Spring Final Review

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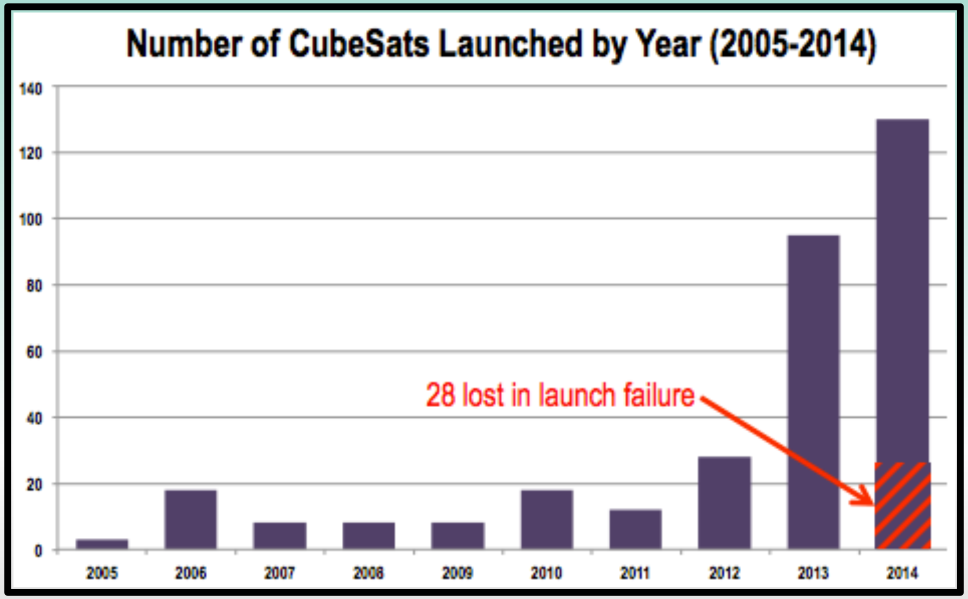
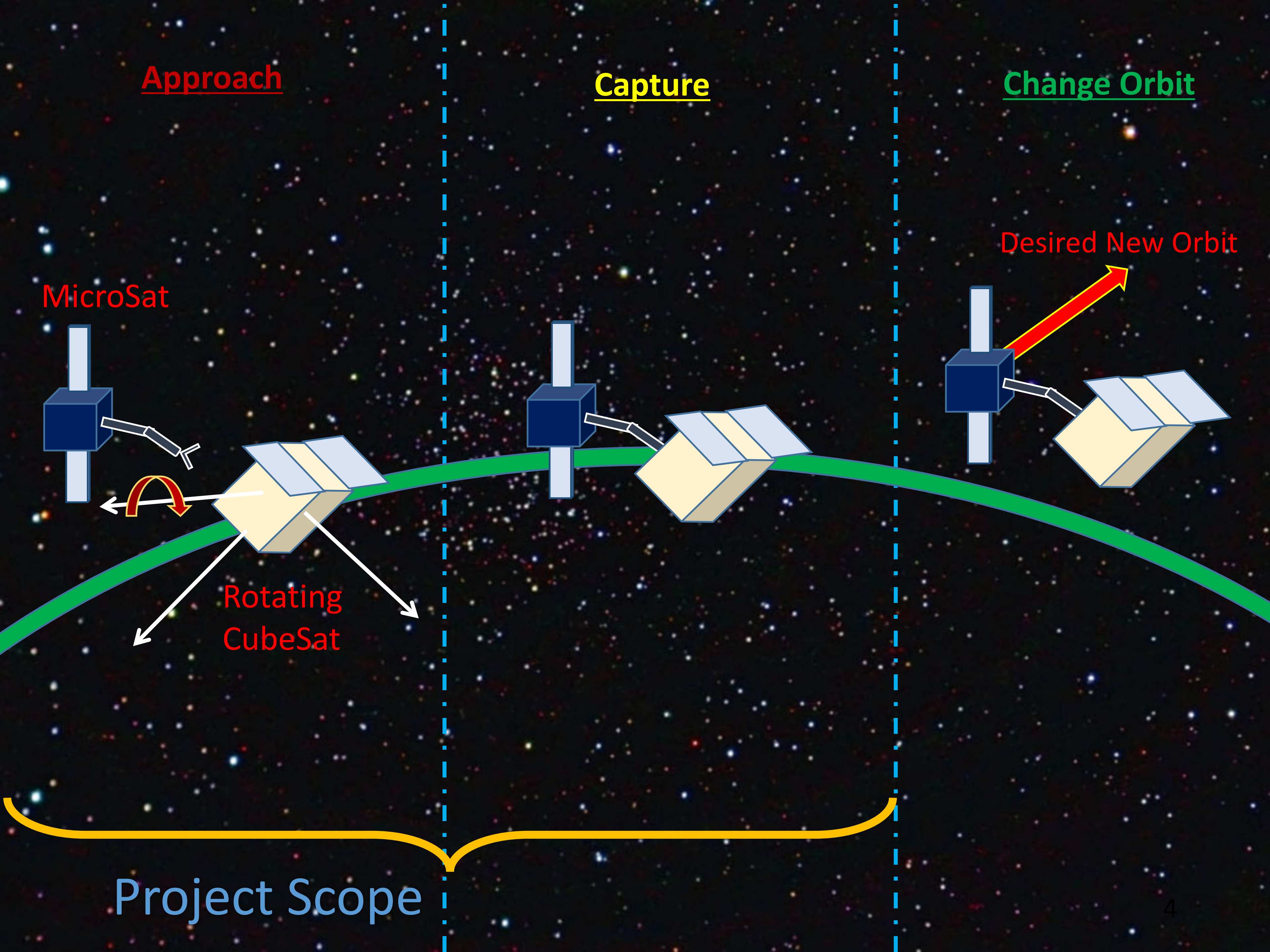
Project Purpose and Objectives

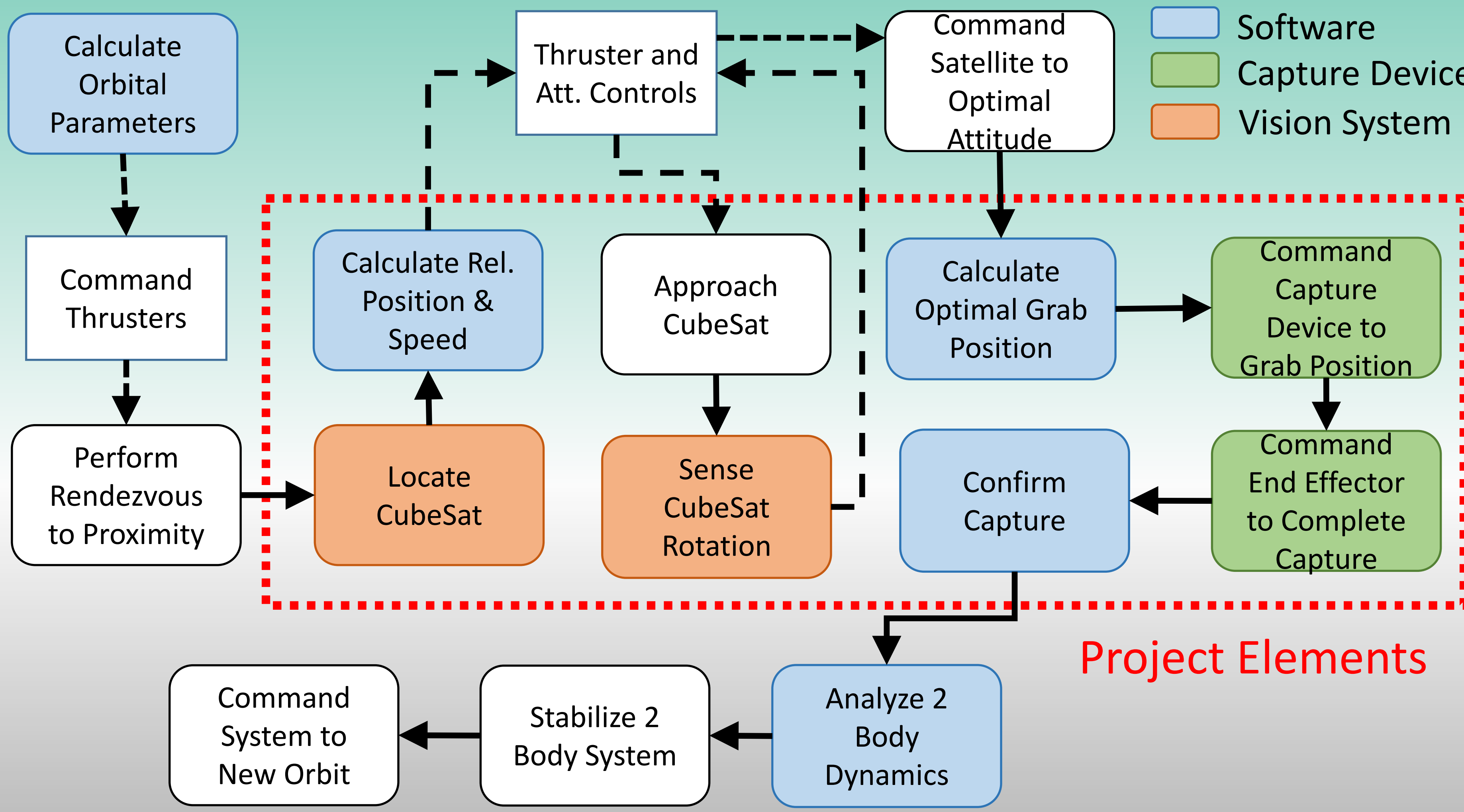
Project Motivation

- CubeSats market is growing exponentially.
- Existing CubeSats have little or no propulsive capabilities.
- Sierra Nevada Corporation would use a capture device and vision system in order to **recover** and **repurpose** CubeSats.




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

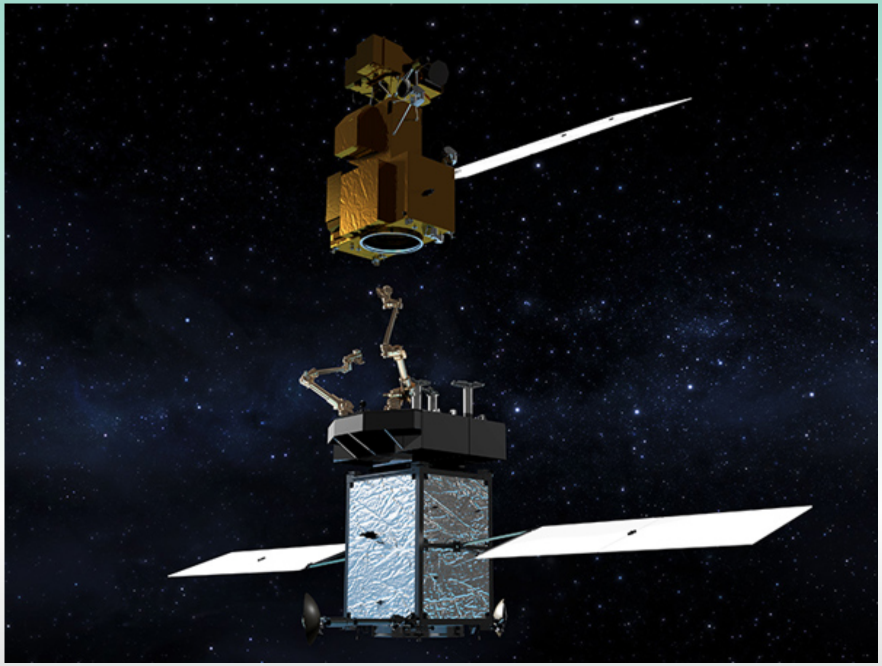
Mission FBD



Calculate Orbital Parameters
Command Thrusters
Perform Rendezvous to Proximity
Thruster and Att. Controls
Command Satellite to Optimal Attitude
Calculate Rel. Position & Speed
Locate CubeSat
Approach CubeSat
Sense CubeSat Rotation
Calculate Optimal Grab Position
Command Capture Device to Grab Position
Command End Effector to Complete Capture
Confirm Capture
Analyze 2 Body Dynamics
Stabilize 2 Body System
Command System to New Orbit
Software
Capture Device
Vision System
Project Elements

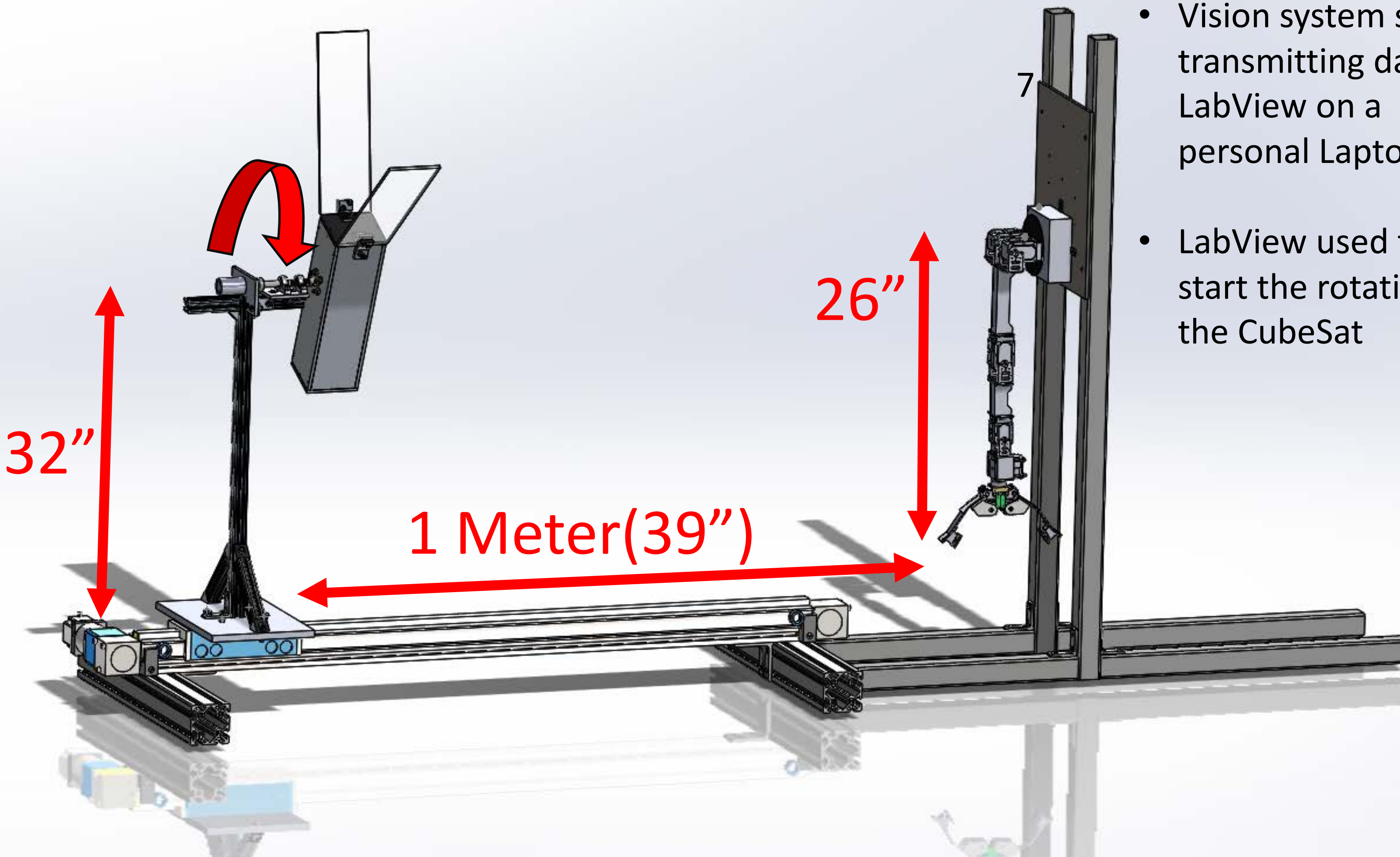
Project Statement

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**.

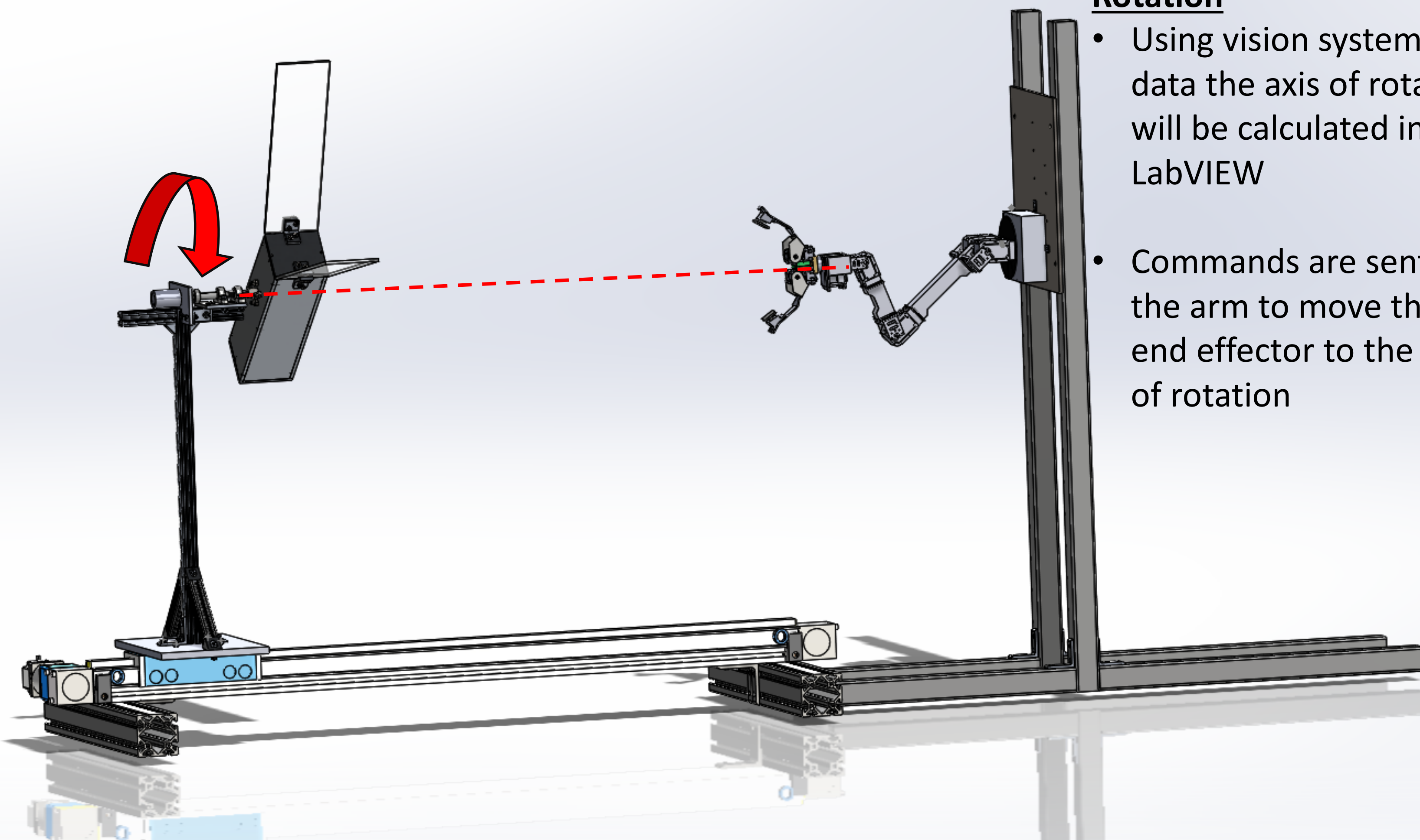
Test Bed CONOPS



0.) Initiation of Demonstration

- Vision system starts transmitting data to LabView on a personal Laptop
- LabView used to start the rotation of the CubeSat

Test Bed CONOPS



1.) Move to Axis of Rotation

- Using vision system 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

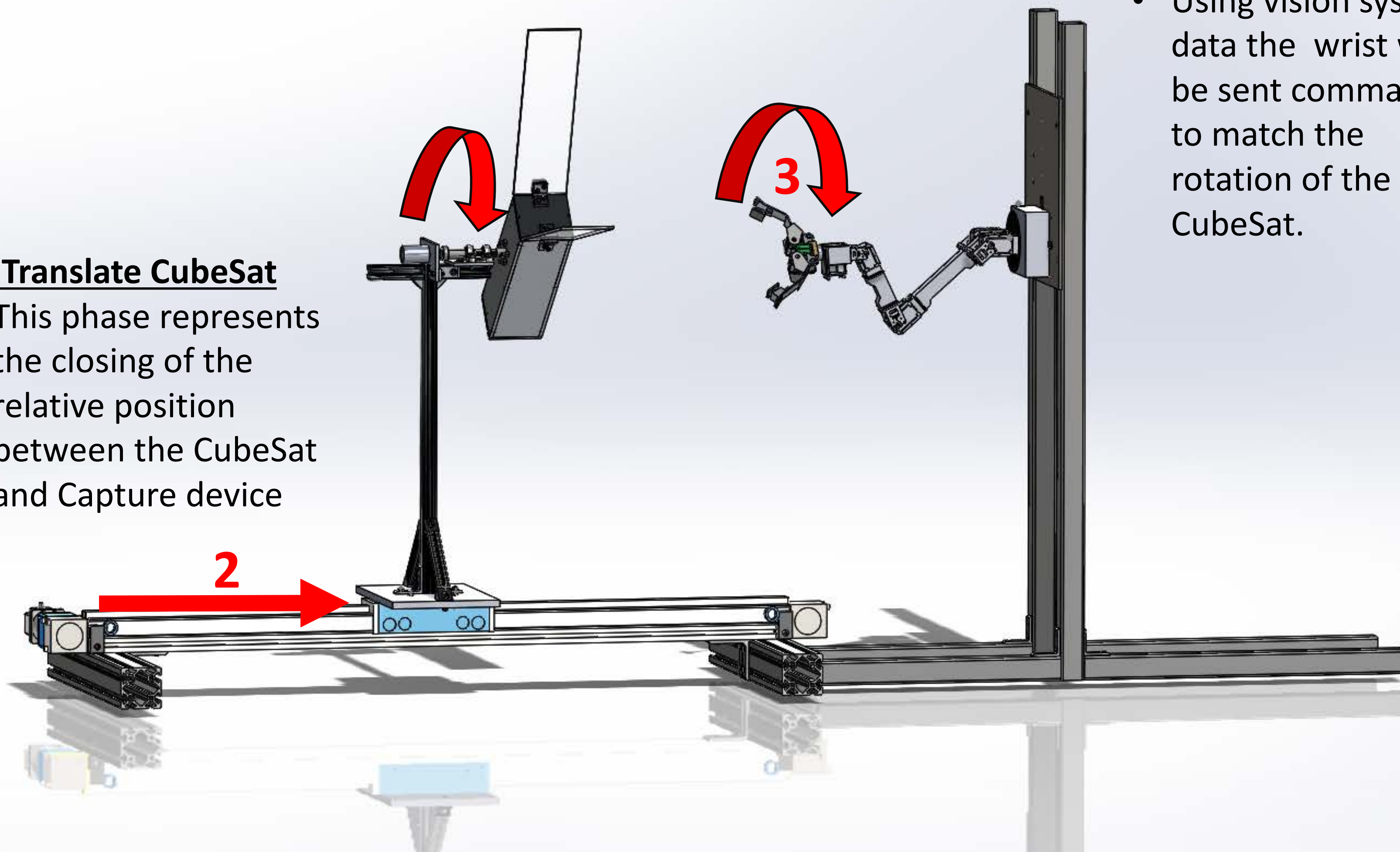
Test Bed CONOPS

3.) Wrist Rotation

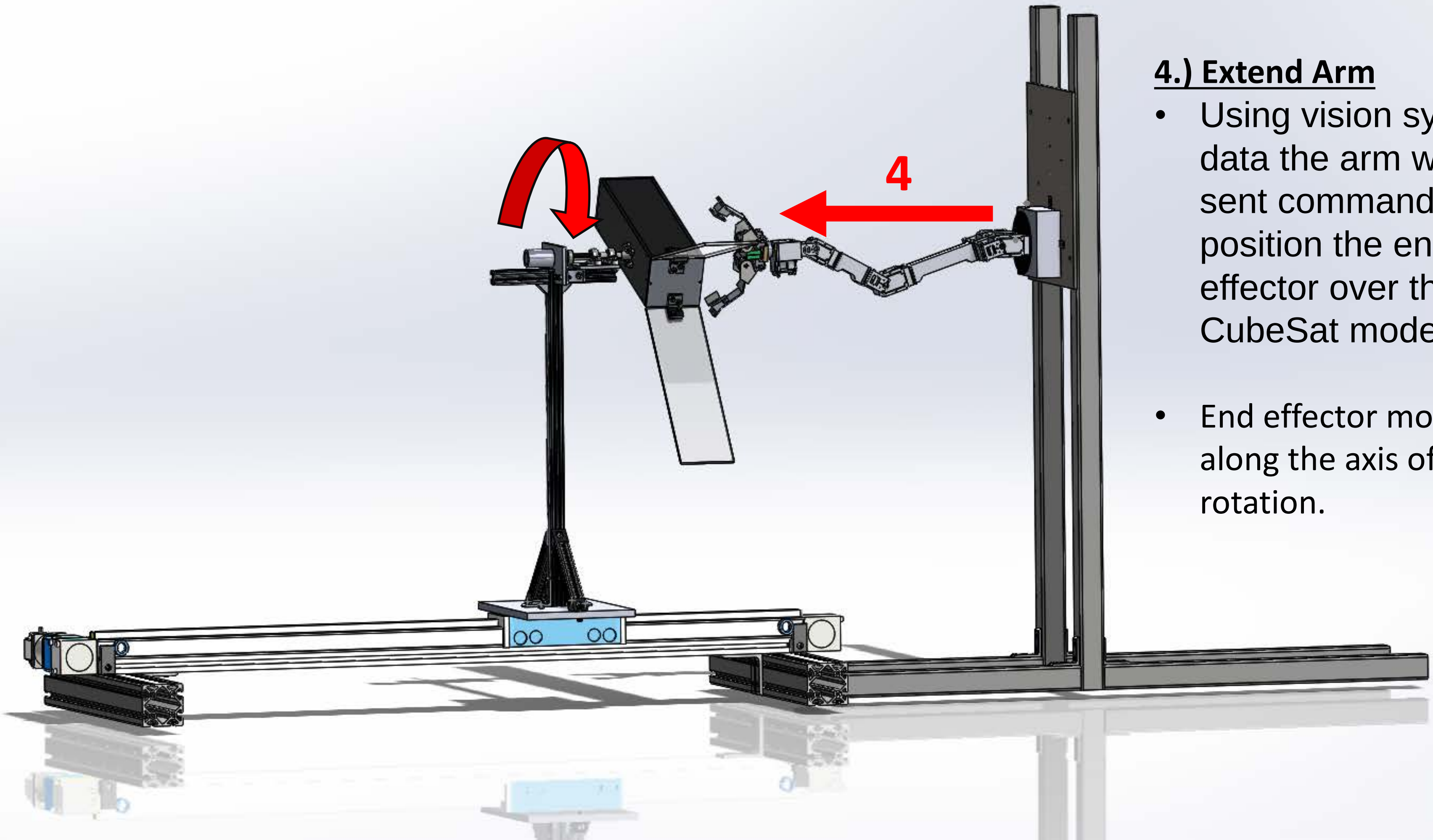
- Using vision system data the wrist will be sent commands to match the rotation of the CubeSat.

2.) Translate CubeSat

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



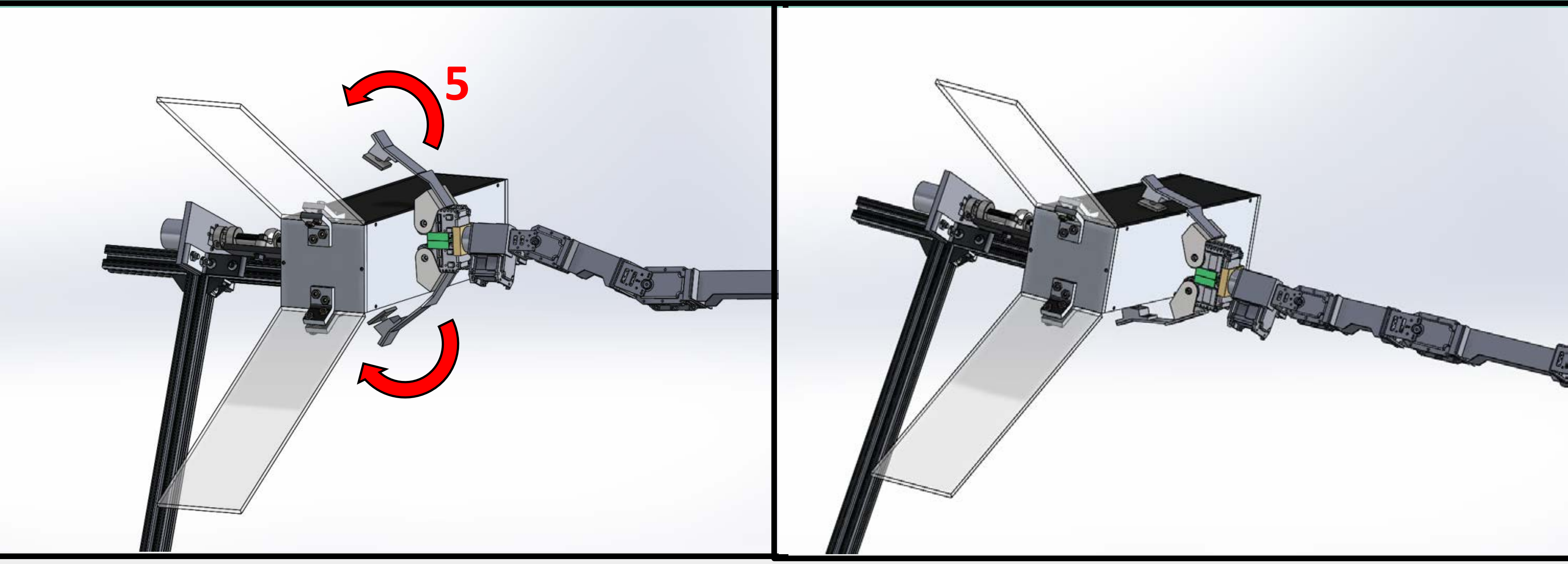
Test Bed CONOPS



4.) Extend Arm

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

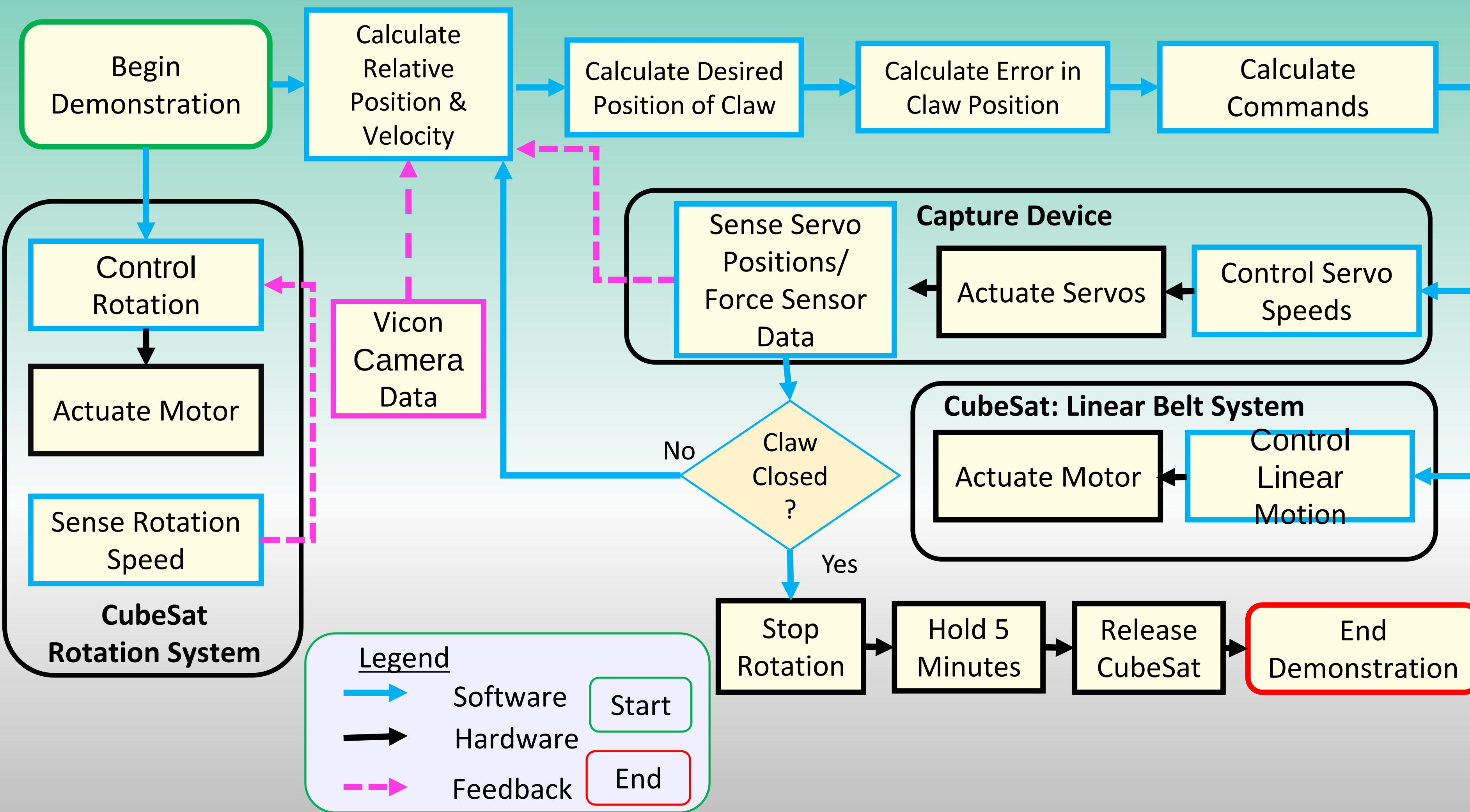
Test Bed CONOPS



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.

