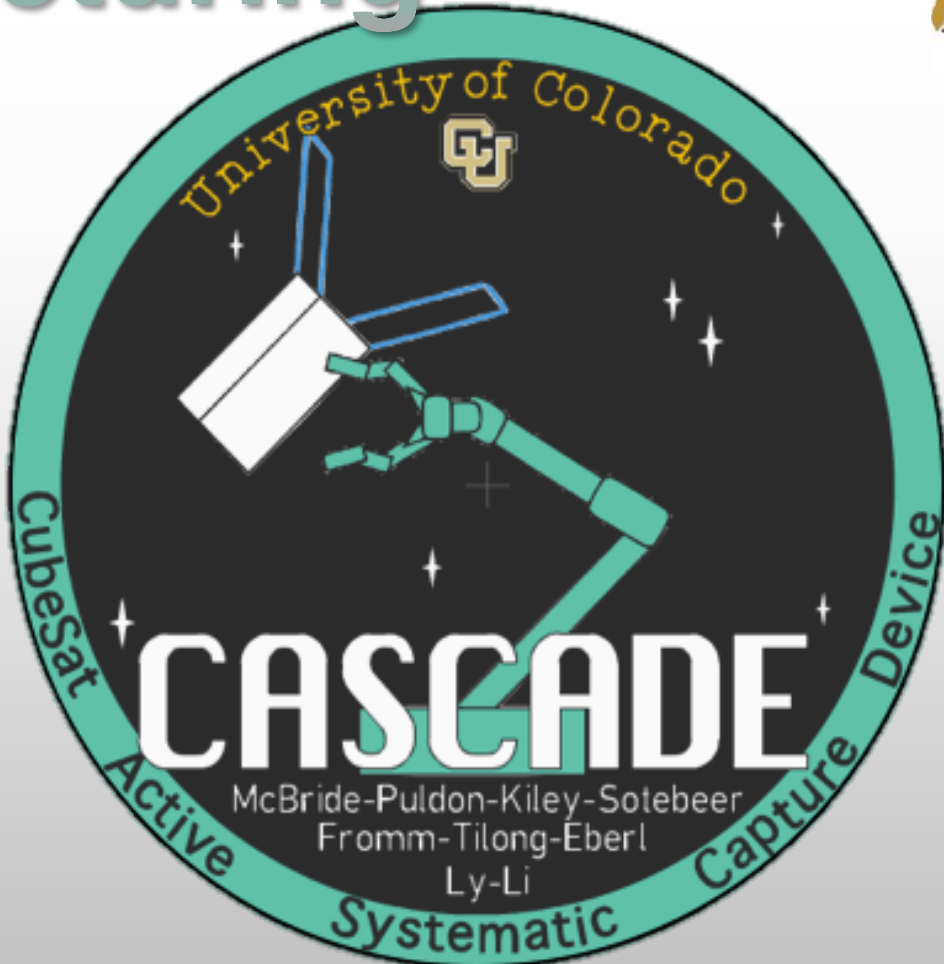
Manufacturing Status Review



<u>Team</u>: Chad Eberl, Matthew Fromm, Timothy Kiley, Tony Ly, Haoyu Li, Andrew McBride, Noel Puldon, Keegan Sotebeer, Morgan Tilong

<u>Customer</u>: Henry "Lad" Curtis (Sierra Nevada Corp.)

<u>Advisor</u>: Dr. Jelliffe Jackson

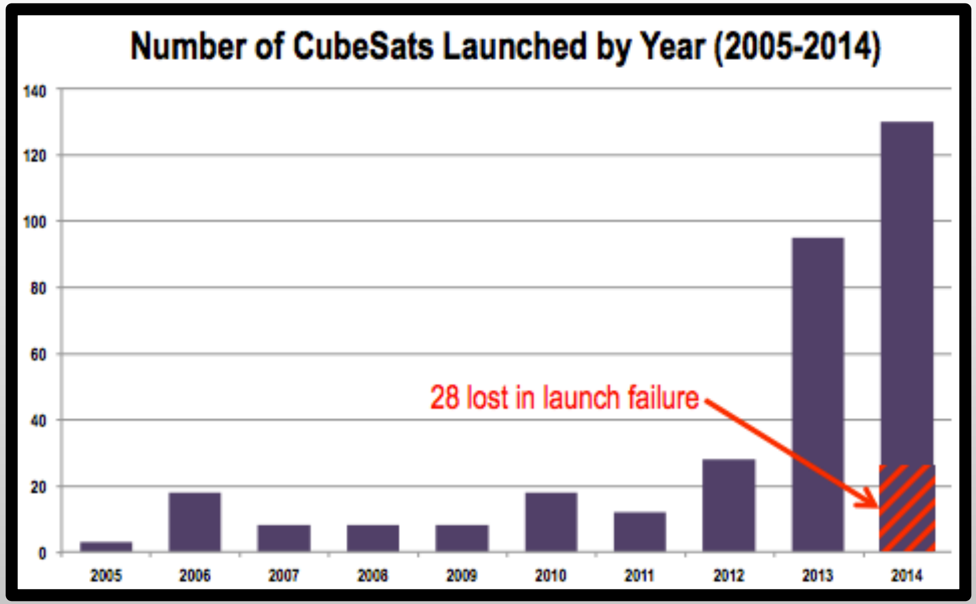
Project Overview

Project Motivation

- With the growing industry for CubeSats a method of capturing an uncontrollable CubeSat is desirable.

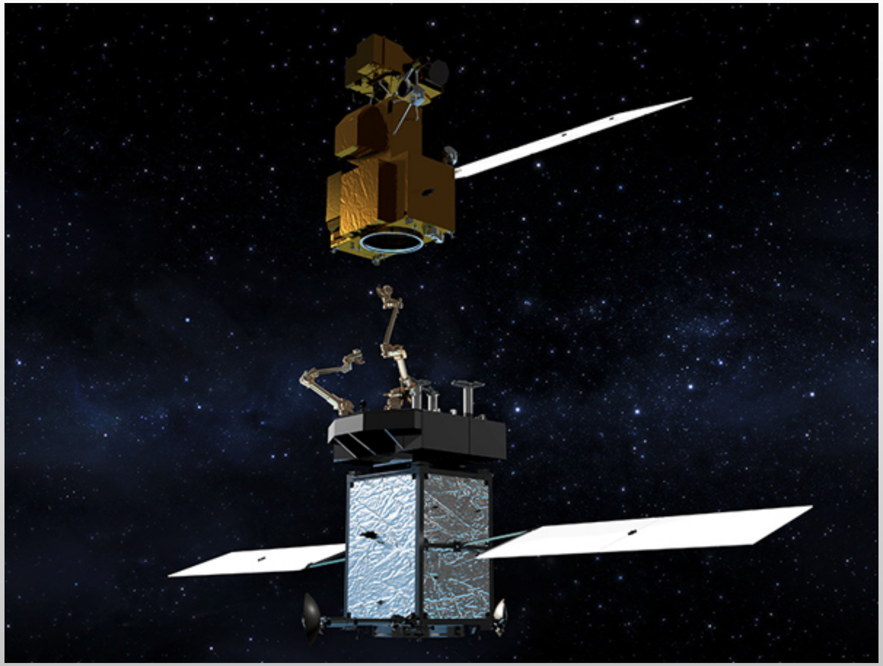
- Existing CubeSats have little or no propulsive capabilities, with no ability to change the orbit drastically and leaving them stuck if major failures occur.

- Sierra Nevada Corporation would use a capture device and vision system in order to **recover** and **repurpose** CubeSats.



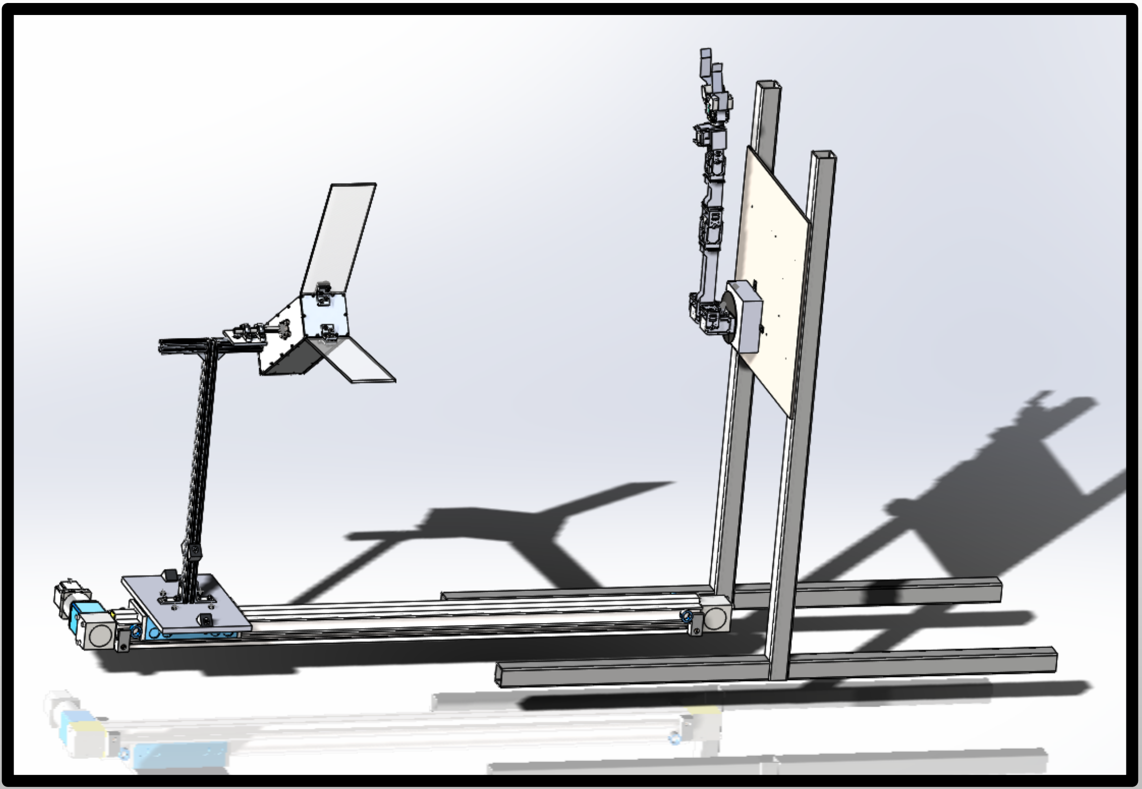
Project Statement

Team CASCADE will demonstrate the implementation of an algorithm to **autonomously** capture a rotating 3U CubeSat model.



In order to accomplish this goal, Team CASCADE will design and build a CubeSat Recovery System Testbed (**CRST**) used to validate both the **algorithm** and a physical **capture device**.

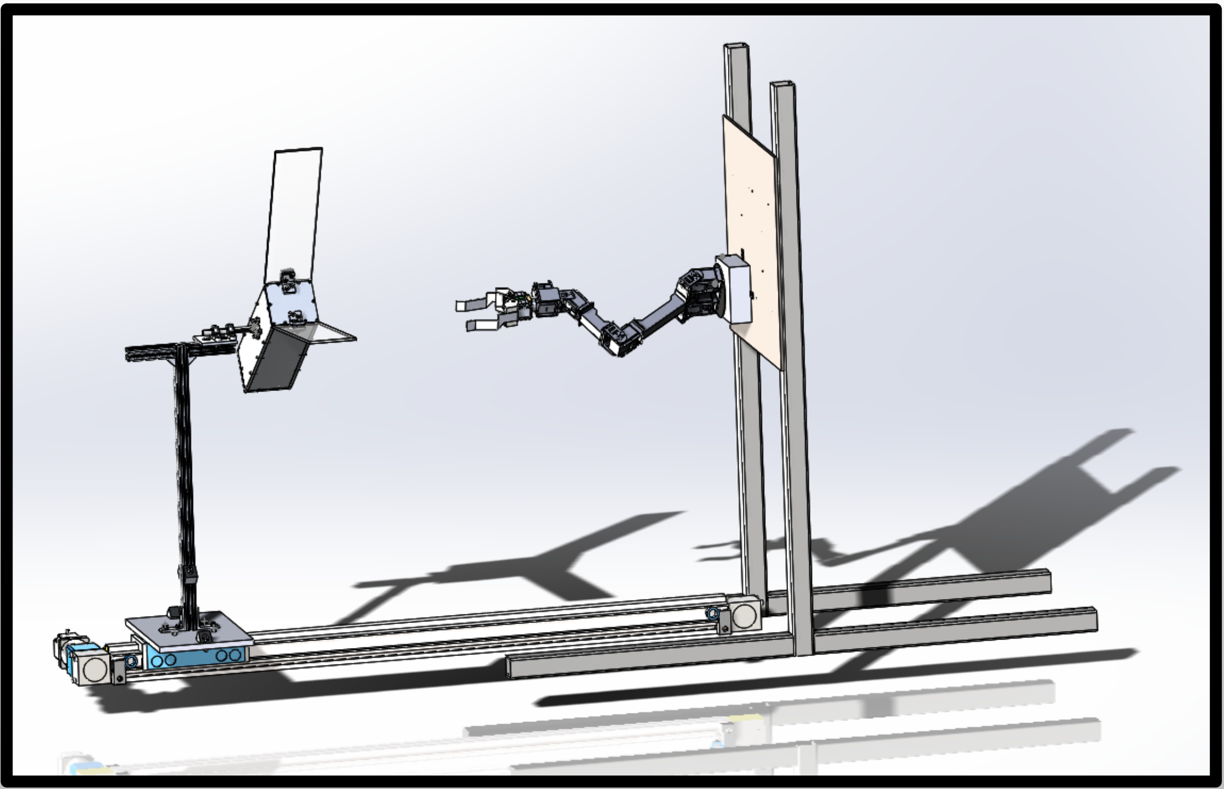
Test Bed CONOPS



<u>0.) Initiation of Demonstration</u>

- Arm stowed in zero torque configuration
- Vicon Cameras start transmitting data to LabView on a personal Laptop
- LabView used to start the rotation of the CubeSat
- CubeSat starts 1 meter away

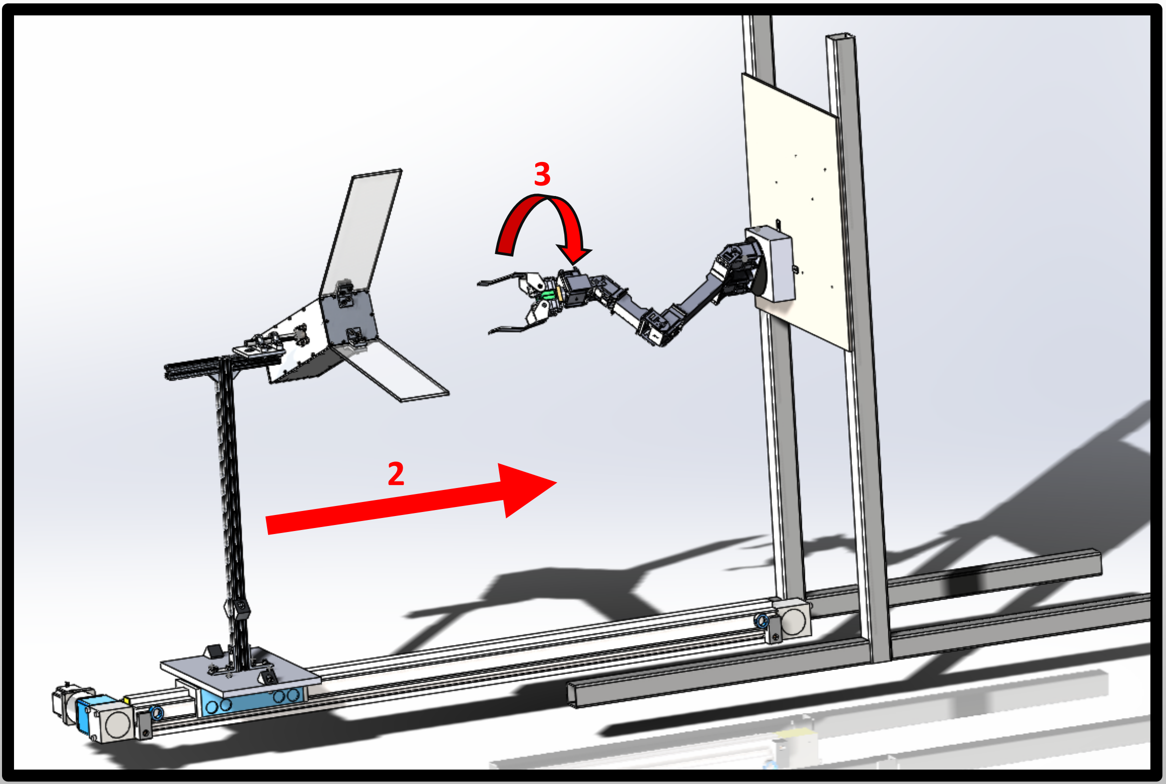
Test Bed CONOPS



<u>1.) Move to Axis of Rotation</u>

- Using Vicon data the axis of rotation will be calculated in LabView
- Commands are sent to the arm to move the end effector to the axis of rotation

Test Bed CONOPS



<u>2.) Translate CubeSat</u>

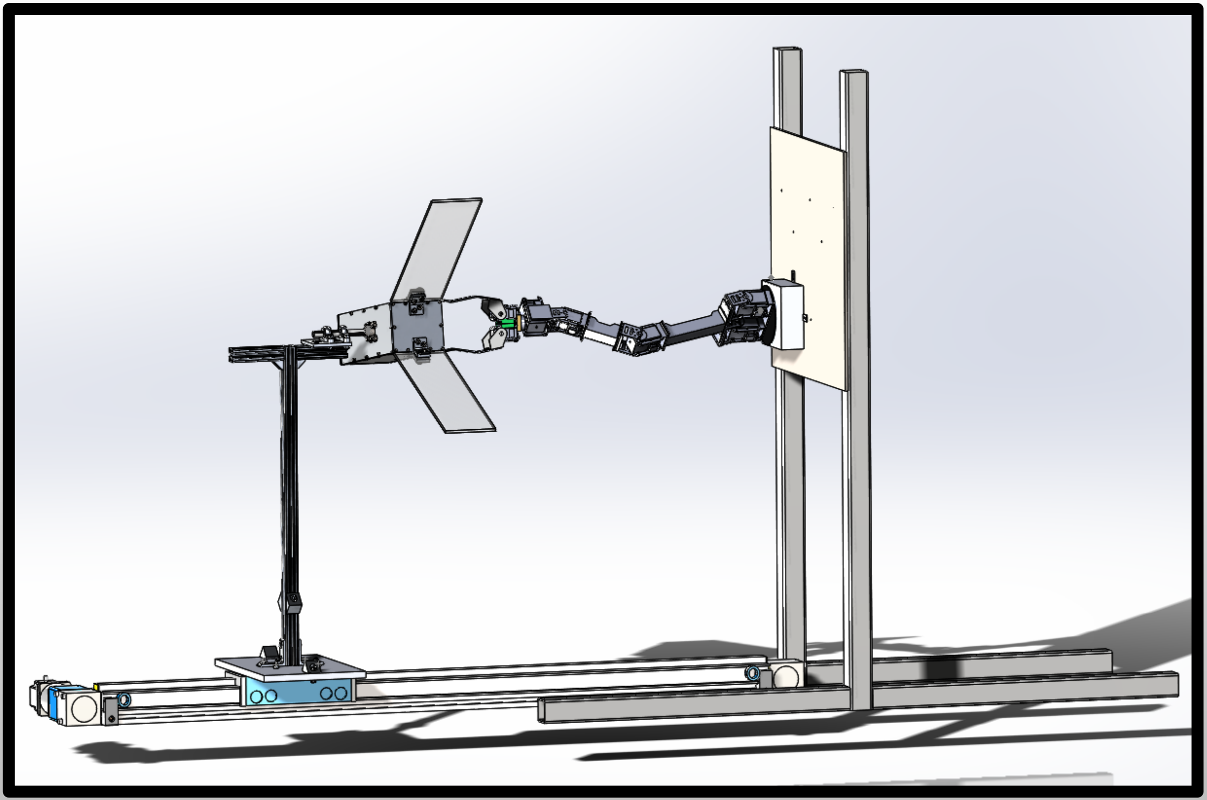
- This phase represents the closing of the relative position between the CubeSat and Capture device

- In space thrusters would be used to approach the CubeSat

<u>3.) Wrist Rotation</u>

- Using Vicon Data the wrist will be sent commands to match the rotation of the CubeSat.

