Test Readiness Review

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Customer: Henry "Lad" Curtis (Sierra Nevada Corp.)

Advisor: Dr. Jelliffe Jackson

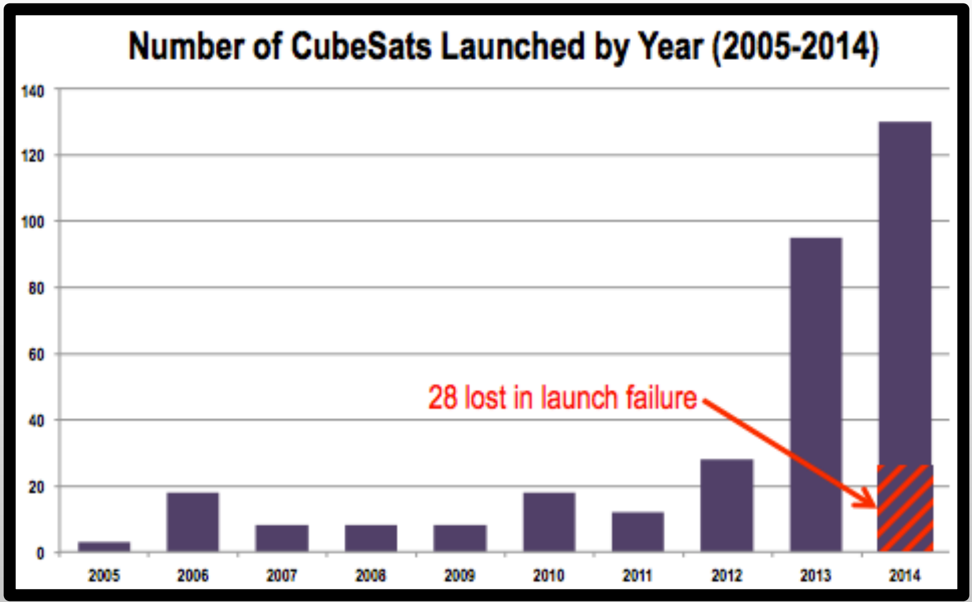
Project Overview

Project Motivation

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

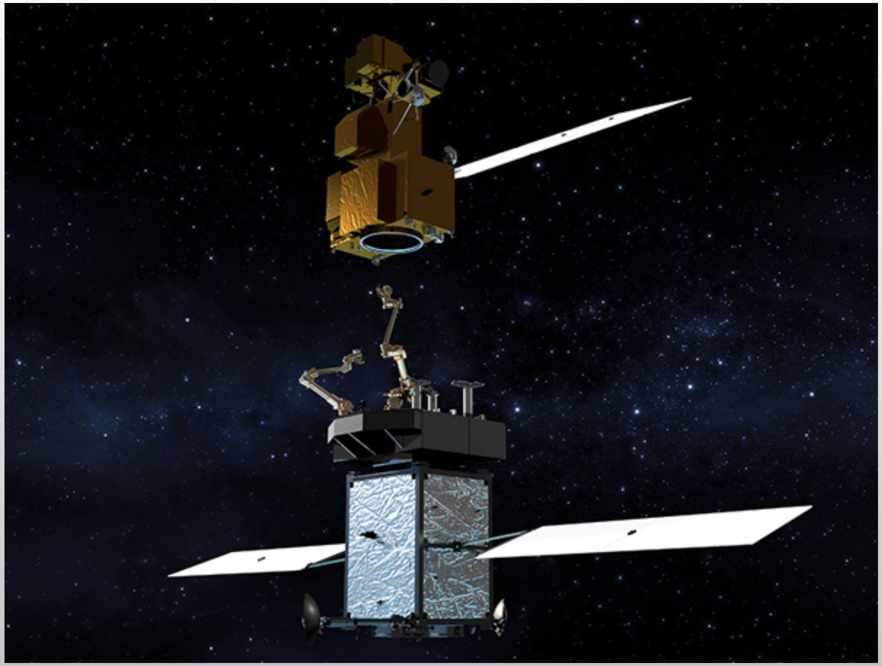
- Existing CubeSats have little or no propulsive capabilities, with no ability to change the orbit drastically and leaving them stuck if major failures occur.

