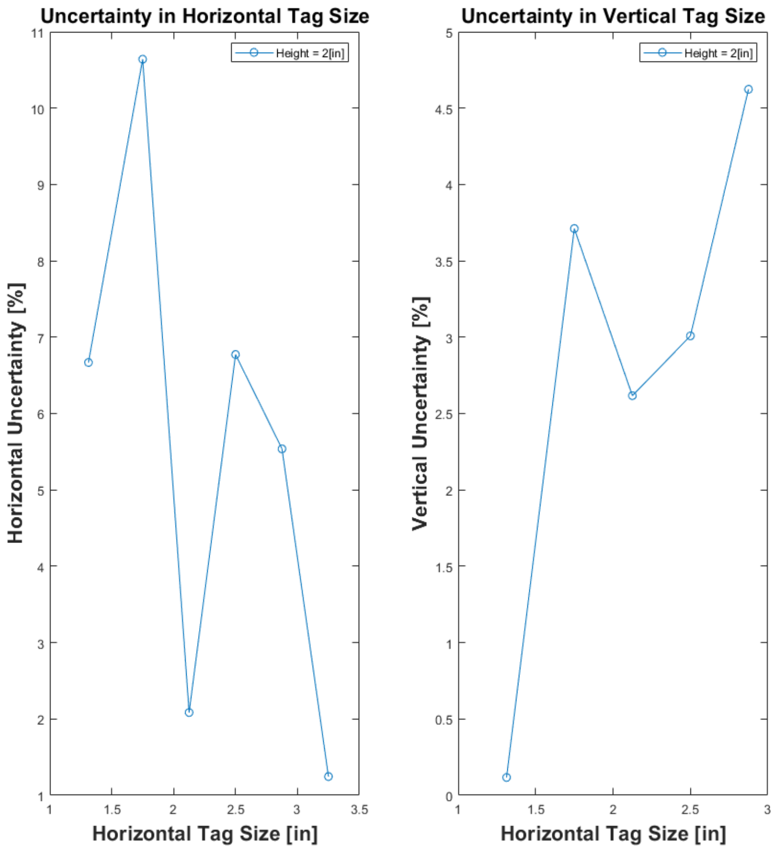
1) Test #	2) Distance to wall [in]	3) Individual Tag Dimensions [in]	4) Plane Width [in]	5) Physical Tag Width %	6) Pixel coordinate	7) Pixel Tag Width %	8) Error [%]
1	27.5"	1" x 7/8"	31.75"	3.149%	10.22	3.245%	3.05%
2	41.125"	1" x 7/8"	47.487"	2.125%	7.667	2.433%	13.2%
3 (old settings)	41.125"	2" x 7/8"	47.487"	4.25%	14.83	4.709%	10.8%
4 (new settings)	41.125"	2" x 7/8"	47.487"	4.25%	12.65	4.016%	5.50%
5	61"	2" x 7/8"	70.437"	2.839%	9.45	3.000%	5.67%
6	61"	2" x 1 3/8"	70.437"	2.839%	9.25	2.937%	3.45%
7	85.5"	3" x 1 3/8"	98.727"	3.039%	10.15	3.222%	6.03%