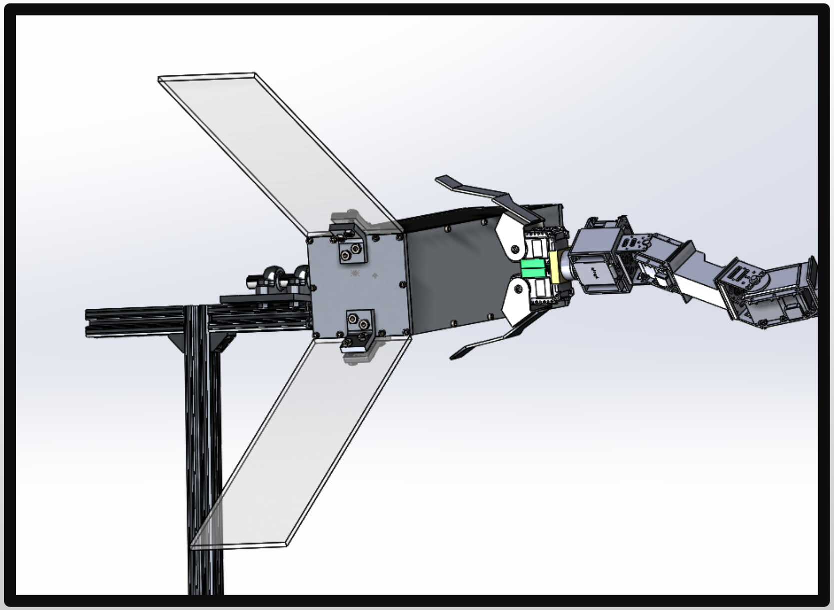
Test Bed CONOPS

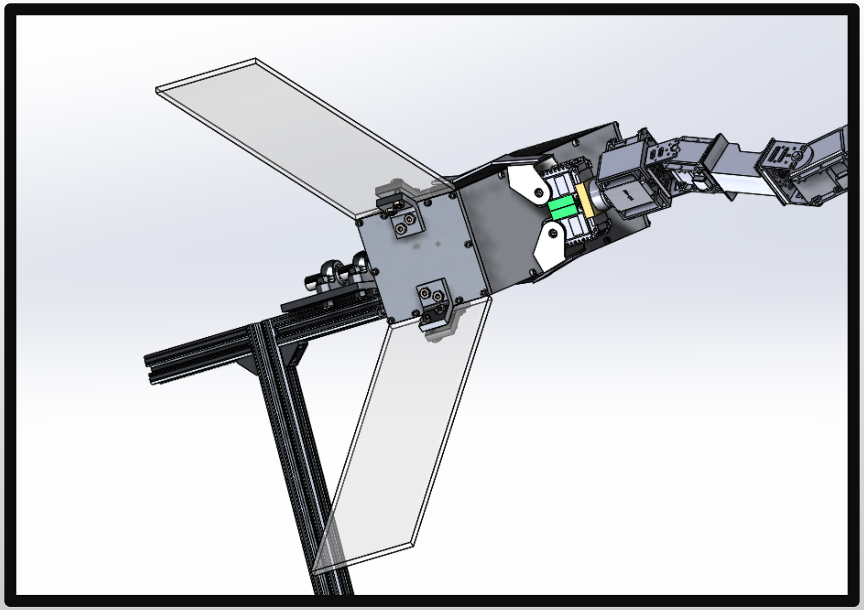


4.) Extend Arm

- Using Vicon data the arm will be sent commands to position the end effector over the CubeSat model.
- End effector moves along the axis of rotation.

Test Bed CONOPS

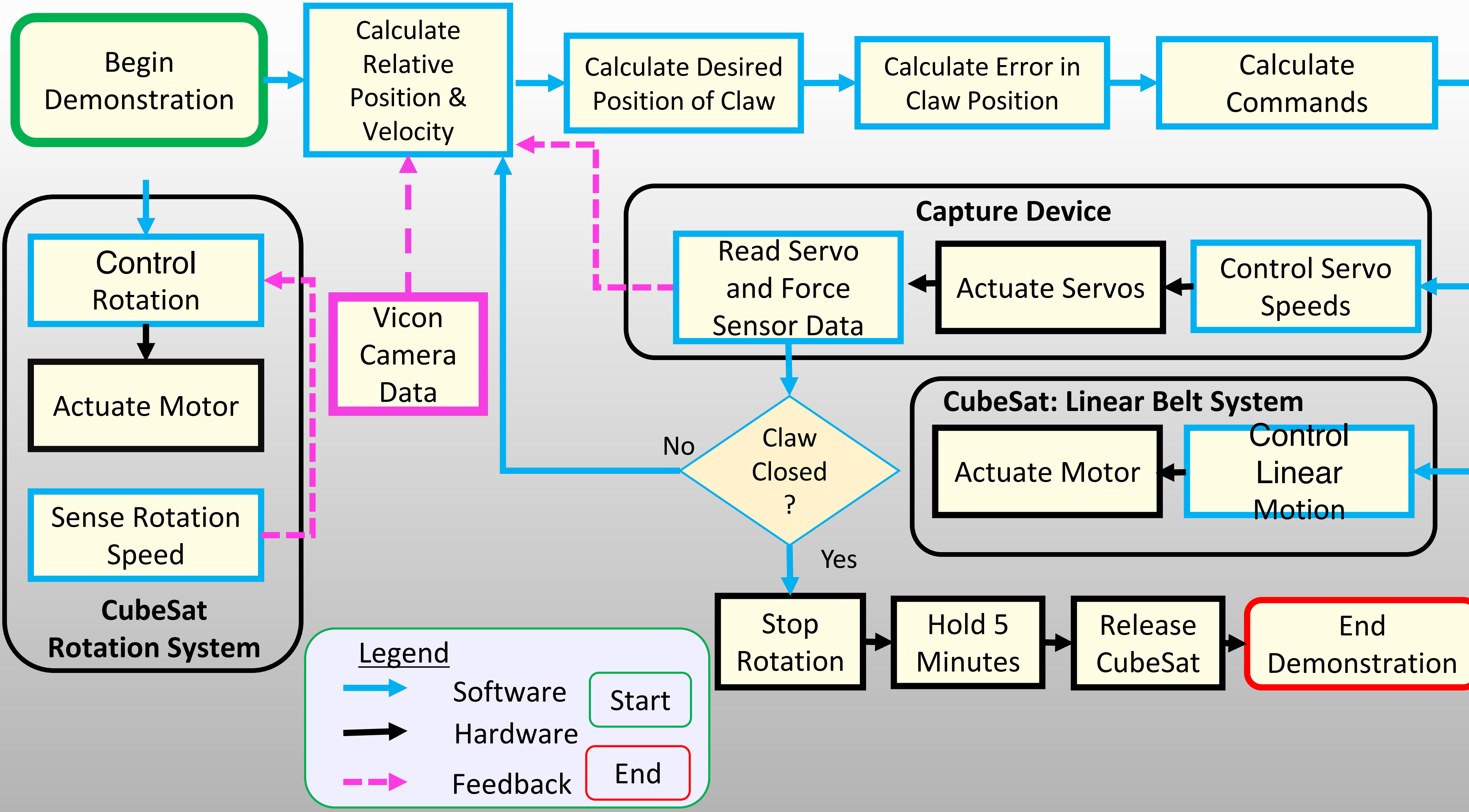




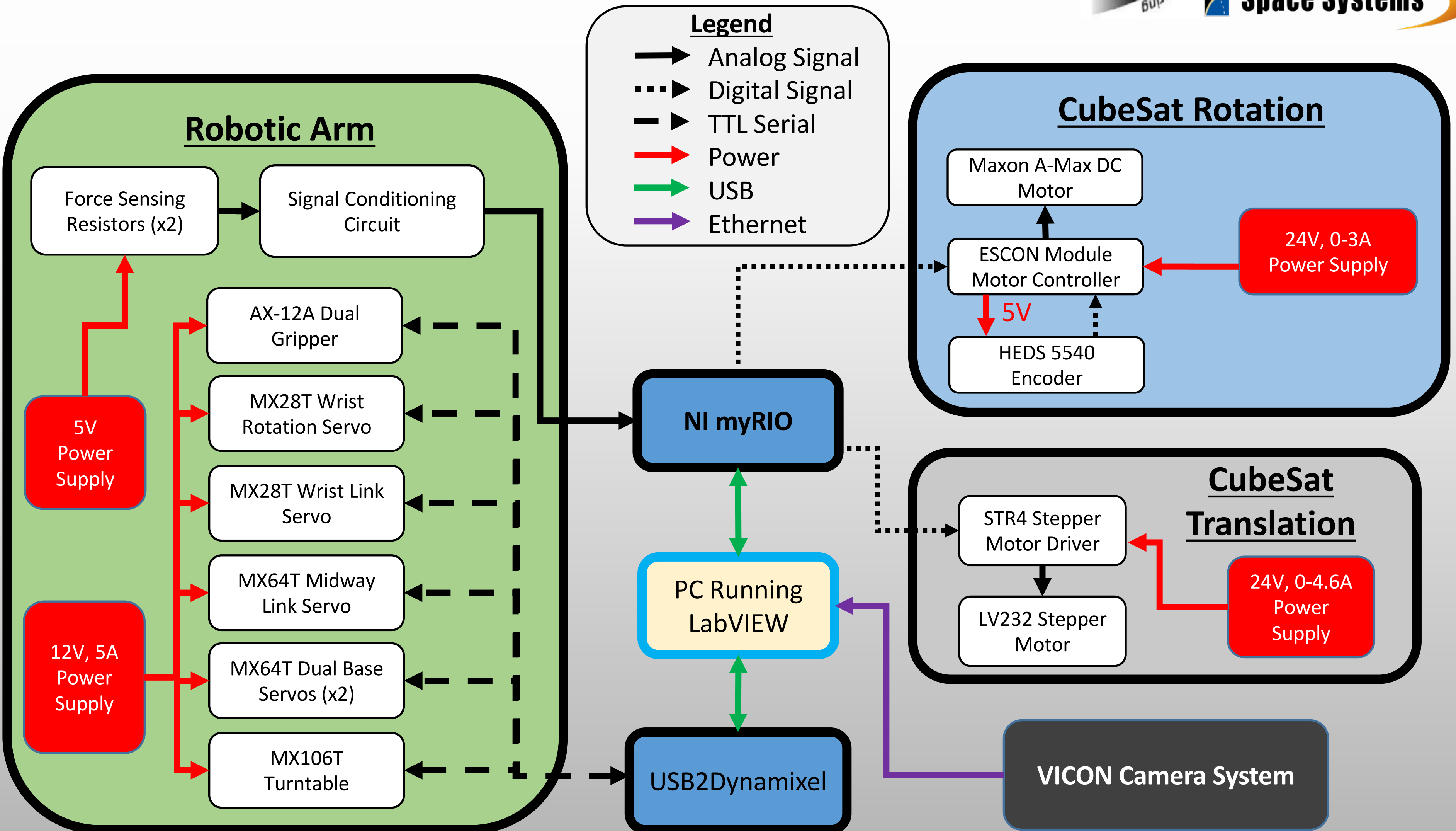
5.) Claw Closure

- Finally the claw is closed on the CubeSat surface, capture is confirmed, servo and motors are stopped, and the CubeSat is held for 5 minutes until released.

Functional Flow Diagram



Hardware Block Diagram

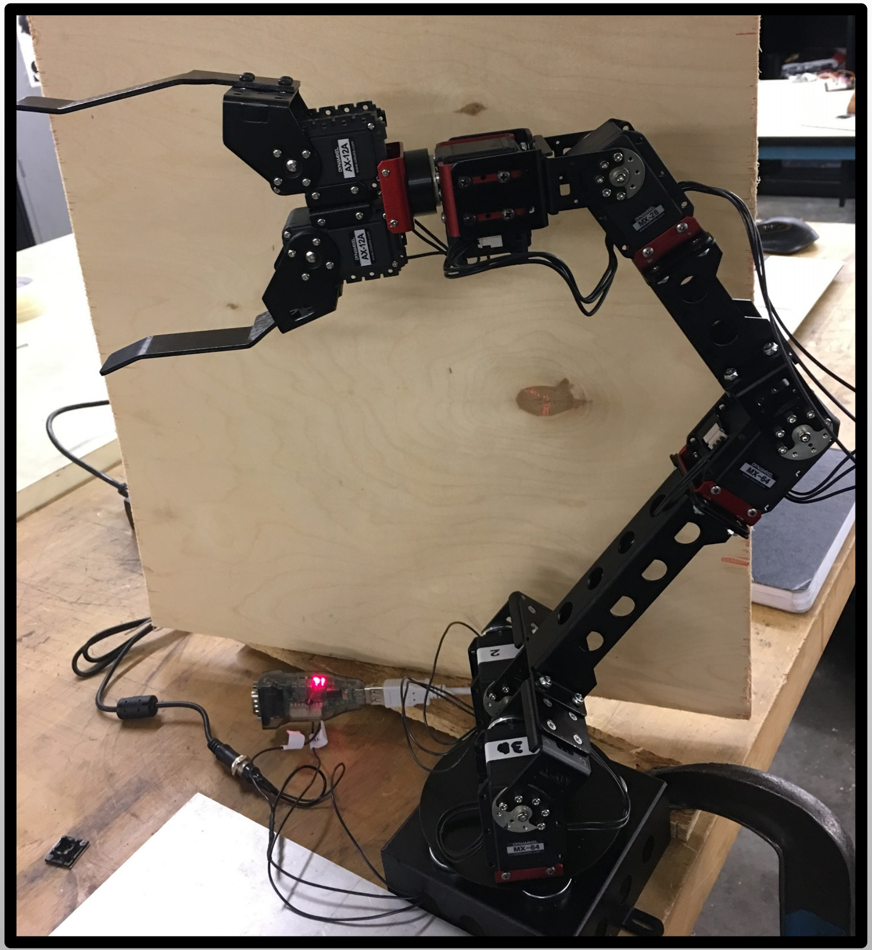


Critical Project Elements

Critical Project Element	Component
The CRST shall determine the axis of rotation and relative attitude of the CubeSat.	Software and Vision
The robotic arm will operate within safe limits.	Software and Control
The robotic arm shall travel along the axis of rotation as it approaches the CubeSat.	Software and Control
The CRST will confirm capture through the use of the robotic arm’s tactile feedback.	Software, Mechanical, and Electrical

Executive Summary

- **Changes from CDR**
  - Robot State definition
  - Wrist rotation on separate control loop as a consequence

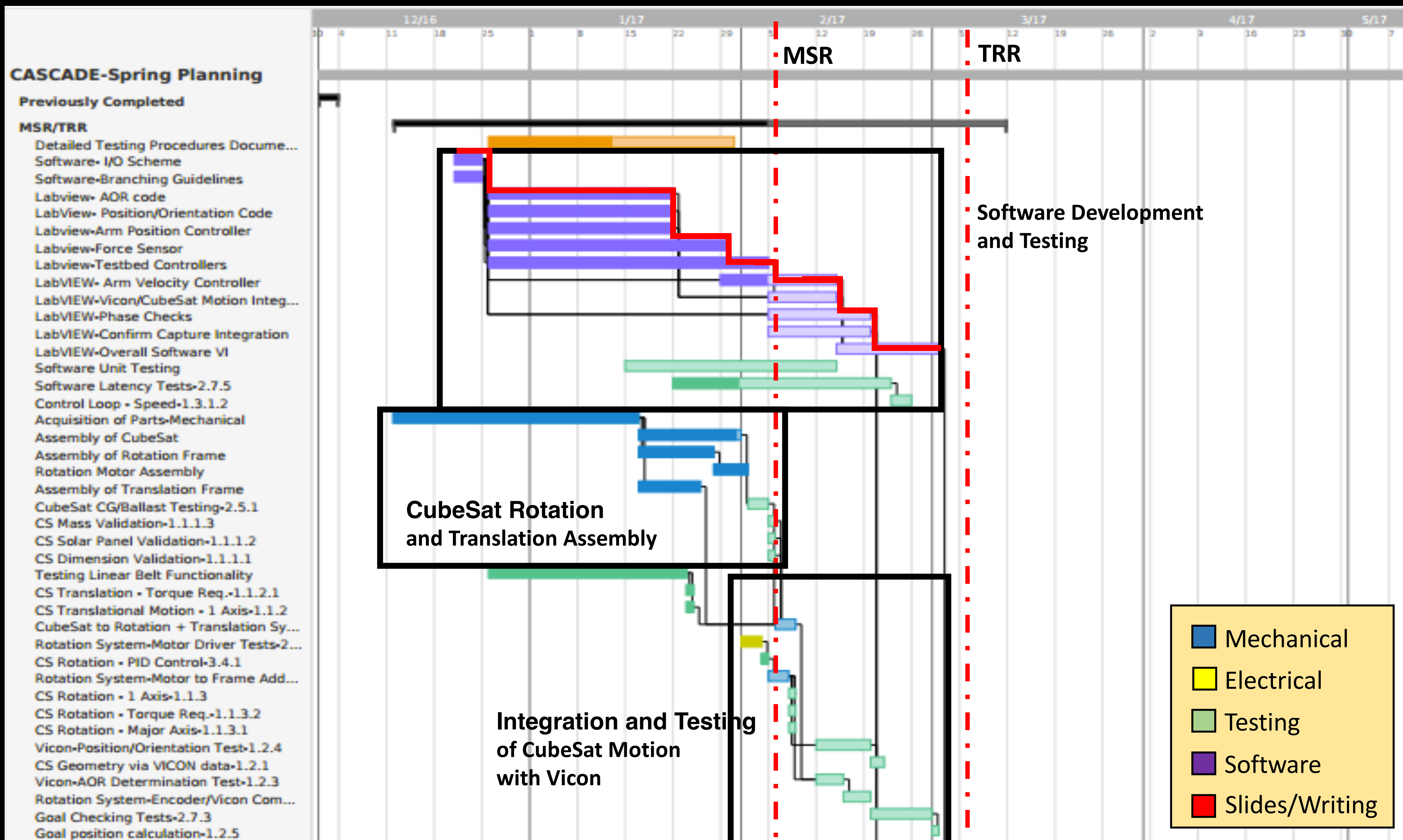


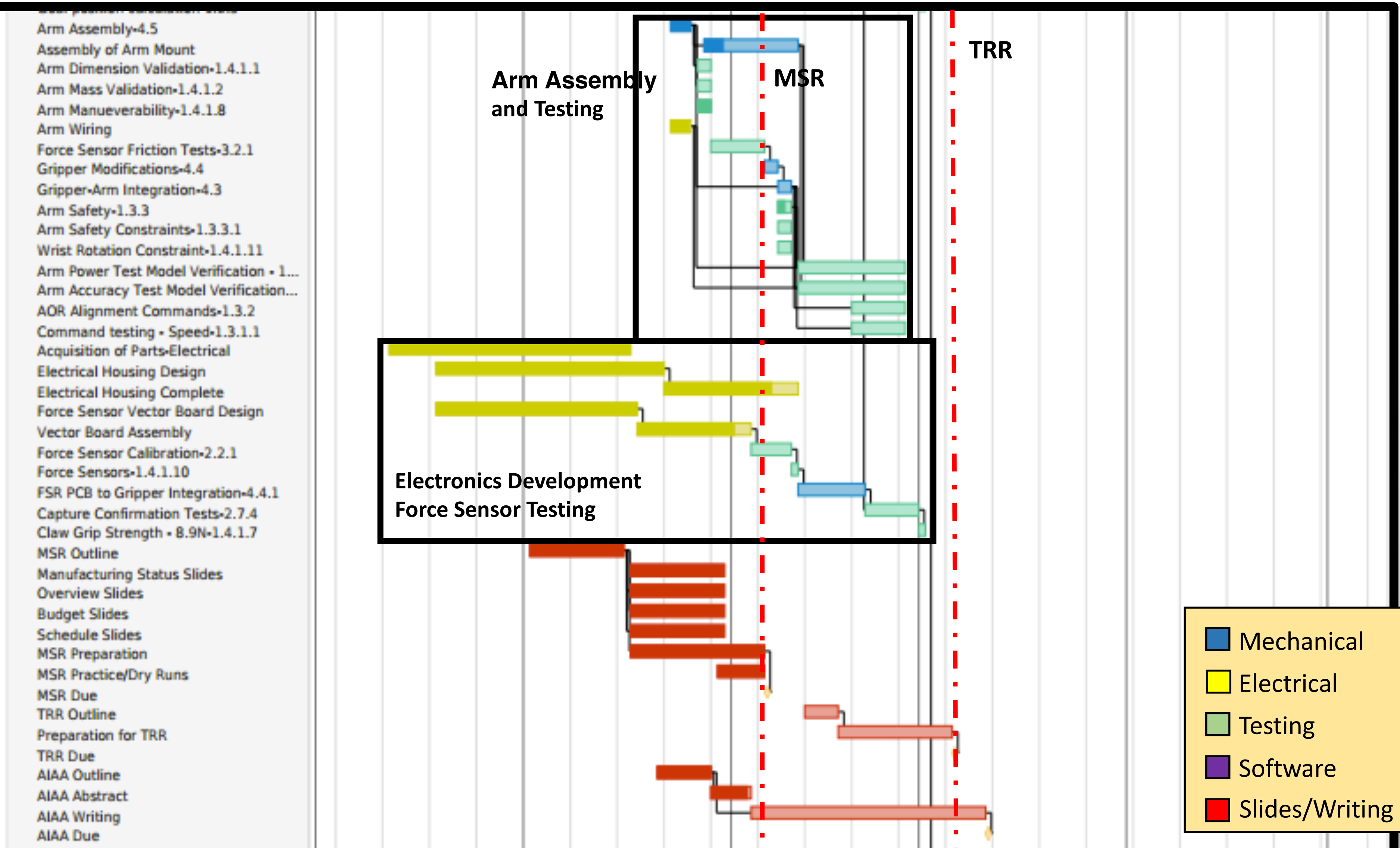
- **Schedule**
  - On schedule
  - 1 Item behind schedule
  - 2 Items ahead of schedule

- **Budget**
  - No risk to budget
  - $4,263.92 spent so far, ~15% margin.
  - $175 estimated future spending.