Test Bed Functional Flow Diagram



Critical Project Elements

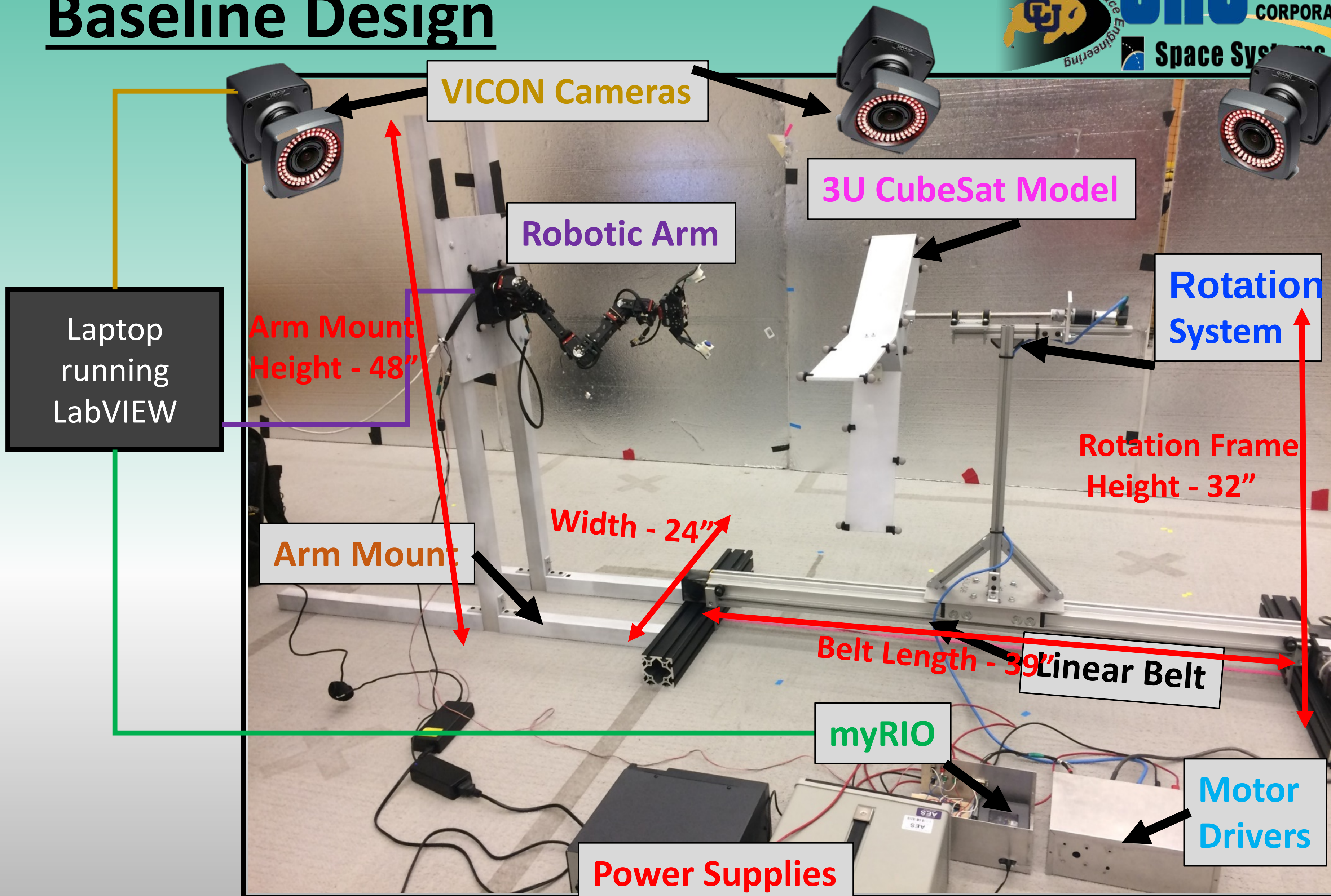
Critical Project Element	Component
The CRST shall determine the axis of rotation and relative attitude of the CubeSat.	Software and Vision
The robotic arm will operate within safe limits.	Software and Control
The robotic arm shall travel along the axis of rotation as it approaches the CubeSat.	Software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

Levels of Success

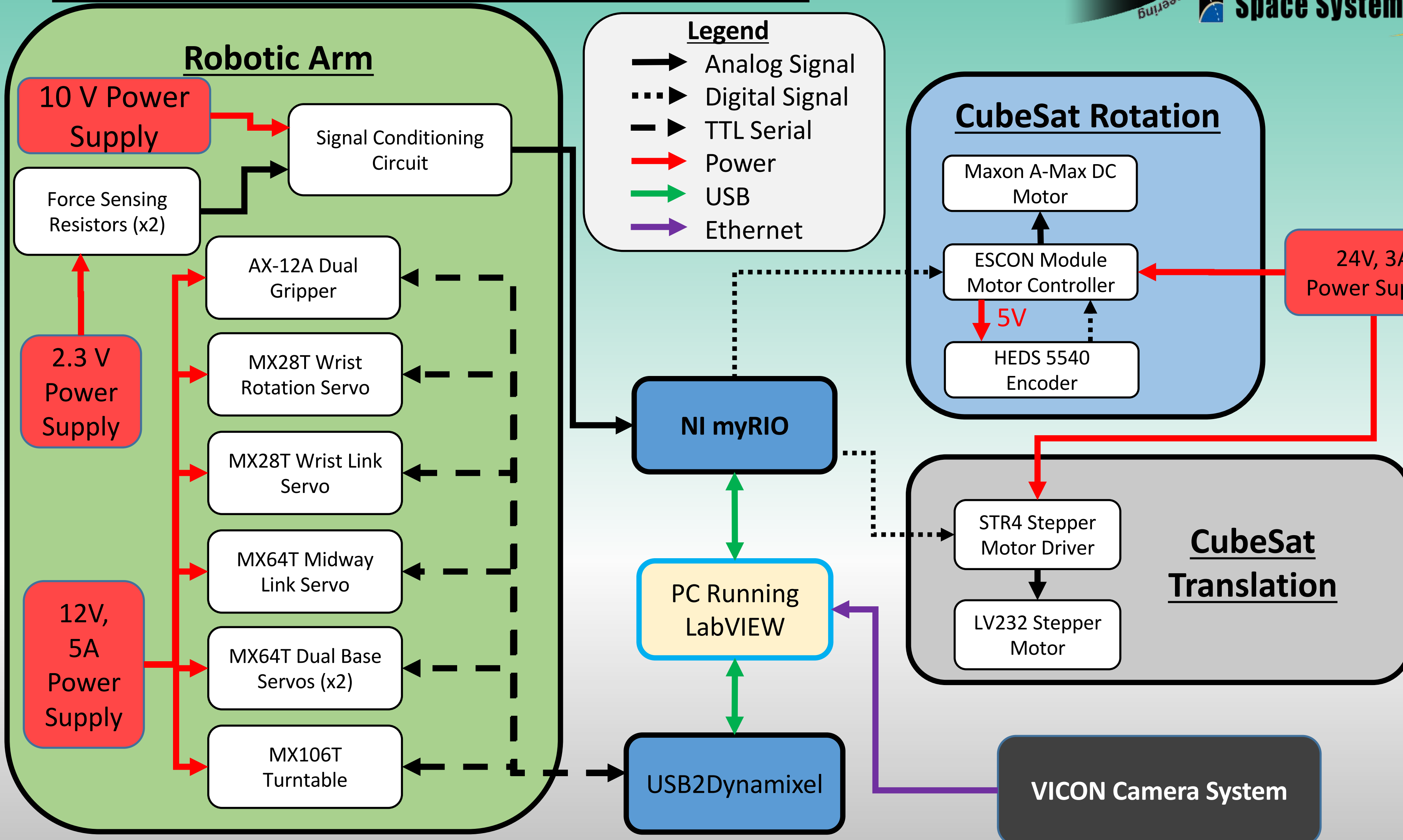
Success Levels	Testbed Demonstration	Capture Device Control
Level 1	1 DOF Translation	Open Loop (Commanded 1 Stage at a time)
Level 2	1 DOF Rotation at 3°/sec	Closed loop using VICON data to know when to move on to next stage **(FR 1.2-1.4)**
Level 3	1 DOF translation and 1 DOF rotation at 3°/sec **(FR 1.1)**	

Design Description

Baseline Design



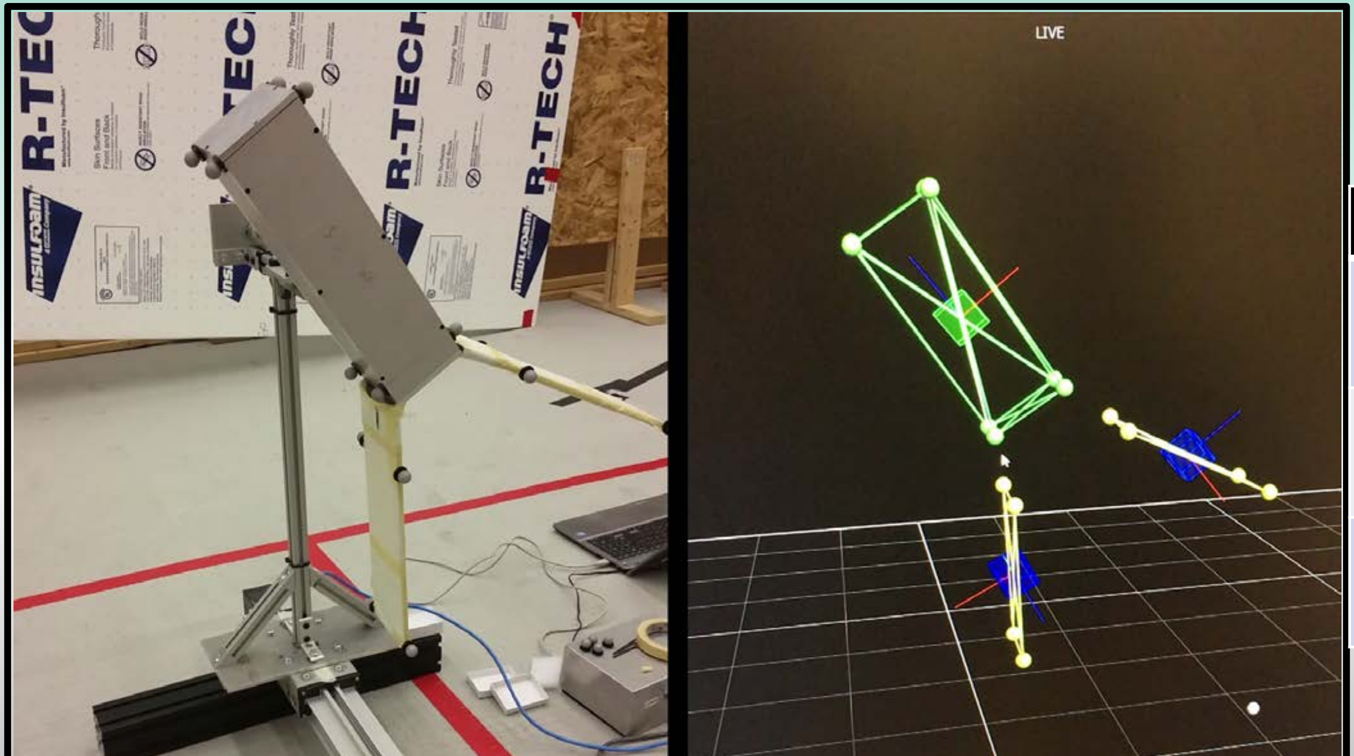
Hardware Block Diagram



RECUV Vision Lab

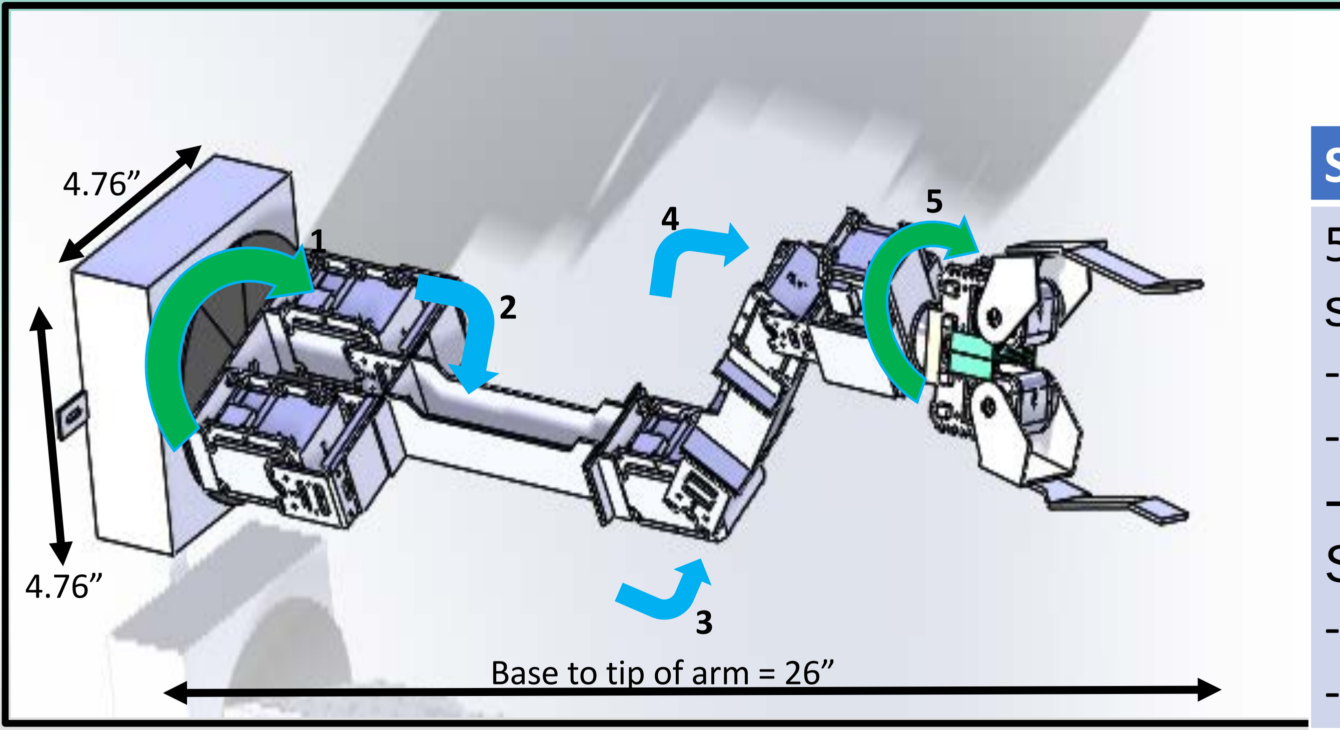
Uses infrared cameras that track an object defined by reflector spheres.

The VICON System gives us:
[x, y, z, roll, pitch, yaw] for the centroid of each object.



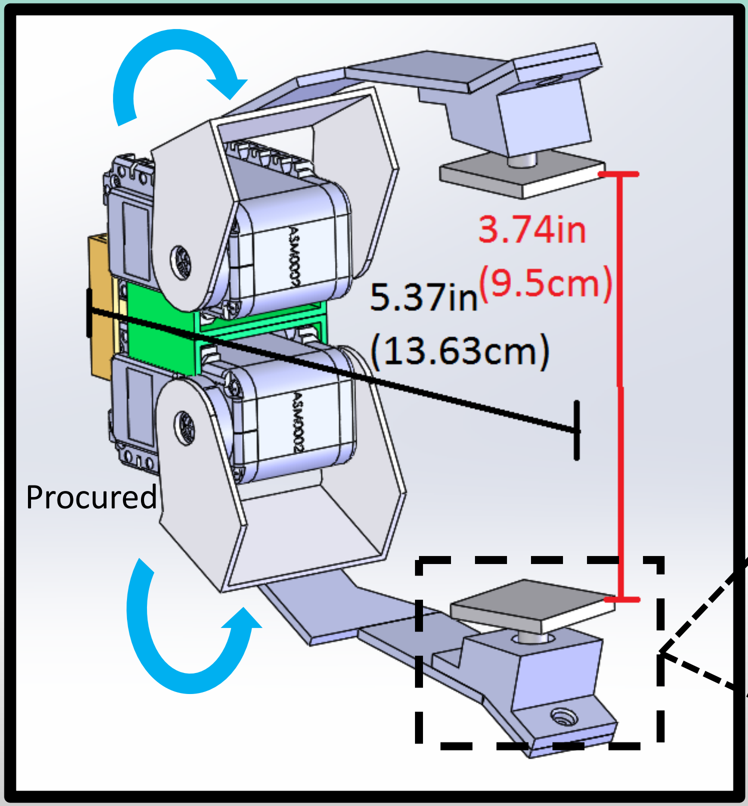
Specifications:
Interface: Port 800 Ethernet
Average Static Error: 0.0775 mm
Average Latency: 16.87 ms

Capture Device: Robotic Arm

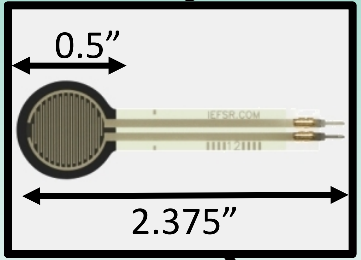


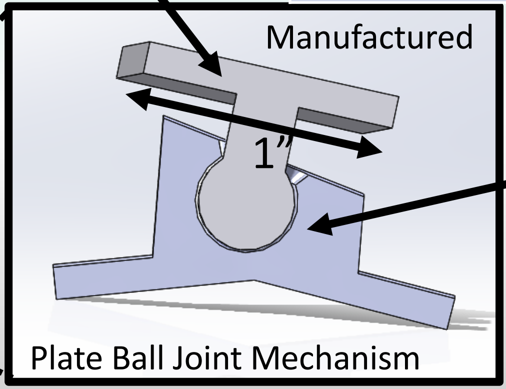
Specifications:
5 DOF arm with 6 servos -Base Rotation (1 Servo) -Base Bend (2 Servos) -Midway Bend (1 Servo) -Wrist Bend (1 Servo) -Wrist Rotator (1 Servo)
Crust-Crawler Modular Arm: Customizable arm girder lengths and joint servo sizes.
Cost: $2,754

Capture Device: Modified Gripper



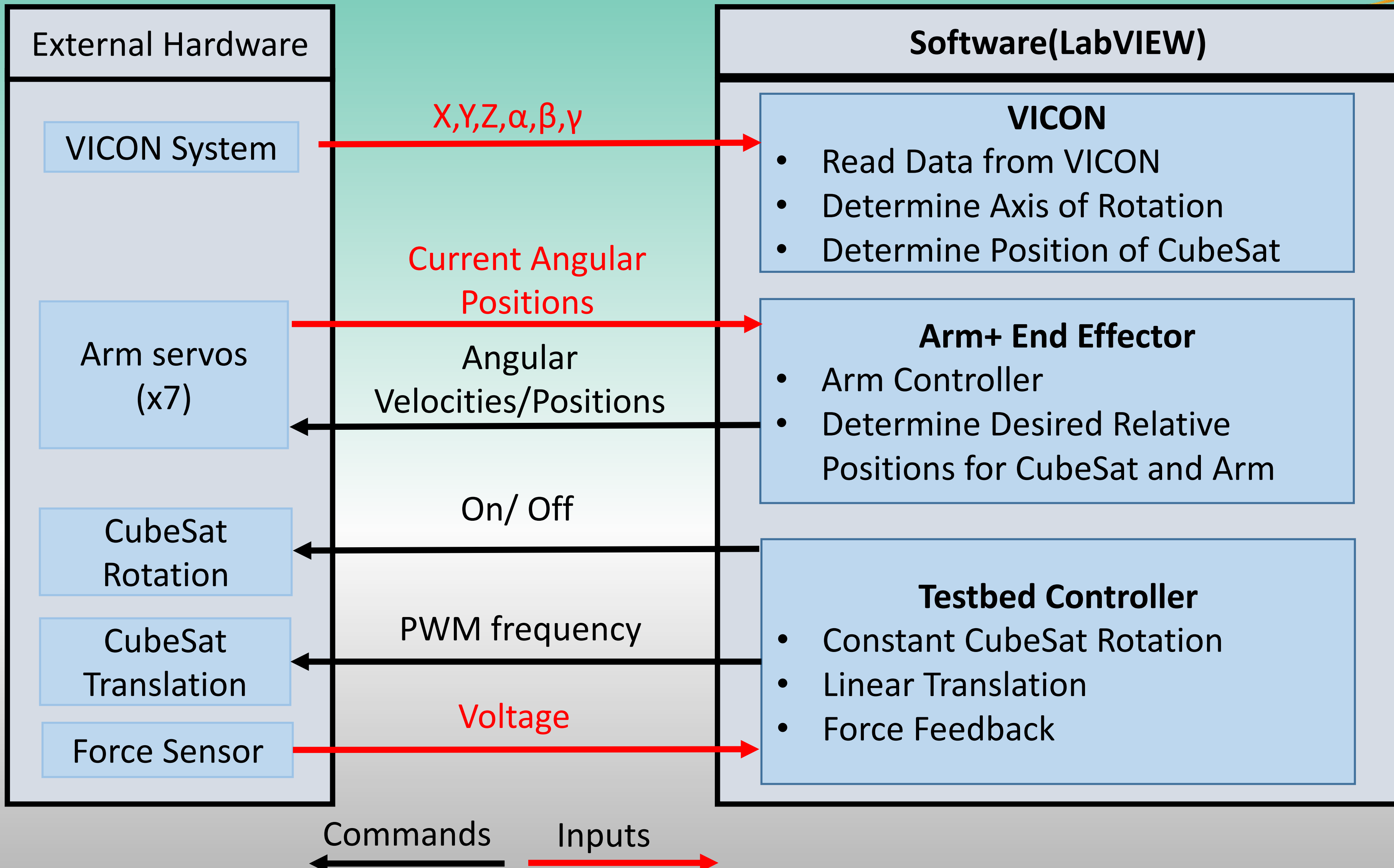
Force Sensing Resistor:





Specifications:
-Rotational Closing with 2 Servos -3D Printed Gripper Plates
Will use force sensing resistors on the plates to verify capture
Difference amp and low pass filter circuit used to linear output and reject noise

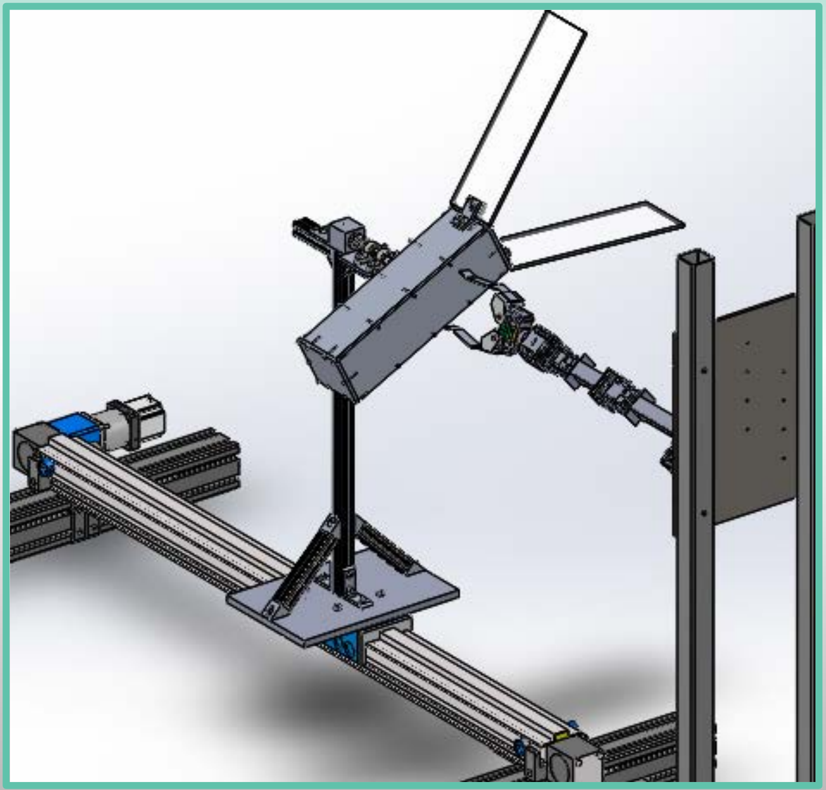
Software Diagram

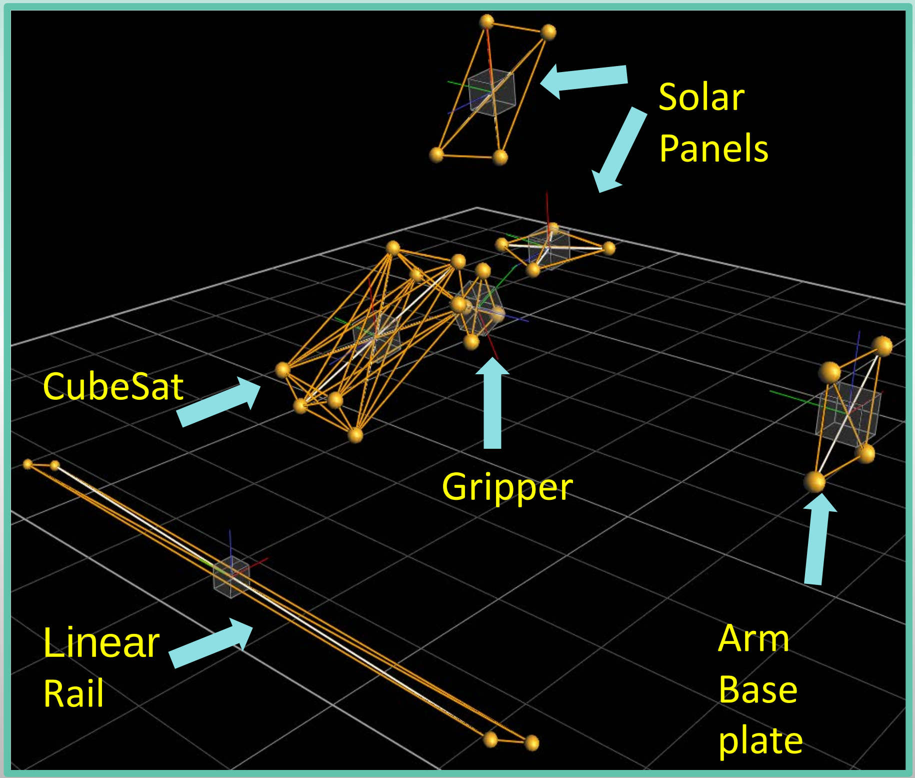


Test Overview

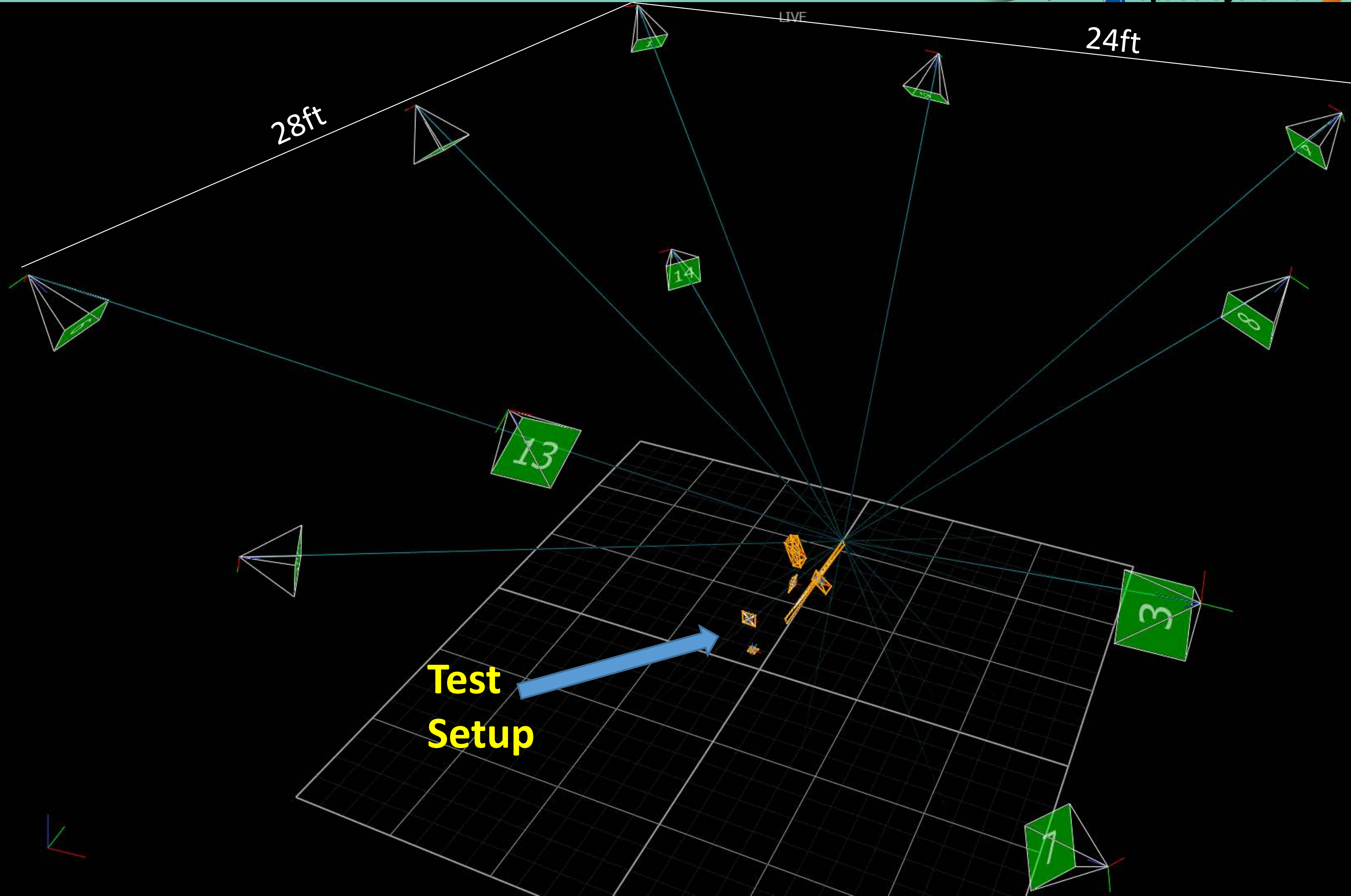
Test Fixtures and Facilities

- **Facility**
  - RECUV Indoor Flying Robot Lab - Fleming Building of CU
- **Test Fixtures**
  - 11 Bonita-10 VICON Cameras