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



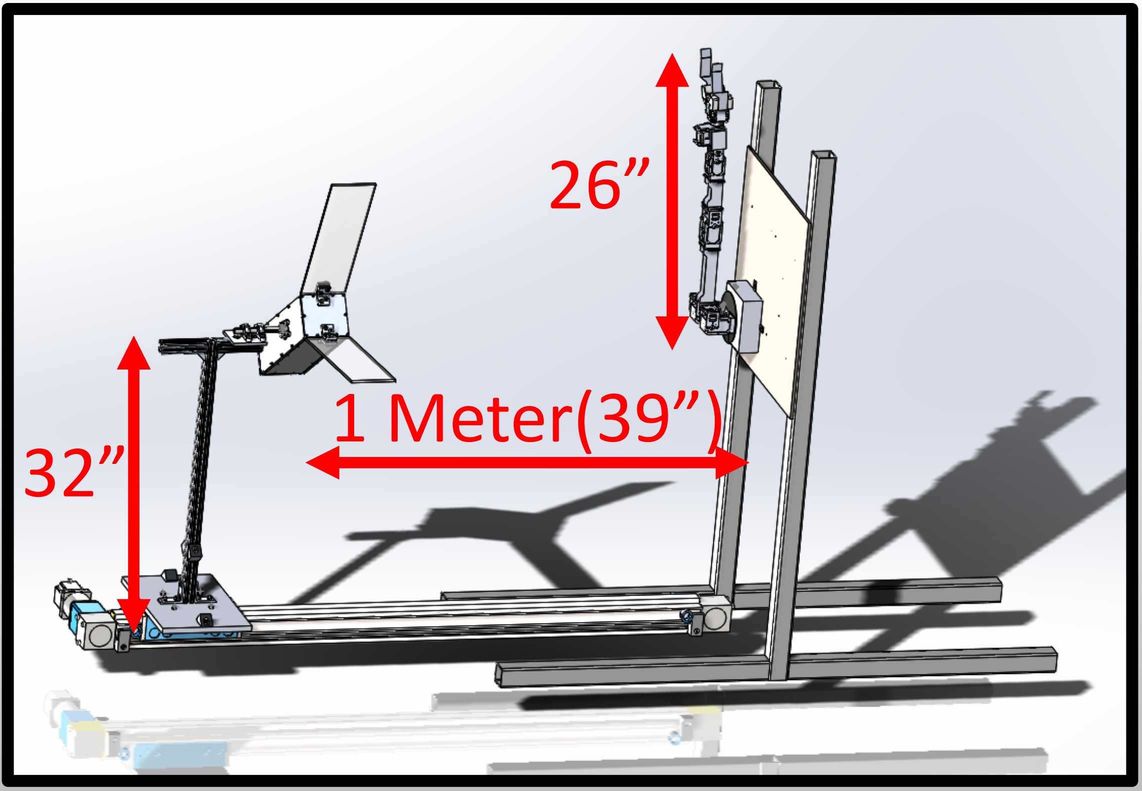
Project Statement

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**.