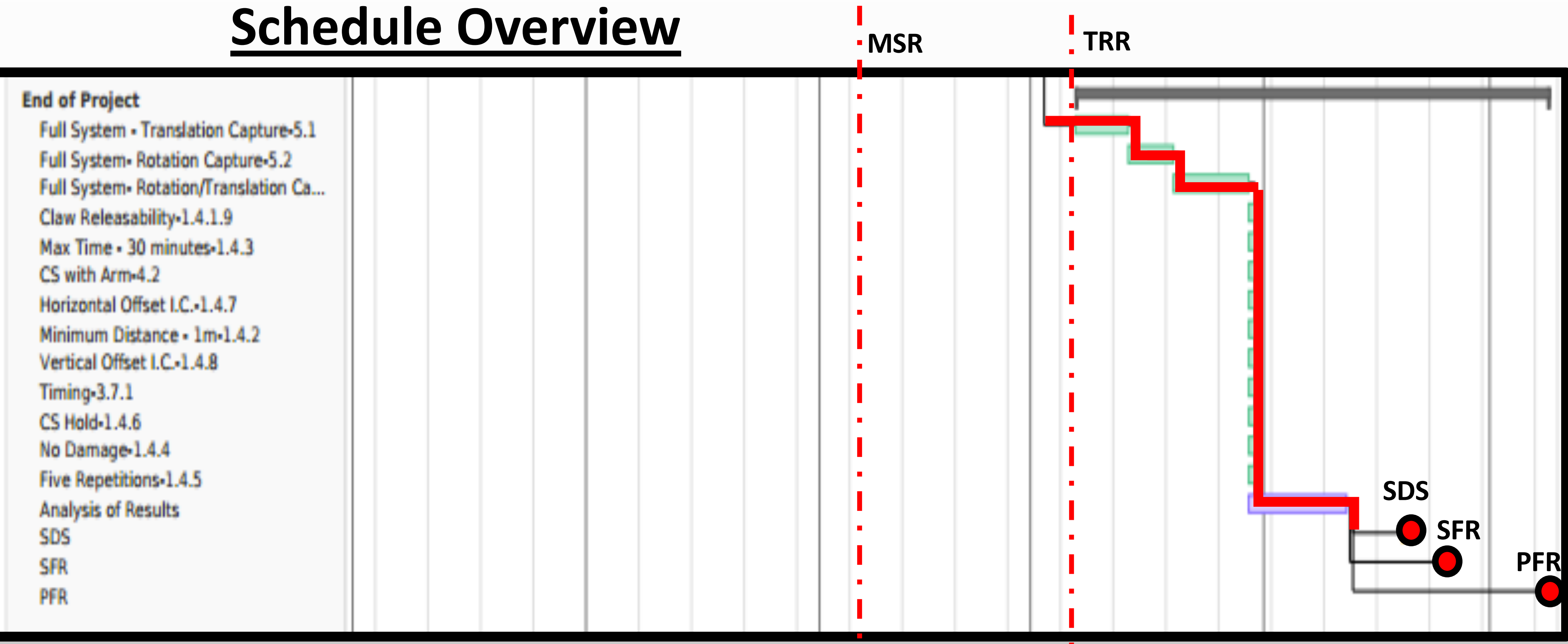
Schedule

Schedule Overview




Arm Assembly-4.5
Assembly of Arm Mount
Arm Dimension Validation-1.4.1.1
Arm Mass Validation-1.4.1.2
Arm Manueverability-1.4.1.8
Arm Wiring
Force Sensor Friction Tests-3.2.1
Gripper Modifications-4.4
Gripper-Arm Integration-4.3
Arm Safety-1.3.3
Arm Safety Constraints-1.3.3.1
Wrist Rotation Constraint-1.4.1.11
Arm Power Test Model Verification - 1...
Arm Accuracy Test Model Verification...
AOR Alignment Commands-1.3.2
Command testing - Speed-1.3.1.1
Acquisition of Parts-Electrical
Electrical Housing Design
Electrical Housing Complete
Force Sensor Vector Board Design
Vector Board Assembly
Force Sensor Calibration-2.2.1
Force Sensors-1.4.1.10
FSR PCB to Gripper Integration-4.4.1
Capture Confirmation Tests-2.7.4
Claw Grip Strength - 8.9N-1.4.1.7
MSR Outline
Manufacturing Status Slides
Overview Slides
Budget Slides
Schedule Slides
MSR Preparation
MSR Practice/Dry Runs
MSR Due
TRR Outline
Preparation for TRR
TRR Due
AIAA Outline
AIAA Abstract
AIAA Writing
AIAA Due
Arm Assembly and Testing
MSR
TRR
Electronics Development Force Sensor Testing
Mechanical
Electrical
Testing
Software
Slides/Writing

Schedule Overview



- Mechanical
- Electrical
- Testing
- Software
- Slides/Writing

Summary of Tasks

Completed:

- All procurement
- LabVIEW- Open Loop Linear Belt
- LabVIEW- Closed Loop CubeSat Rotation Control
- LabVIEW- Arm Servo Position Control for Testing
- LabVIEW- Force Sensor VI
- LabVIEW- AOR and Position VI with Vicon
- Rotation Frame Assembly
- Arm Assembly
- FSR Circuitry on Vector Board

Behind Schedule:

- CubeSat Assembly

Ahead of Schedule:

- Arm Velocity Controller
- Electrical Housing

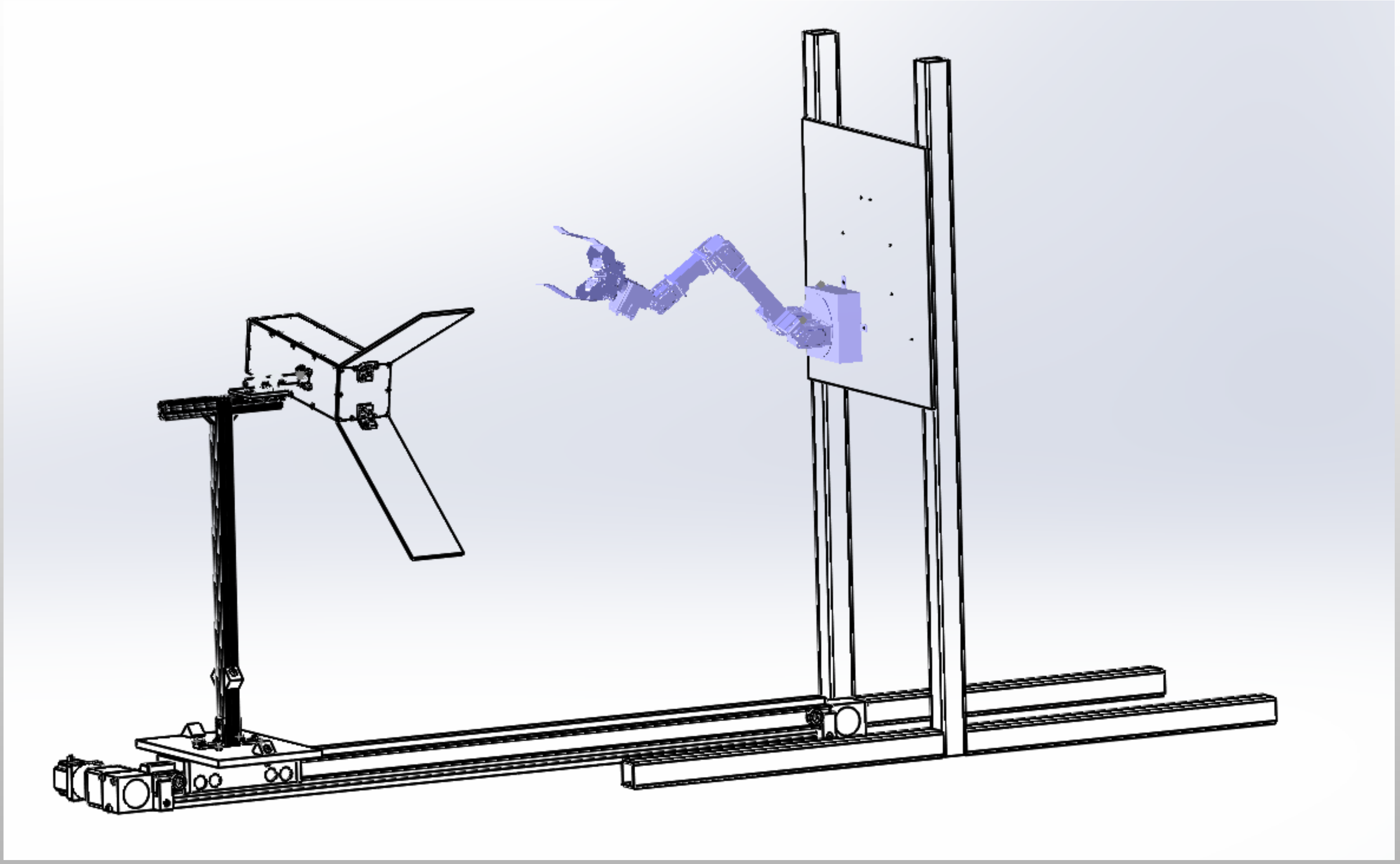
Manufacturing

Manufacturing Status:

Hardware Overview

- CubeSat
  - 3U Structure
  - Solar Panels
  - 4 Hours Remaining
- Rotation System
  - Structure
  - Motor Mount
  - Motor Shaft
  - 4 Hours Remaining
- Capture Device
  - Arm Assembly
  - Arm Wiring
  - Mounting Plate
  - Mount Structure
  - FSR Circuit
  - Gripper Mod.
  - 5 Hours Remaining
- Electronics Housing
  - 1 Hour Remaining

Capture Device Status



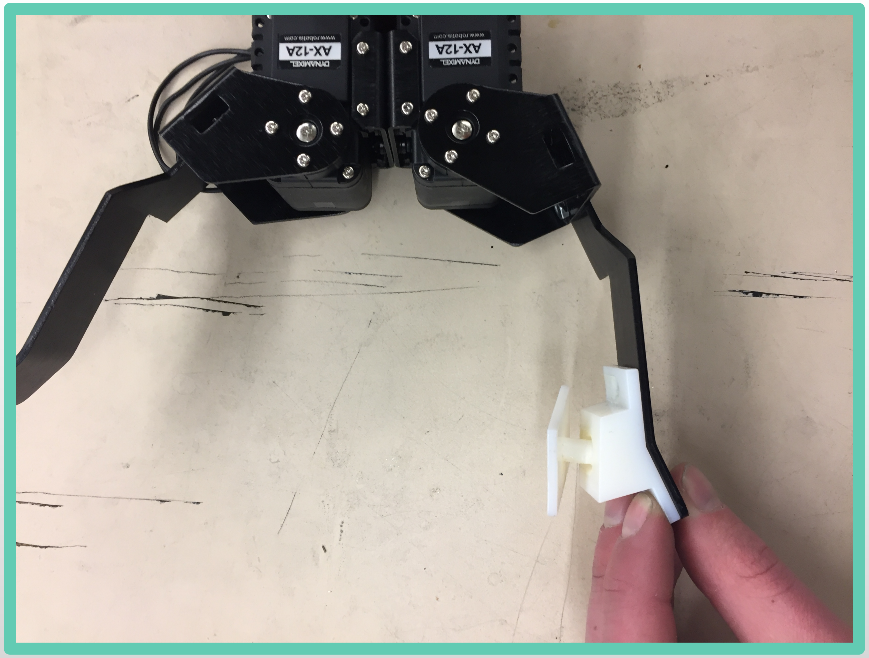
Robotic Arm Status

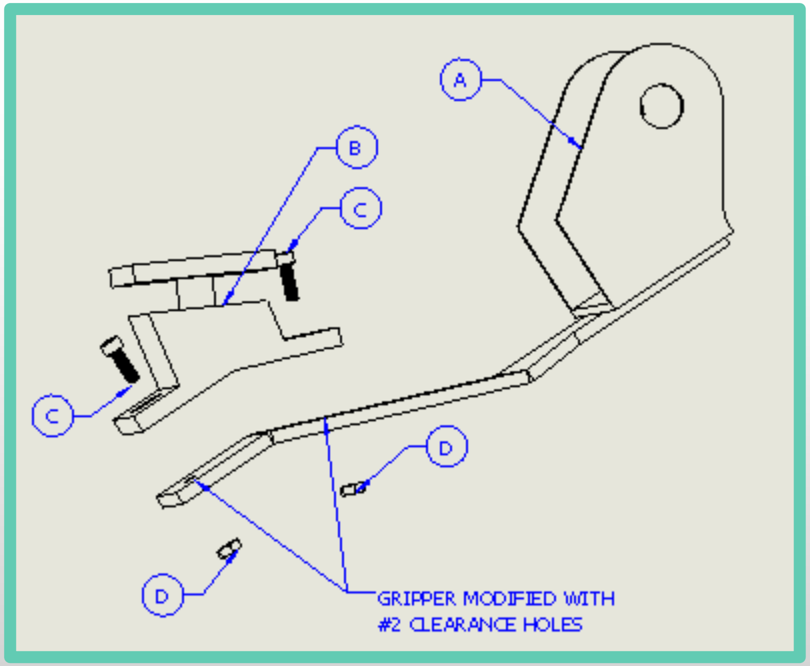
Completed:
- Completely assembled and wired
- Open loop position control of individual joint servos for testing.

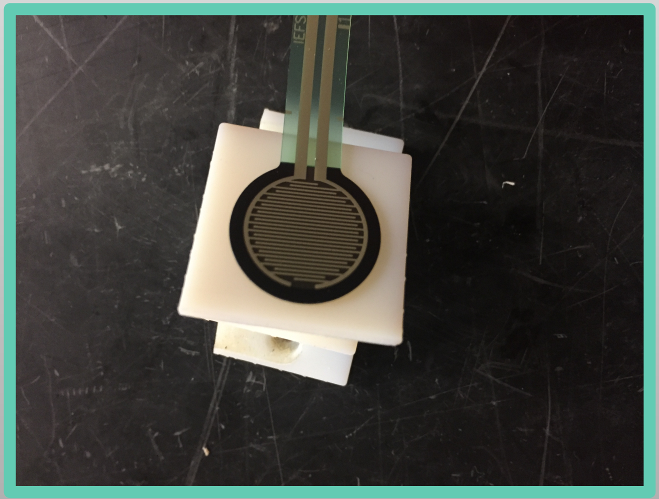
In Progress:
- Secure wires along arm joints
- Create longer wires for the unlimited rotation joints
- Wire Sheathing
- Arm Mount
- Gripper Modification

5-6 Hrs. Remaining

Force Sensing Status: Ball Joint



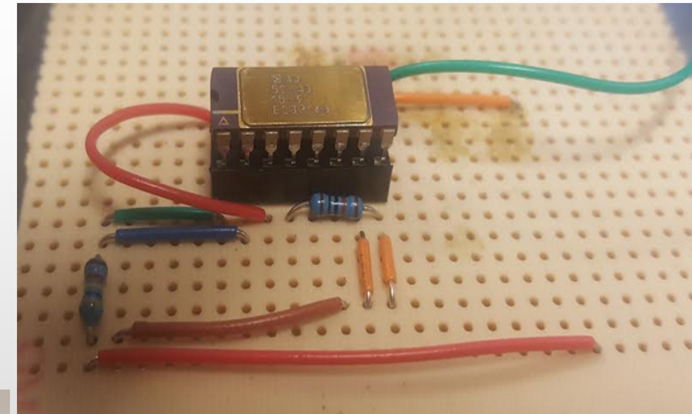


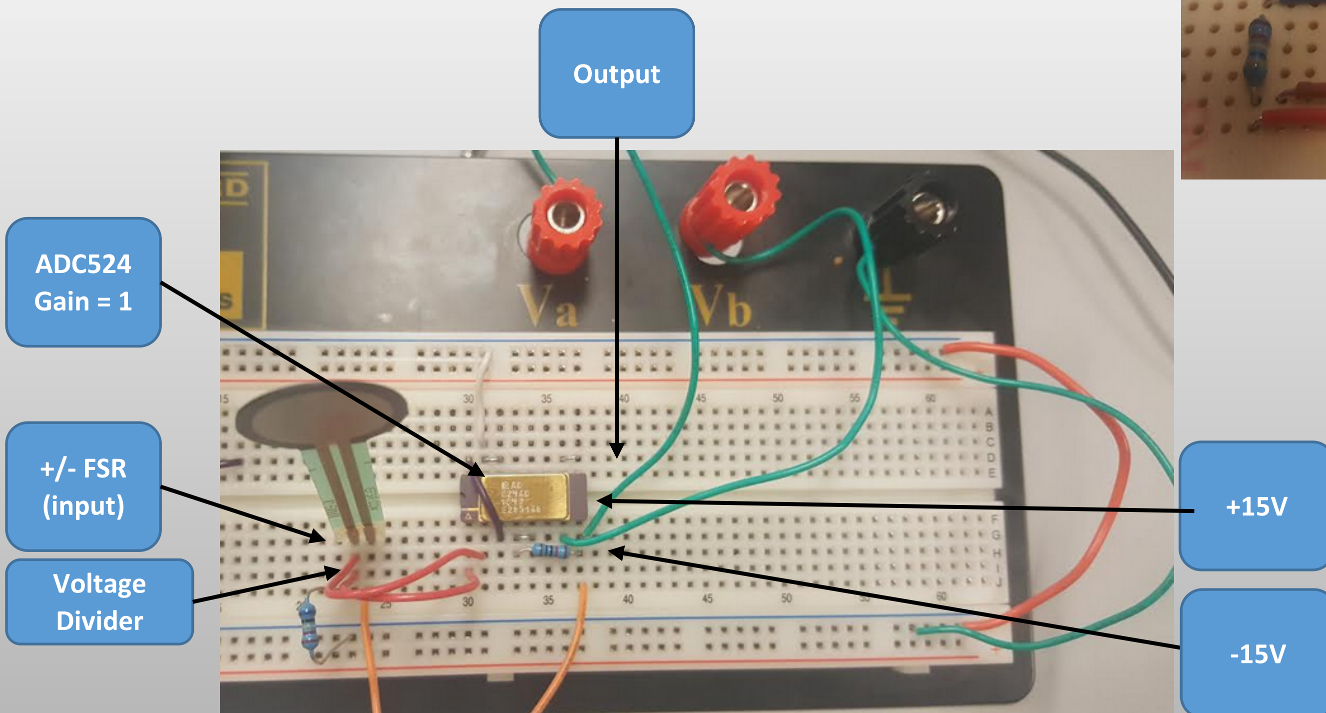


- Prototype printed and tested for functionality
- Overnight printing in ITLL at $10 per
- Printed with counter bore for 2-56 socket screw mounting
- Modifications to gripper yet to be made but scheduled for later this week.

FSR Signal Conditioner

- Signal conditioner circuit built and tested.
- AD524 used to reject common mode noise, and linearize the voltage divider/FSR output.





- Status: The first vector board has been built and tested.
- The second vector board will be built within the week. Estimated time: 2 hours.

Design Changes: Arm Control

- Changes Made:
  1. Removed wrist rotate from joint space
     - Commanded separately to match CubeSat spin angle
  2. Robot state definition: reduced to 5 DOF
     - Orientation only concerned with pointing direction

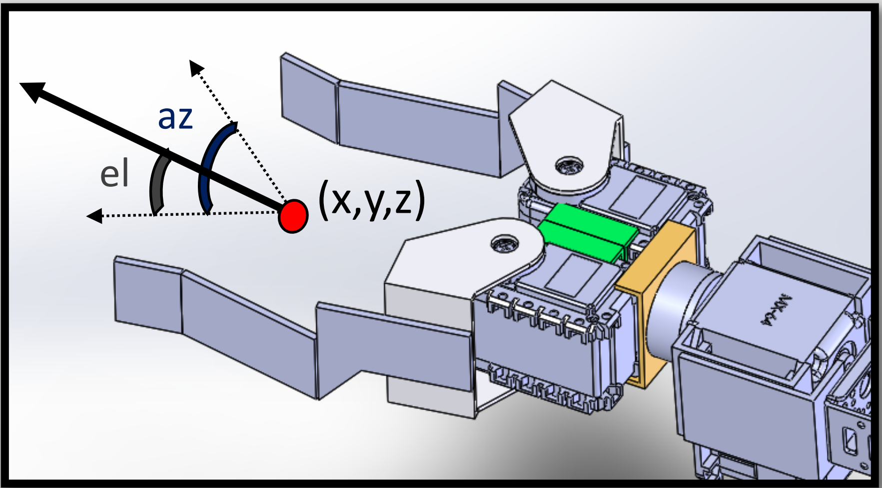
$$X = \begin{bmatrix} x \\ y \\ z \\ roll \\ pitch \\ yaw \end{bmatrix}$$