Uncertainty Based on Tag Size

Varying Height With Constant Width



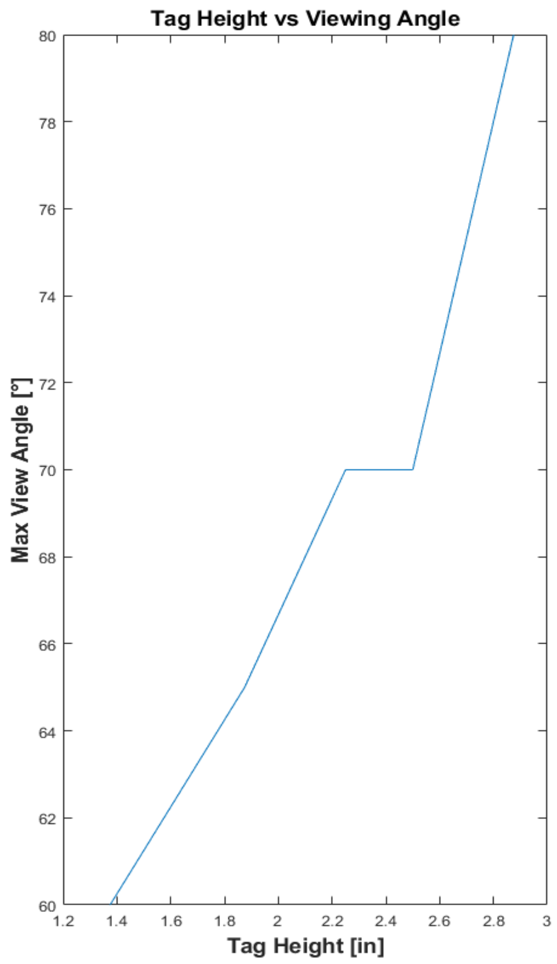
Varying Width With Constant Height

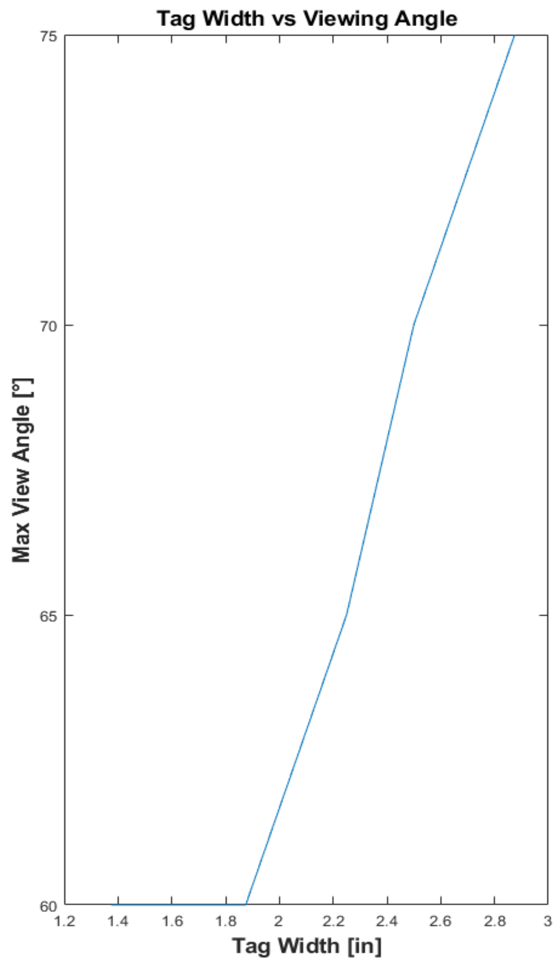


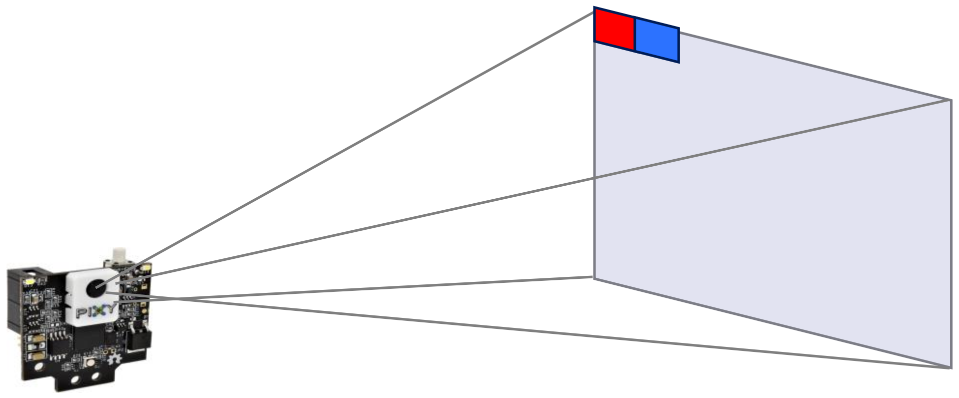
Horizontal accuracy proportional to tag width and height
Vertical accuracy dominantly proportional to tag height
Tests evaluated with default sensitivity settings
Accuracy can still be improved