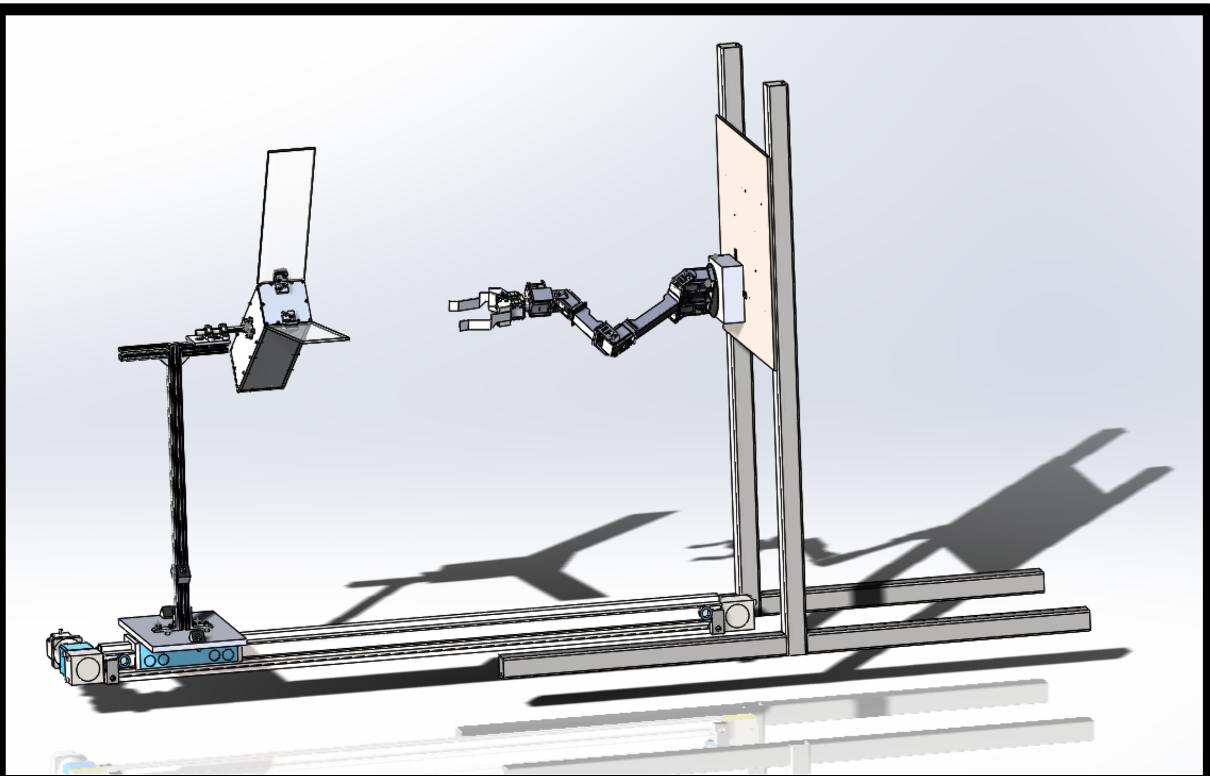
Test Bed CONOPS



0.) Initiation of Demonstration

- 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

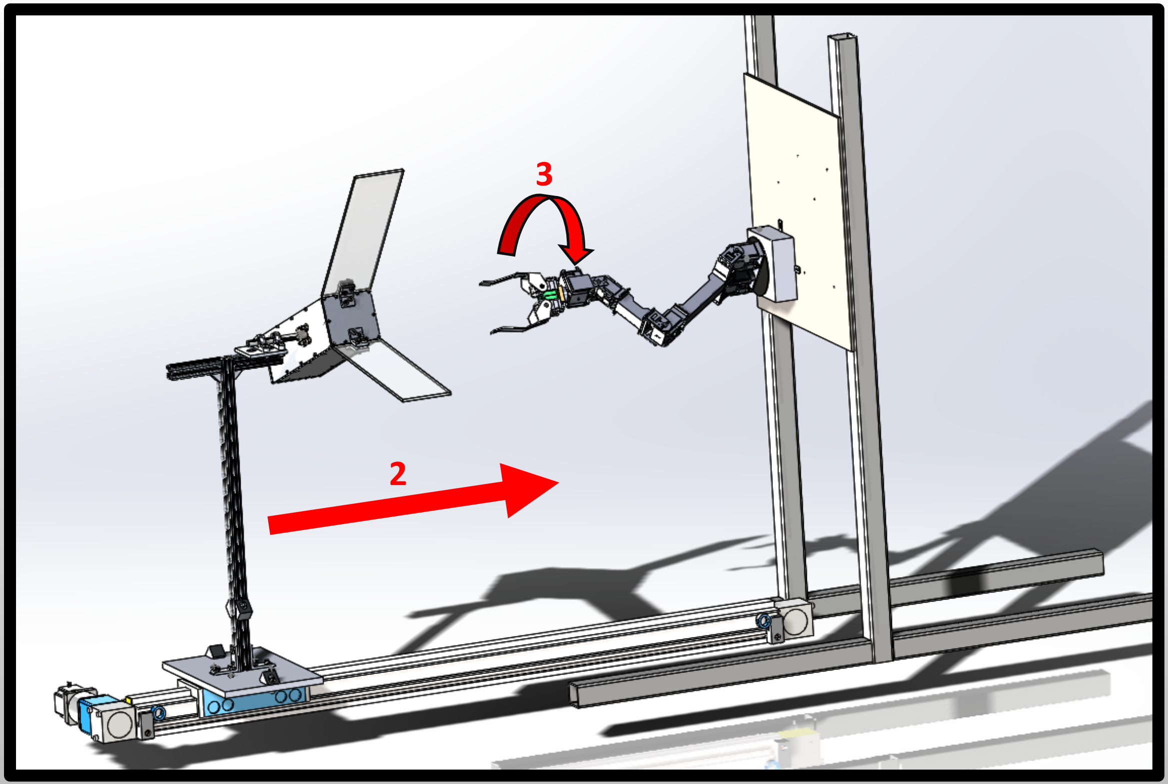
Test Bed CONOPS