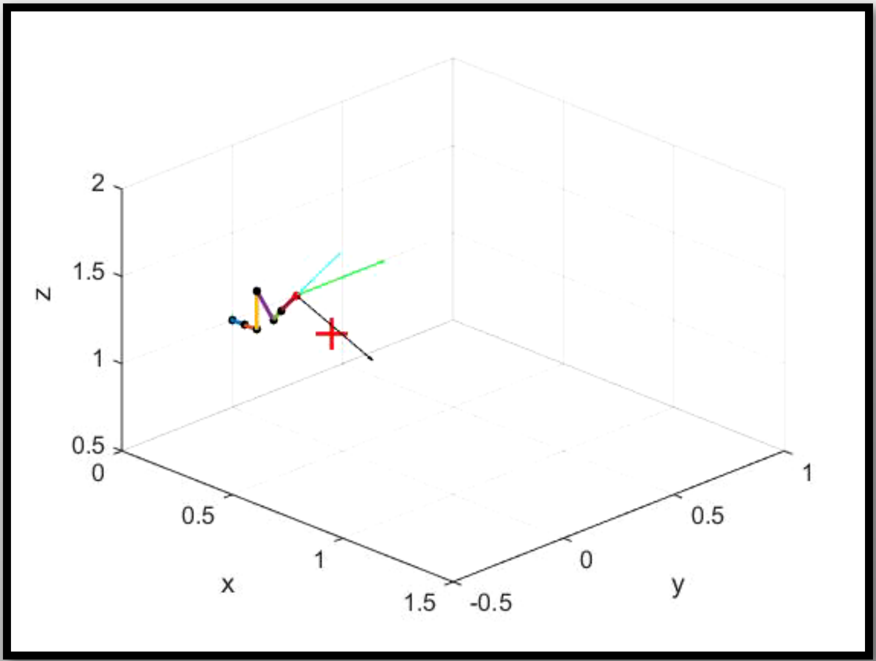
Old State

$$X = \begin{bmatrix} x \\ y \\ z \\ azimuth \\ elevation \end{bmatrix}$$

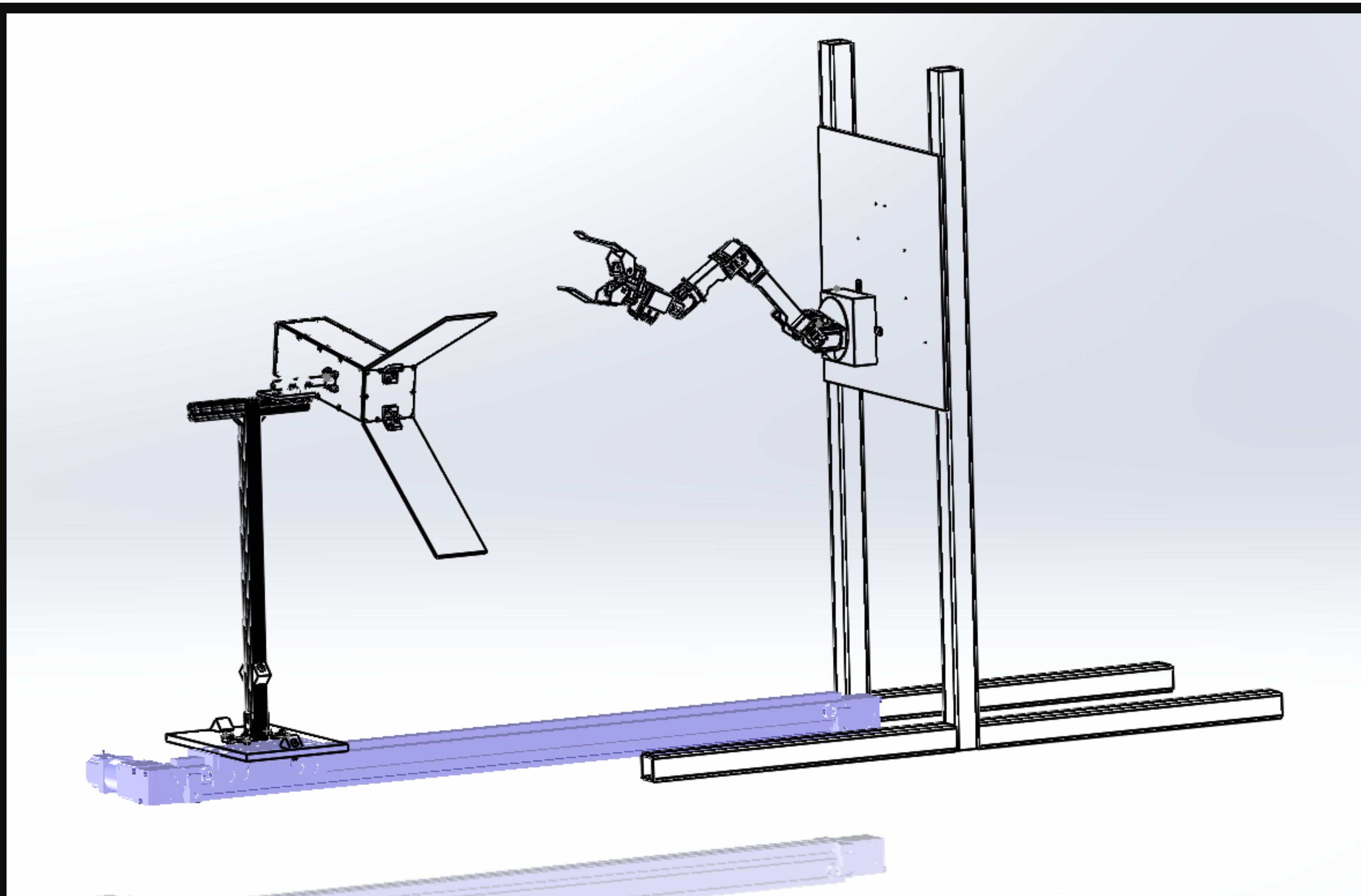
New State

- Benefits:
  - No wrist rotation singularities or instability
  - Smoother extension along axis of rotation
  - No problems controlling orientation



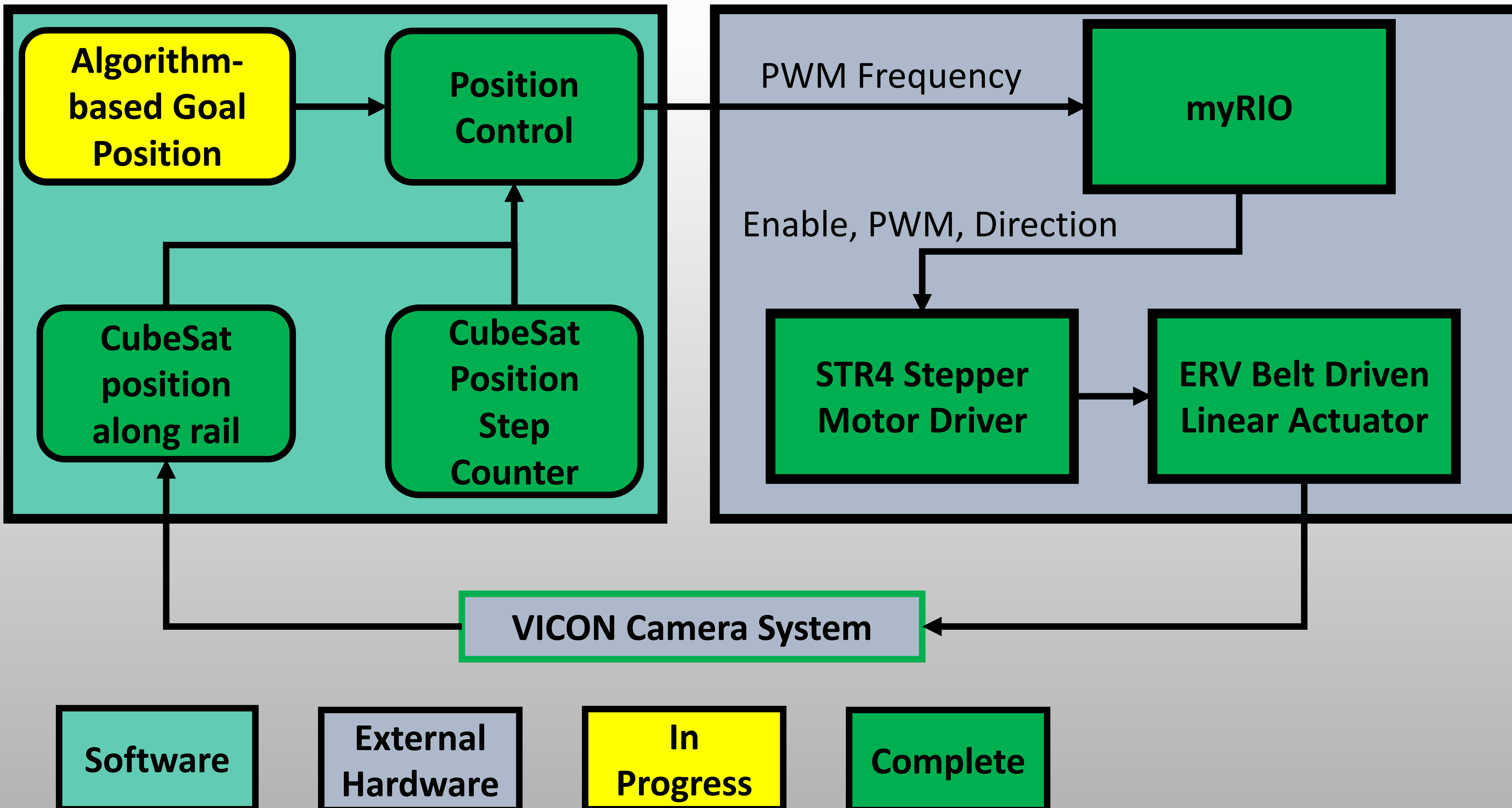


CubeSat Translation System



CubeSat Translation System

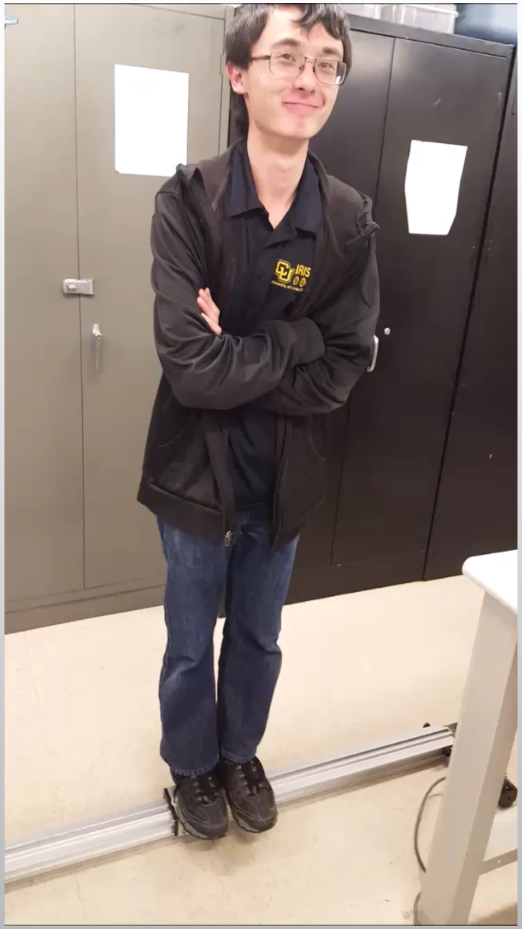
Closed Loop



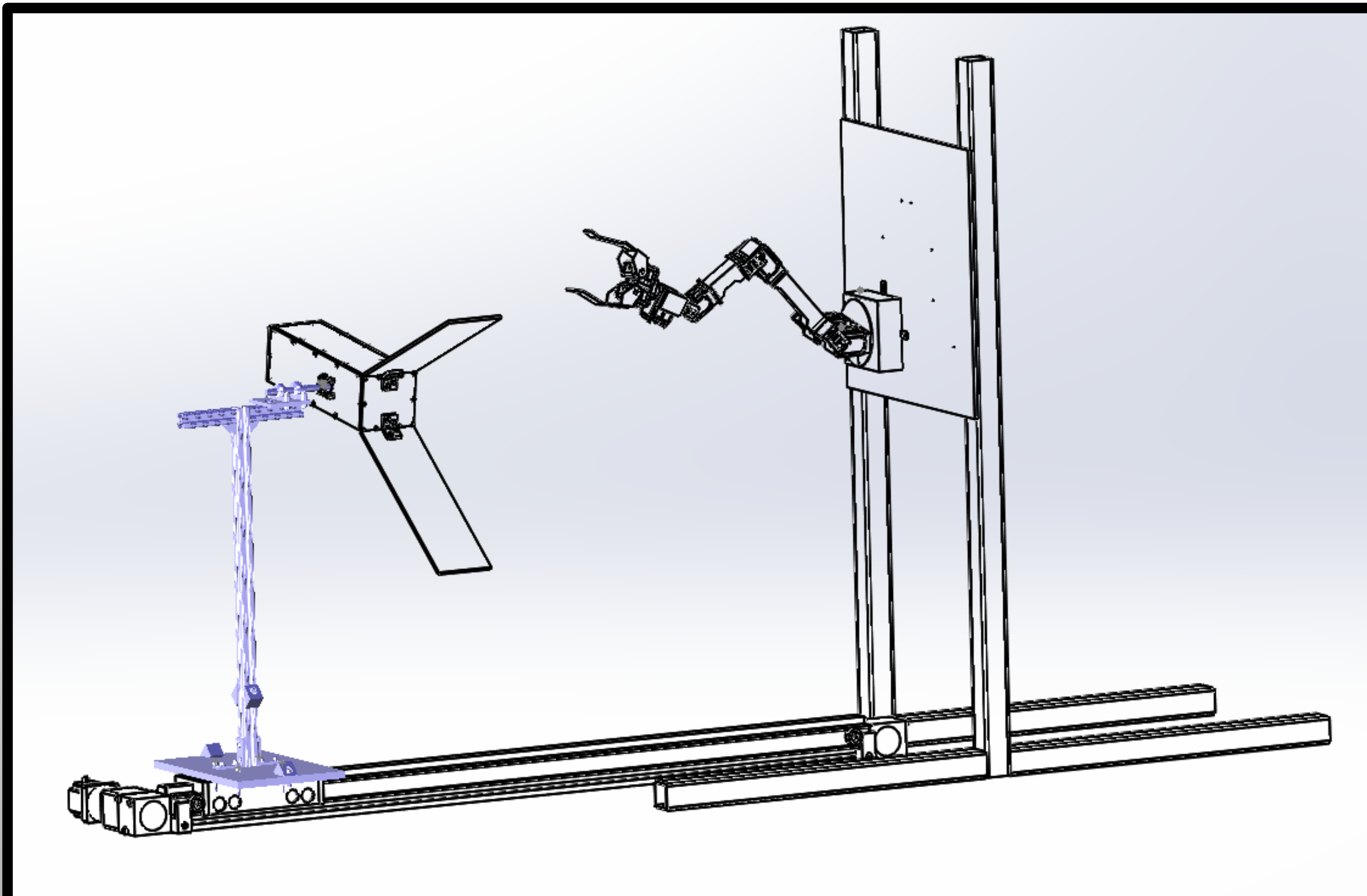
CubeSat Translation System

- Hardware
  - myRIO Signal I/O
  - STR4 Driver PWM Interface
  - Wiring and Connectors
- Software
  - Open Loop: Step Counting
  - Closed Loop: PWM Control
  - Closed Loop: Goal Position

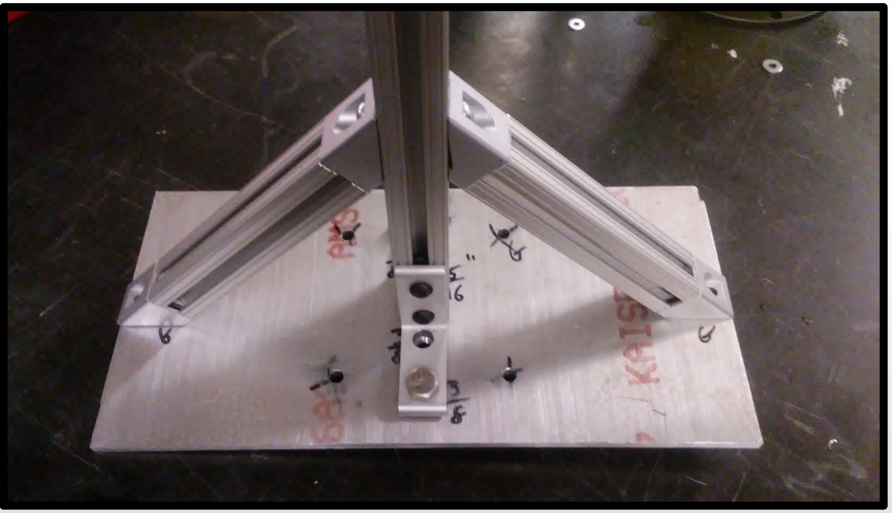
4 Hrs Remaining



CubeSat Rotation System

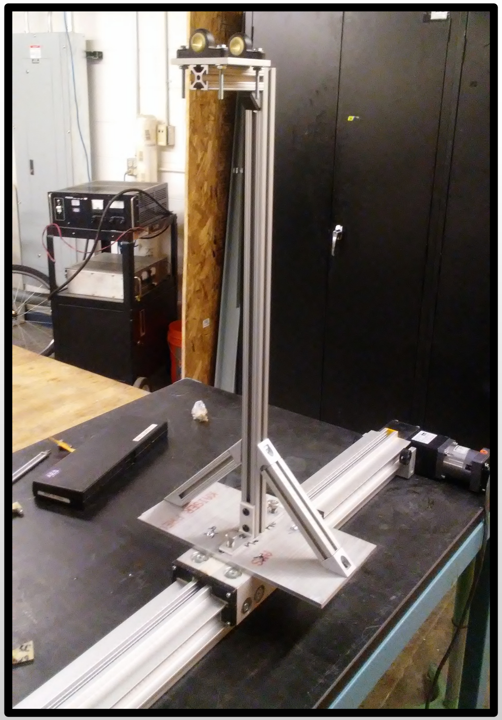


CubeSat Rotation Support System Assembly



Design Updates:

- Reduced **Interface Plate width** to save on cost
- Changed **size of clearance holes** -> allows for **tapped holes**



Completed:

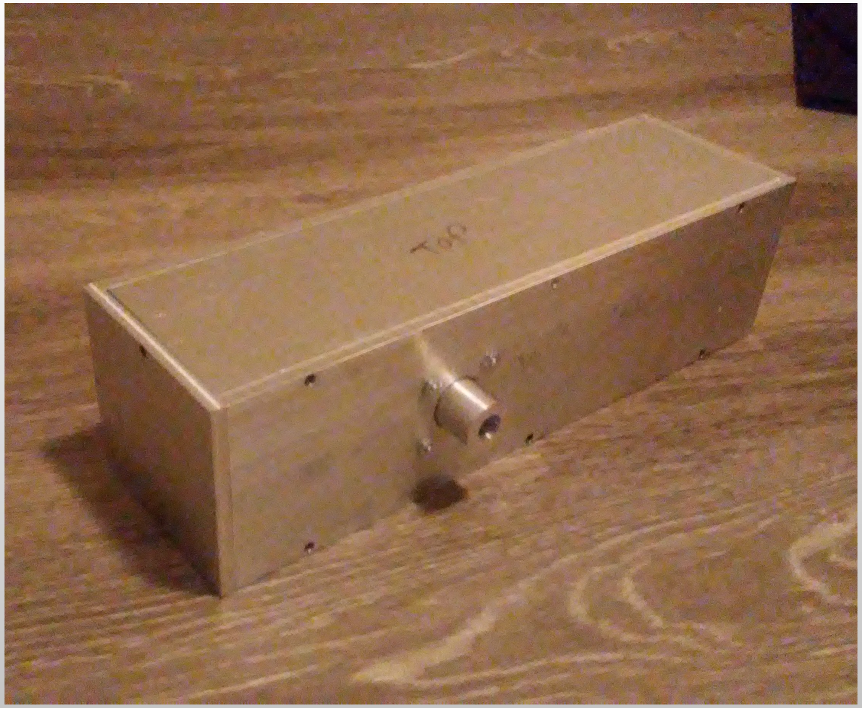
- ESCON speed control configuration to 3 deg/s
- Electrical Connector to myRIO
- Preliminary system functionality testing
- Support Structure

Incomplete:

- Motor Mount
- Electrical Connector to Motor

2-3 Hrs Remaining

CubeSat Assembly



Completed:
- CubeSat main structure (3U)
- Rotation shaft interface
- Mass with solar panels: 2.97kg (satisfies requirement)
- Dimensions: 10 cm x 9.5 cm x 33.8 cm (satisfies requirement)

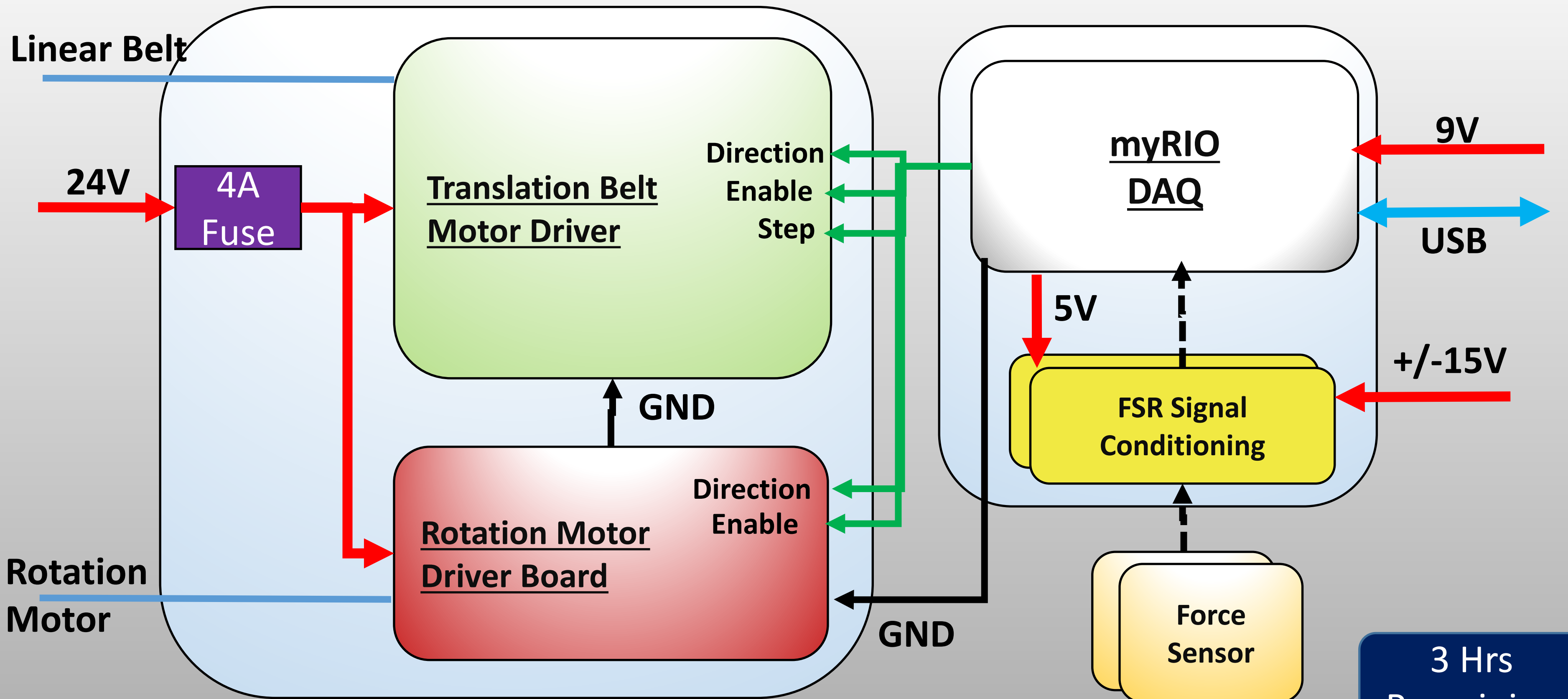
Incomplete:
- Solar Panel finish and mount
- Measure C.G.
- Ballast for C.G. correction
- Mount to rotation assembly