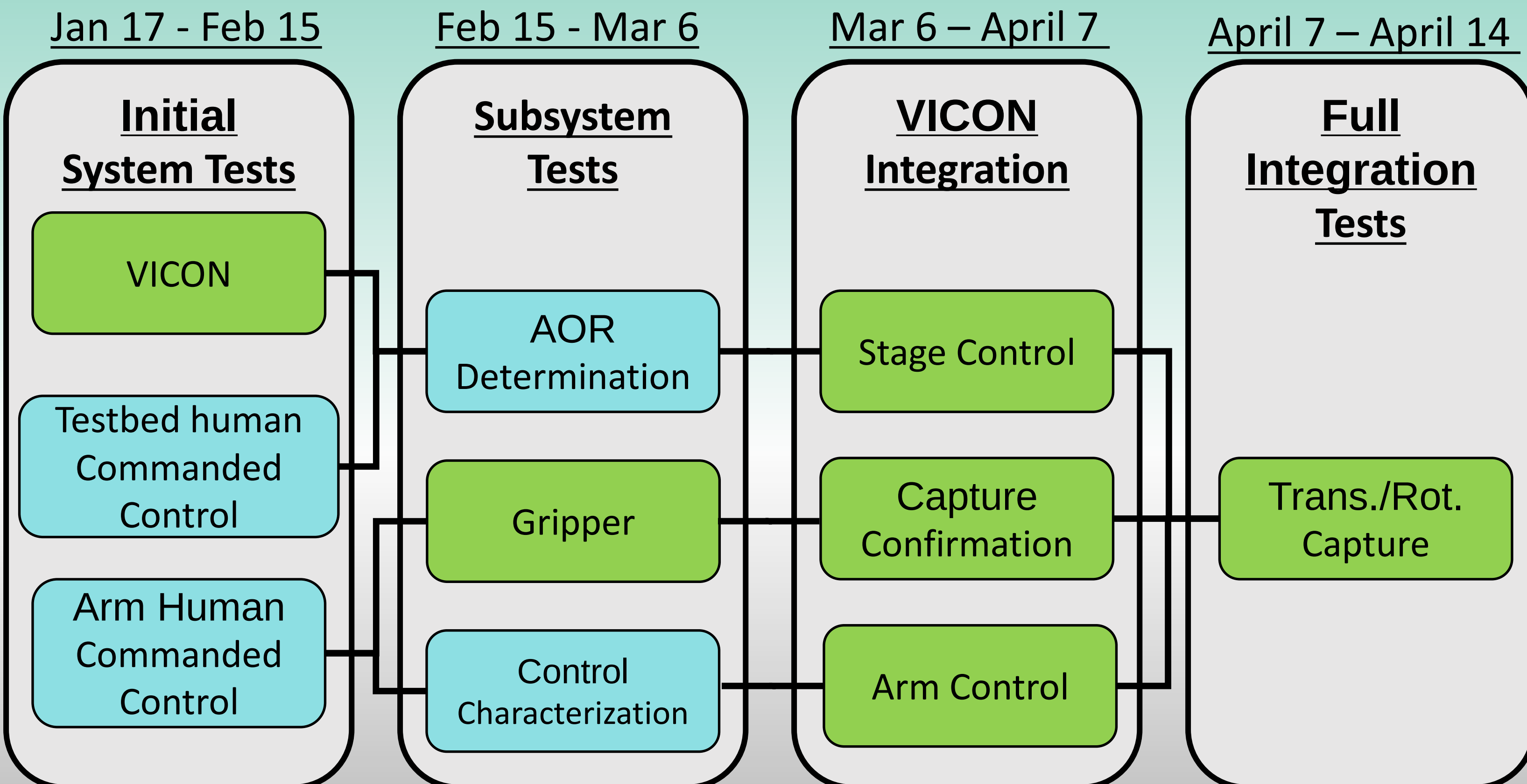


VICON Camera Setup



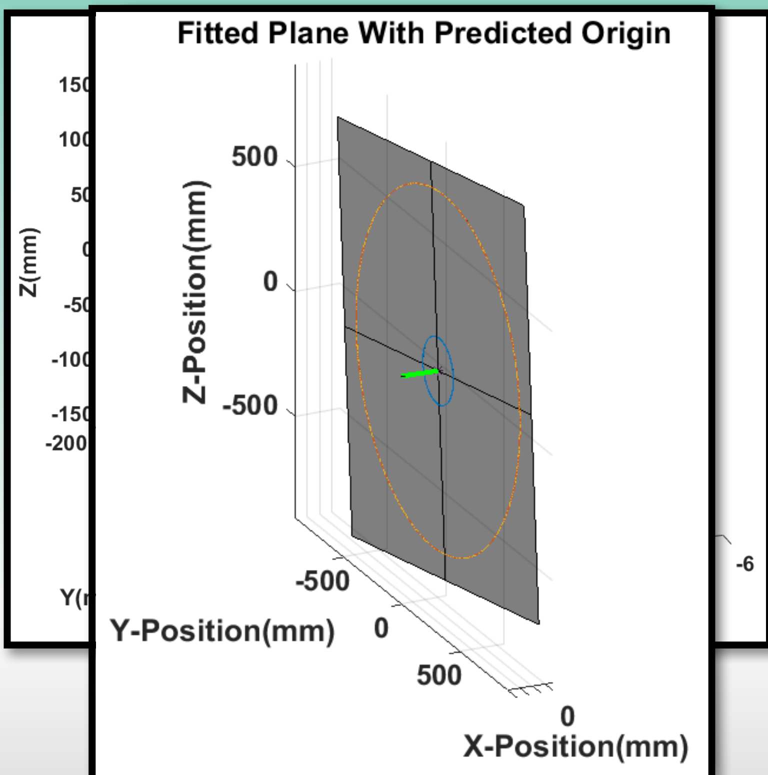
Testing Overview

Key
Functional Requirements
Model



Test Results

Axis of Rotation Determination Model



Assumption:

1. 1-D Rotation about a fixed point
   - Components travel in a 2-D circular path
   - Results in 1-D angular velocity vector

Method:

Goal 1: Determine Center of Rotation:

1. Collect data from VICON system
2. Apply Butterworth filter
3. Calculate the Cartesian maxima and minima

Goal 2: Determine Best Fit Plane:

$z = Ax + By + C$

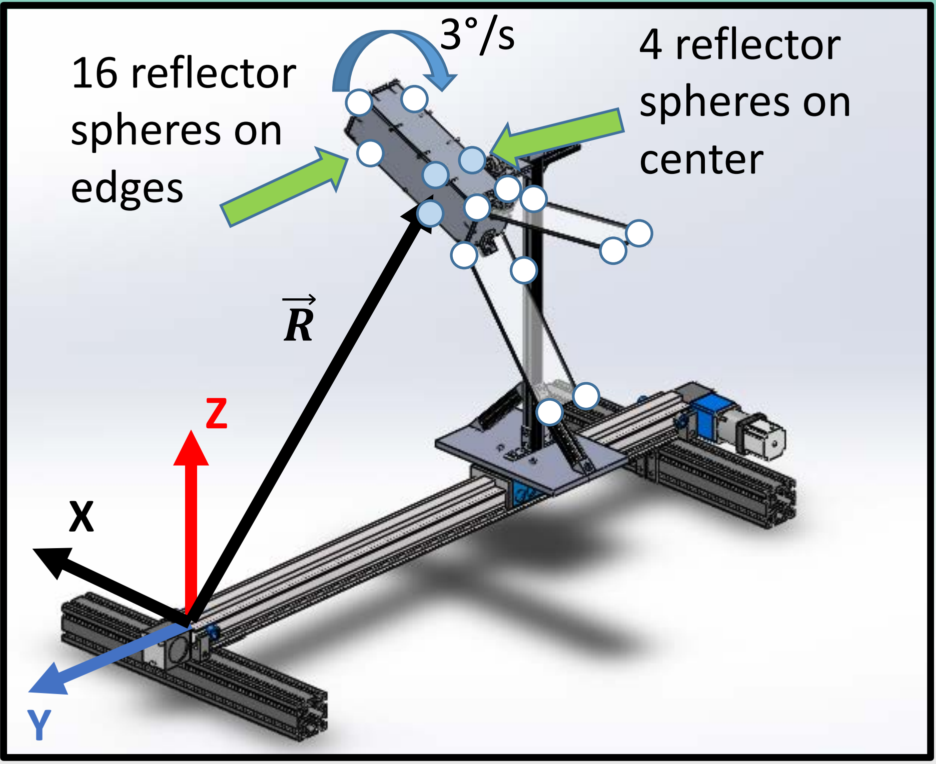
Error Function:

$$E(A,B,C) = \sum_{i=1}^{n} [(Ax_i + By_i + C) - z_i]^2$$

Minimization:

$$\nabla E = (0,0,0)$$

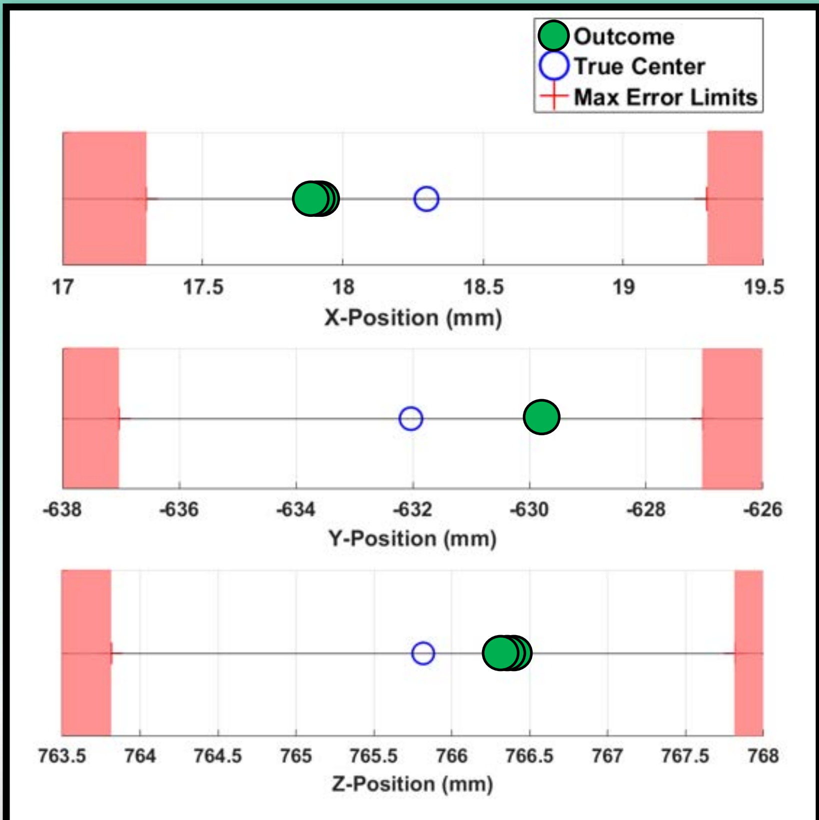
AOR Stationary Position Test



- **Objectives:**
1. Verify CubeSat AOR position determination algorithm
2. Characterize behaviors of VICON
- **Location:** RECUV Motion Capture Lab
- **Test type:** Subsystem
- **Duration:** 2 hour
- **Requirements Met:** FR 1.2, DR 1.2.3-4
- **Risk Reduction:** Increases confidence within prediction of desired end effector placement
- **Data Collected**
  1) Position of the 3 CubeSat components from VICON camera system
  2) Center position of CubeSat hub from VICON camera system

Requirement	Description	Motivation
DR 1.2.3	• The CRST shall determine the axis of rotation of the CubeSat model.	Predicting how the end effector needs to be oriented
DR 1.2.4	• The CRST shall determine the relative linear position of the CubeSat model.	Predicting where the end effector needs to be placed

AOR Stationary Position Results

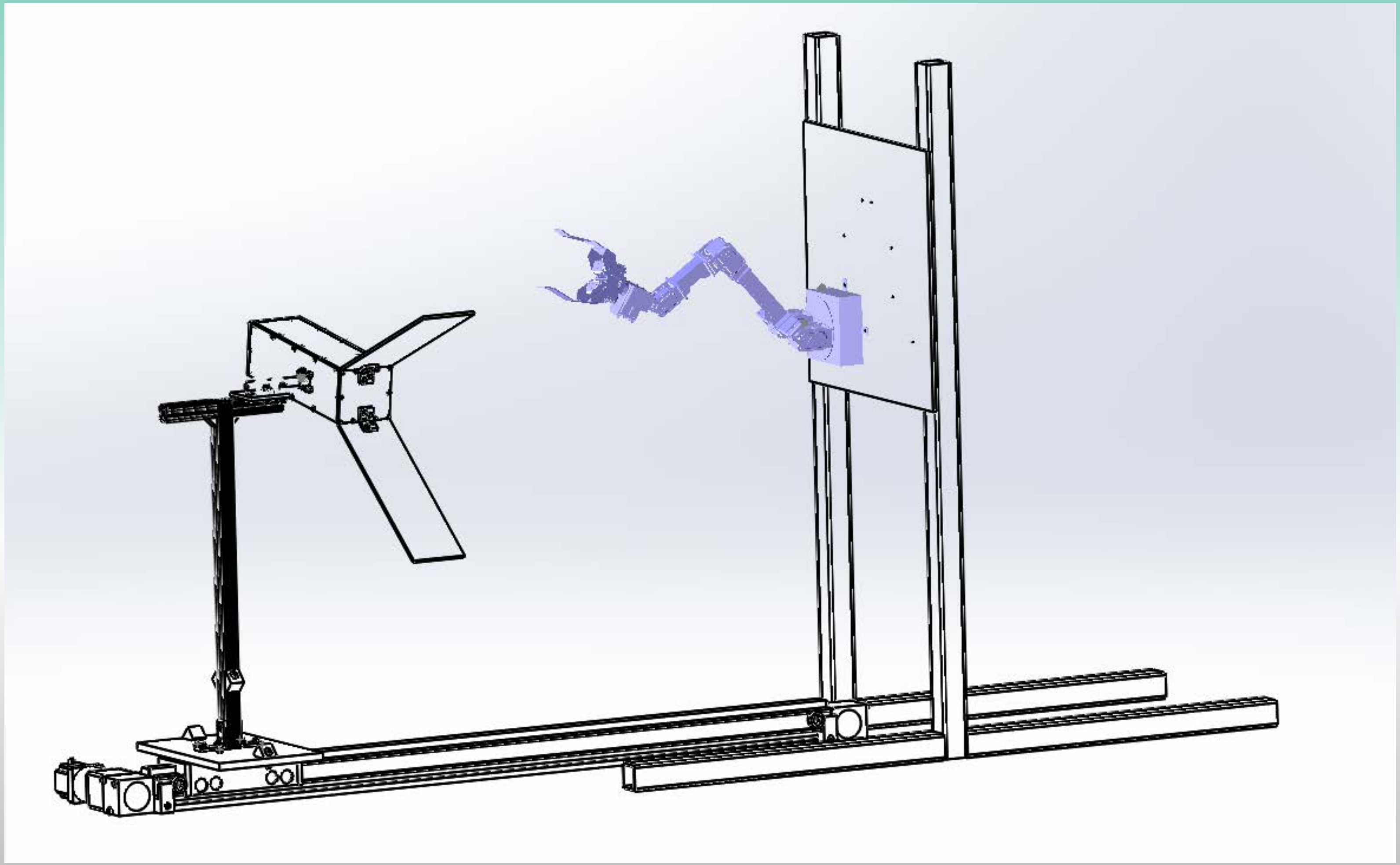


	Prediction		Model
Axis	Difference (mm)	Error Margin	Difference (mm)
X	**0.37**	**62.94 %**	**0.4875**
Y	**2.25**	**55.00 %**	**0.4803**
Z	**0.62**	**68.96%**	**0.5155**

- Predictions lie within maximum error tolerances and aligns with model
- Error limits determined from gripper/ball joint geometry - see backup for details

FR 1.2: The CRST shall determine the relative position and attitude between the CubeSat and capture device during the demonstration.

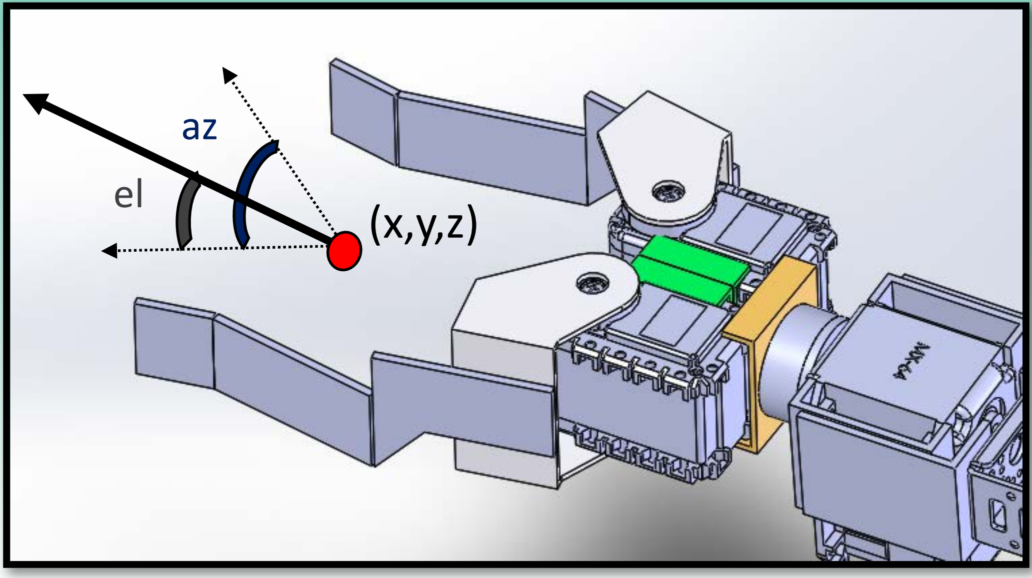
Capture Device Tests



Arm Control: Inverse Kinematics

Inverse kinematics performed using feedback control with the inverse Jacobian technique

$$\boxed{\dot{q} = J^{+}\dot{X}}$$



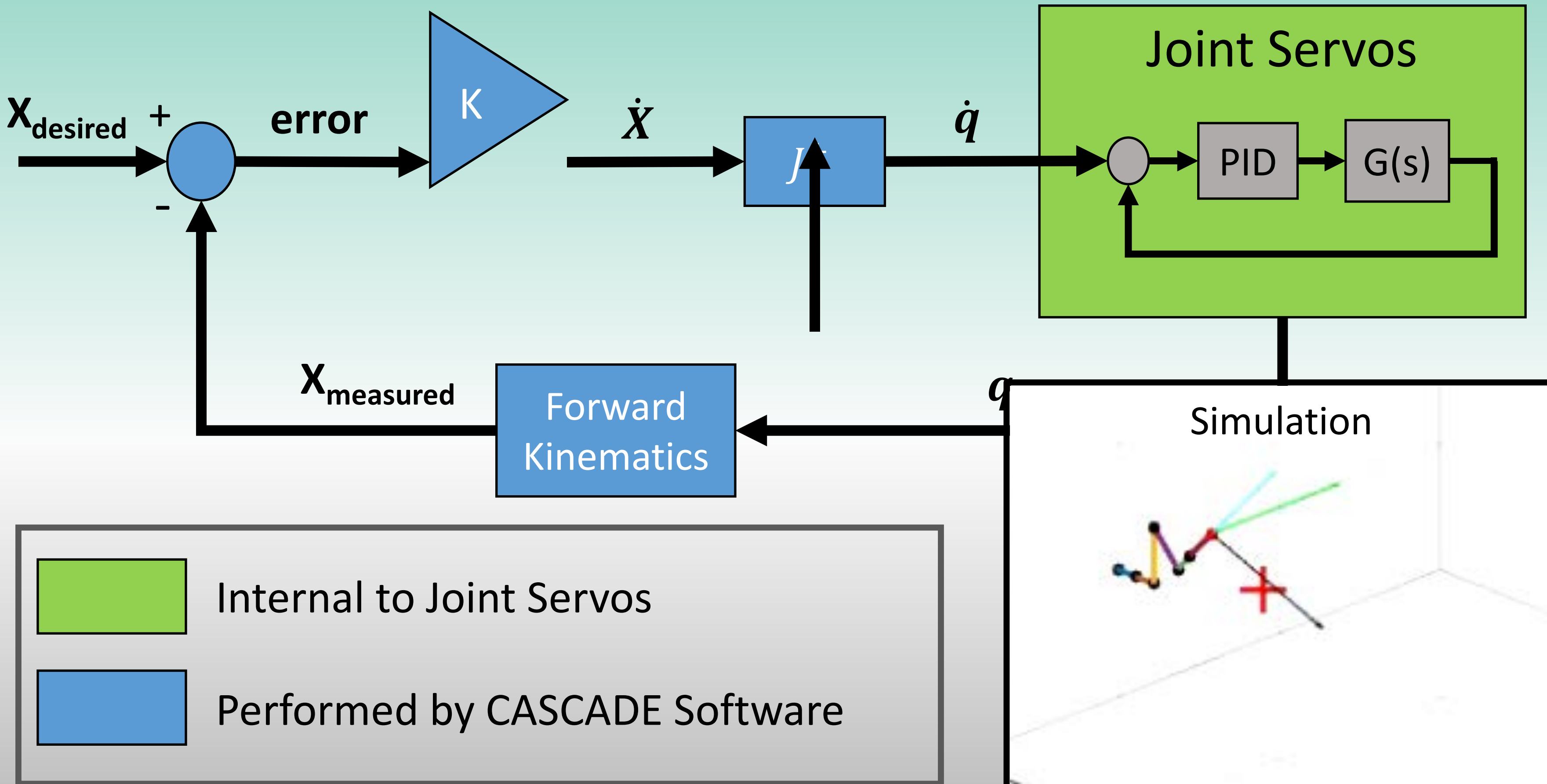
- q = Array of joint angles
- X = Position and orientation of end effector in inertial space
- J = Jacobian matrix
- J^{+} = Pseudo-Inverse of Jacobian

$$J_{5x4} = \begin{pmatrix} \frac{\partial x}{\partial \theta_1} & \cdots & \frac{\partial x}{\partial \theta_4} \\ \vdots & \ddots & \vdots \\ \frac{\partial \varepsilon}{\partial \theta_1} & \cdots & \frac{\partial \varepsilon}{\partial \theta_4} \end{pmatrix} \qquad q = \begin{bmatrix} \theta_1 \\ \theta_2 \\ \theta_3 \\ \theta_4 \end{bmatrix} \qquad X = \begin{bmatrix} x \\ y \\ z \\ azimuth \\ elevation \end{bmatrix}$$

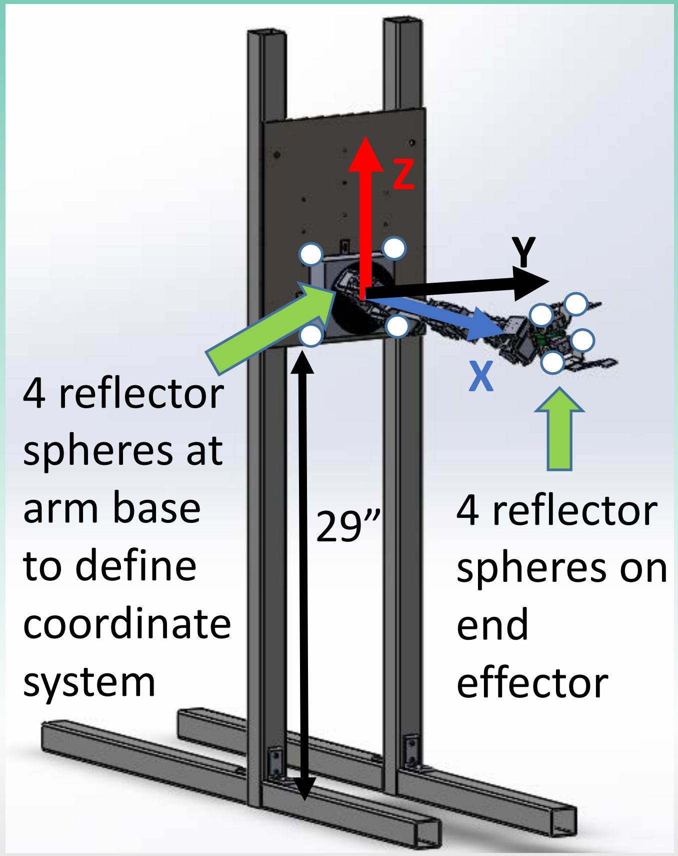
- First four joints used to control position and pointing angle
- Final wrist rotate joint controlled separately to match CubeSat rotation angle

Arm Control: Inverse Kinematics

$$\dot{q} = J^{+}\dot{X}$$



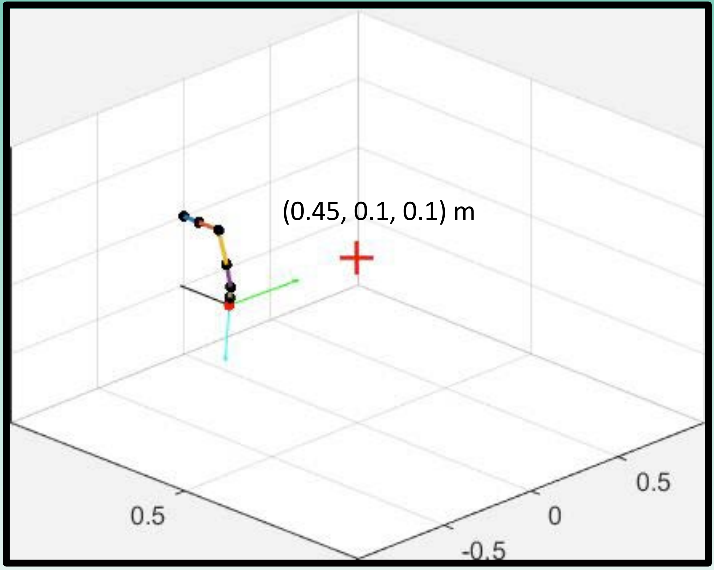
Arm Accuracy Test

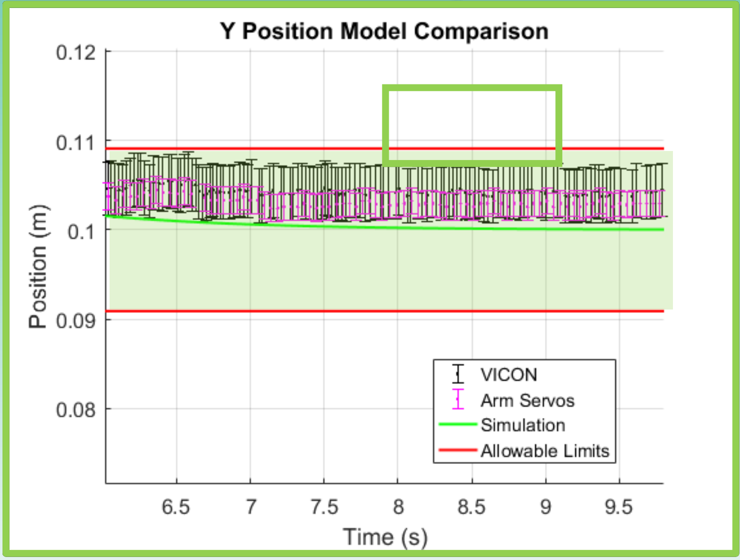


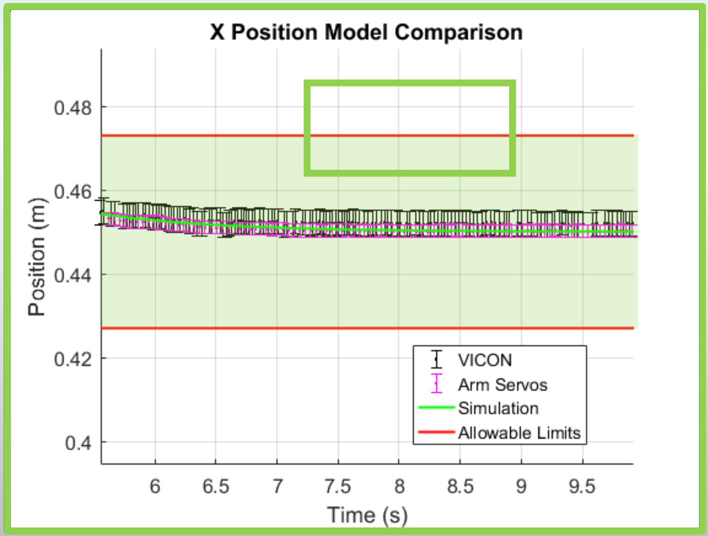
- **Objectives:**
  1) Ensure that arm can be commanded within allowable position limits
  2) Verify arm control model
- **Location:** RECUV Motion Capture Lab
- **Test type:** Subsystem
- **Duration:** 1 hour
- **Requirements Met:** FR 1.3
- **Risk Reduction:** Increases confidence that arm will not collide with CubeSat
- **Data Collected**
  1) End effector position from joint angle kinematics
  2) End effector position from VICON camera system