<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



2.) Translate CubeSat

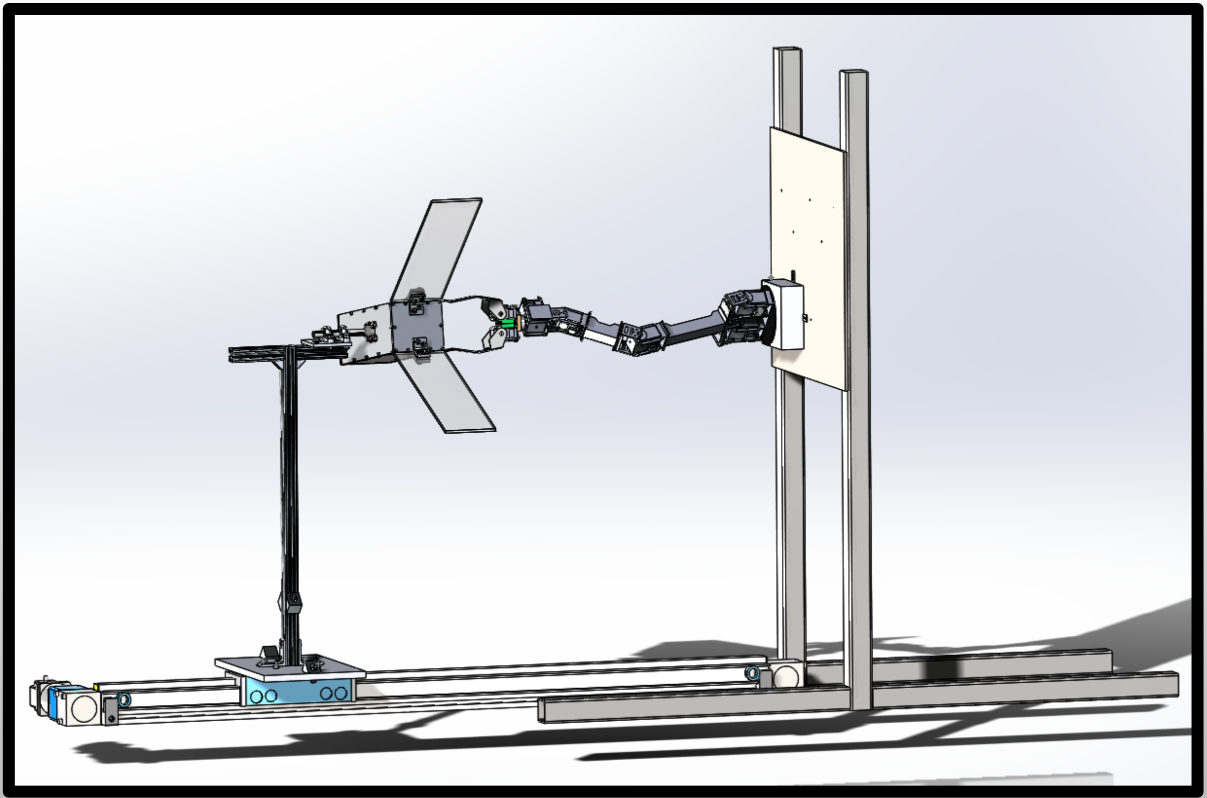
- This phase represents the closing of the relative position between the CubeSat and Capture device