4 Hrs Remaining

Electronics Housing Overview

Aluminum electronic housing units used to protect and organize electronic hardware includes:

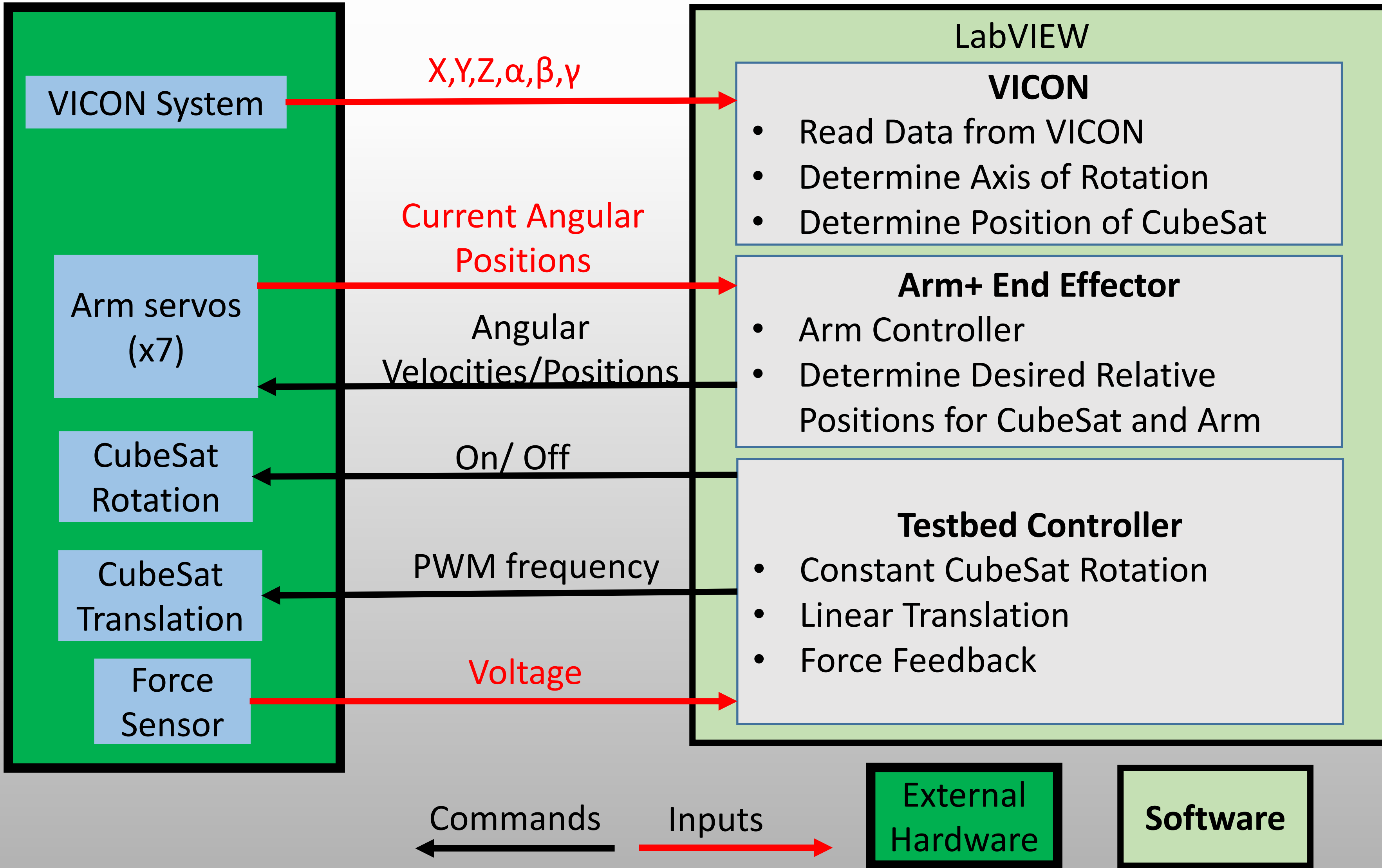
- Overcurrent protection through the use of a fuse.
- Prevents wire damage from external hazards, EM interference, and noise.



3 Hrs Remaining

Software Integration Plan

Software I/O


VICON System
Arm servos (x7)
CubeSat Rotation
CubeSat Translation
Force Sensor
X,Y,Z,α,β,γ
Current Angular Positions
Angular Velocities/Positions
On/ Off
PWM frequency
Voltage
LabVIEW
VICON
• Read Data from VICON
• Determine Axis of Rotation
• Determine Position of CubeSat
Arm+ End Effector
• Arm Controller
• Determine Desired Relative Positions for CubeSat and Arm
Testbed Controller
• Constant CubeSat Rotation
• Linear Translation
• Force Feedback
Commands
Inputs
External Hardware
Software

Software Integration Plan: 3 Step Process

Step 1: Create All Individual Functions

- Allows use to verify functionality of each function
- Allows for easier integration

Step 2: Sub Integration

- Create each individual closed loop controllers
  - Jacobian Velocity controller
  - Claw Rotation w/ VICON
  - Linear testbed controller w/ VICON
  - Cubesat rotation system controller
  - Claw-Force Sensor Controller

Step 3: Final Integration

- Integrate each closed loop controller with commands

70 Hrs
Remaining w/ Margin

Status: Software Functions

Arm Controller Code
- Send Commands
- Read Registers
- Forward Kinematics
- Inverse Jacobian
- Arm Control Sub Integration

24 Hrs Remaining w/margin

VICON Code
- Read VICON DataStream
- Determine Position of CubeSat
- Determine AOR

1 Hr Remaining

Testbed Code
- Command Linear Rail
- Force Sensor
- CubeSat Rotation
- Closed Loop Sub Integration

20 Hrs Remaining w/ margin

Final Integration

Possible Risk	Mitigation	Risk
Step 2 Behind Schedule	Dan Godrick/ Team allocation	
Arm Control Implementation	Dr Correll, Dr Frew	

Final Integration done by March 1st.

Loop	Requirement	CDR Time	MSR Prediction	Risk
VICON	10.5 Hz	100.0 Hz	100.0 Hz	
Arm Control	10.5 Hz	144.4 Hz	30.2 $\pm$2Hz	
Testbed	13.4 Hz	166.6 Hz	>166 Hz	

- VICON and Testbed loops are of no concern
- Arm Controller--no concern: ~185% margin

25 Hrs
Remaining w/ Margin

Risk
Low High

Overview Schedule Manufacturing Budget

Budget

Procurement Status

All Project Procurements:

CrustCrawler Pro Series Robotic Arm and Gripper: Delivered

Motor, Driver, Gearhead, and Encoder: Delivered

Aluminum Plates,80-20, Fasteners: Delivered

Estimating Spending: $4,422.46
Total Spending: $4,263.92

Future Procurements

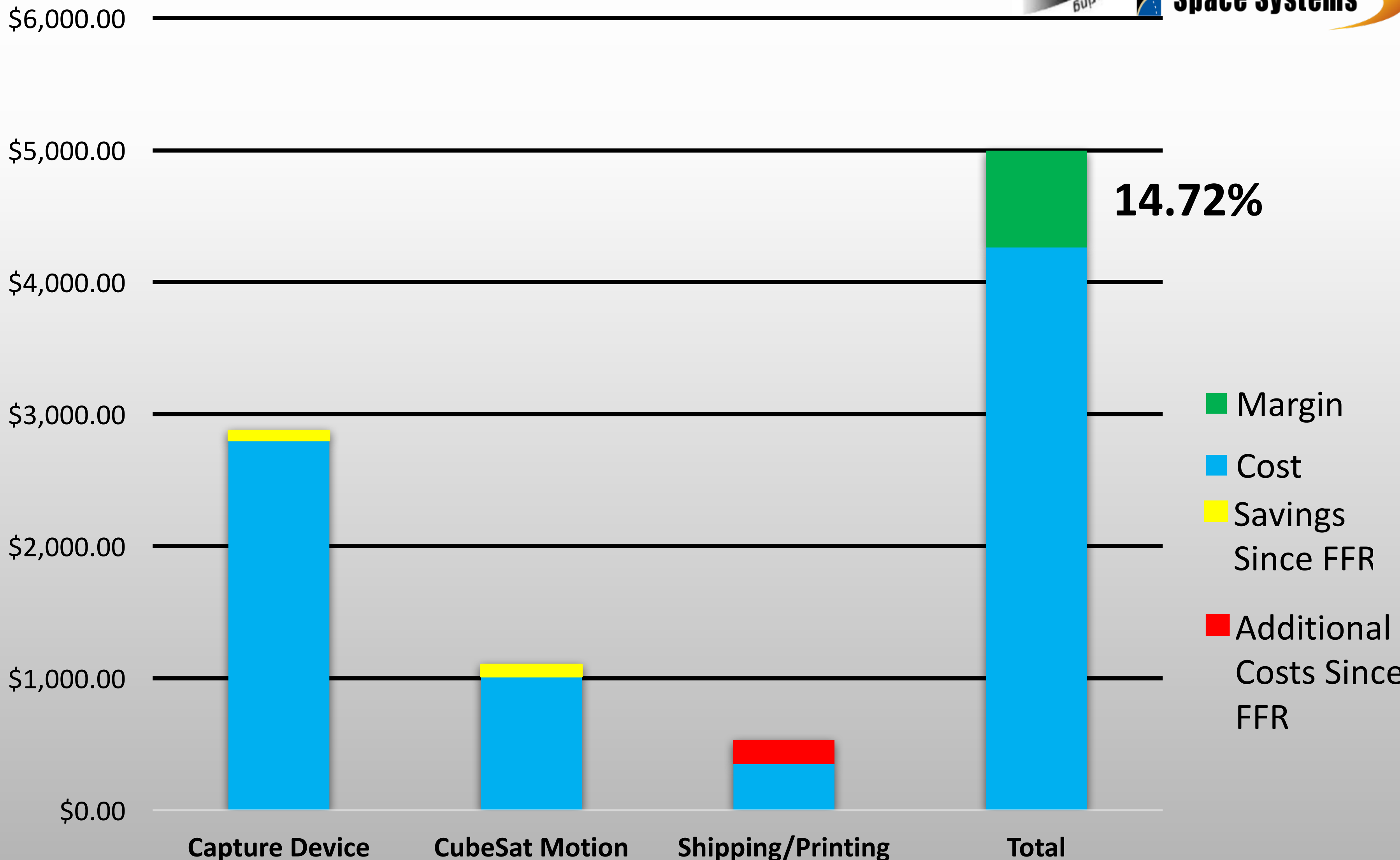
$175 allotted for printing

Updated Budget Estimate

$4437.77

No Risk to Budget

Budget Status



Budget Status

Component	Estimated Cost	Actual Cost	Projected Cost	Difference
CubeSat Model	$250.00	$101.68	$0.00	$148.32
CS Rotation Frame	$135.78	$192.26	$0.00	-$56.48
CS Rotation Motor	$695.01	$695.01	$0.00	**$0.00**
CS Translation Frame	$124.92	$124.92	$0.00	**$0.00**
Arm Mount	$231.56	$64.42	$0.00	$167.54
Pro Series Arm	$2474.79	$2512.95	$0.00	-$38.16
Gripper and FSR circuit	$169.40	$222.90	$0.00	-$53.90
Shipping	$0.00	$182.63	$0.00	-$182.63
Printing	$341	$167.15	$173.85	**$0.00**
Total:	$4422.46	$4263.92	$173.85	-$15.31

Conclusion

Thanks for your time!

Acknowledgments:

Our Customer

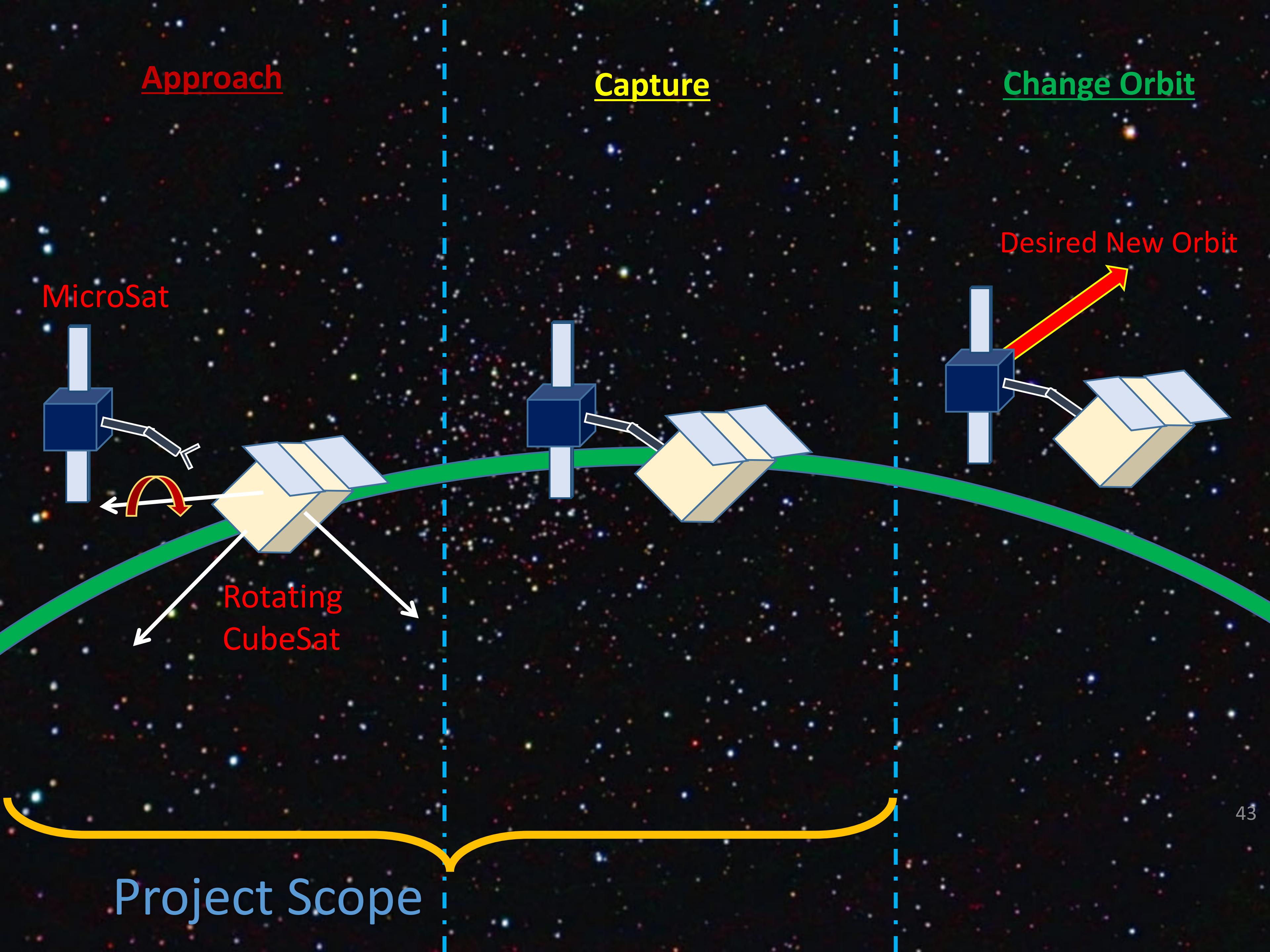
Henry "Lad" Curtis

Sierra Nevada Corporation

Faculty Advisor: Jelliffe Jackson

Robotics Help: Nikolaus Correll

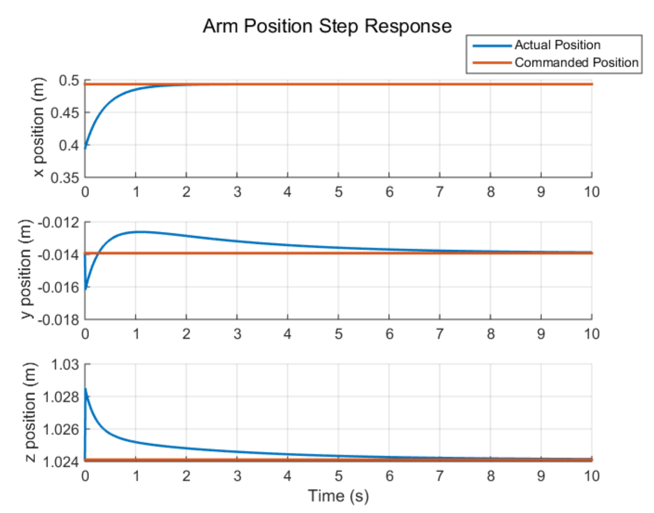
CU Faculty and Staff

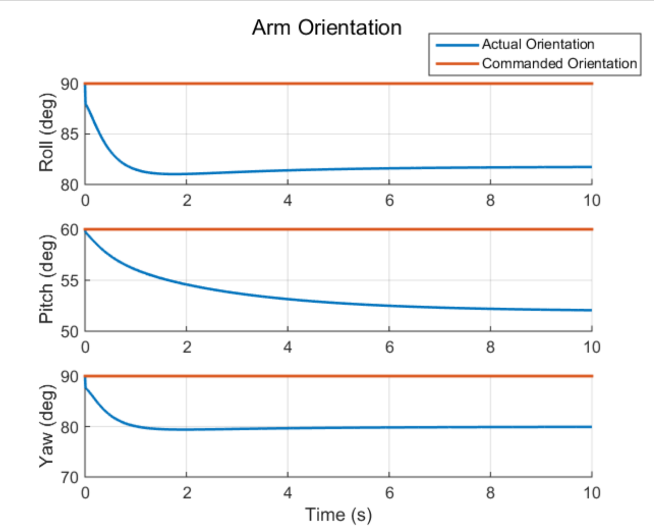

Approach
Capture
Change Orbit
Desired New Orbit
MicroSat
Rotating
CubeSat
Project Scope

Design Changes: Arm Control

- Issues with previous design
  - Large deviations from reference position
  - Difficulty controlling orientation
  - Began finding unstable trajectories
- Causes
  - Wrist rotate joint caused singularity in Jacobian matrix in common configurations
  - Orientation definition not unique