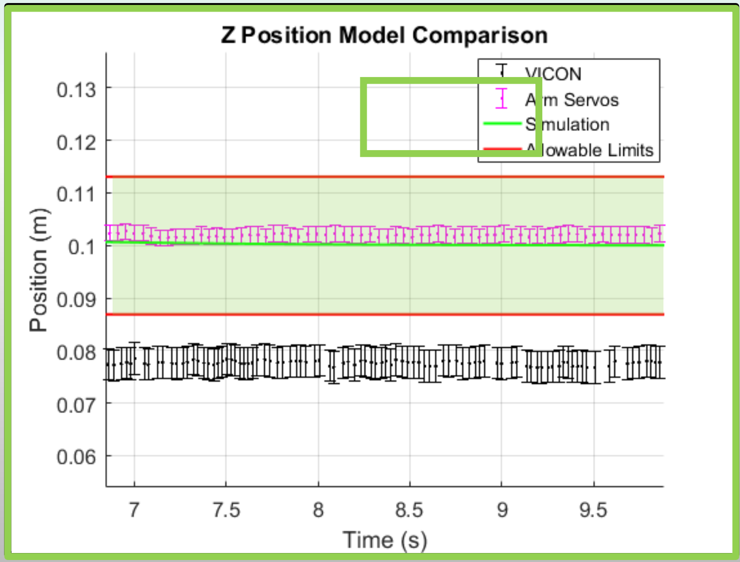
Requirement	Description	Motivation
DR 1.3.2	End Effector shall align with CubeSat spin axis	Lowest risk approach to capturing CubeSat
DR 1.3.3	Capture device shall not collide with support structure or itself	Crashing into things is generally bad

Arm Accuracy Test: Phase 1 Results

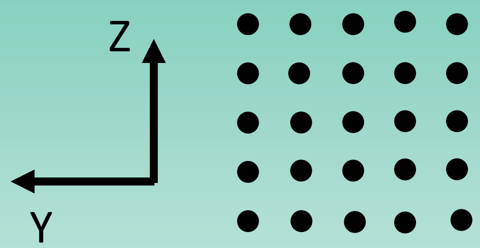








Arm Z-Offset Characterization



Move arm to Y-Z test point

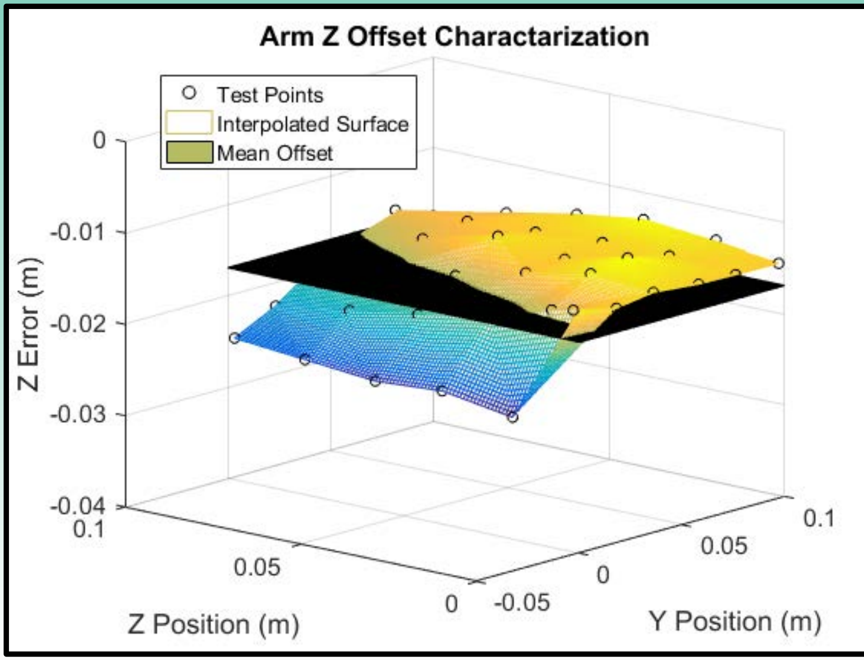
Extend arm in X direction

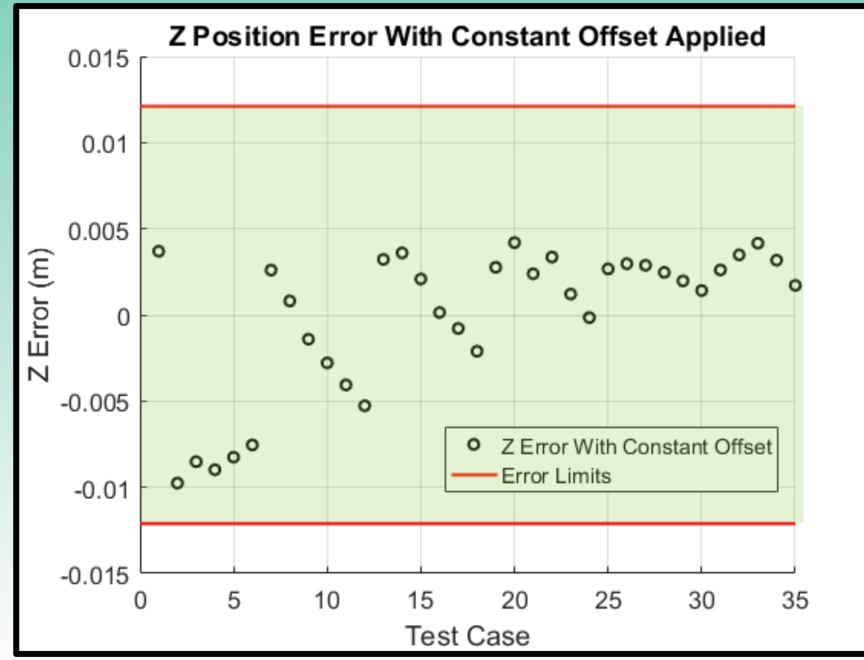
Each data file involves extending in X direction for particular Y-Z test point

- **Objective:** Empirically characterize arm droop in Z position
- **Location:** RECUV Motion Capture Lab
- **Test type:** Subsystem
- **Duration:** 4 hours
- **Requirements Met**: FR 1.3
- **Risk Reduction:** Reduces risk of arm crashing into CubeSat
- **Data Collected:** End effector position from VICON and from joint angles

Requirement	Description	Motivation
DR 1.3.2	End effector aligns with CubeSat spin axis	Lowest risk approach to capturing CubeSat

Arm Z-Offset Characterization Results

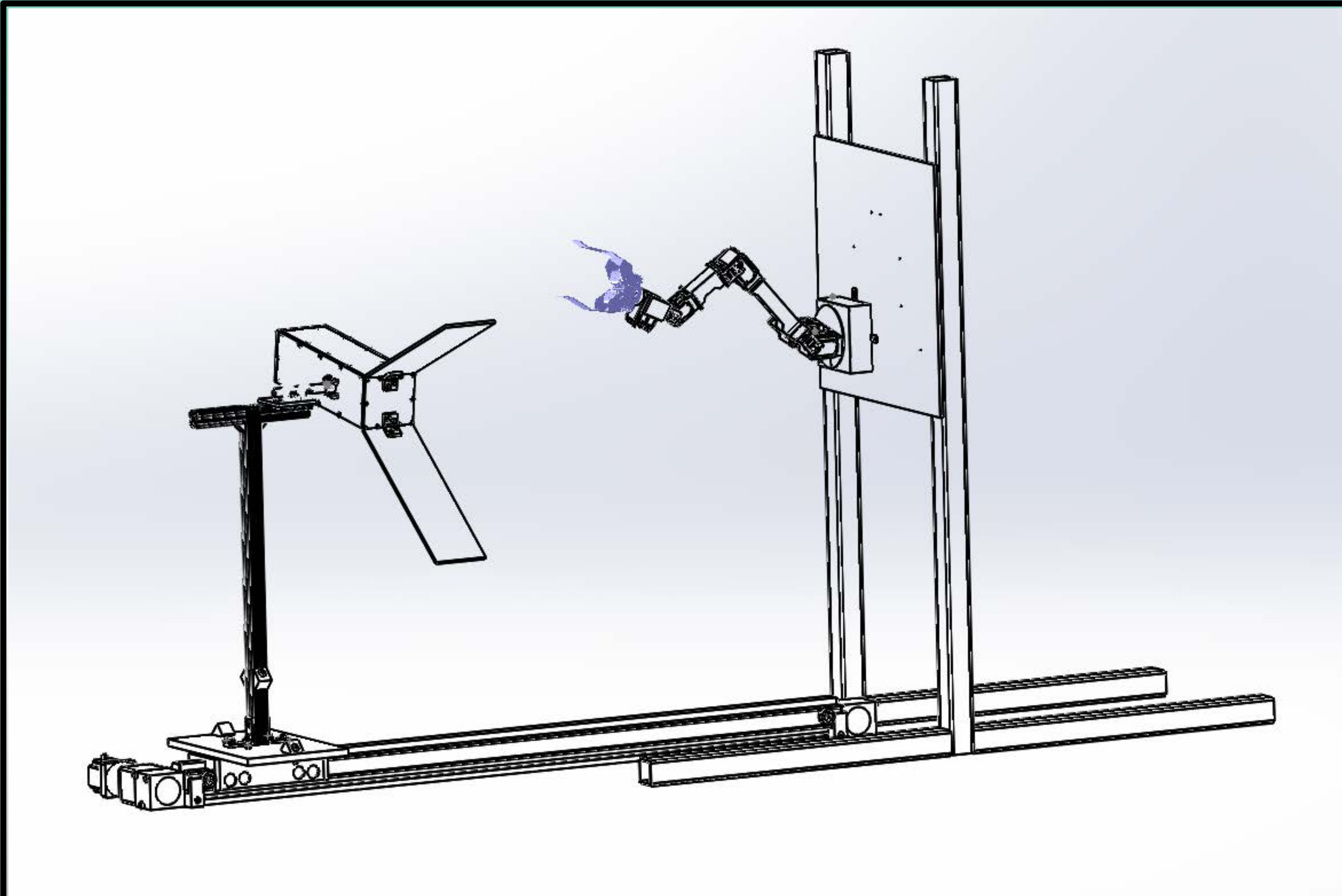




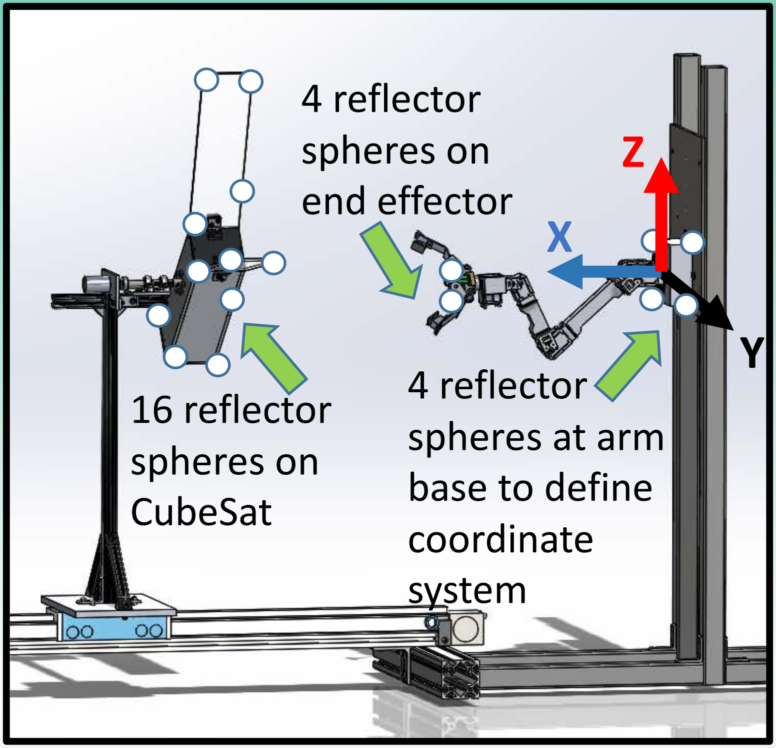
- 2 Possible approaches
  1) Use interpolation to apply a specific offset depending on arm position
  2) Apply the same offset to all arm positions
- Solution chosen: Applied constant offset of **1.69 cm** (mean of 3D surface)
  - This brought all data points within tolerable limits

FR 1.3: CRST shall command the motion of the capture device

End Effector Tests



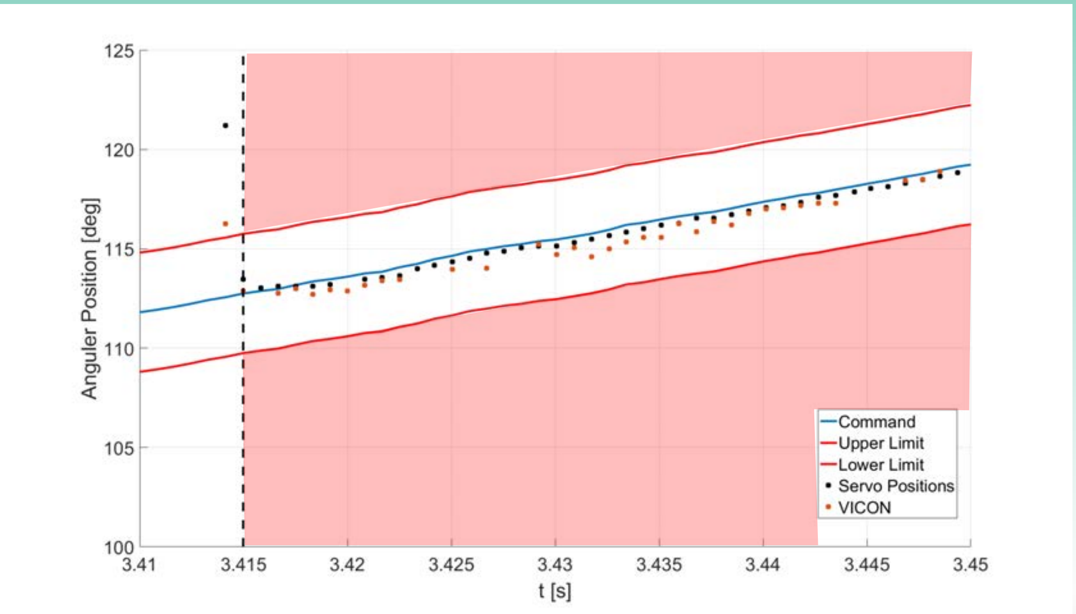
Wrist Matching Test

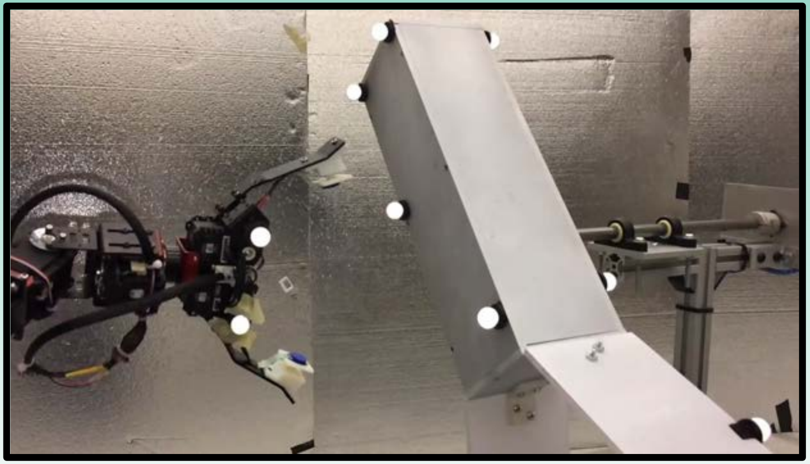


- **Objectives**
  1) Verify phase matching between arm wrist and CubeSat
- **Test type:** Subsystem
- **Location:** RECUV Motion Capture Lab
- **Duration:** 1 hour
- **Requirements Met:** DR 1.3.2
- **Risk Reduction**: Ensure safe phase matching for successful capture
- **Data Collected**: CubeSat and arm wrist servo phase angles

Requirement	Description	Motivation
DR 1.3.2	The end effector shall align with the CubeSat's spin axis, and remain aligned until the end of the capture sequence.	Matching the orientation of the CubeSat provides the lowest risk and eases the time requirement during the final phase of capture.

Wrist Matching Results





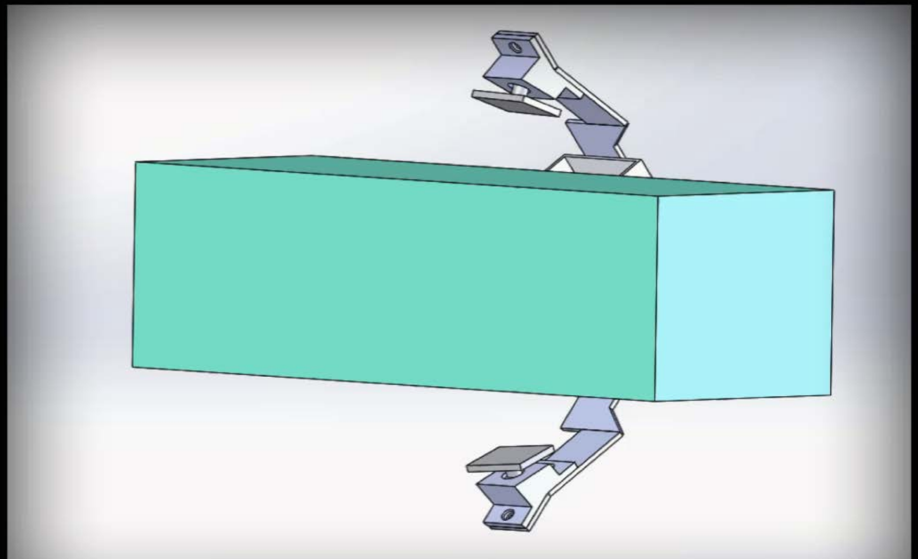
Phase 3

Phase 4

Mean Difference	0.55°
Standard Deviation of Difference	0.29°
Minimum Margin	98%

DR 1.3.2: The end effector shall align with the CubeSat's spin axis and orientation, and remain aligned until the end of the capture sequence.

Capture Confirmation Tests

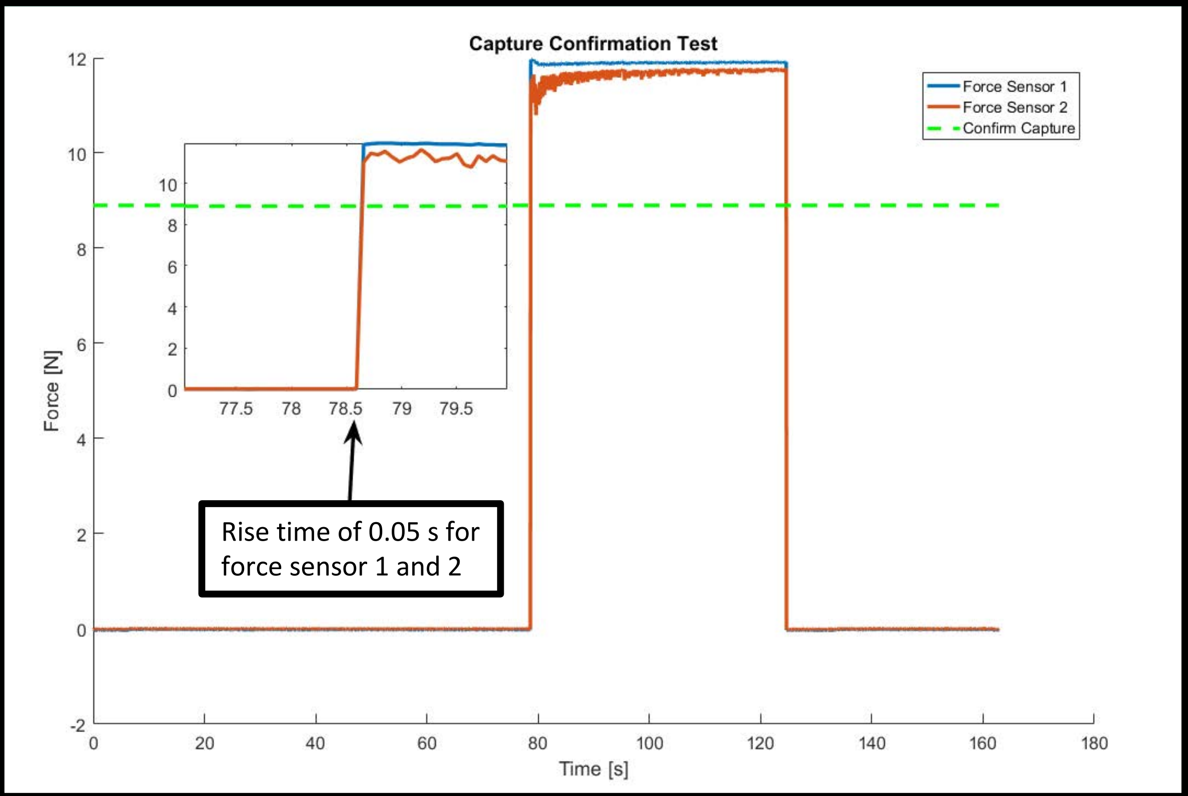


Purposely Misaligned

- **Objectives:** Validates that the force sensor circuit and software can be used to confirm capture
- **Location :** RECUV
- **Test type:** Subsystem Test
- **Duration:** 1 hr 1 hour
- **Data Collected:** Voltage

Requirement	Description	Motivation
FR 1.4	The CRST shall execute capture of the physical CubeSat model autonomously during the demonstration	Customer requirement for the test bed to operate autonomously, and for the highest level of success.
DR 1.4.1.10	The capture device shall be able to confirm the capture of the CubeSat with tactile feedback without human intervention	Confirmation of capture autonomously, in order to **end the demonstration without human intervention.**

Capture Confirmation Tests



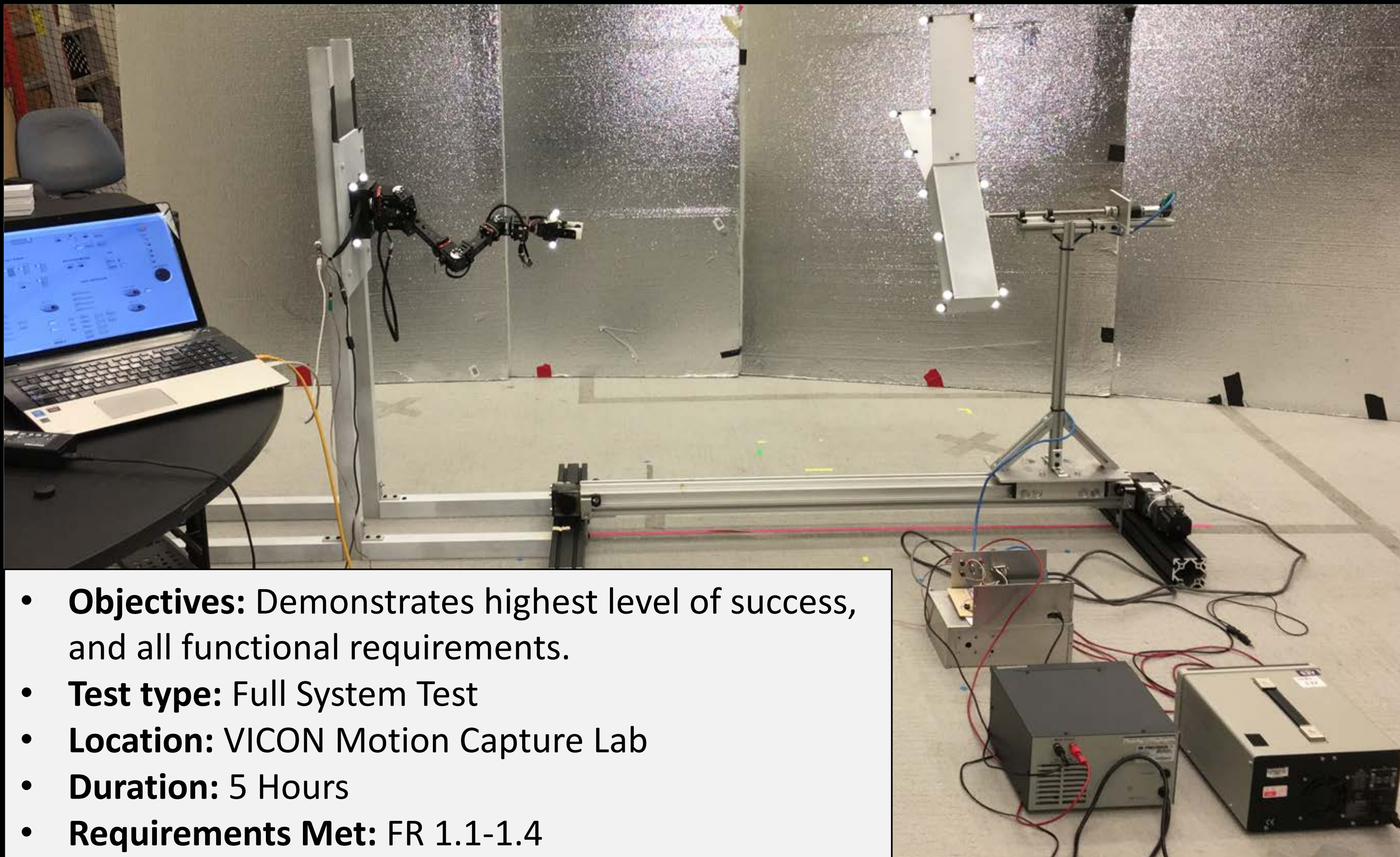
	Force Sensor 1	Force Sensor 2
Response Time	0.05s	0.05s

$$\textbf{Force} = \frac{Force_{voltage} - 12.20}{-0.0065}$$

Exceeds minimum grip force of 8.9 N

DR 1.4.1.10: The capture device shall be able to confirm the capture of the CubeSat with tactile feedback without human intervention

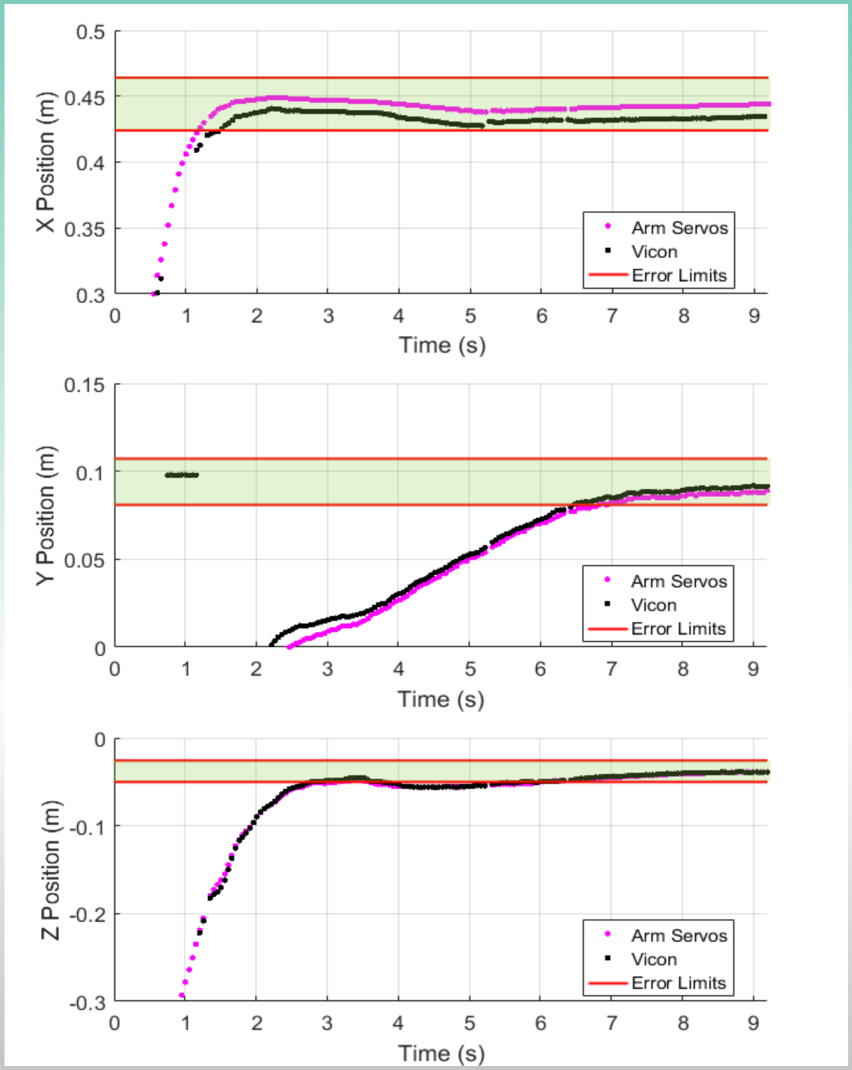
Final System Test



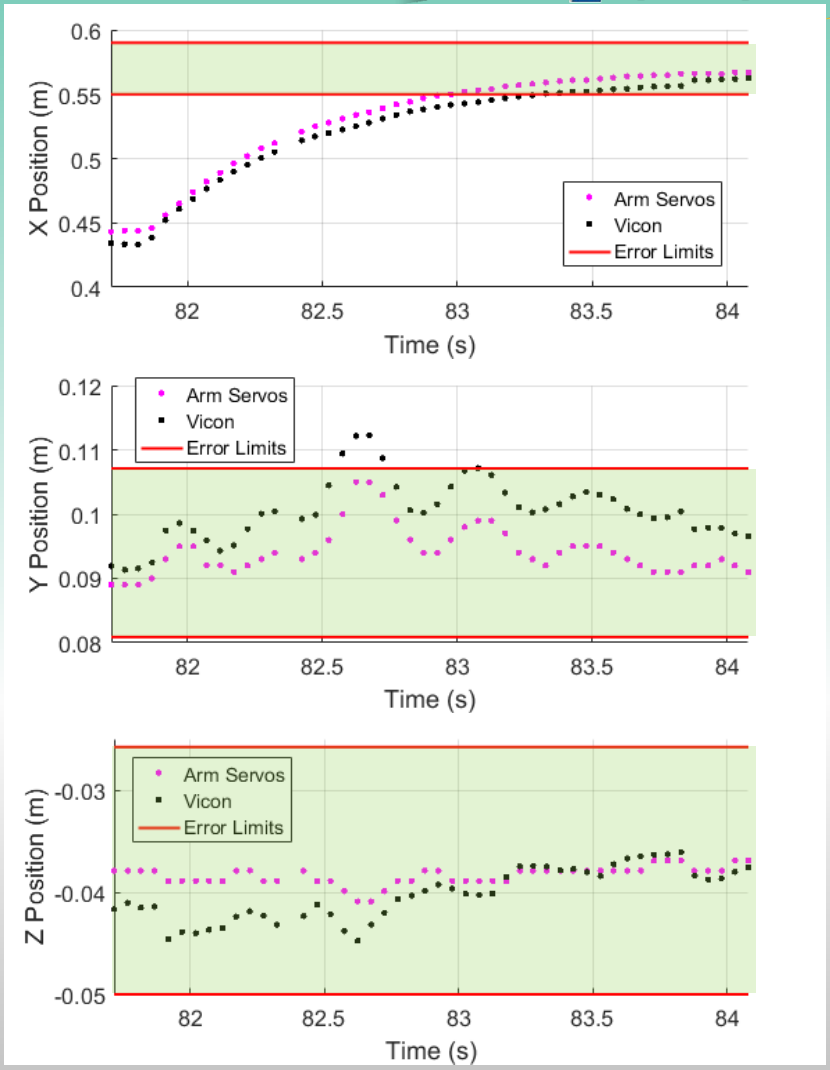
- **Objectives:** Demonstrates highest level of success, and all functional requirements.
- **Test type:** Full System Test
- **Location:** VICON Motion Capture Lab
- **Duration:** 5 Hours
- **Requirements Met:** FR 1.1-1.4