- In space thrusters would be used to approach the CubeSat

3.) Wrist Rotation

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

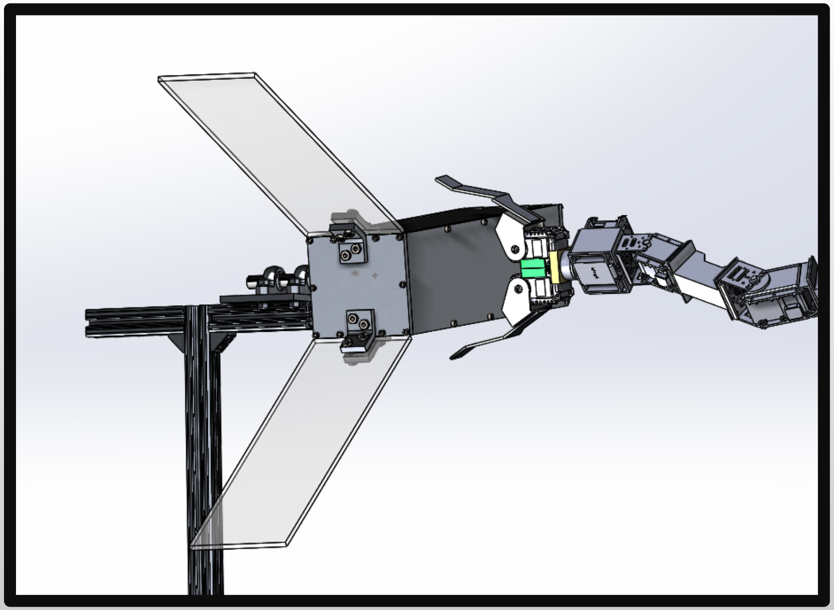
Test Bed CONOPS

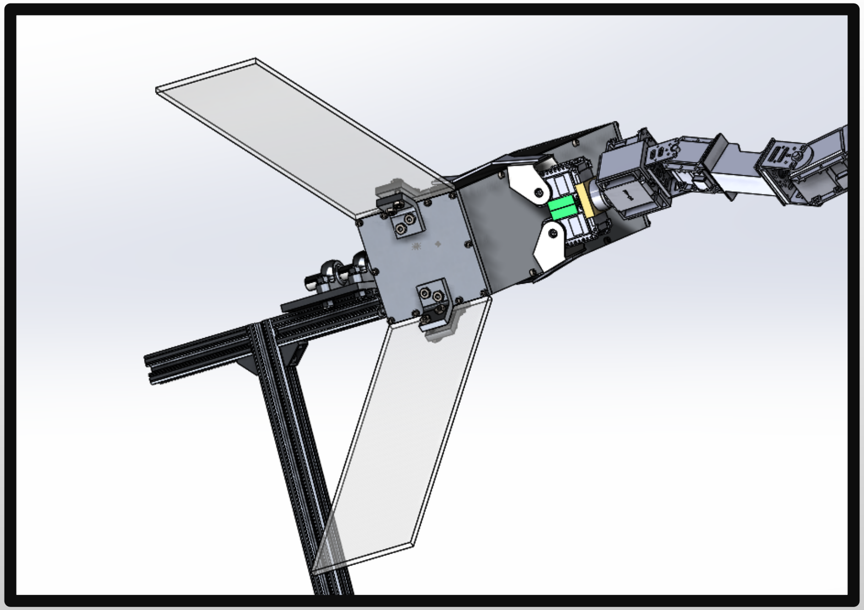