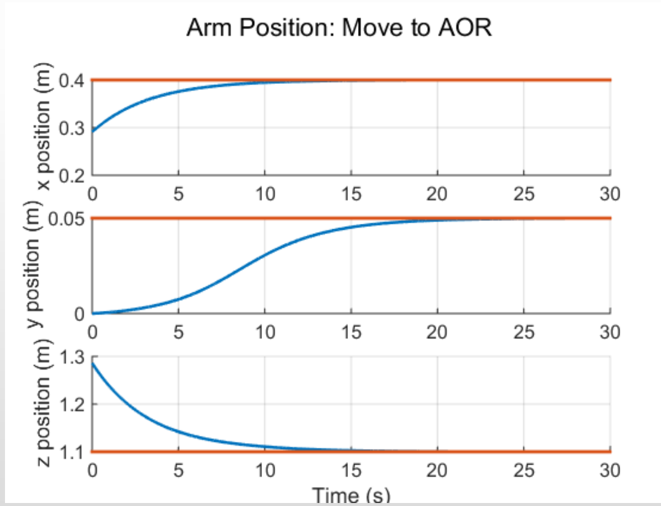
Arm Extension Simulation

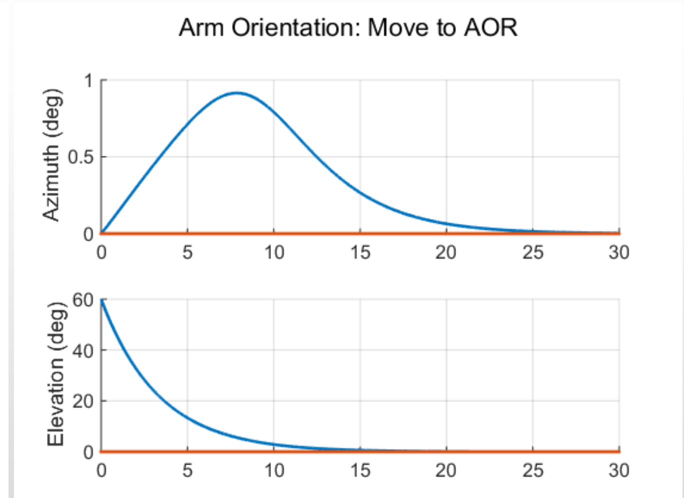




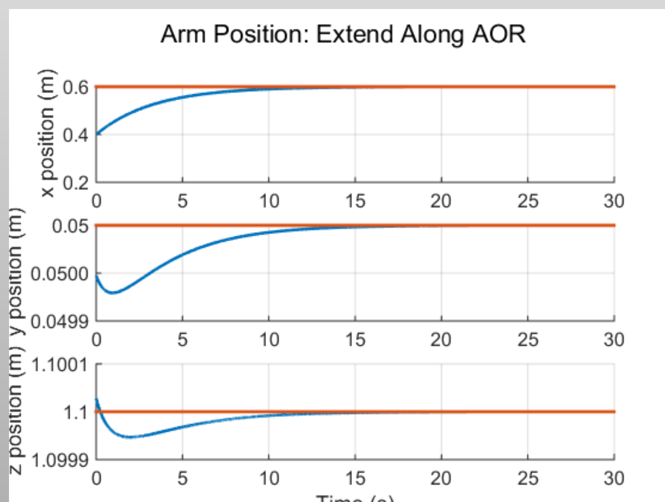
Arm Control Simulation Results

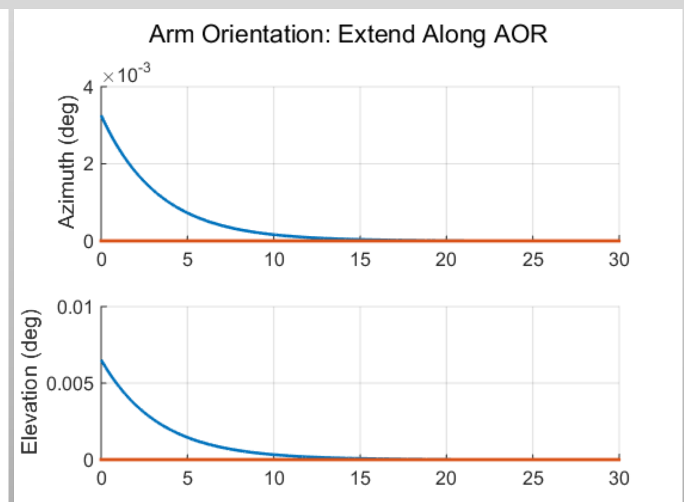
$$X_0 = \begin{bmatrix} 0.29 \\ 0 \\ 1.286 \\ 0^\circ \\ 60^\circ \end{bmatrix} \Rightarrow X_1 = \begin{bmatrix} 0.4 \\ 0.05 \\ 1.1 \\ 0^\circ \\ 0^\circ \end{bmatrix}$$





$$X_1 = \begin{bmatrix} 0.4 \\ 0.05 \\ 1.1 \\ 0^\circ \\ 0^\circ \end{bmatrix} \Rightarrow X_2 = \begin{bmatrix} 0.6 \\ 0.05 \\ 1.1 \\ 0^\circ \\ 0^\circ \end{bmatrix}$$





Arm Control & CubeSat Goal Position

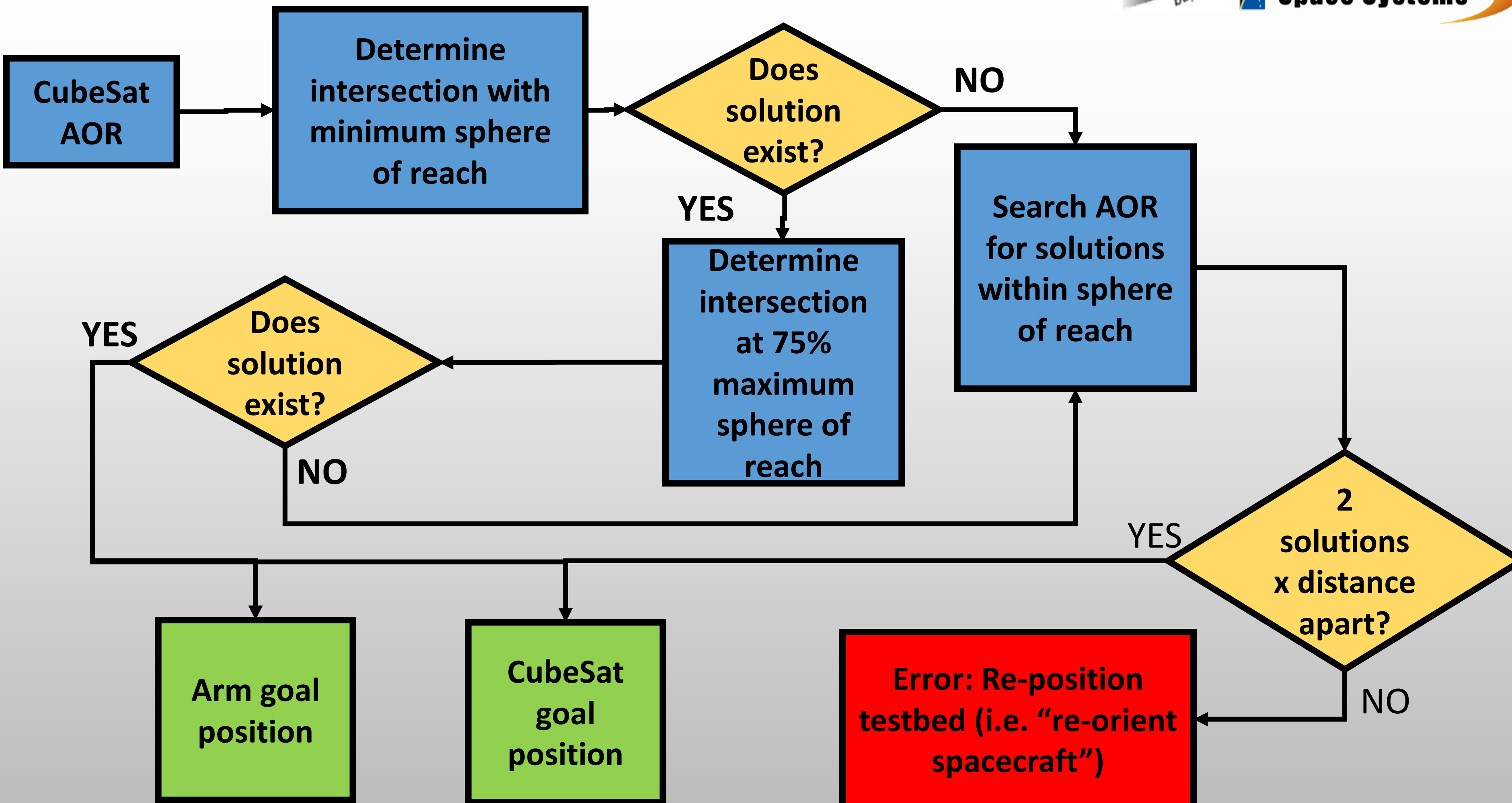
Possible Issue

- Attempting to control 5 states with only 4 degrees of freedom
- Because of this, there are certain poses within the sphere of reach that the arm cannot do
- Happens only with some states where elevation and azimuth pointing angles are **nonzero**
- In simulation, motion remains stable

Solution In Progress

- Check for possible solutions before initiating phase 1 (moving arm to CubeSat axis of rotation)
- Be “smart” about positioning CubeSat
- Diagram on next slide

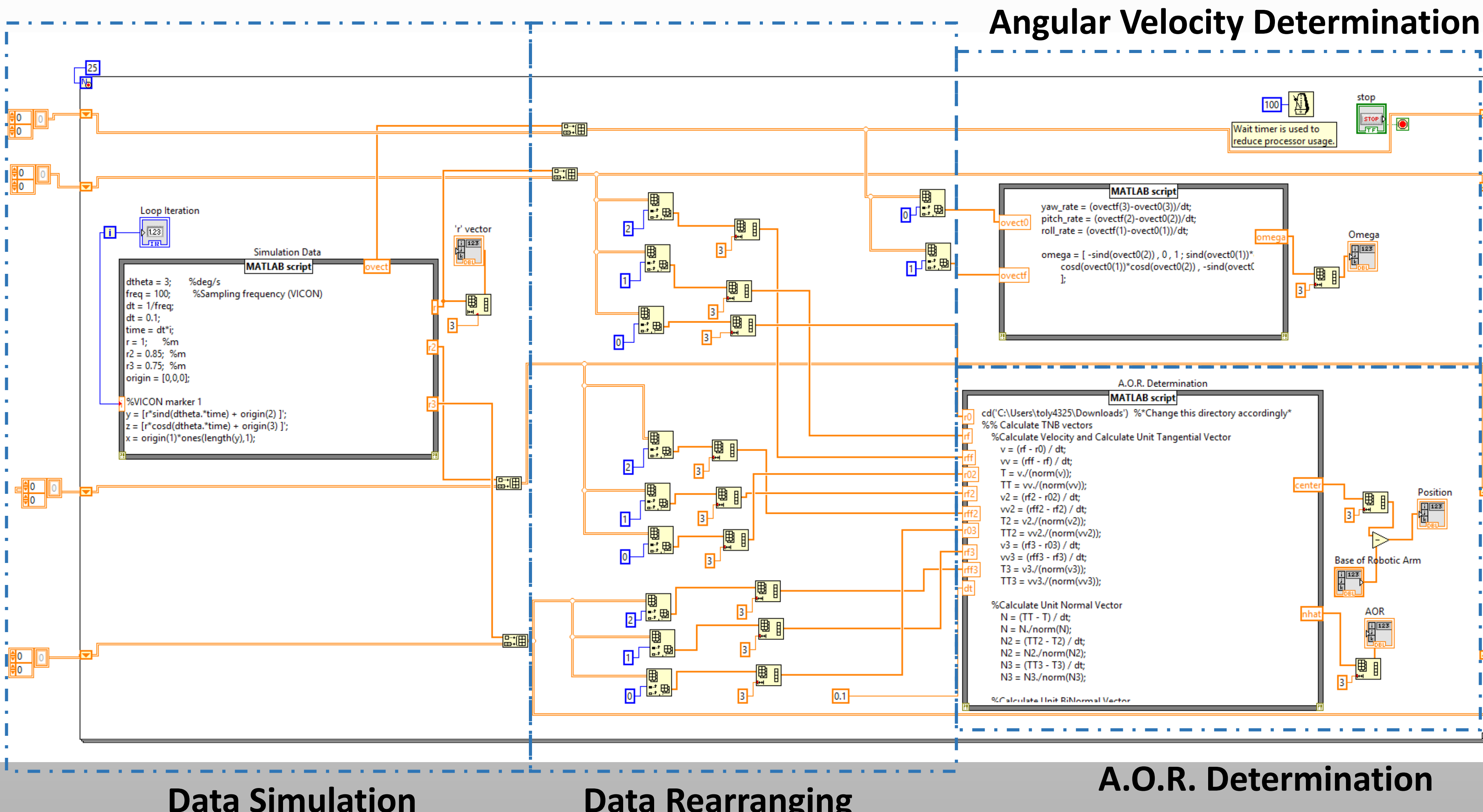
Arm Control & CubeSat Goal Position



*Solution checking done with numerical IK solver written by CASCADE that is essentially what was used for arm control simulations

Software Development Status

- CubeSat A.O.R. & Position/Orientation VI



CubeSat Manufacturing & Tolerances

Target
Dimension
xx.xxx”

POSSIBY A PIC
OF THE REAL
THING

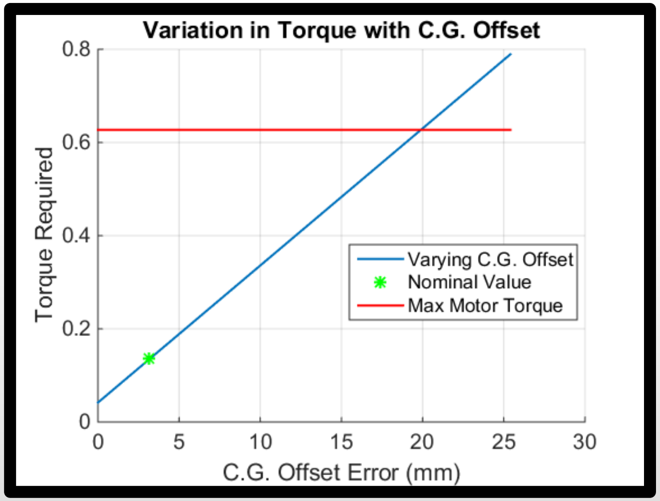
Actual
Dimension
xx.xxx”

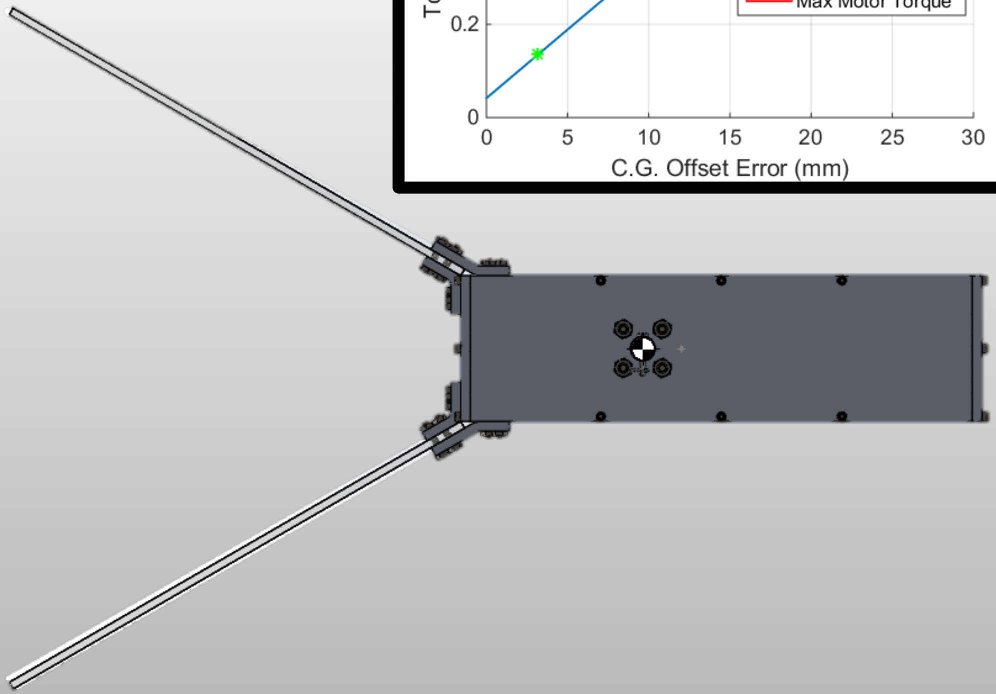
Error Sources:
Plate thickness (Procured): +.0XX”
Caliper measurement: ±.002”
Milling error +.007”

- Requirements still satisfied
- Ball joint can correct for induced angle created by positive tolerance

CubeSat C.G.

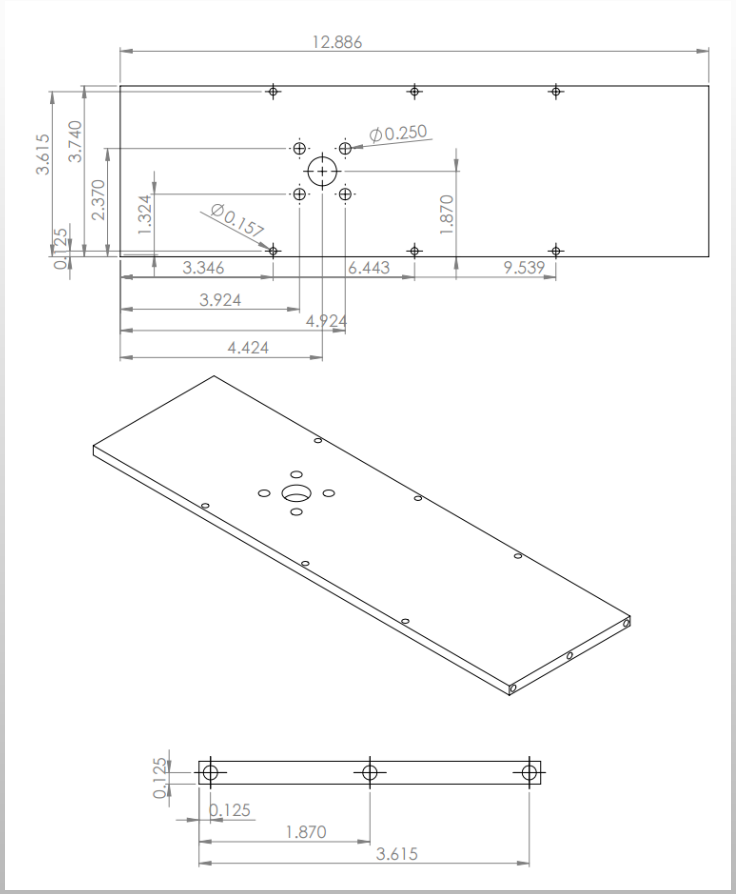
- Ballasting to correct C.G offset
- Developing method to test C.G. location
- 20 mm maximum offset for motor performance