Final System Test

Final Demonstration: Stage 1 & 4

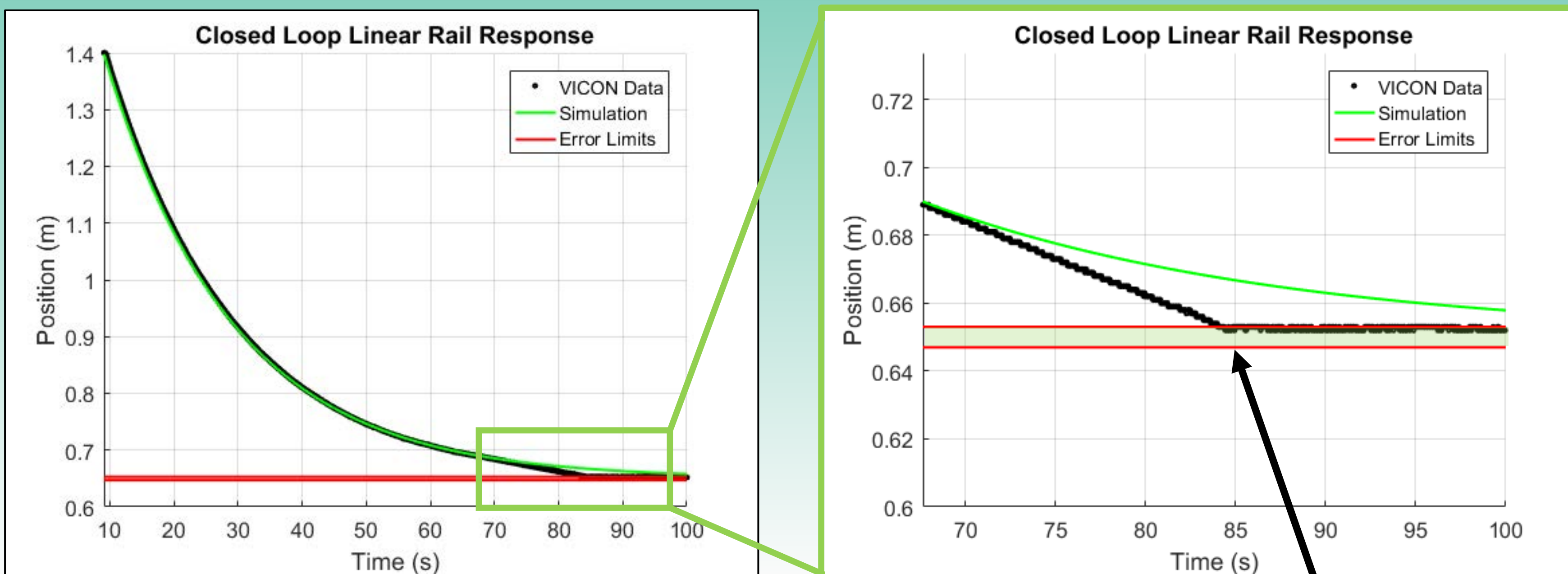


STAGE 1



STAGE 4

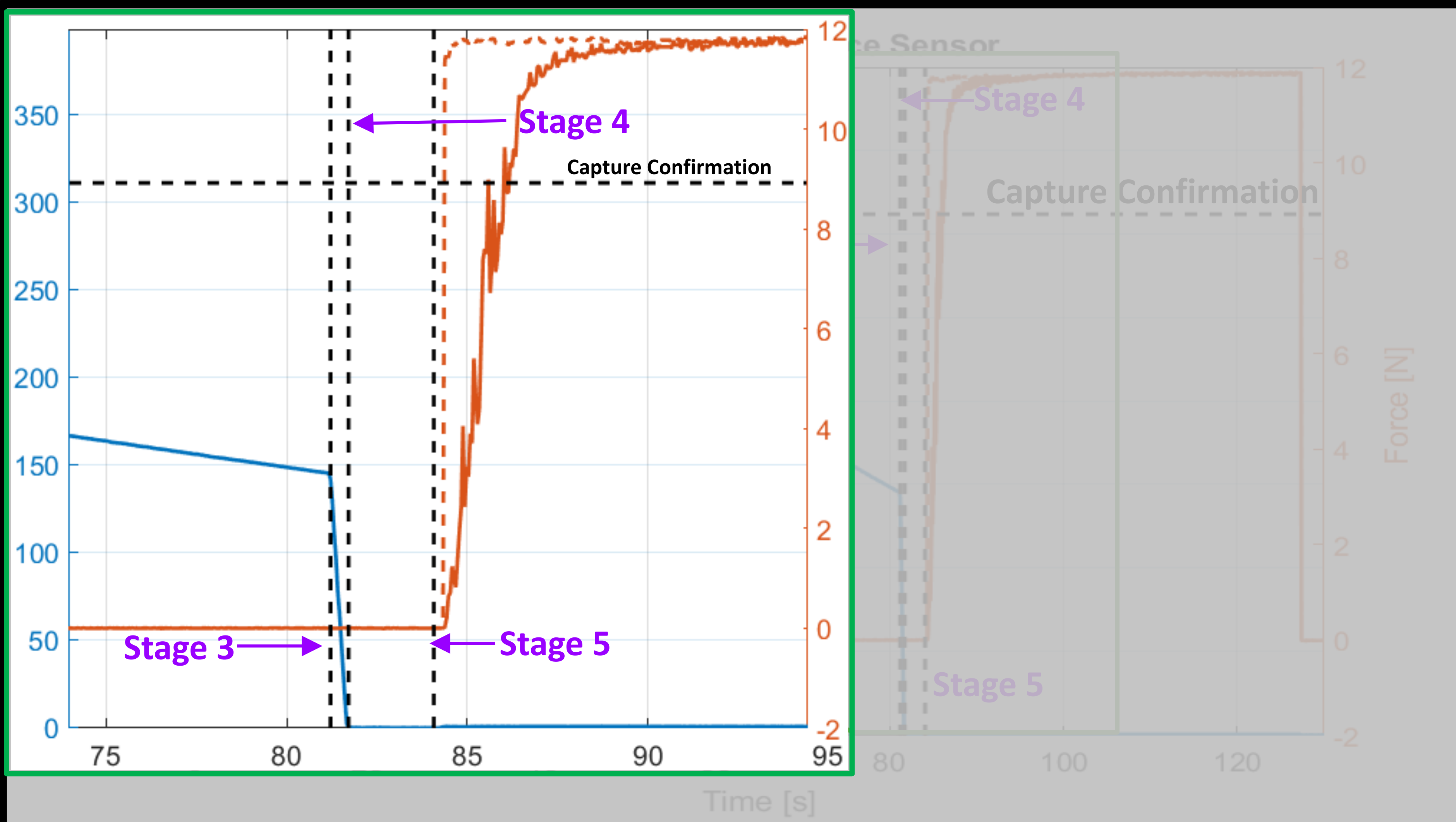
Final Demonstration: Stage 2



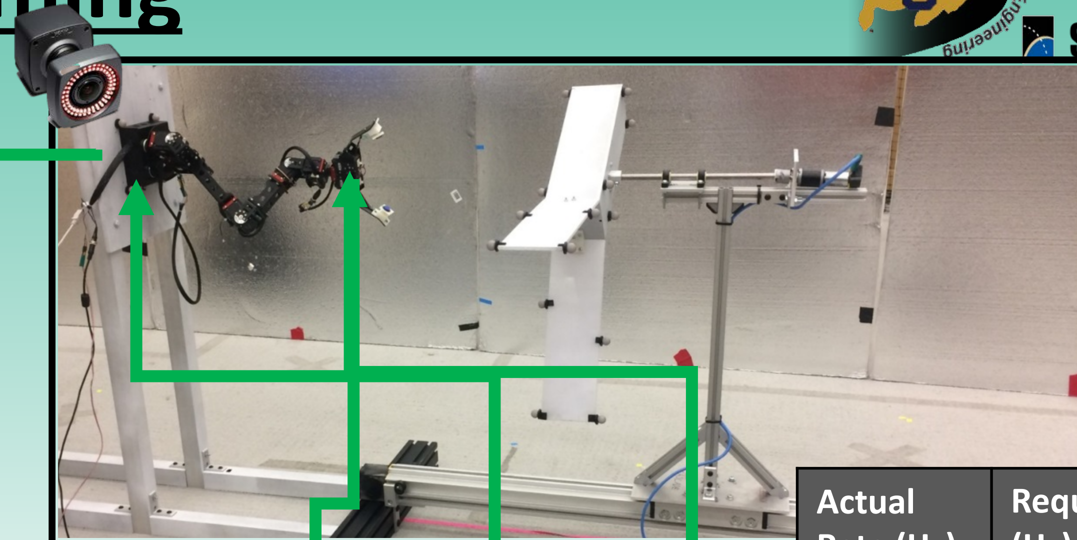
- Deviation from model at the end caused by NI myRIO PWM frequency limitation
  - No effect on system performance
- 30 minutes for entire demonstration
  - No time period concerns at 75 seconds to translate

Stage 3 begins here when CubeSat reaches 3mm error limit

Final Demonstration: Stage 3 & 5



Software Timing



Arm Control Loop

Read Servos	Create arm commands	Create Claw Commands	Write Servo Velocities	Write Wrist Position
~10 ms	~29.9 ms	~7.4ms	~[illegible].7 ms	~1 ms

myRIO Loop

Read Voltage	Create Rail Commands	Send actuator signals
220µs	220µs	220µs

Main Loop

Delay	Read VICON	Phase Checks	Read MyRIO
~47.5 ms	~1.5ms	~1µs	~1µs

Actual Rate (Hz)	Required (Hz)	Margin (%)
~20	10.5	90.5
~1515	13.4	11,205
~20	13.4	49.3

DDR 1.3.1.1: Capture Device shall run at minimum of 10.5 Hz

DDR 1.3.1.2: CRST shall run at a minimum of 13.5 Hz

Final System Testing Summary

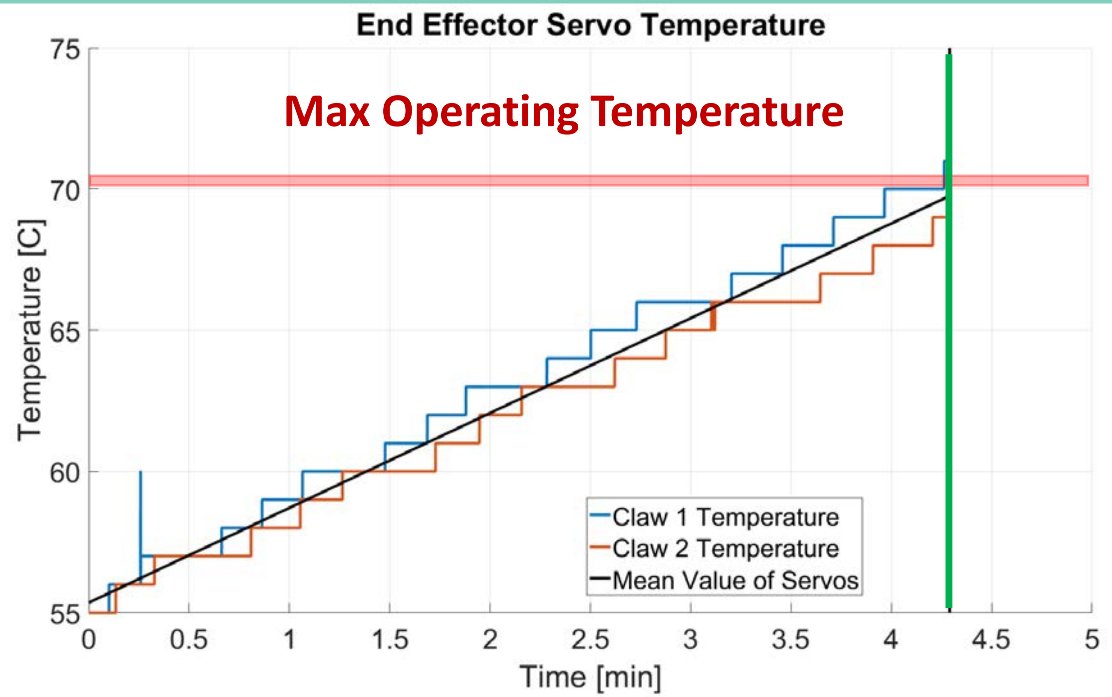
Requirement:	Description:
FR 1.0	CRST Shall Demonstrate the successful capture of a physical CubeSat model
FR 1.1	The CRST shall demonstrate the motion of a CubeSat analogue during the demonstration.
FR 1.2	The CRST shall determine the relative position and attitude between the CubeSat and capture device during the demonstration.
FR 1.3	The CRST shall command the motion of the capture device during the demonstration.
FR 1.4	The CRST shall execute capture of the physical CubeSat model autonomously during the demonstration.

Project SUCCESS:

-Highest level of success met

-**One minor** design requirement not met

Overheating Servos



- **Objectives**
  - Validate that the end effector servos can hold for five minutes within operational limits
- **Test type:** Component
- **Location:** RECUV Motion Capture Lab
- **Duration:** 2 hours
- **Requirements Met:** DR 1.4.6
- **Risk Reduction**: Safety of End Effector Servos

  Data Collected: Temperature (°C)

Lessons Learned:

Thermodynamics model for end effector servos should have been created.

Assumptions:

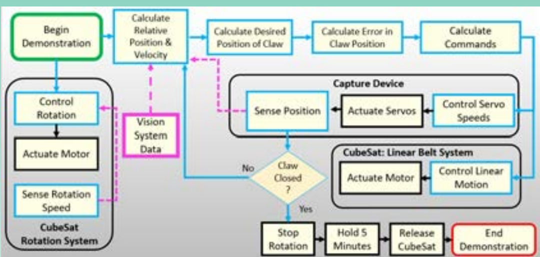
Adiabatic, 1D Heat Transfer, Transient

five minutes after capture confirmation.

dynamics and stabilize the system.

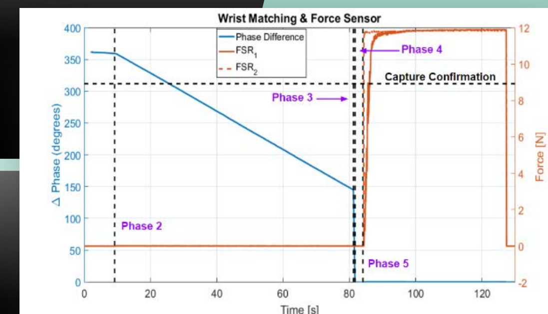
Systems Engineering

Systems Engineering



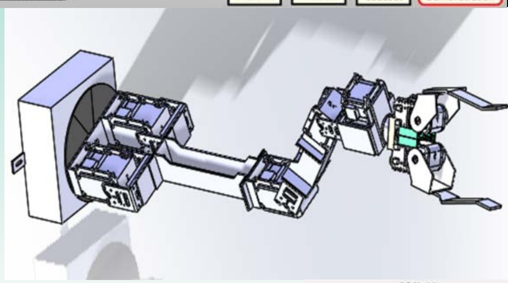
Concept

Project Validation



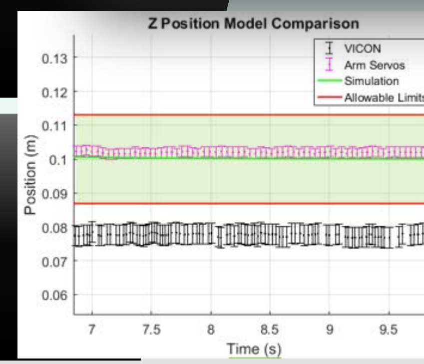
Design

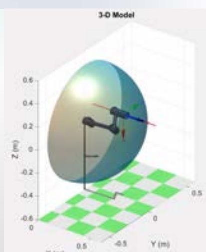
Test



Preliminary

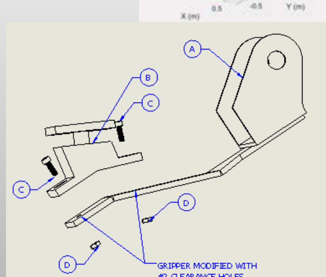
Integration



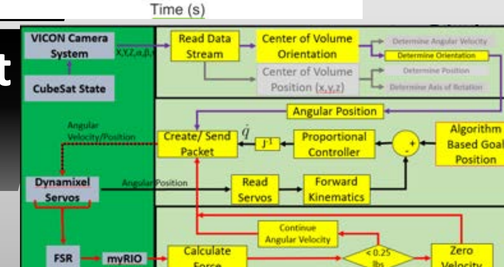


Detailed

Subsystem



Manufacture & Software Development



Build

Risk Assessment

Risk	Mitigation	Result
R1: Overcurrent to CubeSat motor during capture confirmation	Hardware and Software Fail Safes	**Safety systems implemented** and successful.
R2: Capture confirmation failure	Force sensor testing prior to final demo	**Pre-validation testing sufficient** and successful.
R3: LabVIEW coding errors	40% of team devoted to LabVIEW development	**Mitigation necessary**. Software behind planned schedule but caught up.
R4: Control algorithm errors	20% of team devoted to Control development	**Mitigation unnecessary**. Arm control verification completed on schedule.
R5: Arm servo malfunction	New servos, early testing	**Early testing implemented**, no issues during testing
R6: NI myRIO connectivity issues	Unaccounted for prior to testing.	**Workaround implemented**.

Severity

Likelihood

	1	2	3	4	5
5 (Very High)					
4 (High)					
3 (Moderate)					
2 (Low)	R1			R2,R3,R4	
1 (Very Low)				R5,R6	

(red)	Unacceptable
(yellow)	Acceptable with mitigation
(green)	Acceptable

System Summary

System Successes:

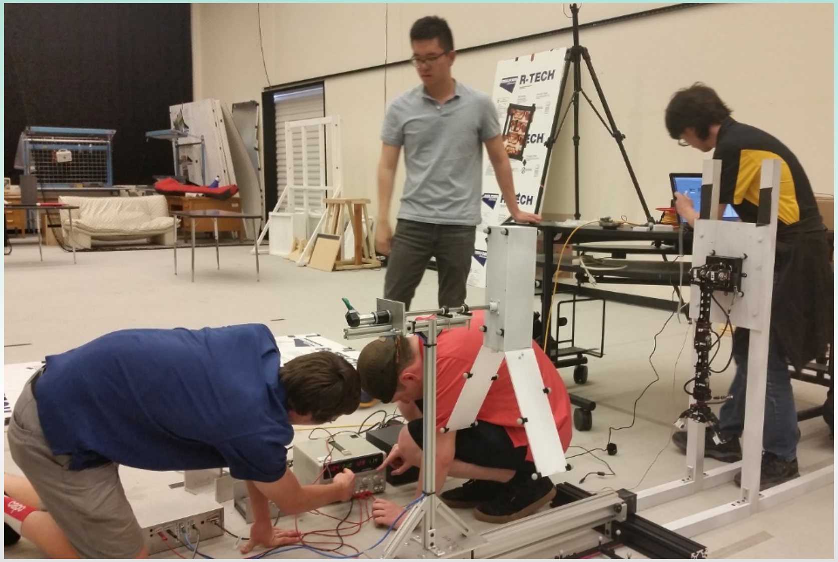
- **Thoroughly evaluated the proposed statement of work (SOW)**
  - Aided team to better understand the project
  - Descope likely critical to mission success
- **Requirements mapped to tests early:**
  - Requirement Verification Matrix (RVM) created in October
  - Ensured all requirements were testable and kept them visible
- **Risk assessment conducted prior to CDR**:
  - Aided Project Manager in allocating resources during spring semester

System Issues:

- **Uncertainty quantification:**
  - Issues with calculating arm control uncertainties led to team confusion
  - Vision system dynamic uncertainty not tested
- **Unforeseen difficulties:**
  - Force sensors and NI myRIO
- **Software planning:**
  - Without early and strong software modularization, labor distribution was difficult
  - Integration path unclear due to lack of planning
  - Team inexperience with LabVIEW

Lessons Learned

- **A well scoped project is a must:**
  - New capstone customer presents both opportunities and challenges
  - Without CU faculty assistance, team may have had to use off-ramps or miss requirements
- **System engineering must work alongside project management to be effective:**
  - Work Breakdown Structure (WBS)
  - Risk Mitigation may effect budget and labor efforts
- **Software planning needs to start early:**
  - Modularization and integration planning critical so that everyone is on the same page



Project Management

Project Management Approach

❖ System Focused Management

- ❖ Focus on understanding the **overall project and subsystems**, rather than just schedule and budget
- ❖ Created **important discussions** by asking questions that traced back to requirements
- ❖ Was **involved technically** by helping with every technical lead, including a lot of systems work.
  - ❖ Involved in the **design** process mainly for the end effector
  - ❖ Helped manufacture and debug electronics and housing
  - ❖ Was involved in the machining process
  - ❖ Wrote LabVIEW code to aid in **software development**
  - ❖ Helped revise requirements, create test plan, and facilitate integration

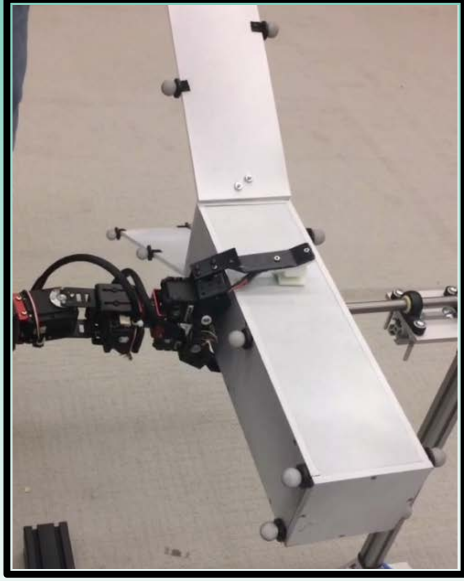
❖ Focused on Current Goal

- ❖ **Milestones** used as reference for overall system planning
- ❖ **Weekly reporting** with advisor to keep the project on track
- ❖ Focusing on addressing problems as soon as they come up to get back on track quickly

Successes, Difficulties, and Lessons Learned

❖ Successes

- ❖ Overall system able to meet **highest level of success**
- ❖ Used **margin** in schedule and budget effectively
- ❖ Managing team while still learning technical skills



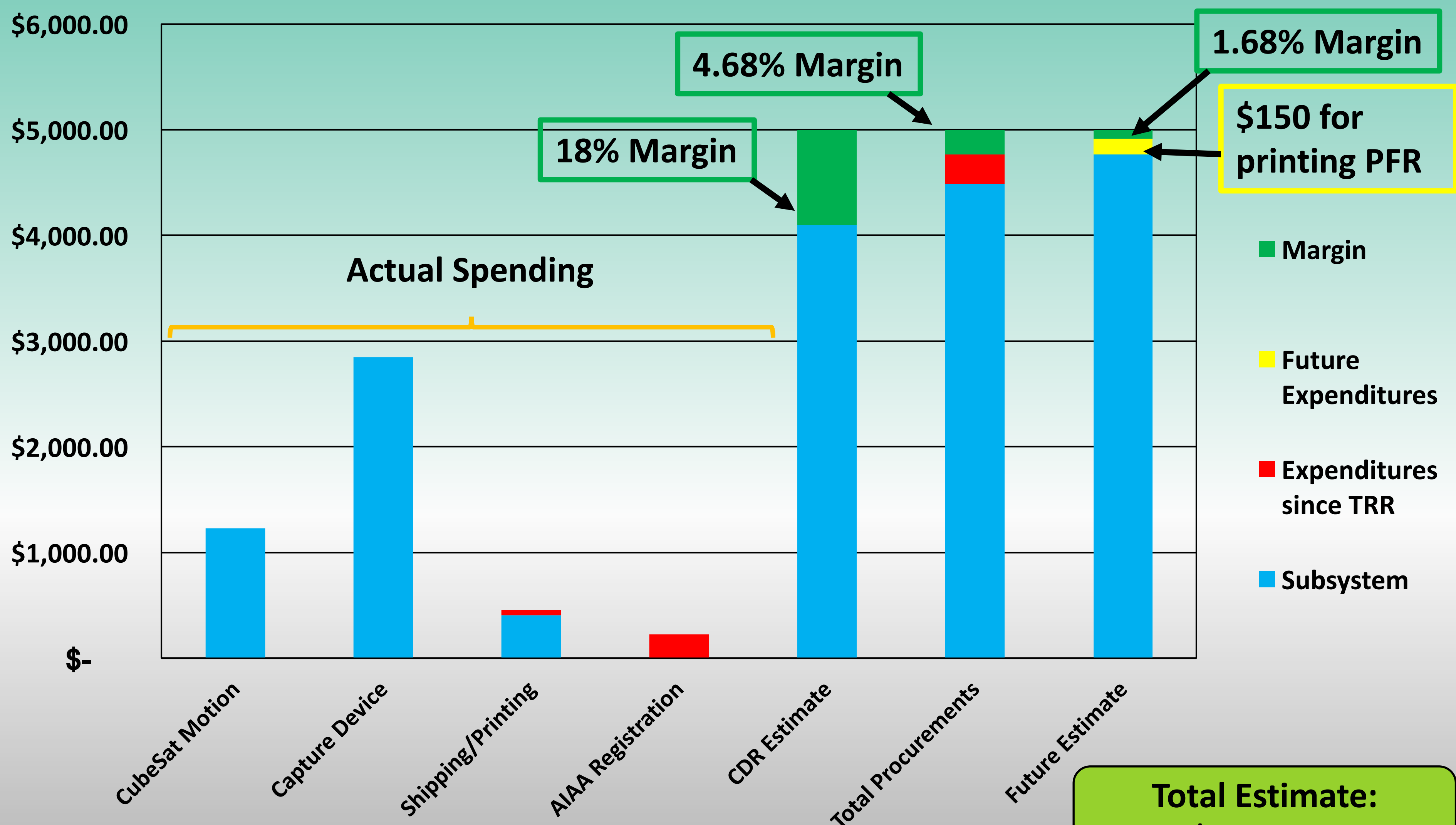
❖ Difficulties

- ❖ Software integration led to schedule slips

❖ Lessons Learned

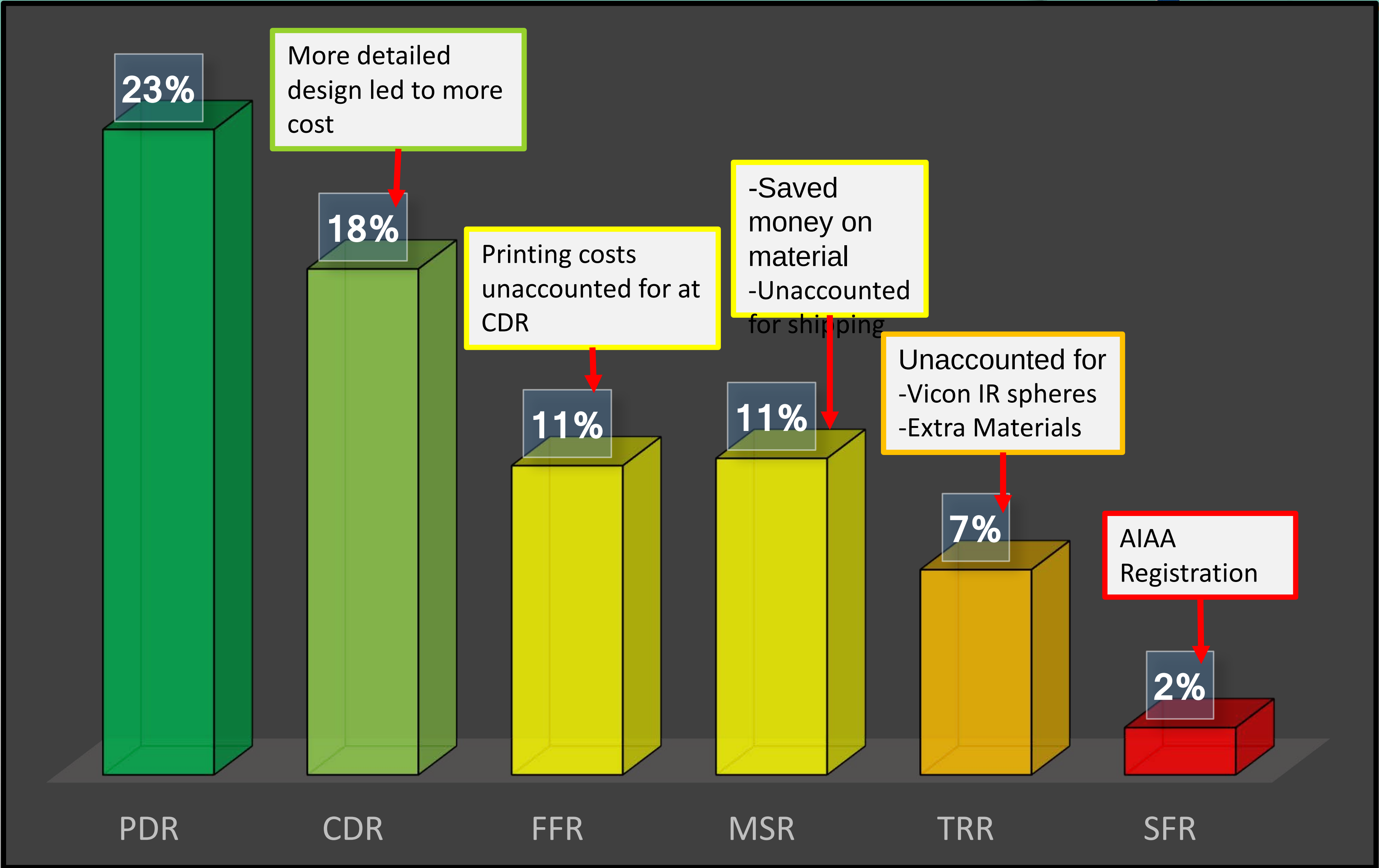
- ❖ How to use margin to create a dynamic schedule
- ❖ Design changes require careful schedule rearrangements and margin
- ❖ It is very difficult to accurately predict all of the necessary expenditures