<u>4.) Extend Arm</u>

- 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

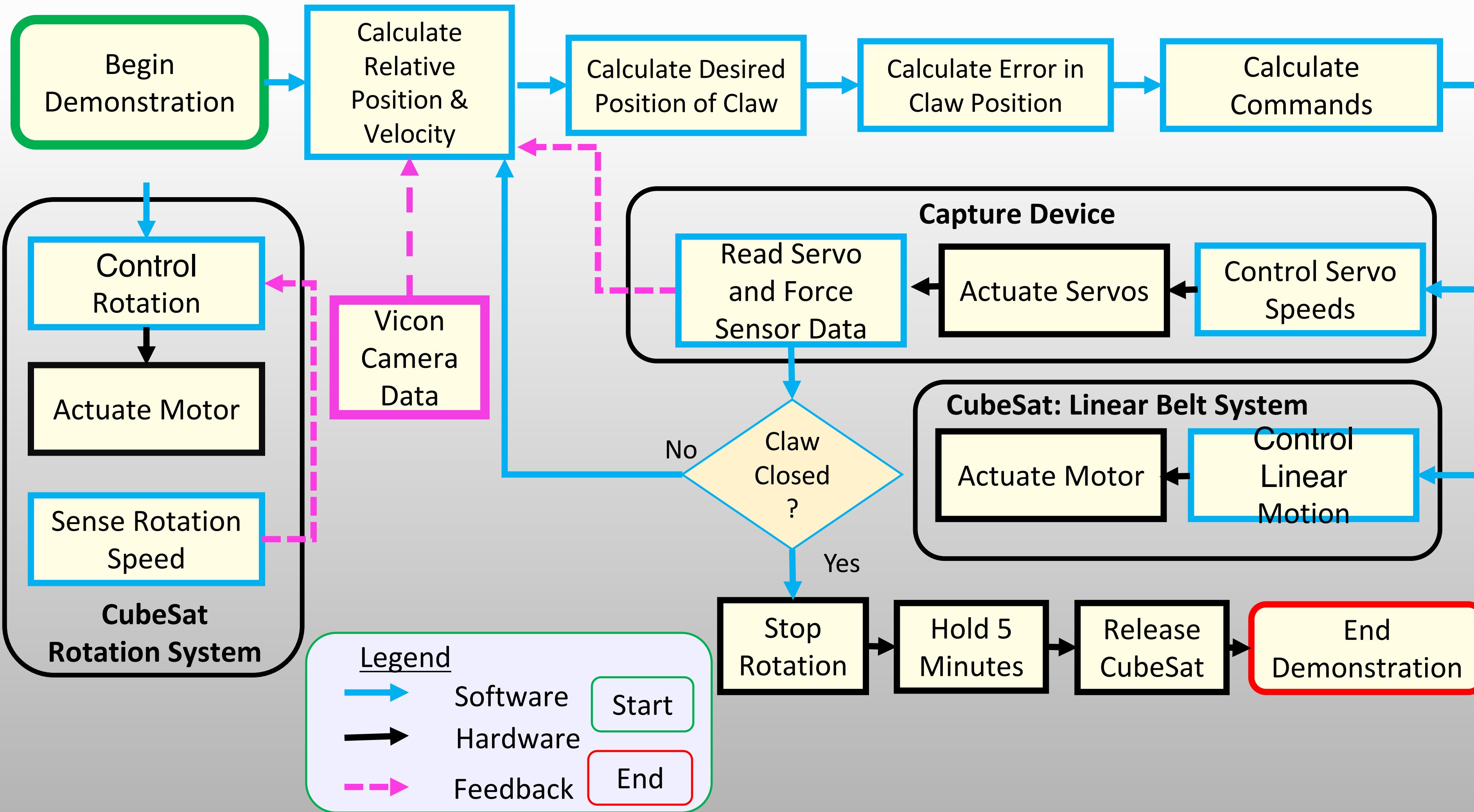




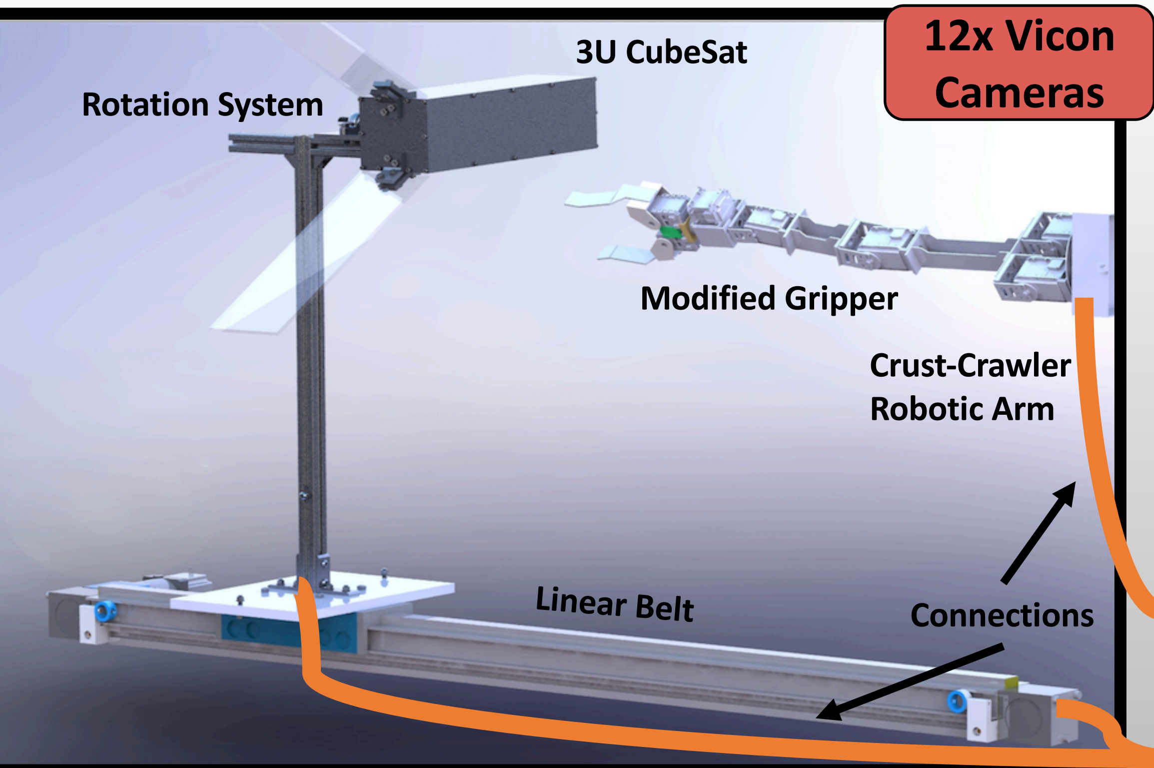
5.) Claw Closure

- 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.