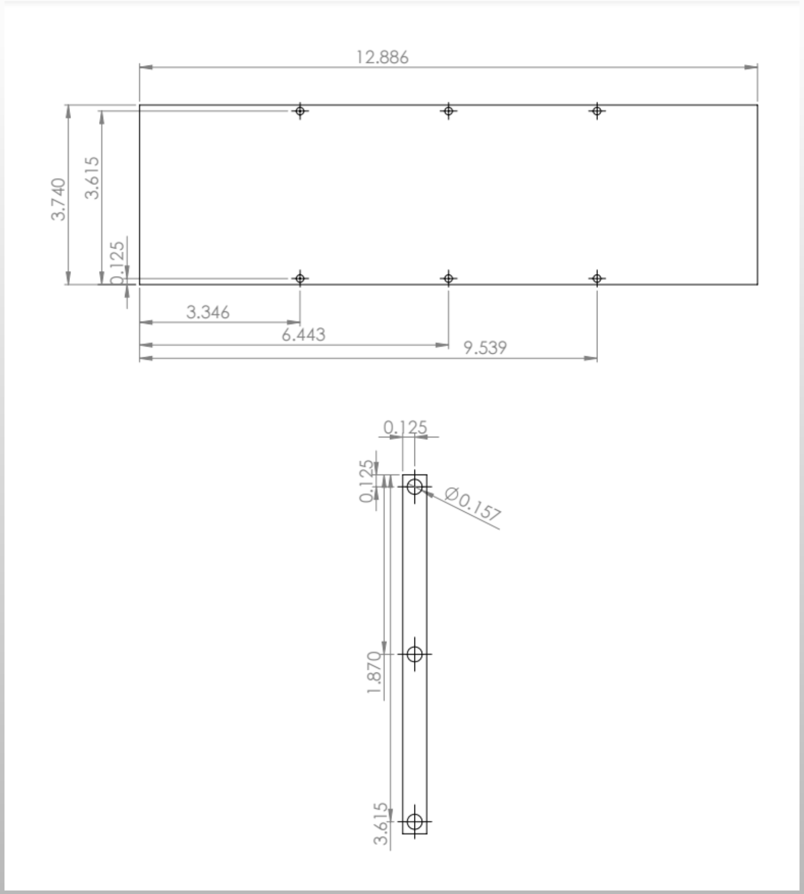




CubeSat Status

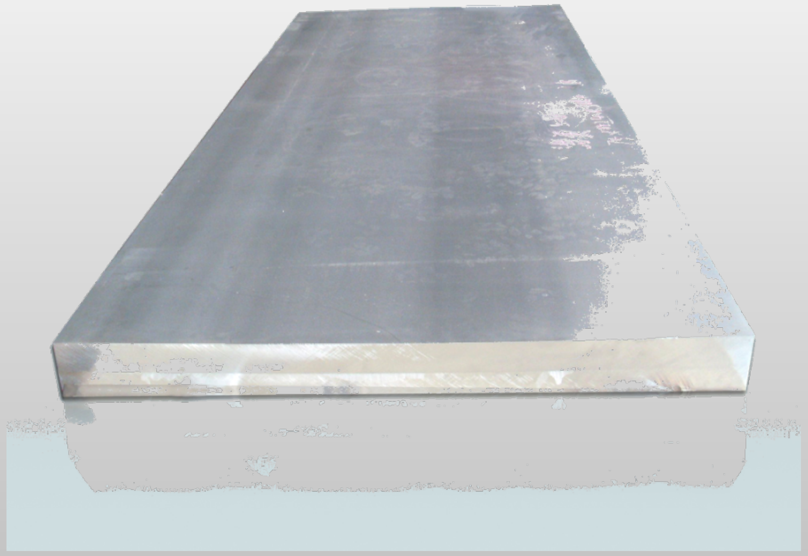
Sides





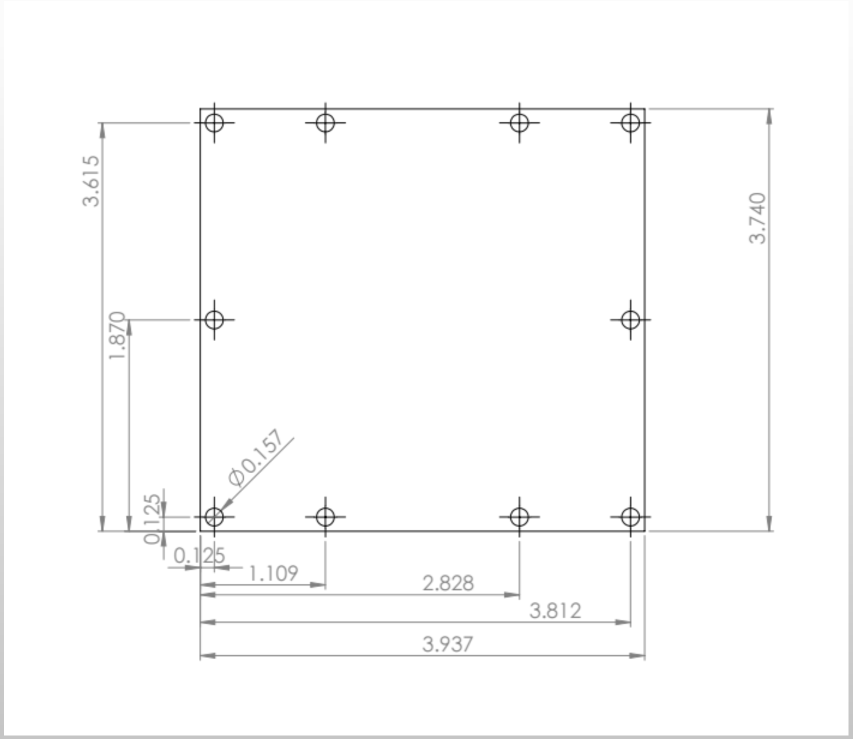
CubeSat Status

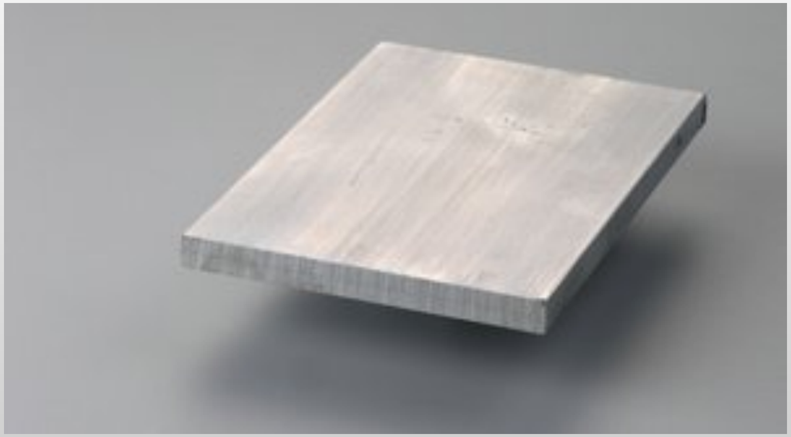
Sides



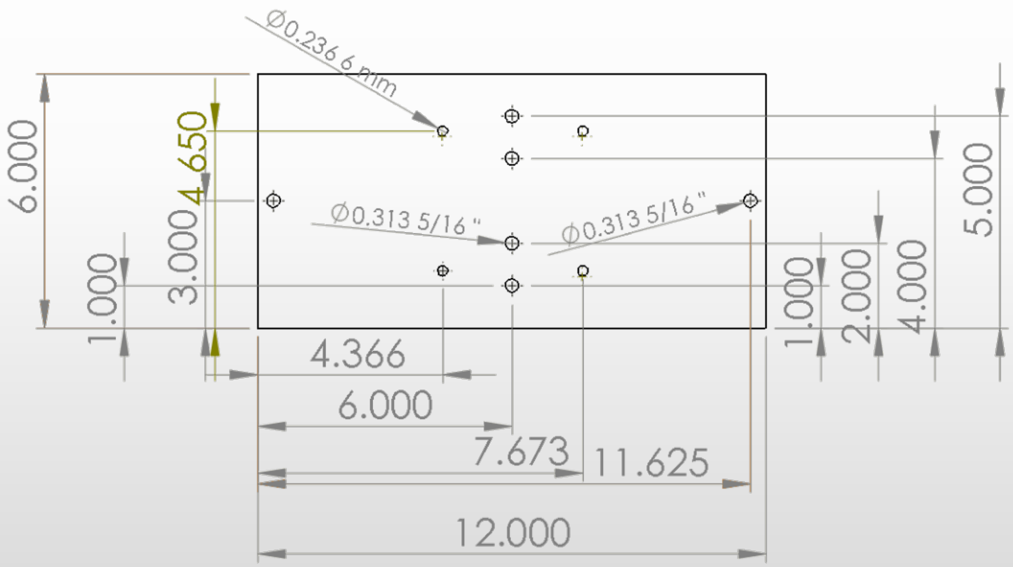
CubeSat Status

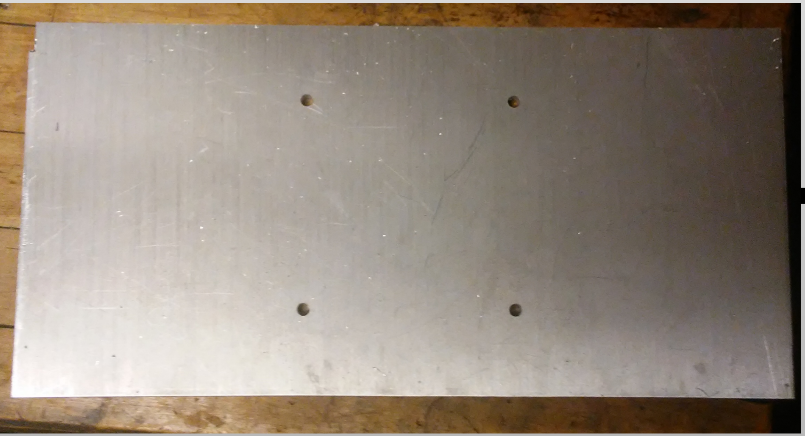
Front and Back plates



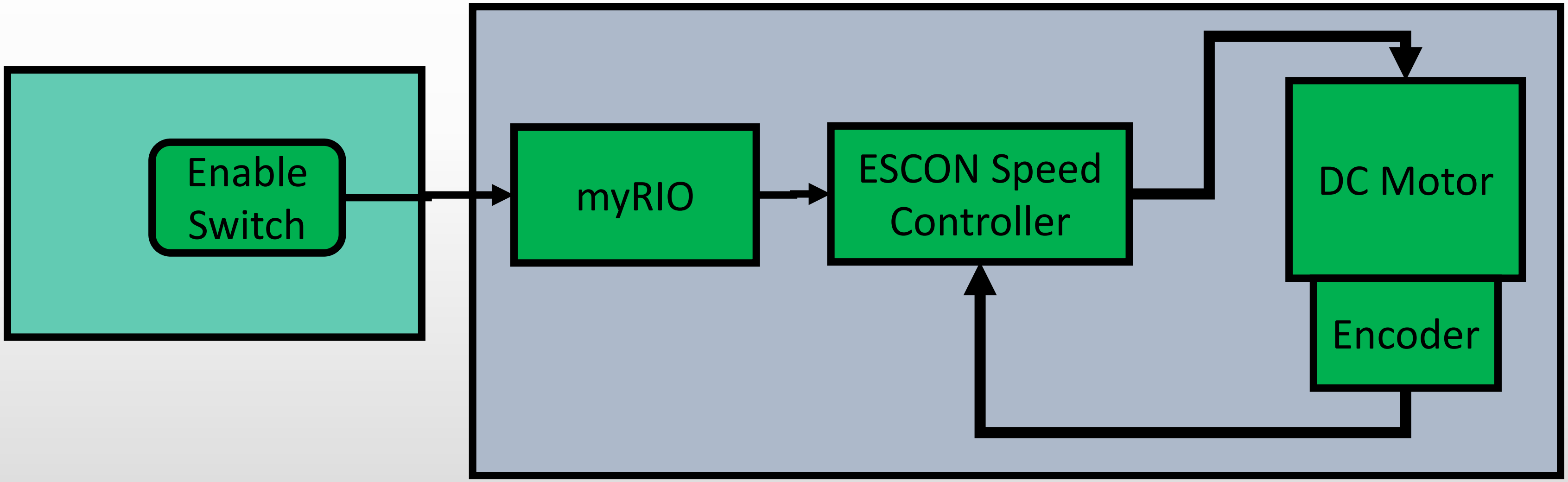


Machining Process – Interface Plate





CubeSat Rotation System



Software

Hardware

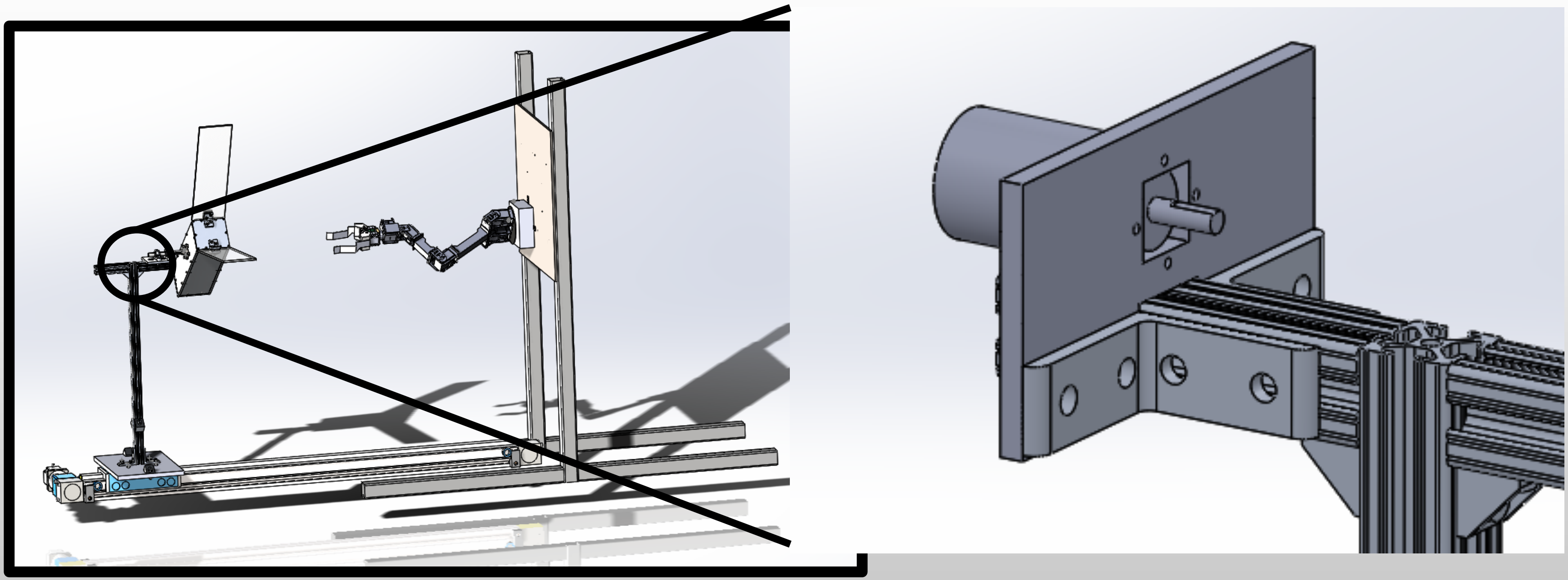
Completed:

- ESCON speed control configuration to 3 deg/s
- Electrical wiring and connectors
- Preliminary system functionality testing

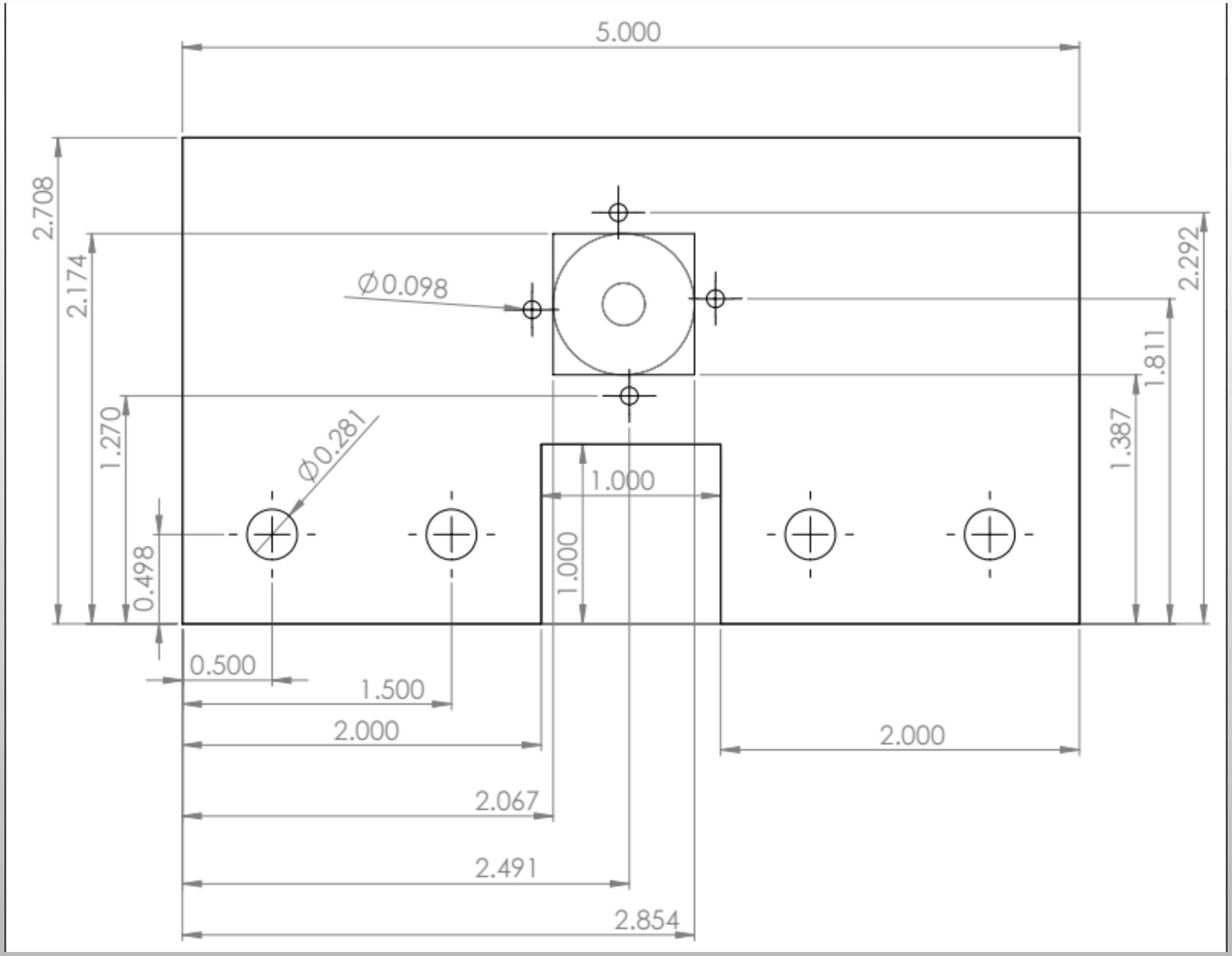
Future Work:

- System test using encoder data to ensure proper rotation rate
- Integration with CubeSat and support structure
- Software integration with master loop

Rotation Motor Mount



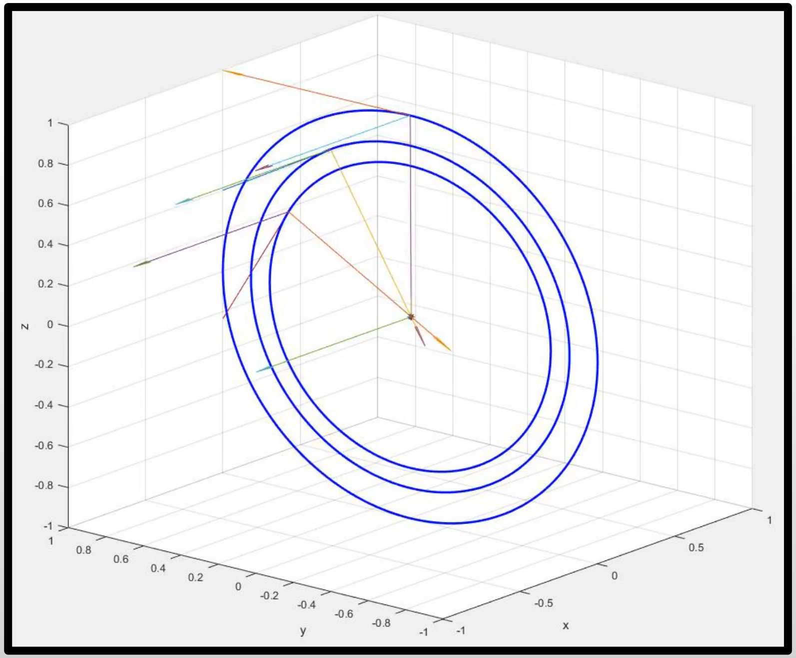
Rotation Motor Mount

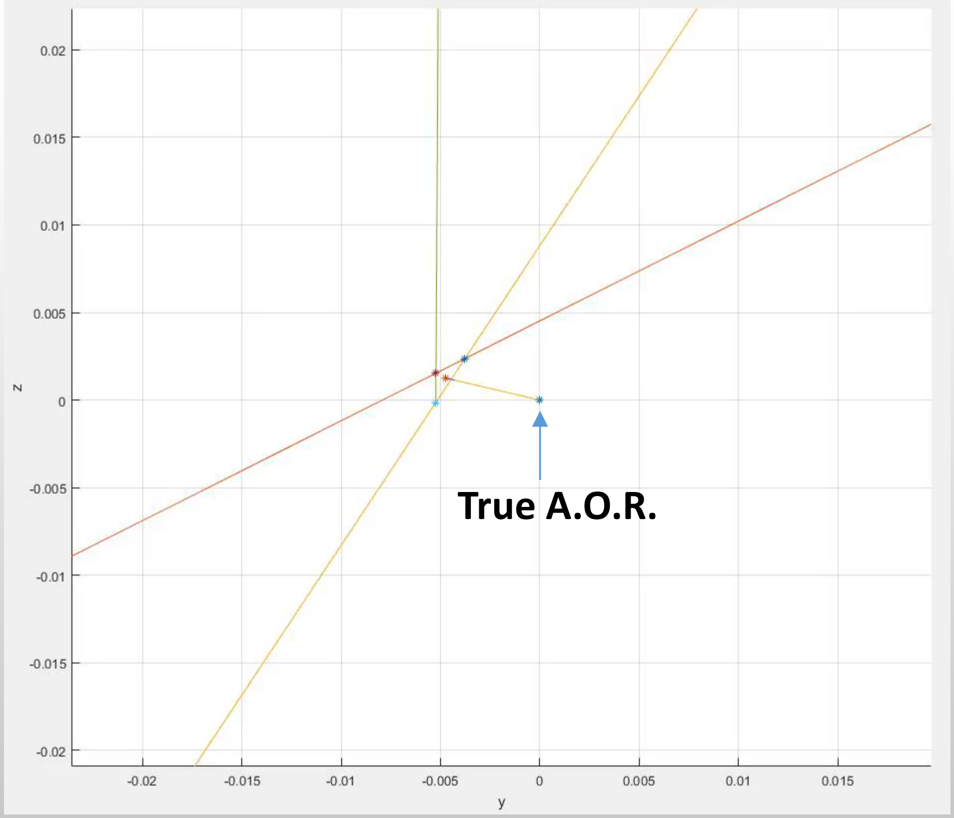


Overview | Schedule | Manufacturing | Budget

Software Development Status

- Axis of Rotation Determination





Error Estimates

Sample Rate	Error (m)
10 Hz	4.908e-03
50 Hz	9.817e-04
100 Hz	4.908e-04

Error Sources

- Numerical Differentiation
- Round-off error

Software Development Status

- Position & Orientation Determination
  1. Position Vector of CubeSat's C.G.
     - Assumption: C.G. is at axis of rotation
  2. Orientation Vector of CubeSat
     - Given: VICON Euler Angles(Yaw, pitch, roll)
  3. Angular Velocity Vector of CubeSat
     - Mapping Matrix

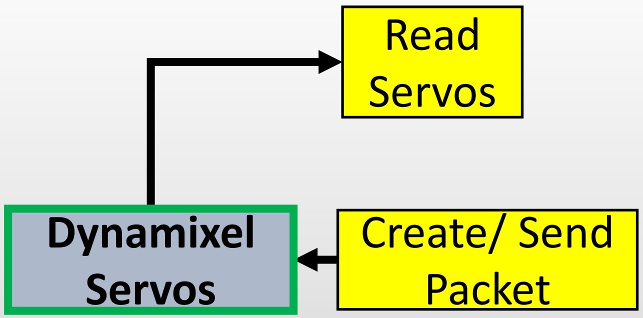
$$
{}^{\mathcal{B}}\boldsymbol{\omega} = {}^{\mathcal{B}}\begin{pmatrix} \omega_1 \\ \omega_2 \\ \omega_3 \end{pmatrix} = \begin{bmatrix} -\sin\theta & 0 & 1 \\ \sin\phi\cos\theta & \cos\phi & 0 \\ \cos\phi\cos\theta & -\sin\phi & 0 \end{bmatrix} \begin{pmatrix} \dot{\psi} \\ \dot{\theta} \\ \dot{\phi} \end{pmatrix}
$$

Backup: Communication Between Loops

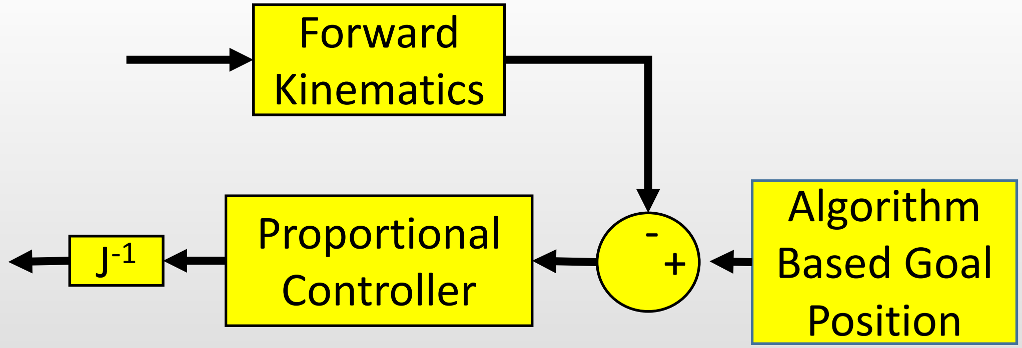
Communication Between Loops
- Set up Producer-Consumer model in labview
- Ran 1st Loop at 100 Hz (VICON)
- Sent Current Time to Queue (FIFO)
- Second Loop Takes (Current time – Time in Queue)