Final Budget

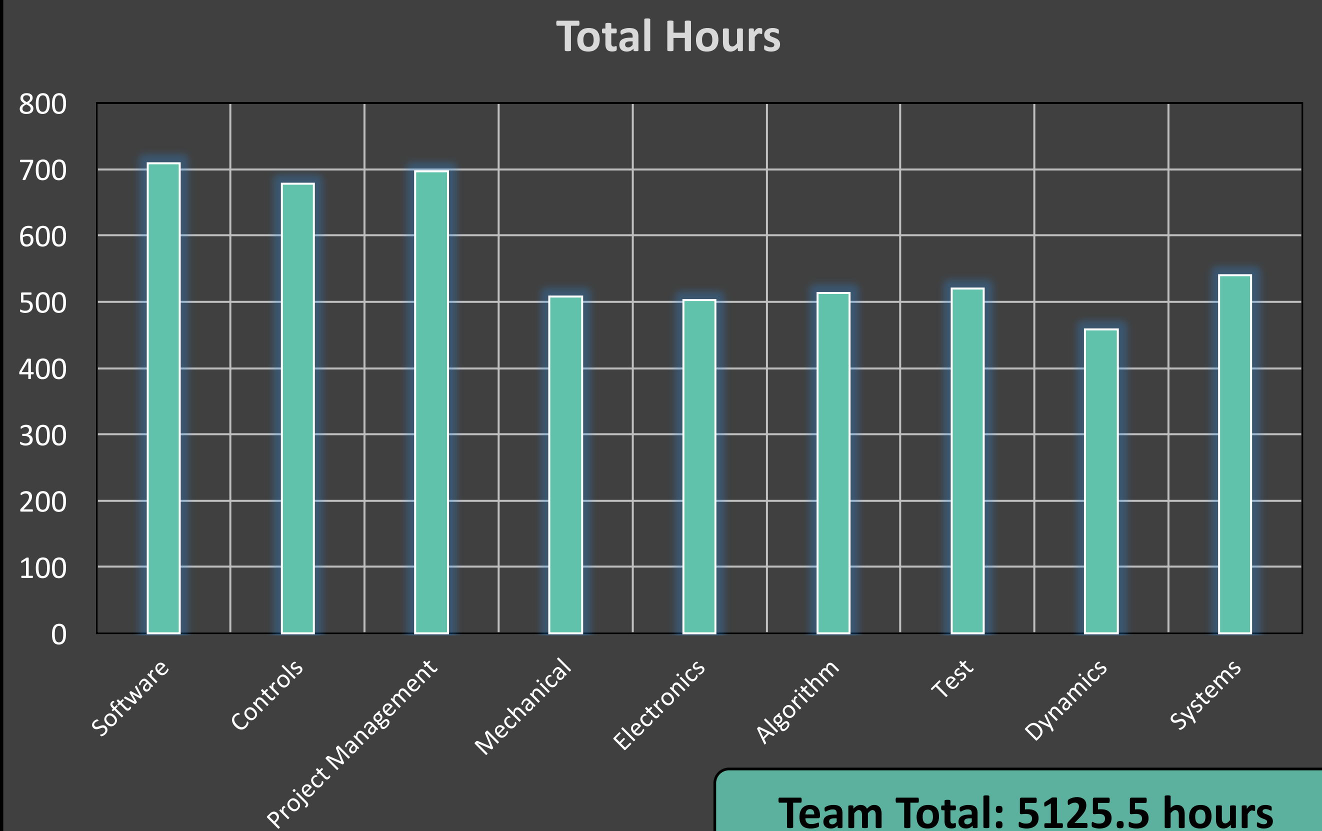


Total Estimate: $4,916.04

Margin Progression



Equivalent Industry Cost



Team Total: 5125.5 hours

Using an average starting salary of $65,000 for entry level engineers,
at 2080 hours of work a year…

Average rate is $31.25/hr

Typical overhead of 200%

Labor: $160,171.88
Overhead:$320,343.75

Material cost of $4,081.88

Equivalent Industry Cost of $484,597.51

Summary

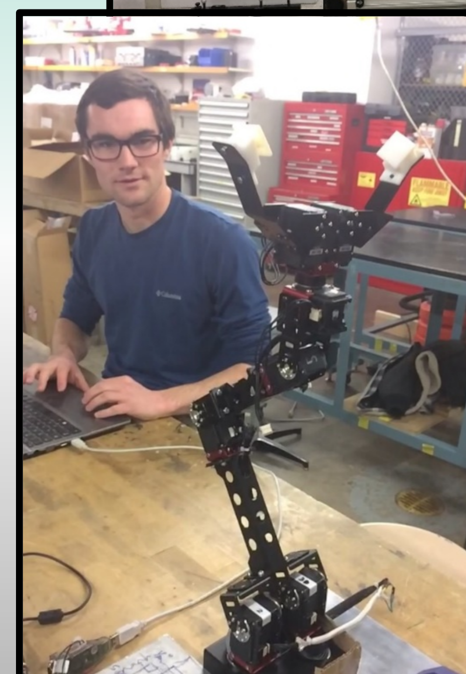
Manufactured and tested CubeSat Recovery test bed

- Completed testing 1 week ahead of schedule with 9 undergraduate students

- Total budget used: **$4,766.04**

Test Bed Accomplishments

- Demonstrate the motion of a CubeSat model
- Closed loop arm control within tolerable limits
- Ability to locate and move arm to axis of rotation autonomously
- Wrist-CubeSat phase matching within 0.5 degrees
- Autonomously confirm the capture of the CubeSat with force sensors



Path Forward

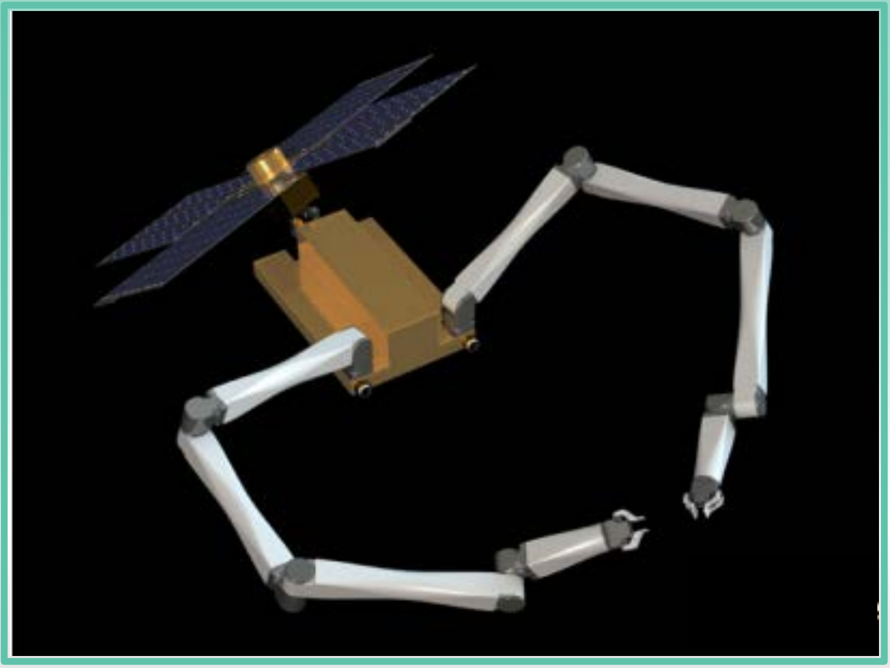


Image Source: http://www.tethers.com/SpecSheets/Brochure_KRAKEN.pdf

- Rendezvous and proximity operation calculations and simulations for reaction wheels and thrusters
- Add an additional DOF to the arm, or entire arm, to allow for a larger solution space
- Develop vision system that uses 2D image recognition
- Flight ready components and testing for space environment

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

Brandon Antoniak

FR 1.1 Breakdown

FR 1.1: The CRST shall demonstrate the motion of a CubeSat analogue during the demonstration.
DR 1.1.1: The CubeSat analogue shall allow for translational motion about only one axis.
Source: Dictated by scope/ levels of success
Verification: Inspection
DDR 1.1.1.1: The CubeSat analogue shall employ a motor with a minimum torque of 0.06 Nm to translate the CubeSat.
Source: Derived based on mass properties and friction of linear rail.
Verification: Test
DDR 1.1.1.2: The linear translation of the CubeSat shall be commanded to perform within motor performance limits.
Source: Needed in order to avoid the risk of overcurrent to the motor.
Verification: Demonstration
DR 1.1.2: The CubeSat analogue shall allow for rotational motion about only one axis.
Source: Dictated by scope/ levels of success
Verification: Inspection
DDR 1.1.2.1: The CubeSat analogue shall employ a minimum torque of 0.14 Nm to rotate the CubeSat Model.
Source: Derived based on angular velocity of the CubeSat and its mass properties along with frictional torques.
Verification: Test
DR 1.1.3: The CubeSat model shall weigh 3kg..
Source: Customer Requirement.
Verification: Inspection

FR 1.2 Breakdown

FR 1.2: The CRST shall determine the relative position and attitude between the CubeSat and capture device during the demonstration.

DR 1.2.1: The CRST shall communicate with the Vicon Motion Capture System to sense the initial conditions and motion of the CubeSat relative to the base of the robotic arm (origin) throughout the demonstration.
Source: Dictated by highest levels of success
<u>*Verification:* Test</u>

DR 1.2.2: The CRST shall determine the axis of rotation of the CubeSat model during the demonstration.
Source: Needed to align the end effector with the CubeSat for ease of capture.
<u>*Verification:* Test</u>

DR 1.2.3: The CRST shall determine the relative linear position of the CubeSat model during the demonstration.
Source: Needed to bring the CubeSat to the grab zone of the arm.
<u>*Verification:* Test</u>

DR 1.2.4: The CRST shall calculate the desired end effector location and orientation during the demonstration.
Source: Needed to align the end effector with the CubeSat for ease of capture
<u>*Verification:* Test</u>

FR 1.3 Breakdown

FR 1.3: The CRST shall command the motion of the capture device during the demonstration.

DR 1.3.1: The CRST shall calculate the current end effector location and orientation during the demonstration.
Source: Dictated by scope/ levels of success.
Verification: Inspection
DR 1.3.2: The commands sent for capture device motion shall be within joint servos performance limits.
Source: Derived based on mass properties and friction of linear rail.
Verification: Test
DDR 1.3.2.1: The CRST shall send commands at a minimum rate of 10.5 Hz.
Source: In order to meet power requirements, operation of the motors must be below the stall current
Verification: Test

FR 1.4 Breakdown

FR 1.4: The CRST shall execute capture of the physical CubeSat model autonomously during the demonstration.

DR 1.4.1: The capture device shall have an average power of no more than 100W.
Source: Customer Requirement
Verification: Test
DR 1.4.2: The capture device shall have an peak power of no more than 168W.
Source: Customer Requirement
Verification: Test
DR 1.4.3: The capture device shall have an peak current draw of no more than 10A.
Source: Customer Requirement
Verification: Test
DR 1.4.4: The capture device shall have an peak voltage draw of no more than 28V ± 6V unregulated
Source: Customer Requirement
Verification: Test
DDR 1.4.5: The end effector of the capture device shall have a minimum grip force of 1.1 N.
Source: Needed to capture the CubeSat based on the coefficient of friction between the force sensors and the CubeSat.
Verification: Test

Continued on next slide…

FR 1.4 Breakdown

FR 1.4: The CRST shall execute capture of the physical CubeSat model autonomously during the demonstration.

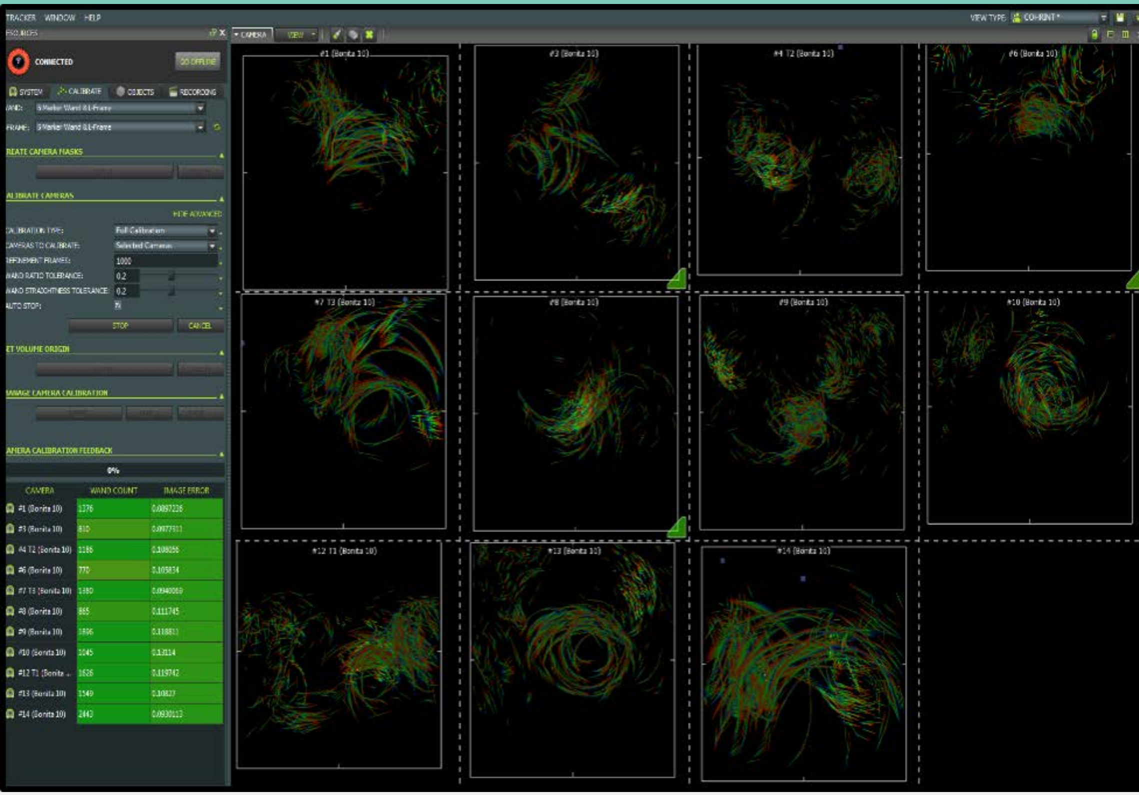
DR 1.4.6: The capture device shall be able to release from the CubeSat after capture without human intervention.
Source: Dictated by scope/ levels of success
Verification: Demonstration

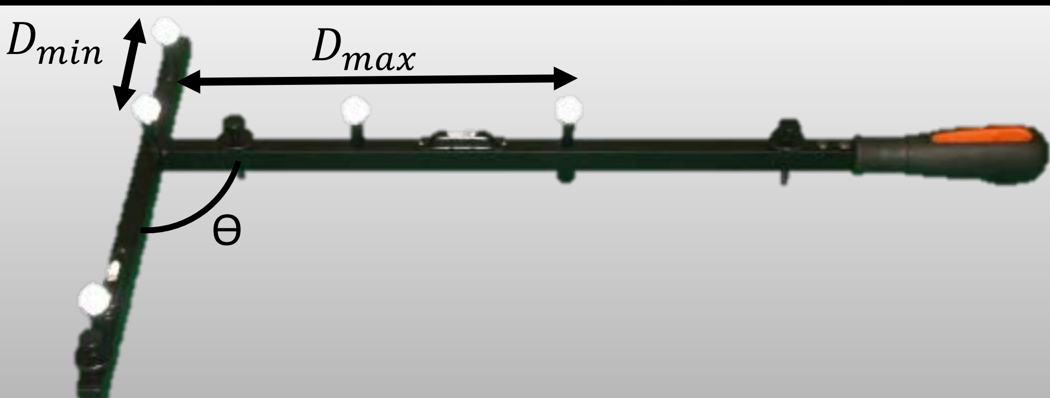
DR 1.4.7: The capture device shall be able to confirm the capture of the CubeSat after capture without human intervention.
Source: Dictated by scope/ levels of success
Verification: Demonstration

DR 1.4.8: The capture device shall confirm capture of the CubeSat model in less than 30 minutes.
Source: Customer Requirement
Verification: Test

DDR 1.4.9: The capture device wrist shall rotate less than two revolutions from its initial orientation.
Source: Needed to reduce the possibility of severing the wires to the force sensors.
Verification: Test

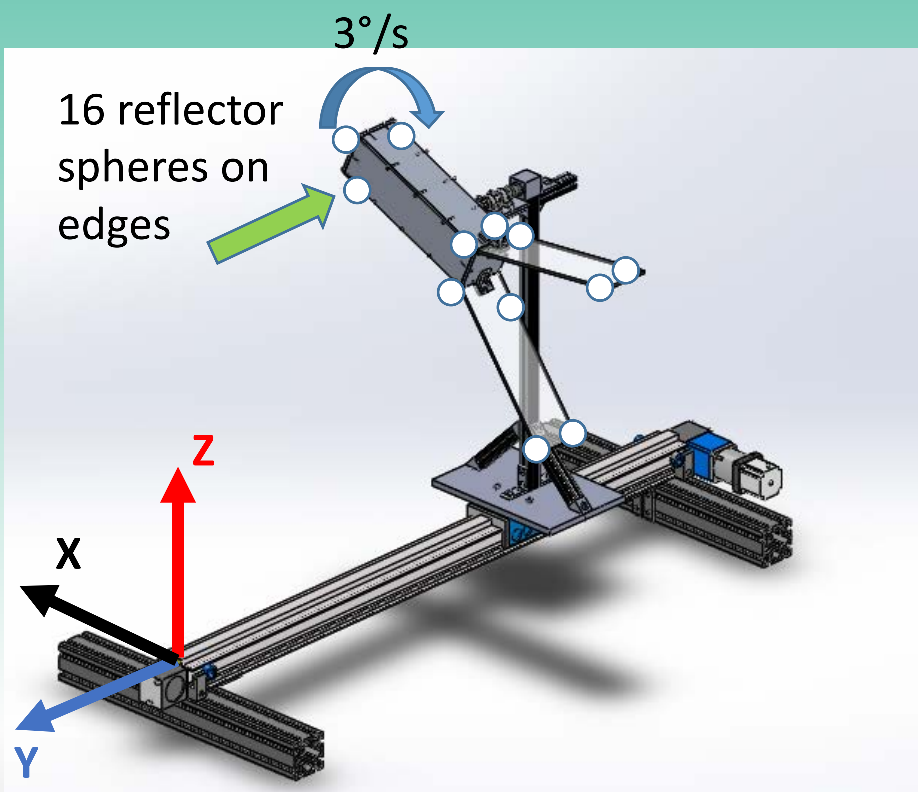
VICON Calibration





- VICON cameras collect data on a fixed geometry calibration wand and determine relative location and orientation through software reconstruction
- Residuals are measured as root mean squared of the distance between the ray from the camera strobe ring to the marker and the reflected ray to the camera lens

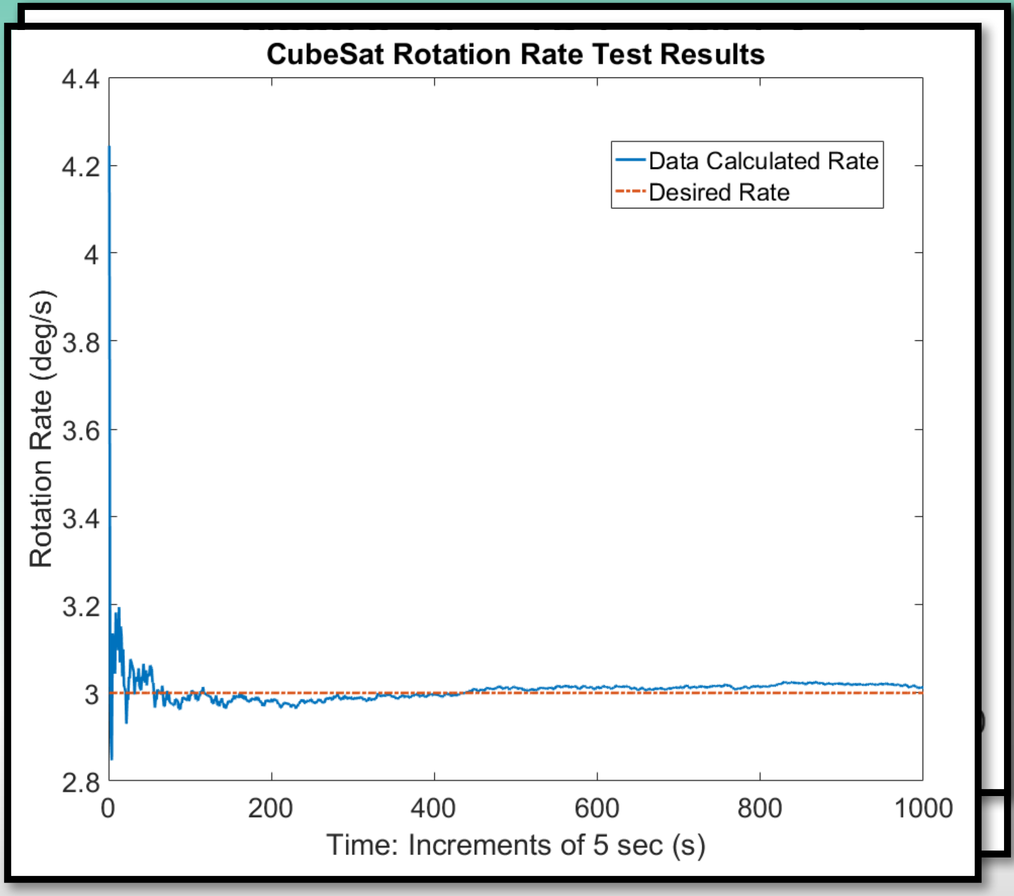
VICON Rotation Rate Test



- **Objectives:**
1. Verify CubeSat's desired rotation rate at 3°/s
- **Location:** RECUV Motion Capture Lab
- **Test type:** Subsystem
- **Duration:** 1 hour
- **Requirements Met:** FR 1.1
- **Risk Reduction:** Ensures that the testbed is operating at the desired condition
- **Data Collected**
  1) Orientation of any CubeSat component from VICON camera system

Requirement	Description	Motivation
DR 1.1.3	The CubeSat analogue shall allow for rotational motion about one axis.	Ensure 1-D rotation as required
DR 1.1.3.1	The axis of rotation of the CubeSat model shall be about its major axis at 3 +- 0.3 deg/s.	Ensure rotation rate as required

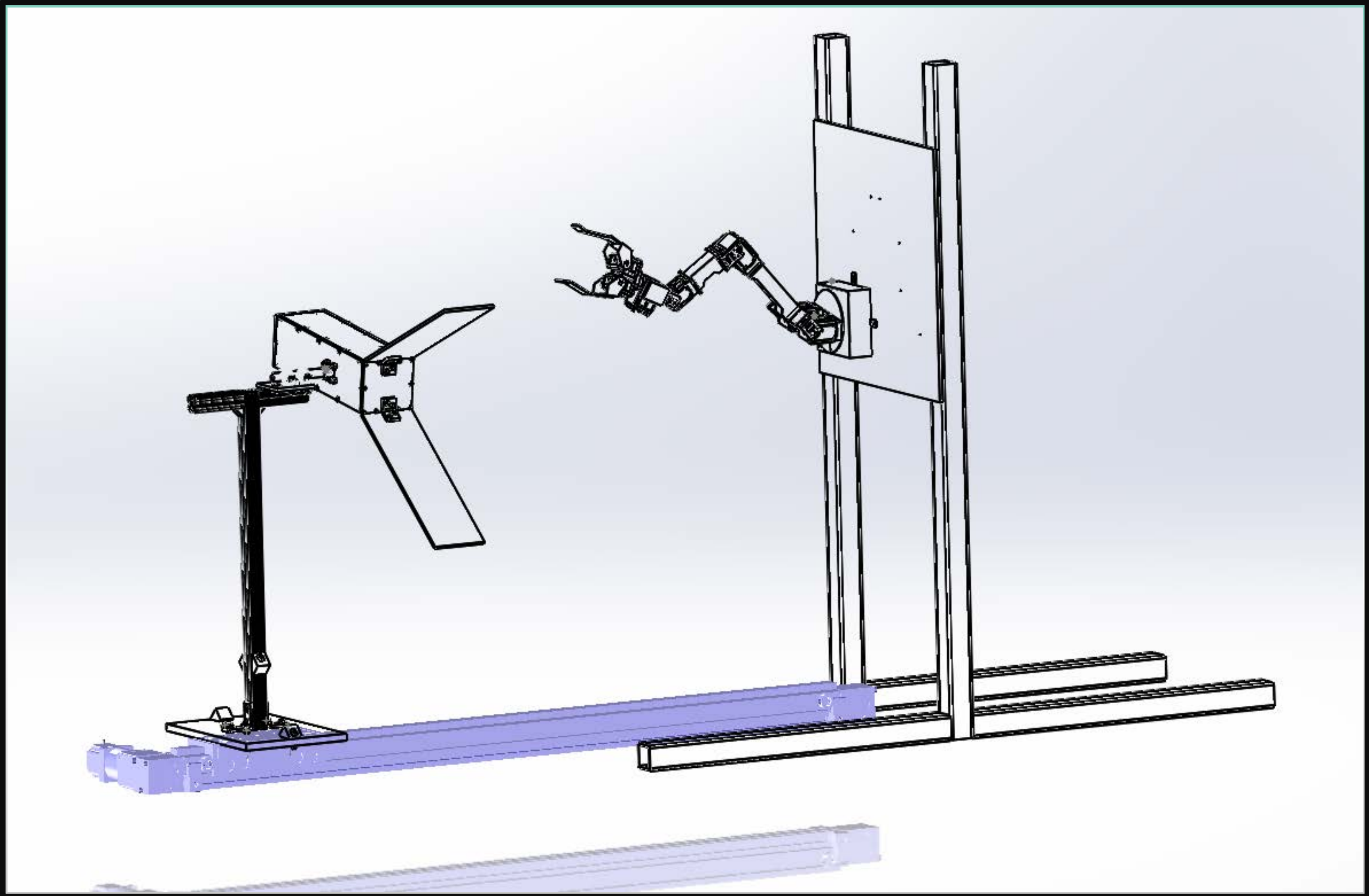
VICON Rotation Rate Results



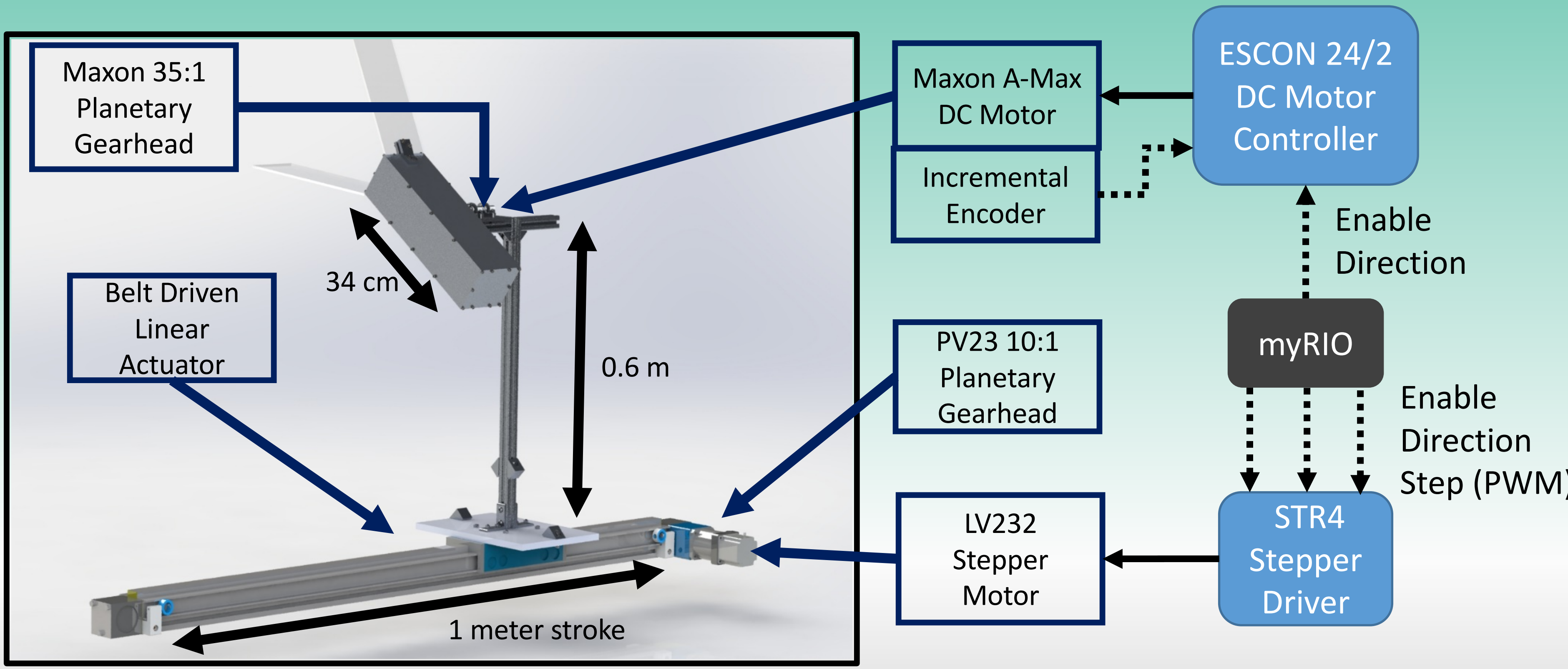
Calculated Rate (deg/s)	Actual Error (deg/s)
~3.0044	0.0044 (0.1459%)

DR 1.1.3.1 : The axis of rotation of the CubeSat model shall be about its major axis at 3 +- 0.3 deg/s.