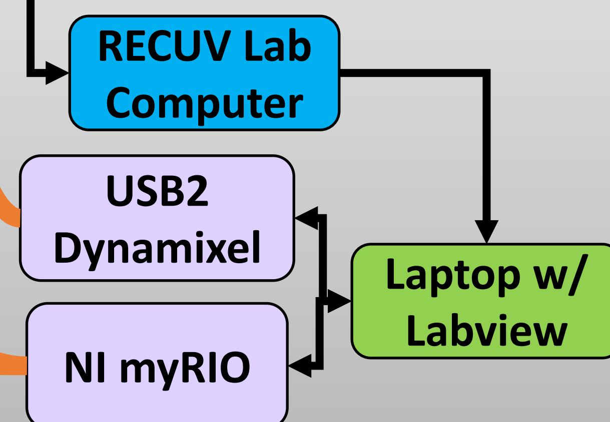
Functional Flow Diagram



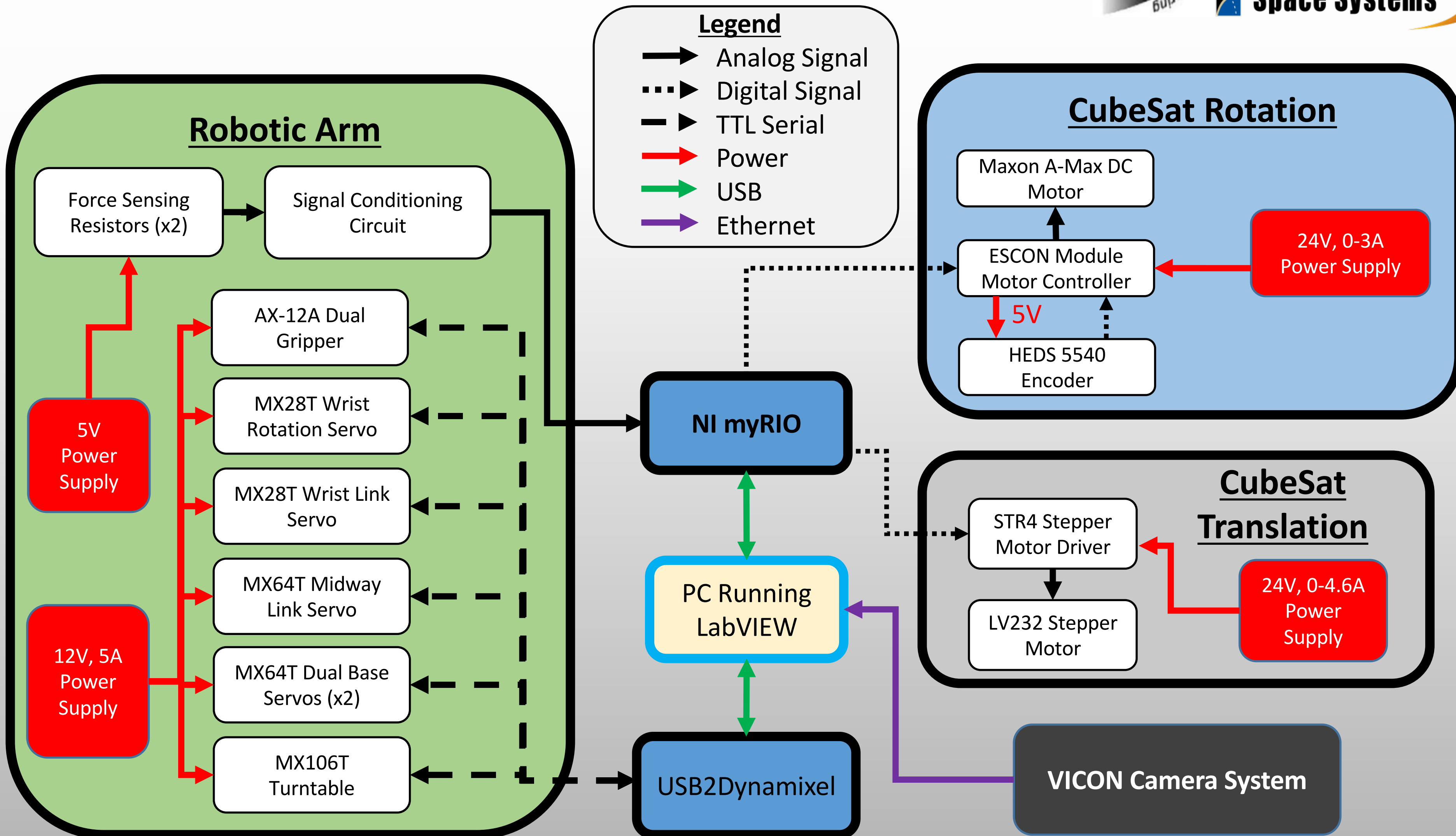
Design Solution



- Linear Belt for **CubeSat Translation**
- Rotation System for **CubeSat Spin**
- Vicon Cameras for **Feedback**
- LabView and NI myRIO for **CDHS**
- Arm and Gripper for **Capture**