Second Loop Rate	Delay [µs]
100 Hz	3.69
166 Hz	24.61
50 Hz	28.72

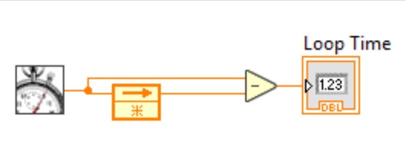
Backup: Timing Methodology



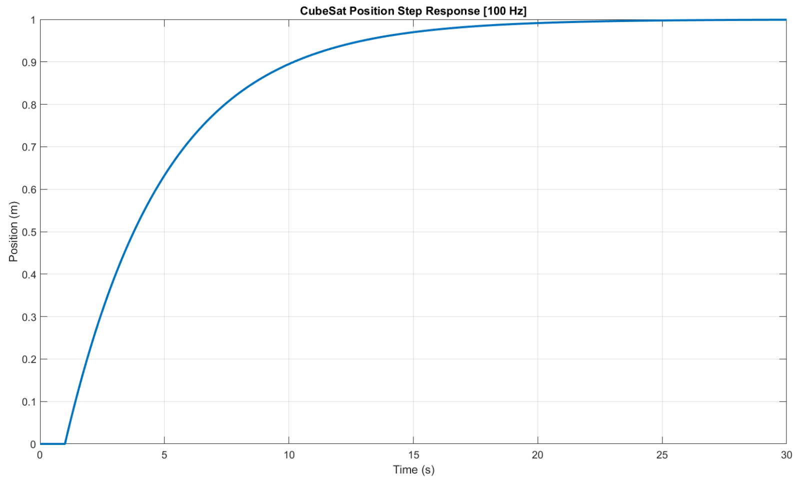
~28±2 ms

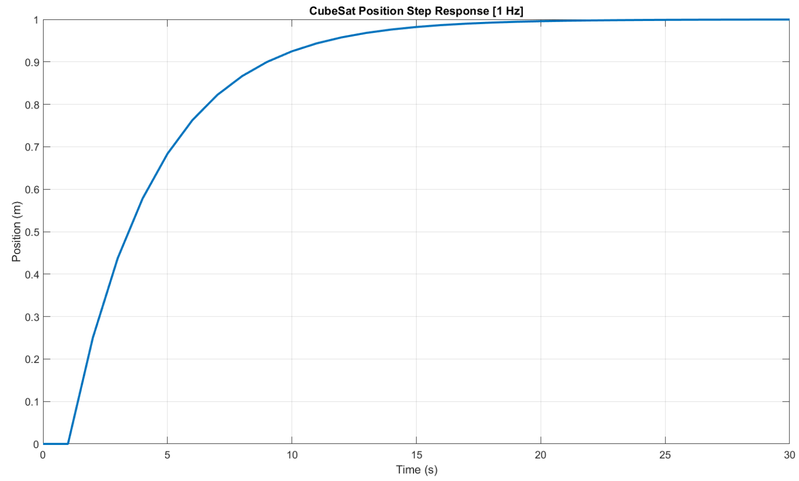


~5.2 ms

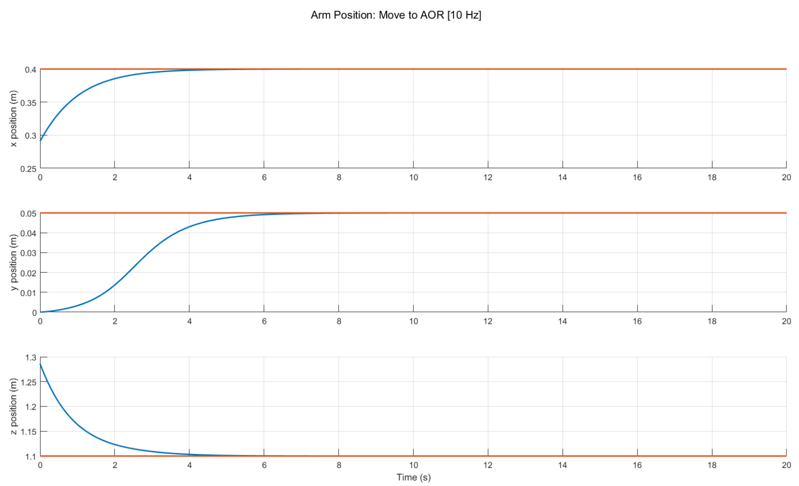


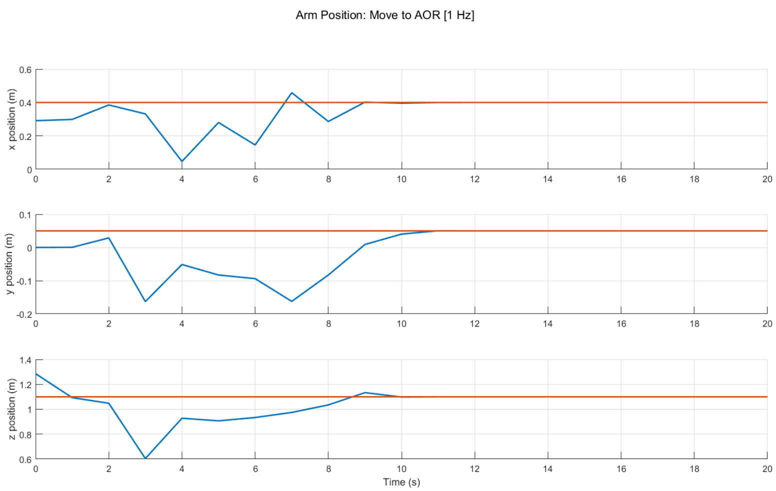
Testbed Simulation results





Arm Controller Timing Simulation Results

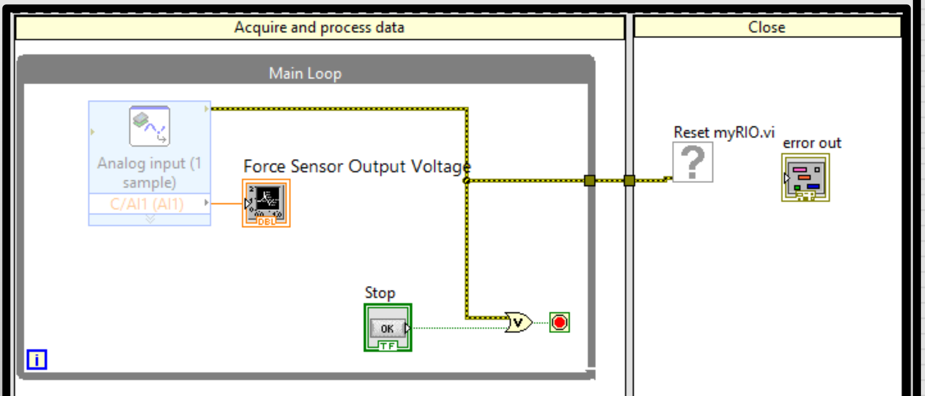




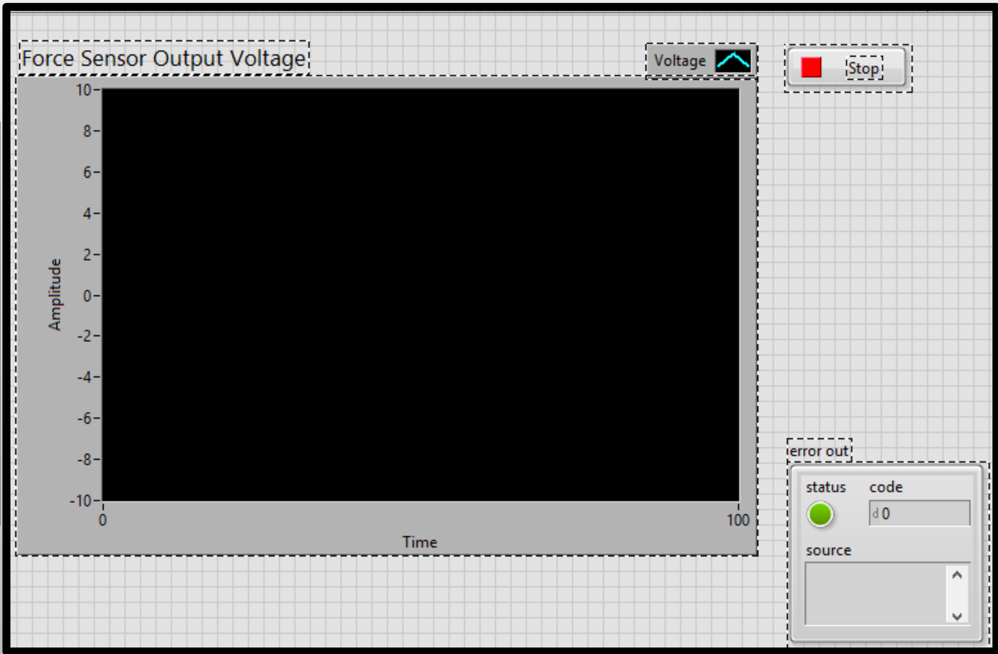
Force Sensing Status: Software

- **The FSR signal Condition will go into the MyRiO DAQ.**

- **Through the FSR VI the capture device will confirm capture when the voltage goes above a predefined voltage level .**

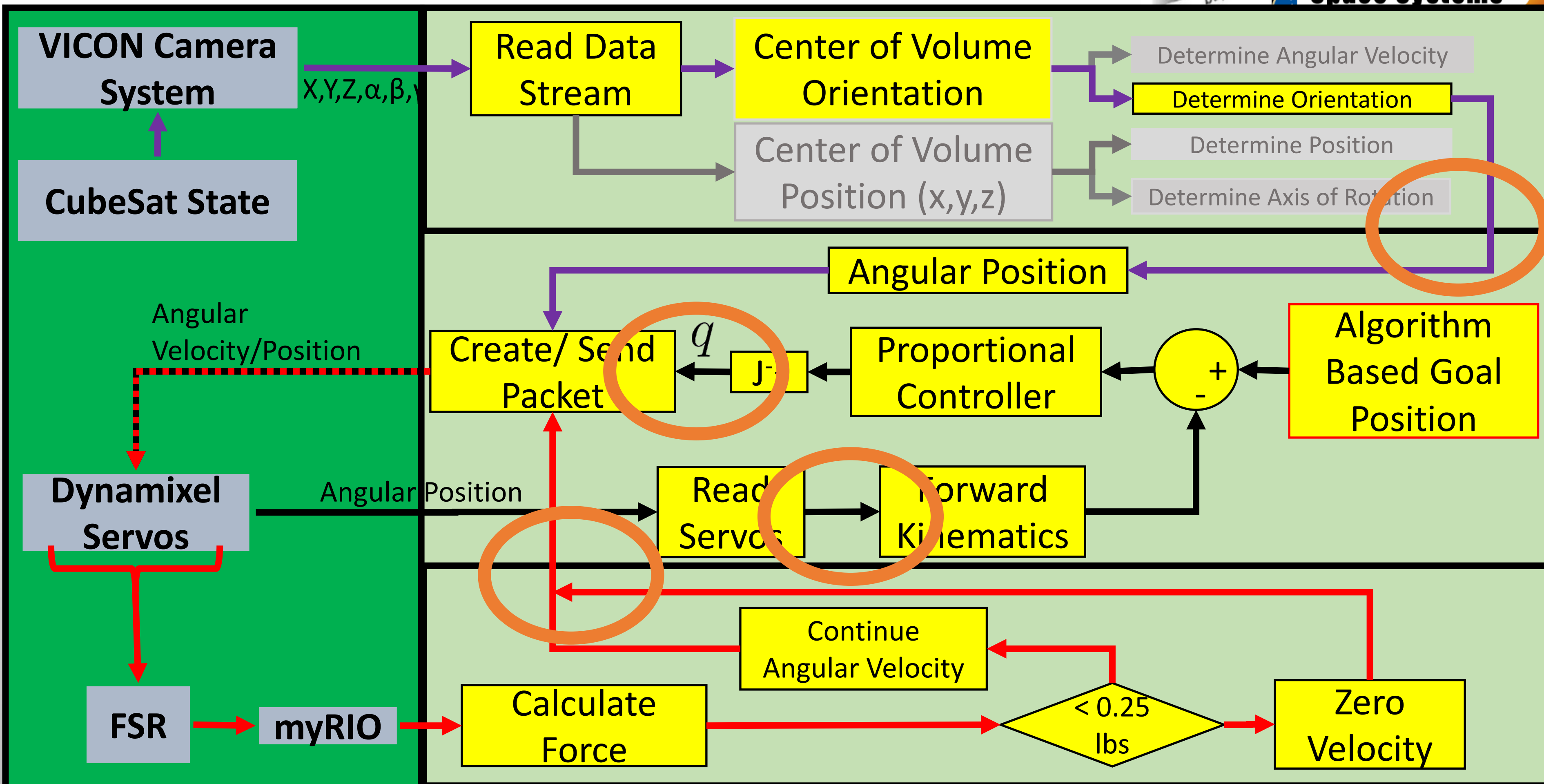


Block diagram of FSR VI



Plot display of FSR_Sensor .Vi

Backup: Arm Controller

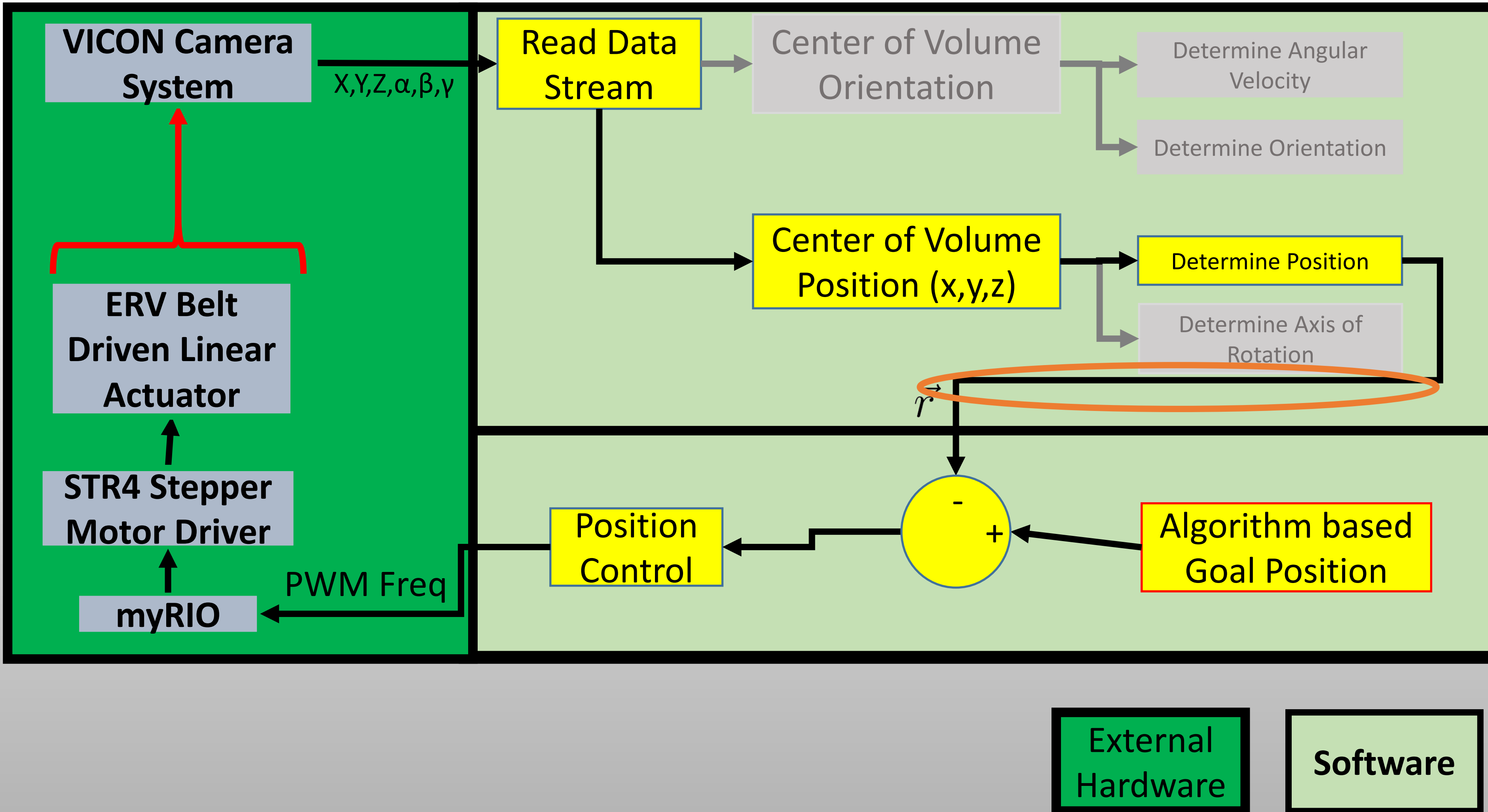


Position control arm, and read from servos
All functions are created, just needs sub integration

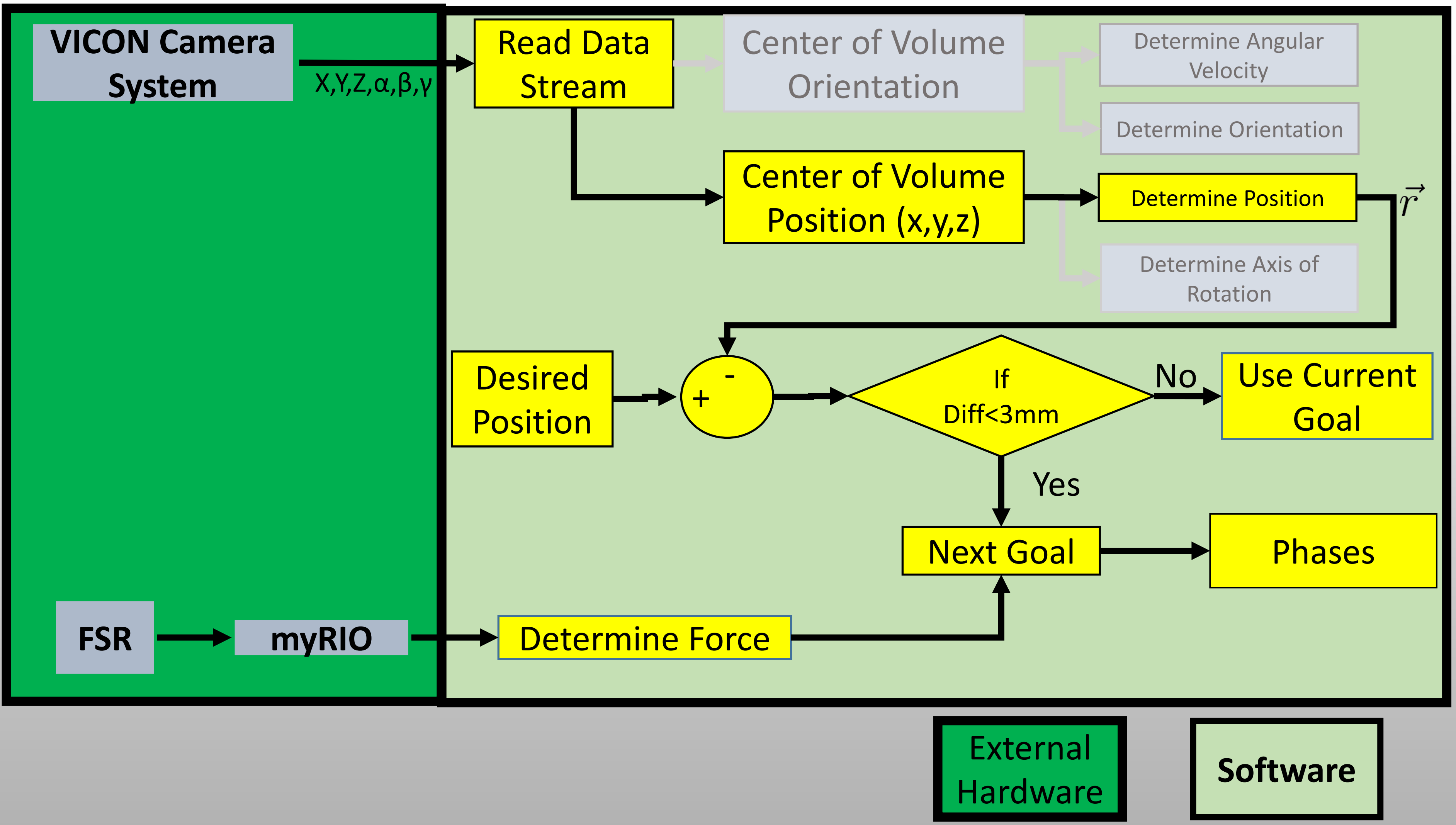
External Hardware

Software

Backup: Linear Rail Controller



Backup: Goal Check/ Command Block



Software's Five Phases To Capture

1: Align with AOR → Position Arm to be max distance from CubeSat along AOR

2: Translate CubeSat to Gripping Position → Position on Rail Based on 75% of Full Extension

3: Spin End Effector → Current Orientation of CubeSat

4: Extend to Grab Position → 75% of Full Extension

5: Close End Effector → Force Sensor 0.25 lbs → Next Step