CubeSat Translation Tests



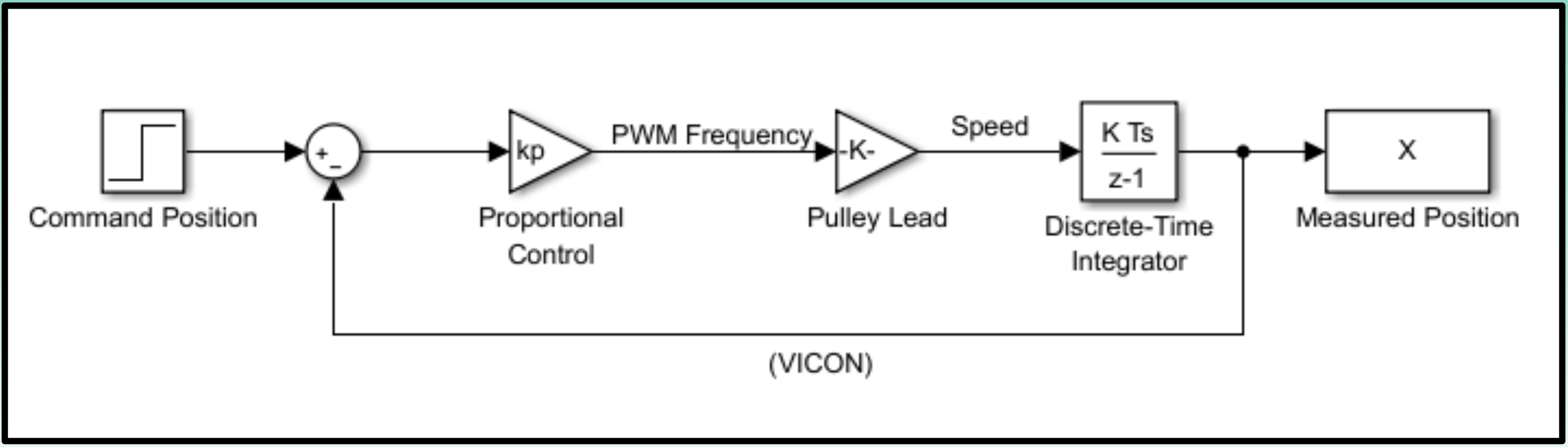
CubeSat Motion System



Digital Signal

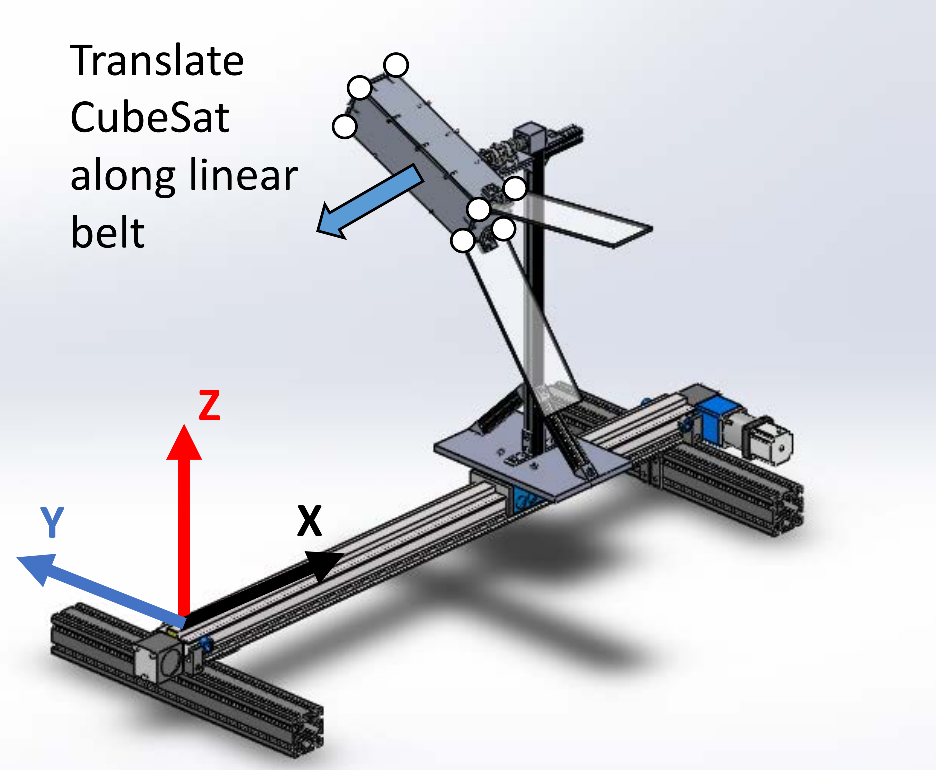
Analog Voltage

CubeSat Translation Model



- Each pulse results in one step of stepper motor
  - PWM Frequency is proportional to speed
  - Allows belt drive to be modeled with just an integrator from speed to position
- When implemented, feedback comes from VICON

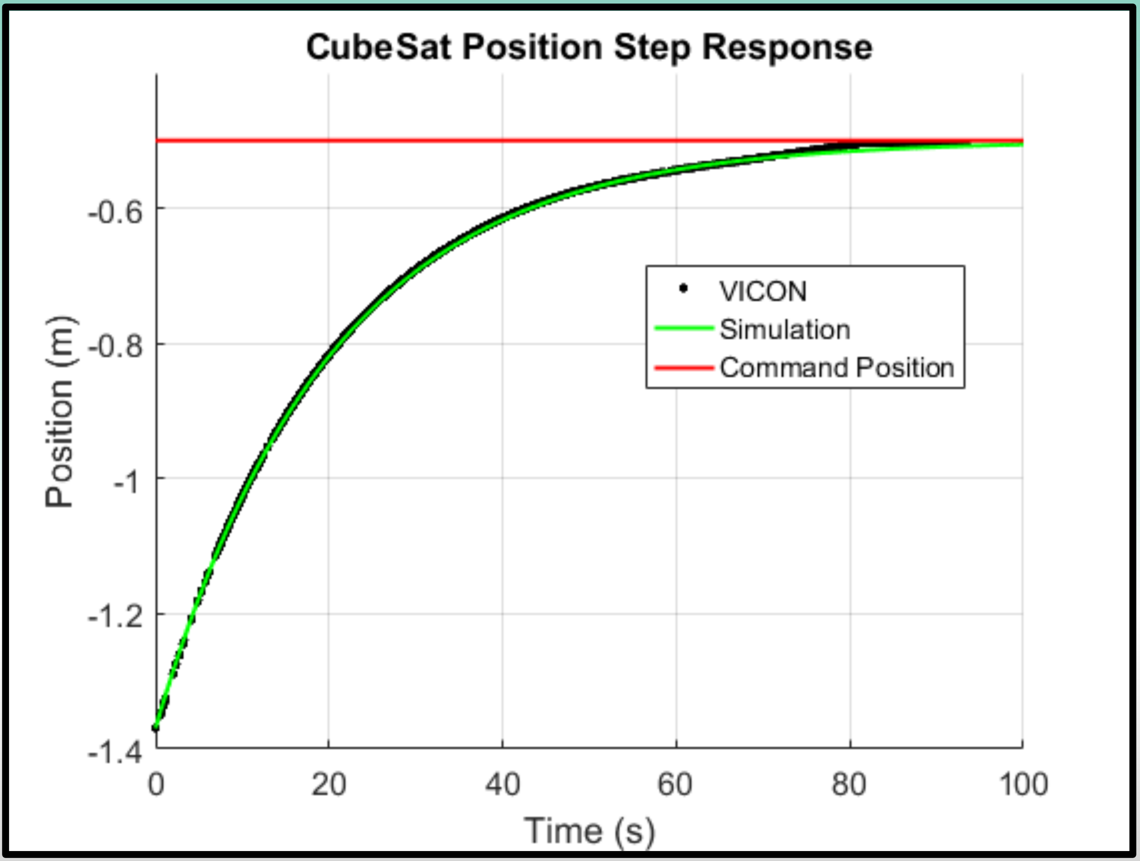
Closed Loop Position Test



- **Objectives**
  1) Verify linear rail closed loop control with VICON feedback
  2) Verify linear rail control model
- **Test type:** Subsystem
- **Location:** RECUV Motion Capture Lab
- **Duration:** 1 hour
- **Requirements Met:** DR 1.1.2, DR 1.2.4
- **Risk Reduction**: CubeSat reaches commanded position, motor operates safely within performance limits
- **Data Collected**: CubeSat X position over time

Requirement	Description	Motivation
DR 1.1.2	CubeSat analogue shall allow for translational motion along one axis	Simulates capture spacecraft closing distance to CubeSat
DR 1.2.4	CRST shall determine relative linear position of CubeSat model	Required to complete capture

Closed Loop Position Results



- VICON data closely follows simulation until the very end
  - myRIO PWM frequency limitation
- Phase 3 (wrist rotation matching) begins when rail is within 3 mm of reference
- VICON uncertainty is ± 1mm

DR 1.1.2 & DR 1.2.4: Translating CubeSat and sensing linear position

Ball Joint Friction Test

Objectives

- Obtain the static frictional coefficient of the ball joint with force sensor from angle of repose measurements
- Determine the required torque to keep hold of the CubeSat

Key Requirements

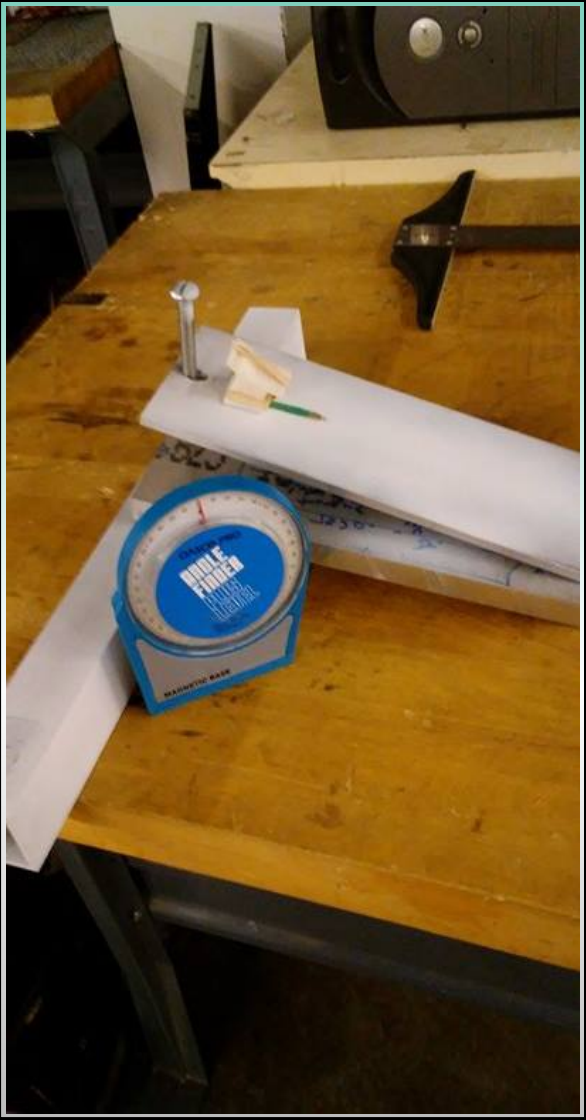
- FR 1.4 - The CRST shall execute capture of the physical CubeSat model autonomously during the demonstration.
- DR 1.4.1.10 - The capture device shall be able to confirm the capture of the CubeSat with tactile feedback without human intervention.
- DR 1.4.1.7 – The end effector of the capture device shall have a minimum grip strength of 8.9 N.

How it Reduces Risk

- Testing the static friction of the ball joint helps to confirm that the capture device will be capable of holding onto the CubeSat with the given torque capabilities

Associated Model: Minimum Grip Force

Ball Joint Friction Test



Location: Senior Projects Room

Testing Procedure:

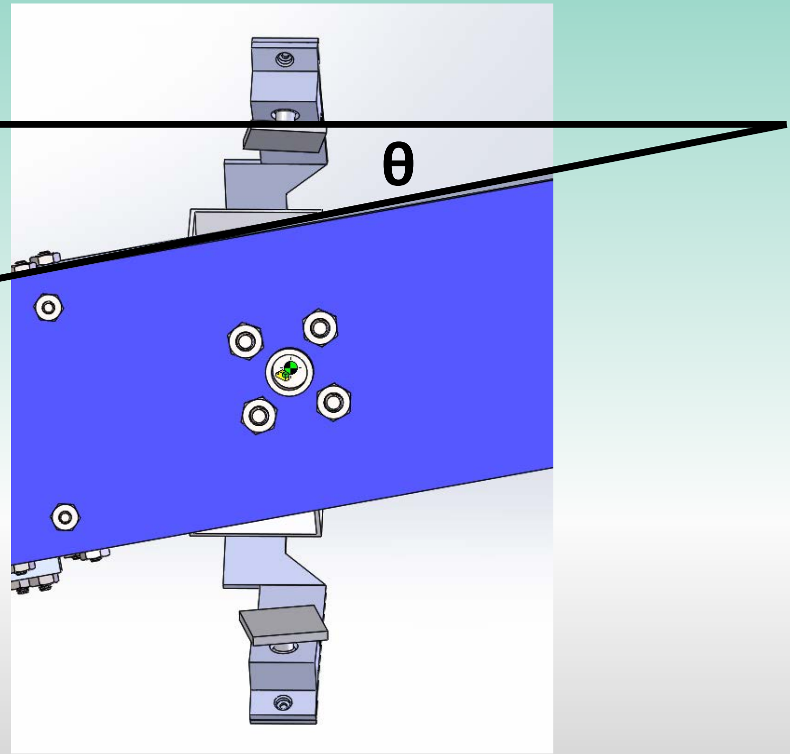
- Force sensor on ball-joint is placed on CubeSat face analog
- The face analog is raised in elevation until the force sensor slides down
- 25 tests are conducted to find the mean and standard deviation
- Tangent of the angle of repose gives static friction coefficient

Mean: 22.58°

Standard Deviation: 1.15°

Coefficient of Friction $\mu = \tan(\theta)$ 0.4159 ± 0.0201

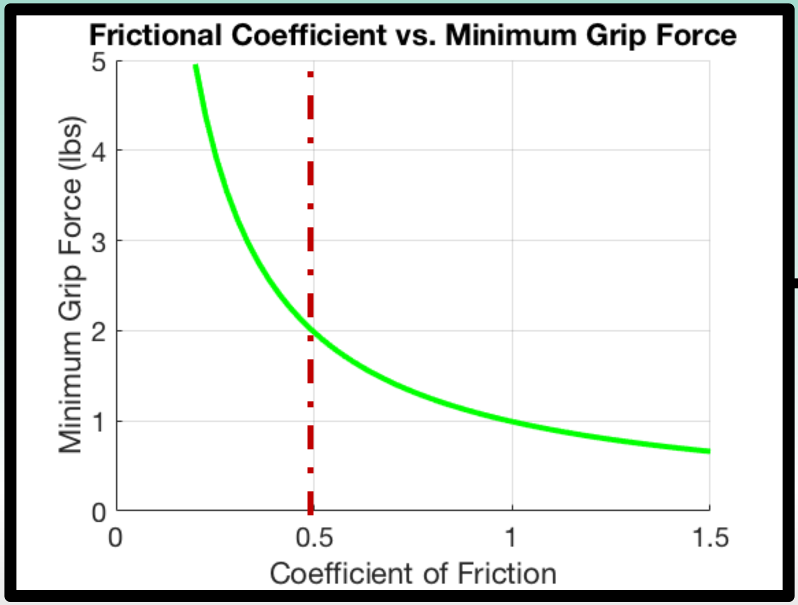
Claw Compliance



Phase Error:

- Ball joint compensates for equivalent 10° of offset
- Based on servo specs and control timing the max expected offset is 0.1°.
  - 0.08° from servo positioning tolerance
  - 0.018° from latency in sending commands
- Error in CubeSat rotation motor can be ignored since Vicon is used to measure orientation

Claw Minimum Grip Force



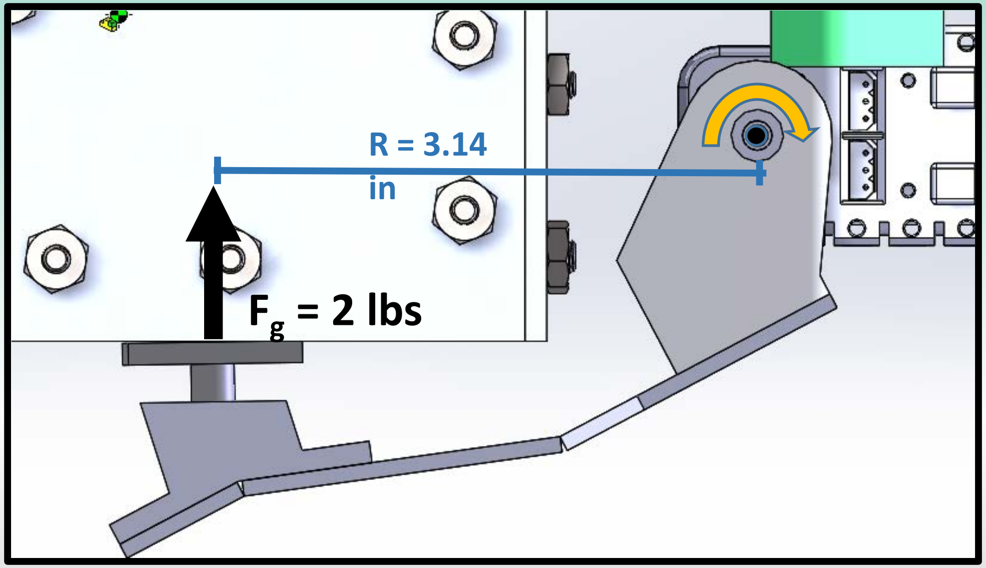
$$F_g = \frac{I\,\delta\omega}{2\mu d\,\delta t}$$

Assumptions:

- Coefficient of friction no less than 0.5.
- Force Sense Resistor (non-uniform) contact to Aluminum surface
- Capture Time (**δt)** is greater than 0.01 seconds
- d = distance from CG to outer surface of CubeSat = 1.87”
- $\delta\omega$ = CubeSat speed = 0.05 rad/s

F_g = 2 lbs (assuming min friction)

Claw Torque Required

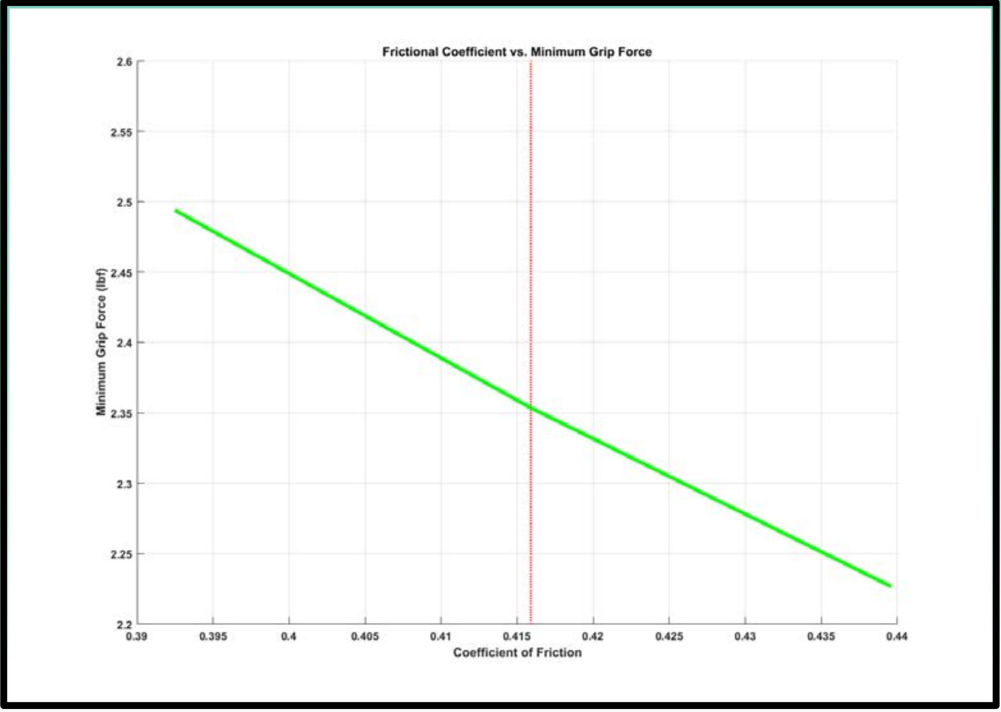


- Determine the minimum gripping force to hold CubeSat (confirm capture)
- Calculate torque on independent gripper servo T = R x F
- Verify torque on servo does not exceed servo specifications

Required Torque	Servo Stall Torque	Margin
100.48 oz-in	226 oz-in	44.46%

DDR 1.4.5: The end effector of the capture device shall have a minimum grip strength of 4 oz.

Updated Claw Torque Required



$$F_g = \frac{I\,\delta\omega}{2\mu d\delta t}$$

- Capture Time (**δt)** is greater than 0.01 seconds
- d = distance from CG to outer surface of CubeSat = 1.87”
- $\delta\omega$ = CubeSat speed = 0.05 rad/s

Minimum Force Required

2.227 lbf

Maximum Force Required

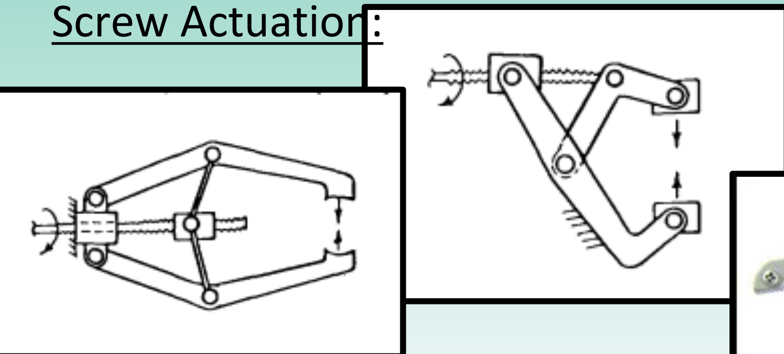
2.494 lbf

Max Required Torque	Servo Stall Torque	Margin
125.29 oz-in	**226 oz-in**	**44.56%**

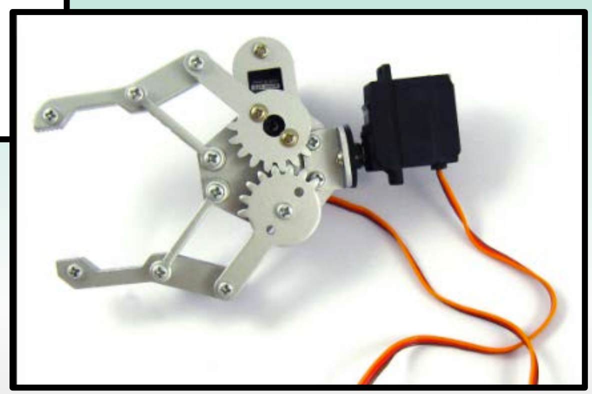
Design Options: Claw End Effector

Parallel Grippers:

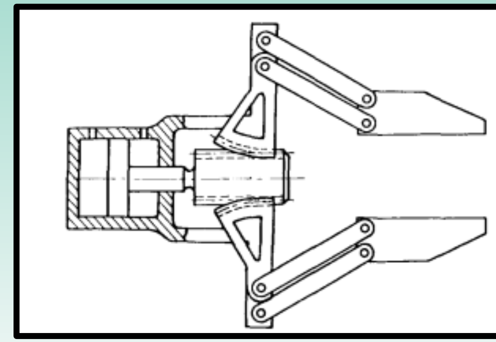
Screw Actuation:



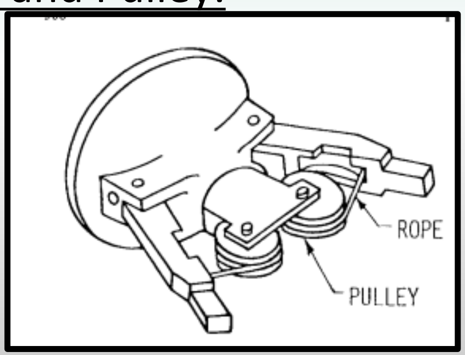
Servo Mechanism:



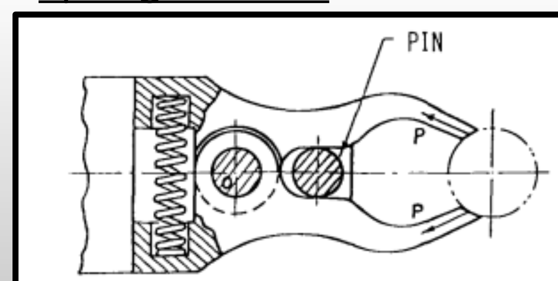
Gear and Rack:



Rope and Pulley:

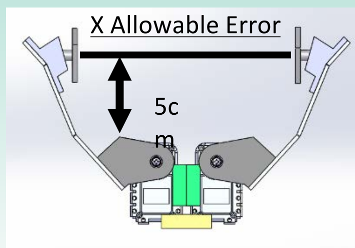


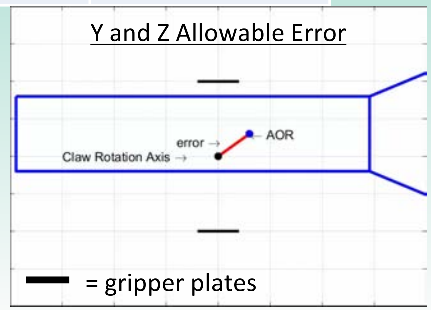
Spring Loaded:



Arm Accuracy Error

Allowable Control Error		
X Position	Y Position	Z Position
±2.5 cm	±1.41 cm	±1.41 cm



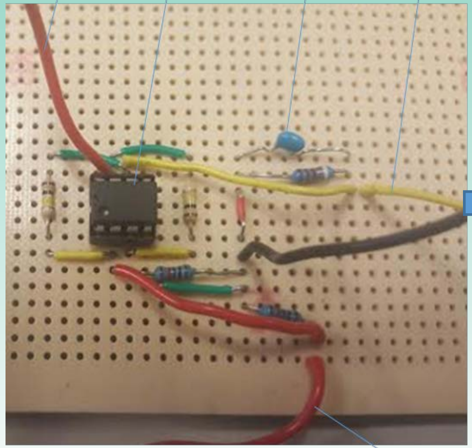


Error Budget:

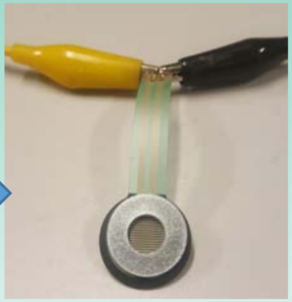
	AOR Determination	Arm Control	Total
X Position	± 0.1 cm	± 1.31 cm	± 1.41 cm
Y Position	± 0.5 cm	± 0.91 cm	± 1.41 cm
Z Position	± 0.2 cm	± 2.3 cm	± 2.5 cm

Force Sensor Characterization

Signal Conditioner



Force sensor set for weight place placement.

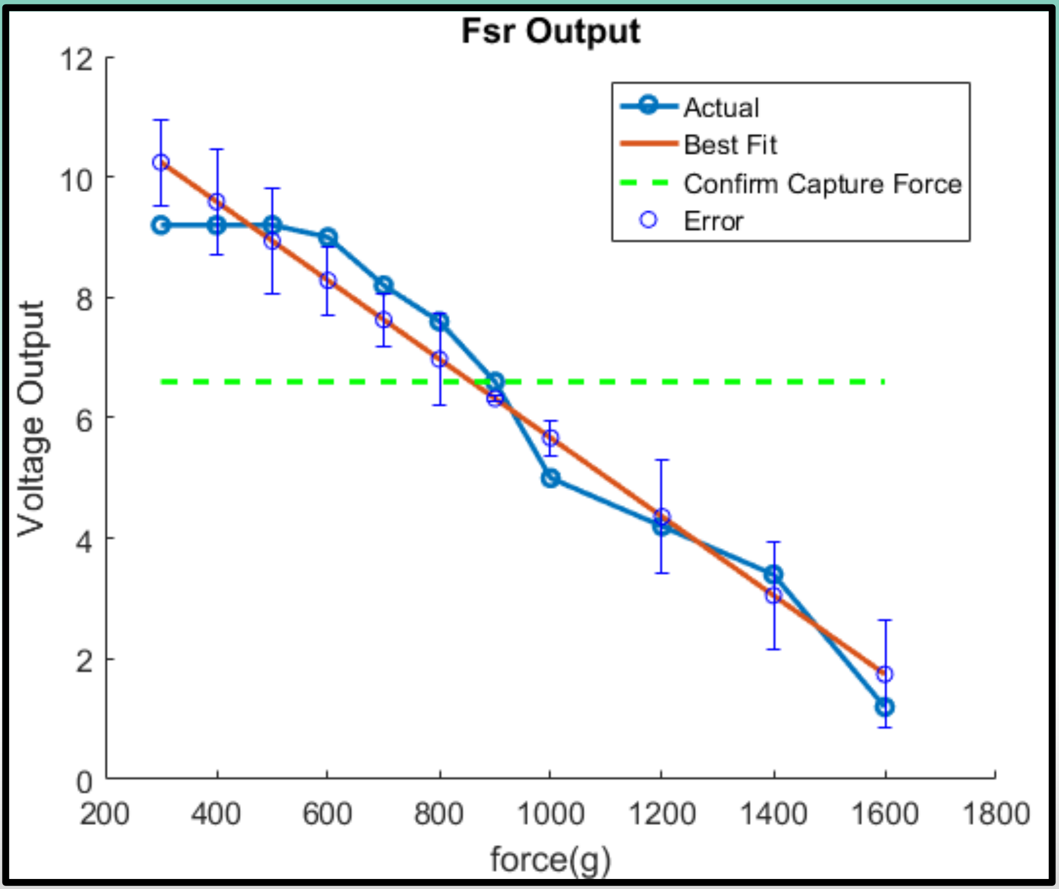


Weights place from 300g to 1600g

- **Objectives:** Sense the capture confirm force.
- **Location :** Aerospace Workshop
- **Test type:** Subsystem Test
- **Duration:** 1 hour.
- **Requirements Met:** Confirm capture force of 2.2lbs = 997 grams was detected.
- **Data Collected:** Voltage

Requirement	Description	Motivation
DR 1.4.8:	The capture device shall confirm capture of the CubeSat model in less than 30 minutes.	Customer requirement specified by SNC, is used to further validate that the demonstration was successful.

Force Sensor Characterization Results



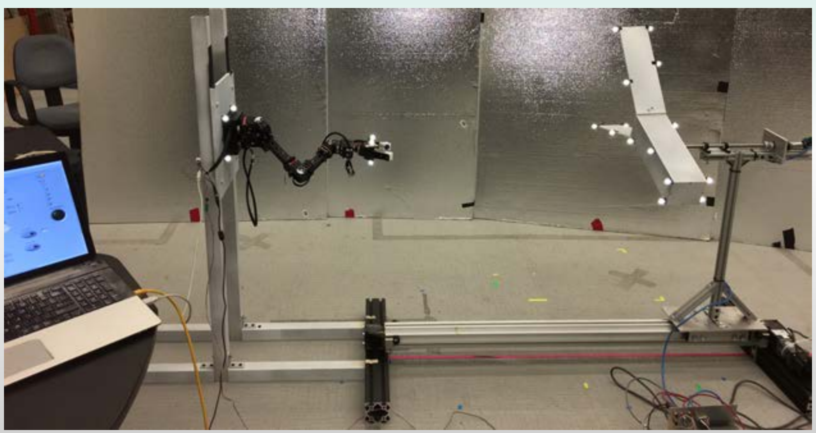
- As Seen By the Oscilloscope scope
- $\mathbf{Vout = -0.0065 * force + 12.20}$
- The green dash line is the threshold force detected by the force sensor.
- Using the Normalized Root Mean Square Error equation to calculate the error.

$$Fit(i) = \frac{\|X_{ref}(:,i) - X(:,i)\|}{\|X_{ref}(:,i) - mean(X_{ref}(:,i)\|}$$

DR 1.4.8: The capture device shall confirm capture of the CubeSat model in less than 30 minutes.