- Tweak sensitivity and range
- Improved Lighting
- Better test setup

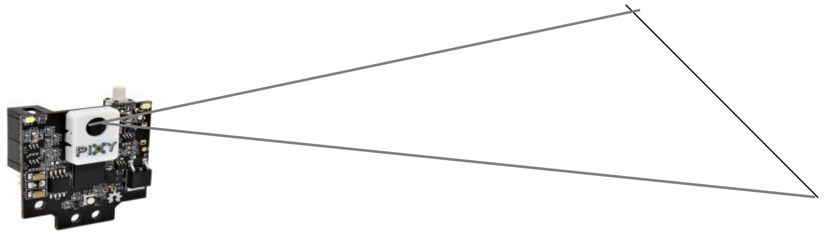
Pixy Viewing Angle Determination





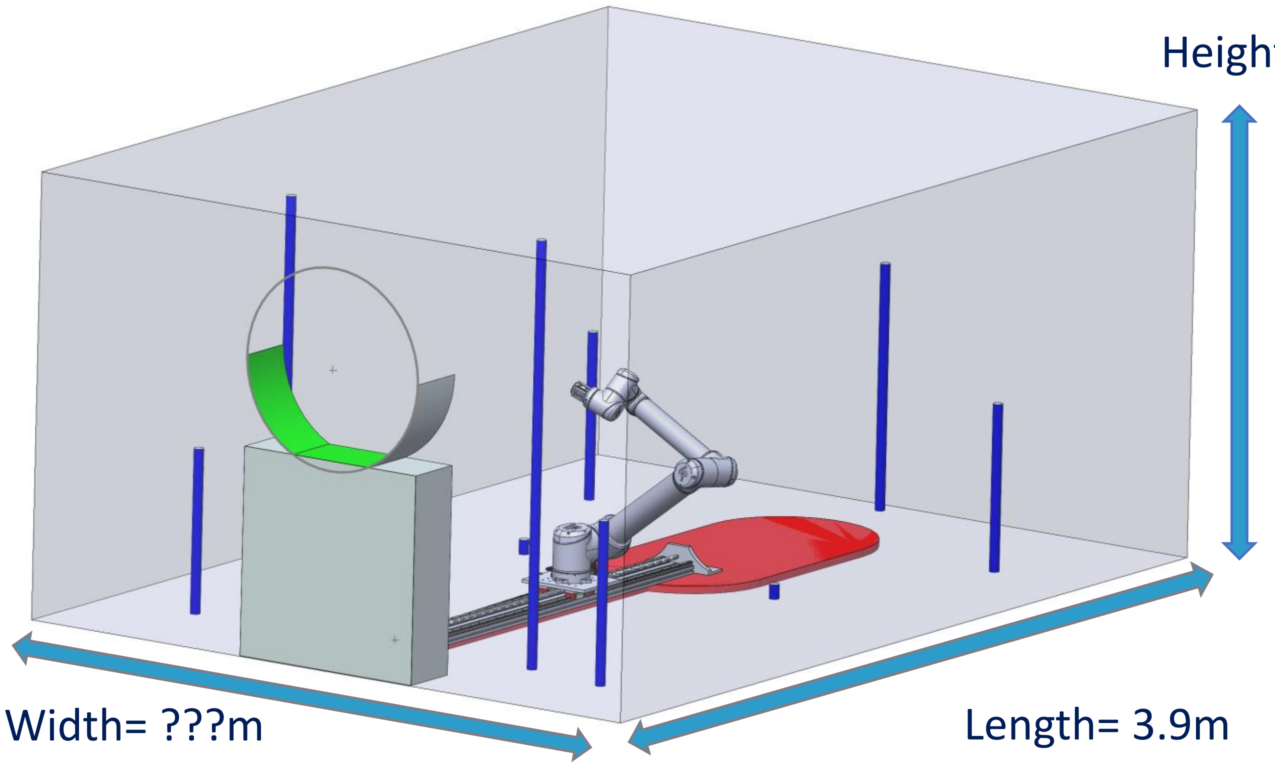


0 ° degree viewing angle



90 ° degree viewing angle

Testing Set Up Version 1



Capture Area

Release Area

Camera Stands

Cameras mounted using square, telescoping rods

Measurements

Measurement	Key Issues	Design Solution
Cargo Bag Images	Image coverage must include at least 3 faces of the bag for orientation determination	Allocate 4-5 cameras for the capture and release locations
	Resolution of bag	Pixy2 Cameras are placed within 1.3 meters of the capture and release locations
	Microcontroller processing limits for data from 10 cameras	Arduino is capable of handling around 15 Pixy2 Cameras
Environment Images	Obstructions to camera views and arm's path	Combination of camera views of entire environment and RViz
Translator: Encoder/ Push Sensor Data	Microcontroller can process limits for translator in addition to sensor system	Arduino is capable of processing data from translator in addition to the 10 cameras

Camera System Verification

Objective:

1. Test Sensory Modeling
2. Verify Arduino can handle heavy processing power

Plan:

- Vary Cargo Bag orientations and positions with the capture and release locations
- Simultaneously communicate data from all the Pixy2 Cameras to the Arduino