Algorithm Step Checking Test

- **Objectives:** To ensure the stages of capture are triggered correctly
- **Test type:** Subsystem
- **Location:** VICON motion capture lab
- **Duration:** 4 Hours
- **Risk Reduction:** Increases confidence for autonomy working
- **Requirements:** FR 1.4



FR 1.4: THE CRST shall demonstrate the successful capture of a physical CubeSat model

Run Initialization

Desired End Effector/
Desired Rail Position

Send Command to TestBed/ Arm

Next Command

Wait until Software thinks it's within tolerance

Check if Software is in tolerance

Yes

Open data file, find data issue to trace back to code

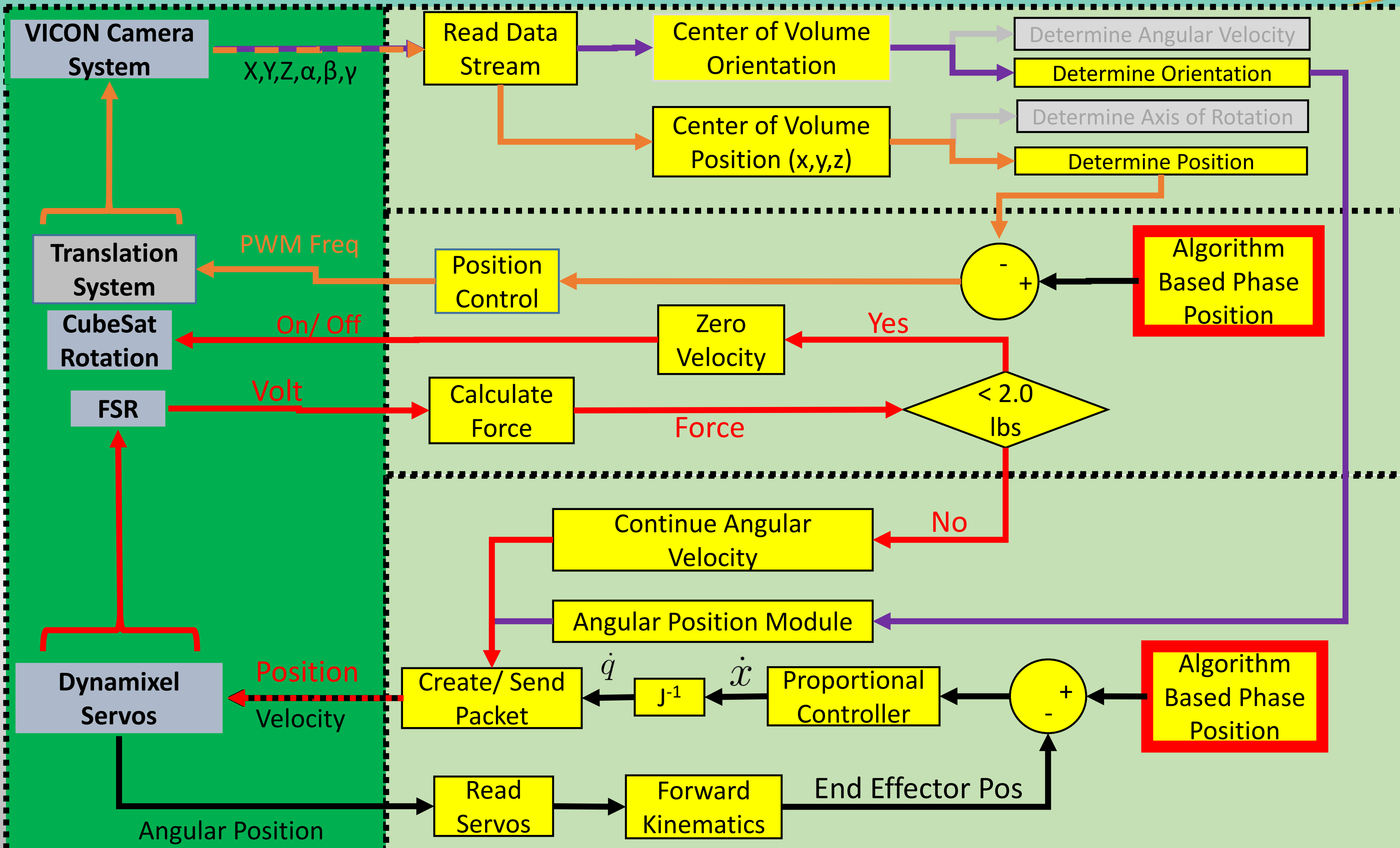
CubeSat - FMEA

Process Function	Potential Failure Mode	Potential Effect(s) of Failure	SEV	Mechanism(s) of Failure	OCC	Current Process Controls	DET	RPN
Rotation of CubeSat (CS)	Motor malfunction	Can't redo demo w/o replacement	6	Overheating	4	Testing for nominal operating range prior to demo	3	72
Translation of Cubesat	Motor malfunction	Can't redo demo w/o replacement	6	Overheating	4	Testing for nominal operating range prior to demo	3	72
Control of CS Translation	Control loop inadequate	Demo failure	6	Poor design, gain limitation on control	3	Testing for nominal operating range prior to demo	3	54
Control of CS Rotation	Control loop inadequate	Demo failure	6	Poor design, gain limitation on control	3	Testing for nominal operating range prior to demo	3	54
Motor Shut off @ end of demo	CS motor or wrist servo stalls	Motor damage, can't redo demo w/o replacement	6	Poorly designed fail safes, indaequate testing	3	Testing for nominal operating range prior to demo	3	54

Robotic Arm - FMEA

Process Function	Potential Failure Mode	Potential Effect(s) of Failure	SEV	Mechanism(s) of Failure	OCC	Current Process Controls	DET	RPN
Arm Motion	Arm damages itself	Demo failure	6	Code error	**5**	Testing prior to final demo	4	120
Claw Motion	Servo hits stall torque	Demo failure, servo damaged, can't redo demo w/o replacement	6	Code error	**5**	Testing prior to final demo	3	90
Capture Confirmation	Pressure sensors inadequate to detect valid capture	Demo failure	6	Sensor placement, sensitivity; electrical failure;	4	Testing prior to final demo	5	120
Arm Motion	Arm offset from AOR	Too much torque on arm joints	6	Code error	**5**	Testing prior to final demo, IR sensors on claw for checking absolute position.	4	120
Wrist Rotation	Wires wrap around too many times and break	Demo failure, claw and wiring potentially damaged	6	Timing error in code	**5**	Testing prior to final demo, software shutoff if wrist rotates too far	3	90

Software Backup



Arm Controller
Claw Controller
Rail Controller
Wrist Phase Controller
External Hardware
Software

Software's Five Phases To Capture

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

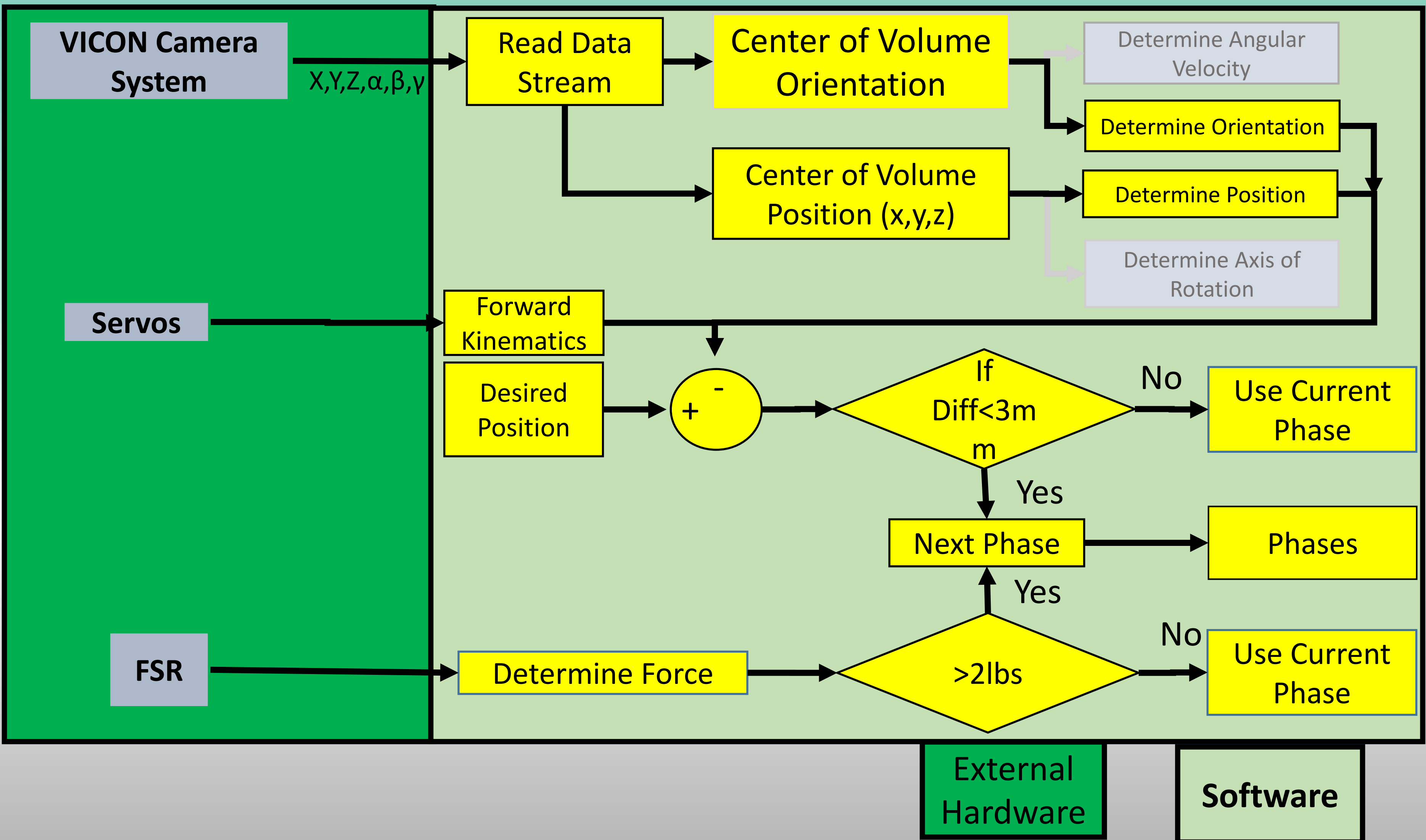
2: Translate CubeSat to Gripping Position → Position on Rail Based on 75% of Full Extension

3: Spin End Effector → Current Orientation of CubeSat

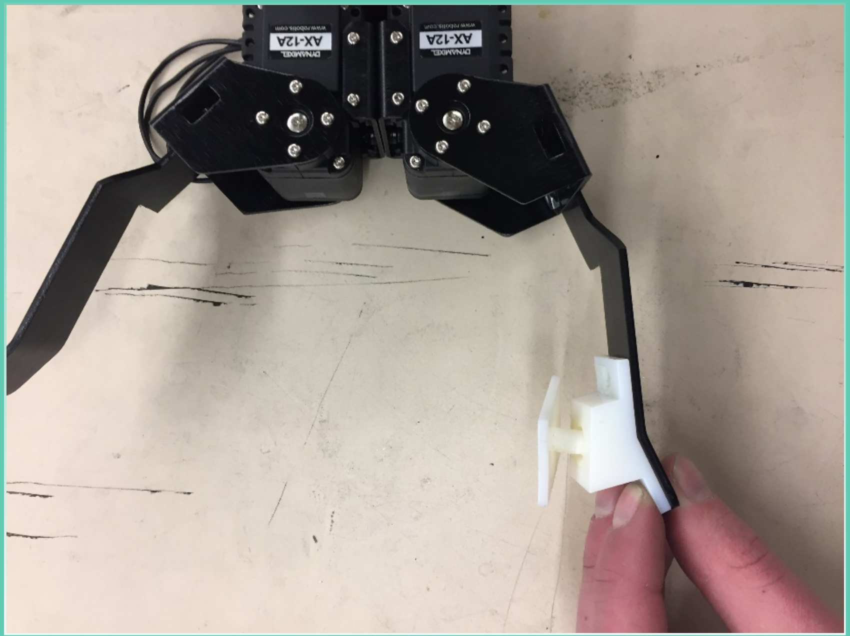
4: Extend to Grab Position → 75% of Full Extension

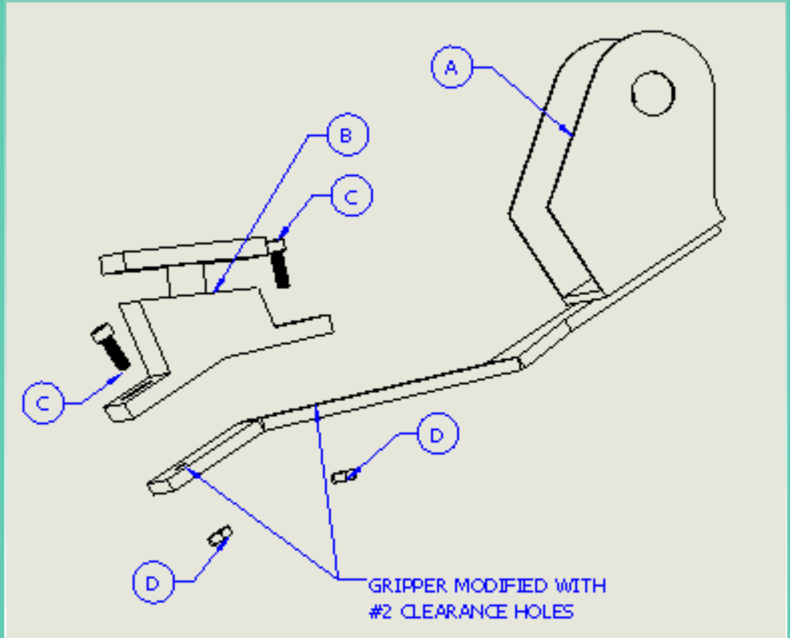
5: Close End Effector → Force Sensor 2.0 lbs → Next Step

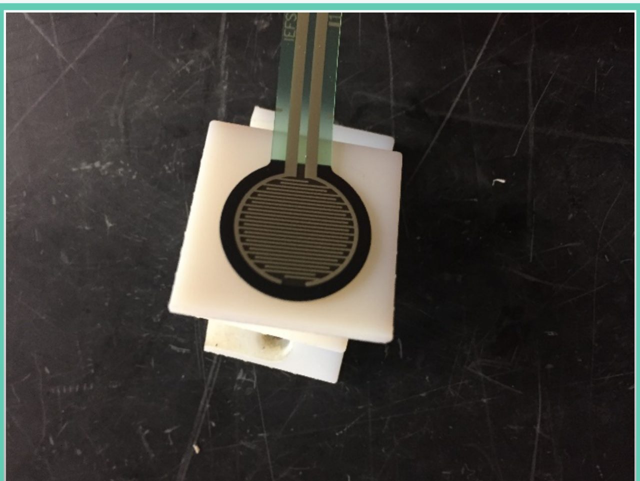
Backup: Phase Check/ Command Block



Ball Joint and FSR Assembly

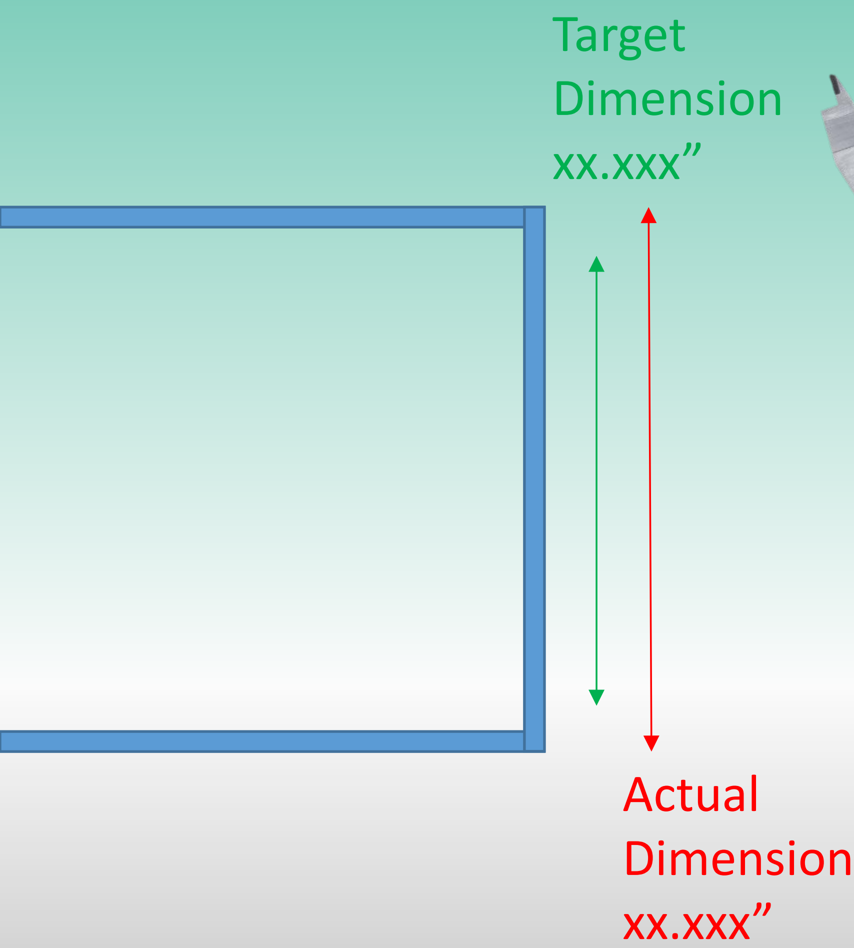


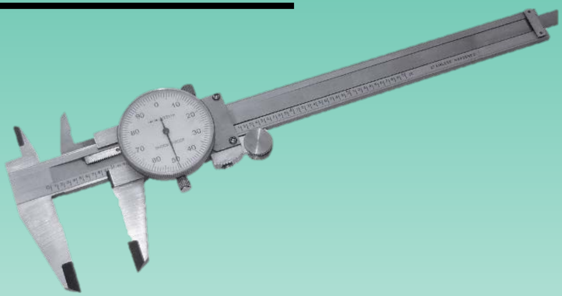




- Overnight printing in ITLL at $10 per
- Printed with counter bore for 2-56 socket screw mounting
- 3D printed puck added for proper force sensor measurement

Manufacturing Tolerances





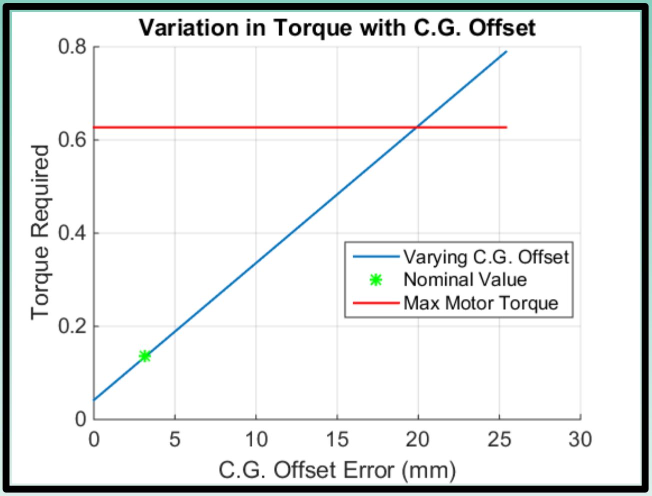
Error Sources:

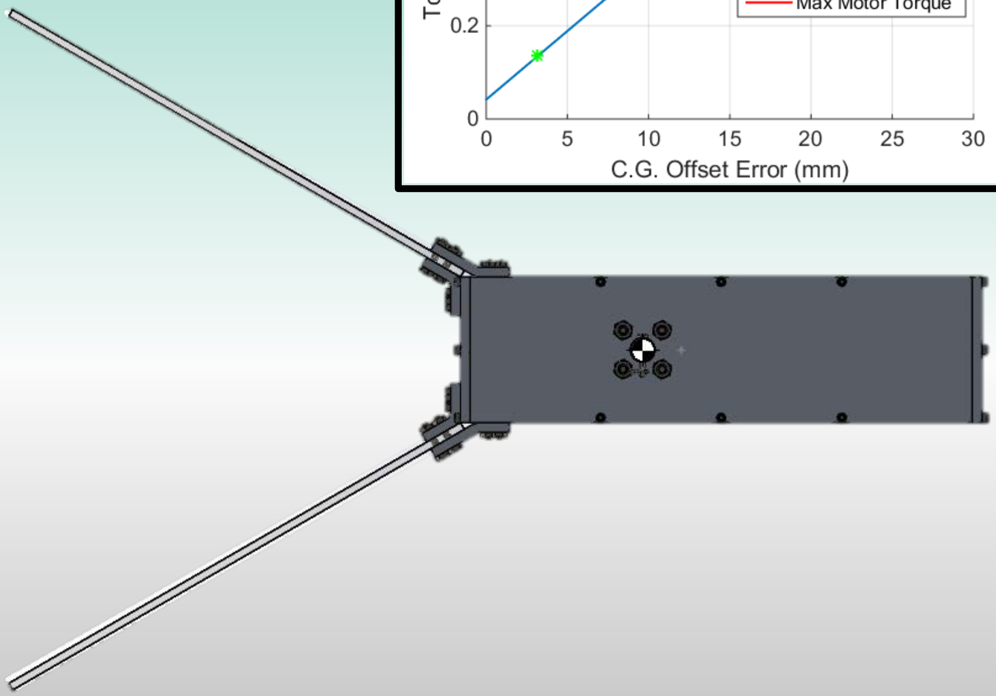
Plate thickness (Procured): +.0XX”
Caliper measurement: ±.002”
Milling error +.007”

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

CubeSat C.G.

- 20 mm maximum offset for motor performance
- C.G. offset identified to be within allowable limit
- No ballasting needed



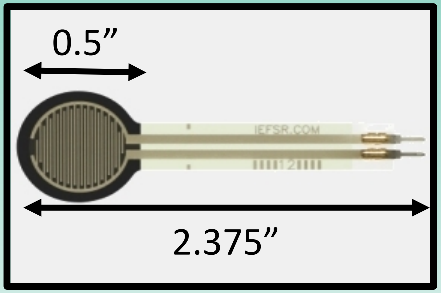


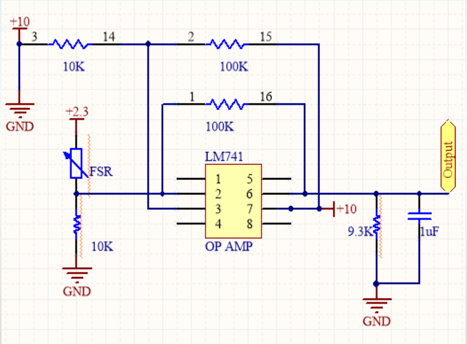
Capture Device: Force Sensors

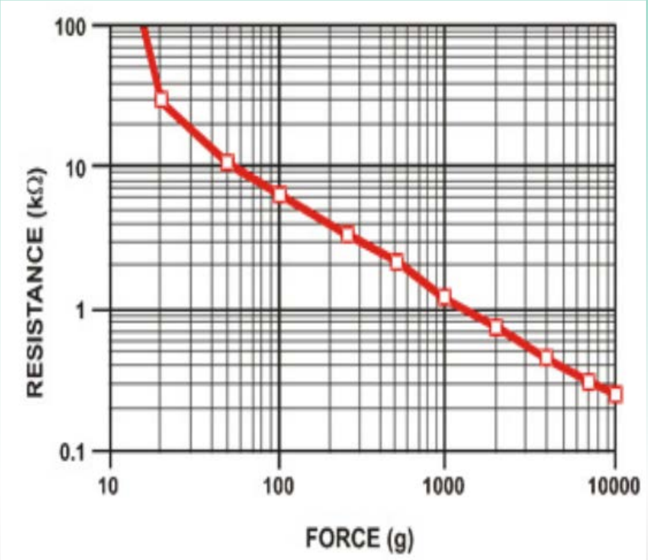
- Provide tactile feedback per DR. 1.4.6.
- A signal conditioner will be used to linearize the voltage output of the FSR as a function of force applied.
- A linearized output signal verifies that the a calculated capture confirm force has sense by the Force Sensor.

Parameters	
CC Voltage/Force	6.6V/2.2lbs
Sampling Freq. BW	45 Hz
Cutoff Frequency	17.5 Hz

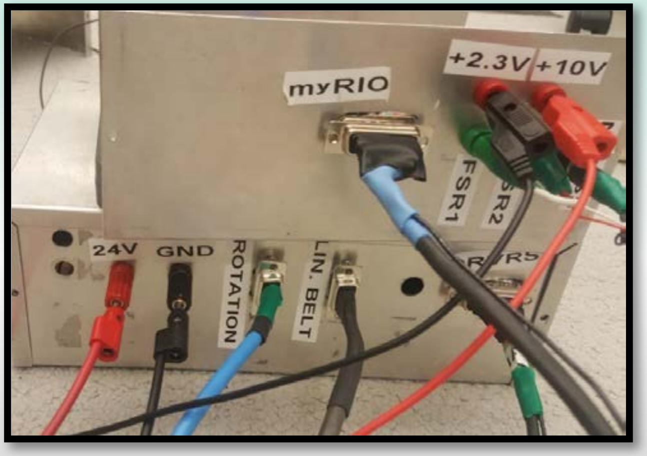
Force Sensing Resistor:





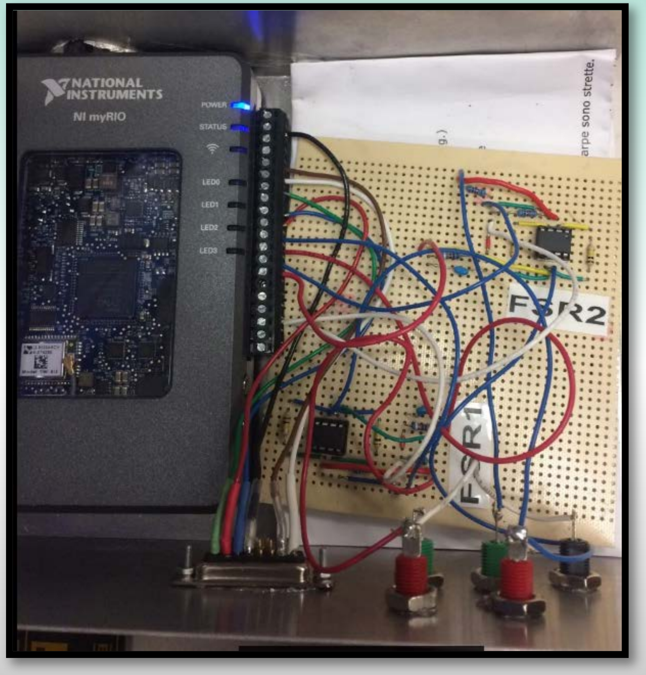


Electronics Hardware Setup

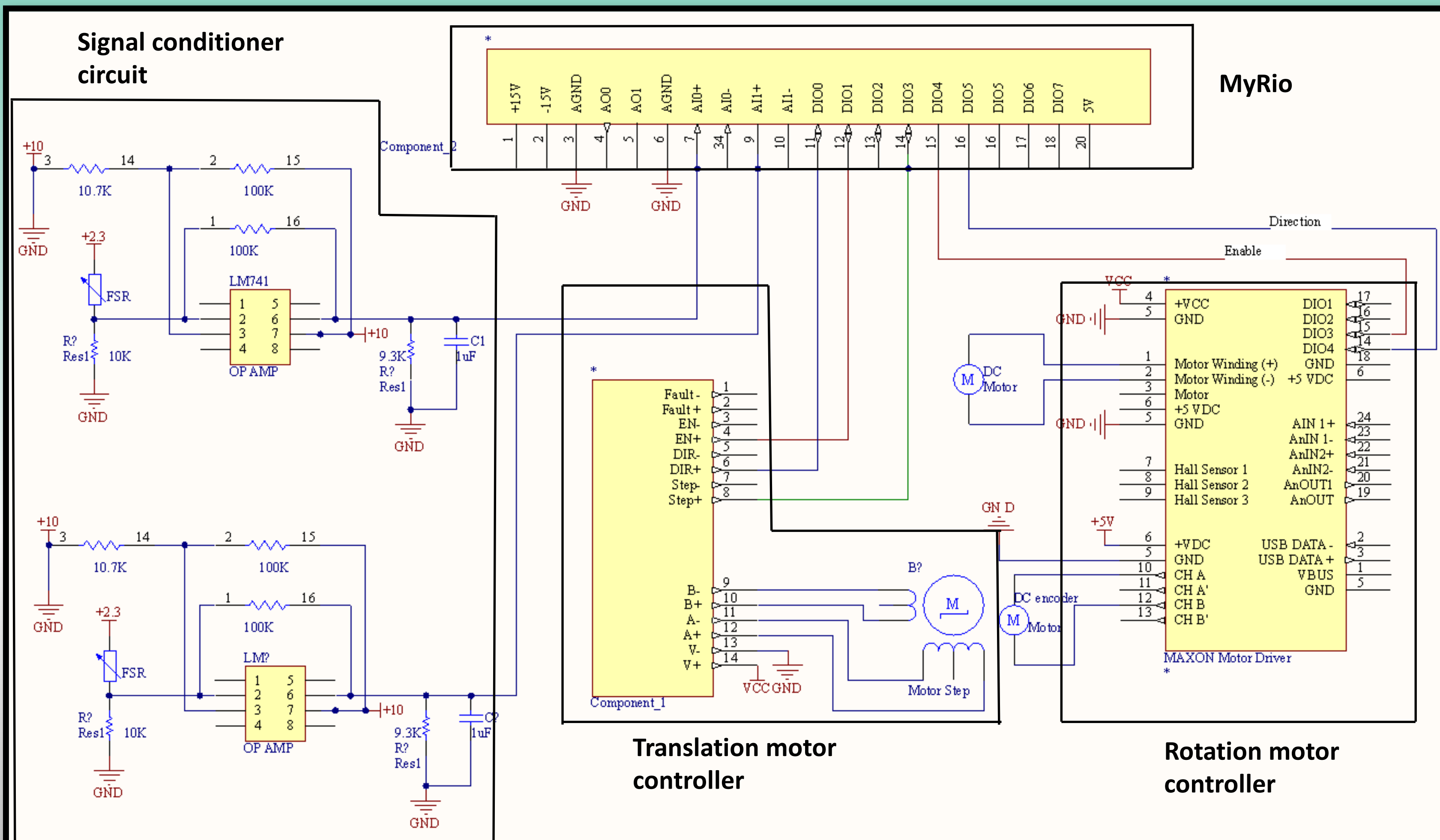


Box 1

Box 2



Electronics Schematic Setup



Appendix

Purpose and objectives	Design Description	Test Overview	Test Results		Systems	Management			
Motivation	Baseline Design	Test Fixtures	AOR Determination	Final System Test	Risk	Approach			
FBD	Hardware Block Diagram	Vicon Cameras	Stationary AOR	Final: Stage 1 & 4	System Summary	Lessons			
CONOPS	RECUV	Testing Overview	Arm Control	Final: Stage 2	Lessons	Budget			
Testbed FBD	Capture Device		Arm Accuracy	Final: Stage 3&5		Margin			
CPE	Software Diagram		Z-offset	Summary		Path Forward			
Levels of Success			Wrist Matching	Software Timing					
			Capture Confirmation	Overheating					

Backup Appendix

Requirements	V&V	Claw Stuff	Force Sensor	Risk	Software	Manufacturing	Electronics	Step Checking	
1.1	VICON Calibrate	Friction	Characterziation			Balljoint/FSR	Force Sensors		
1.2	Rotation Rate	Compliance				Tolerances	Hardware		
1.3	Translation	Min. Force				CG	Schematic		
1.4	Position Test	Torque							
		Alternative Design							
		Accuracy							