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 MSR

- ❖ AOR Calculation Methodology
- ❖ Force Sensor Signal Conditioning Chip

❖ Schedule

On schedule overall

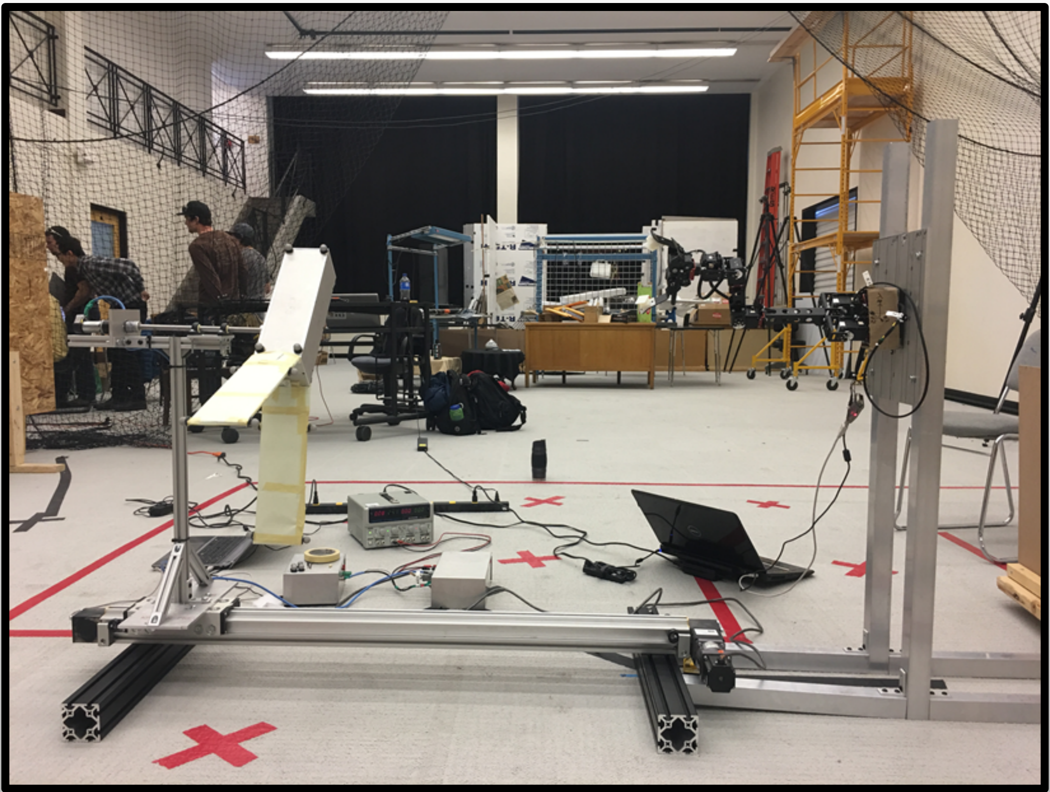
Behind on 1 task

→ FSR to Arm Integration

❖ Budget

$4460.64 Spent

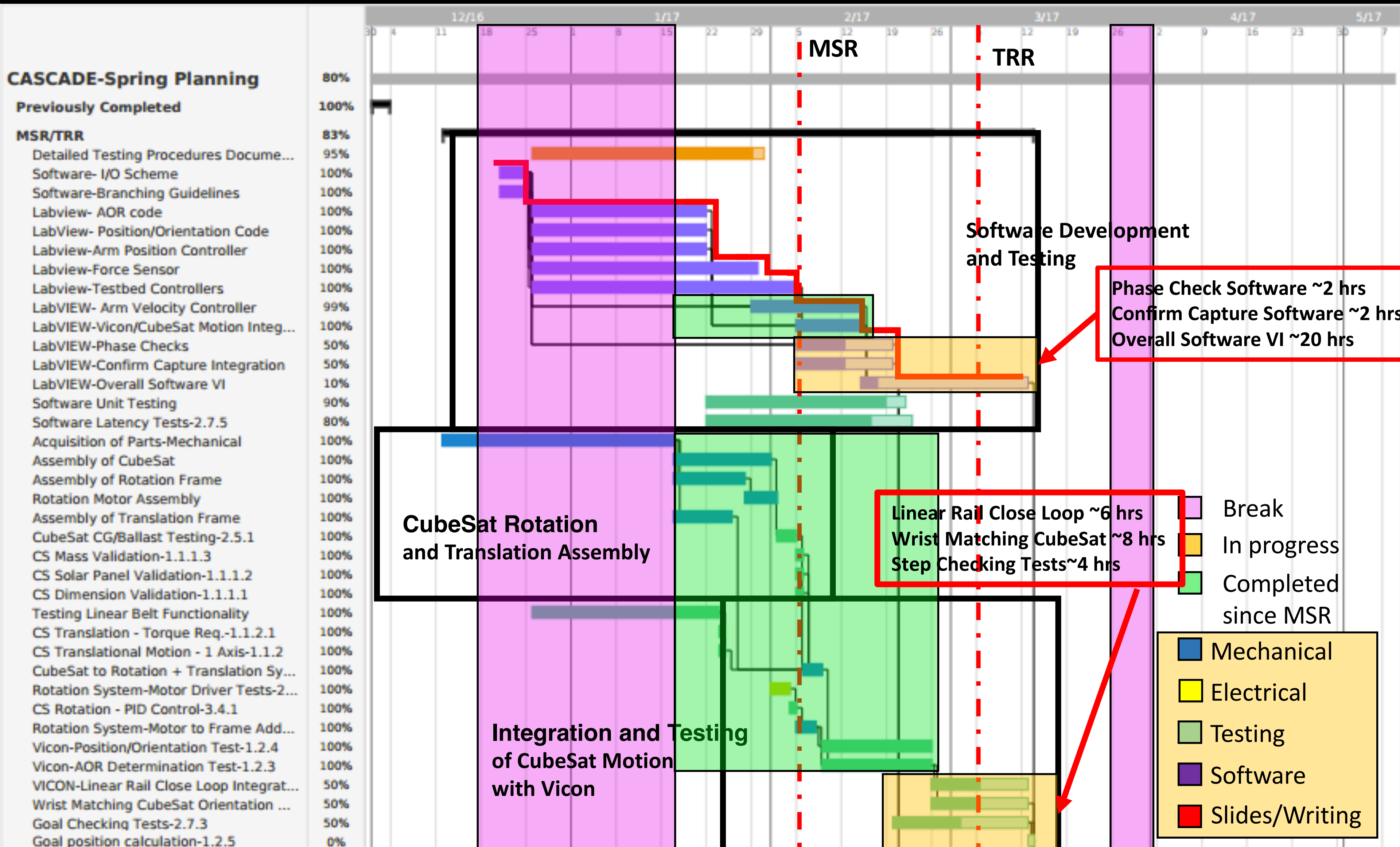
~11% Margin



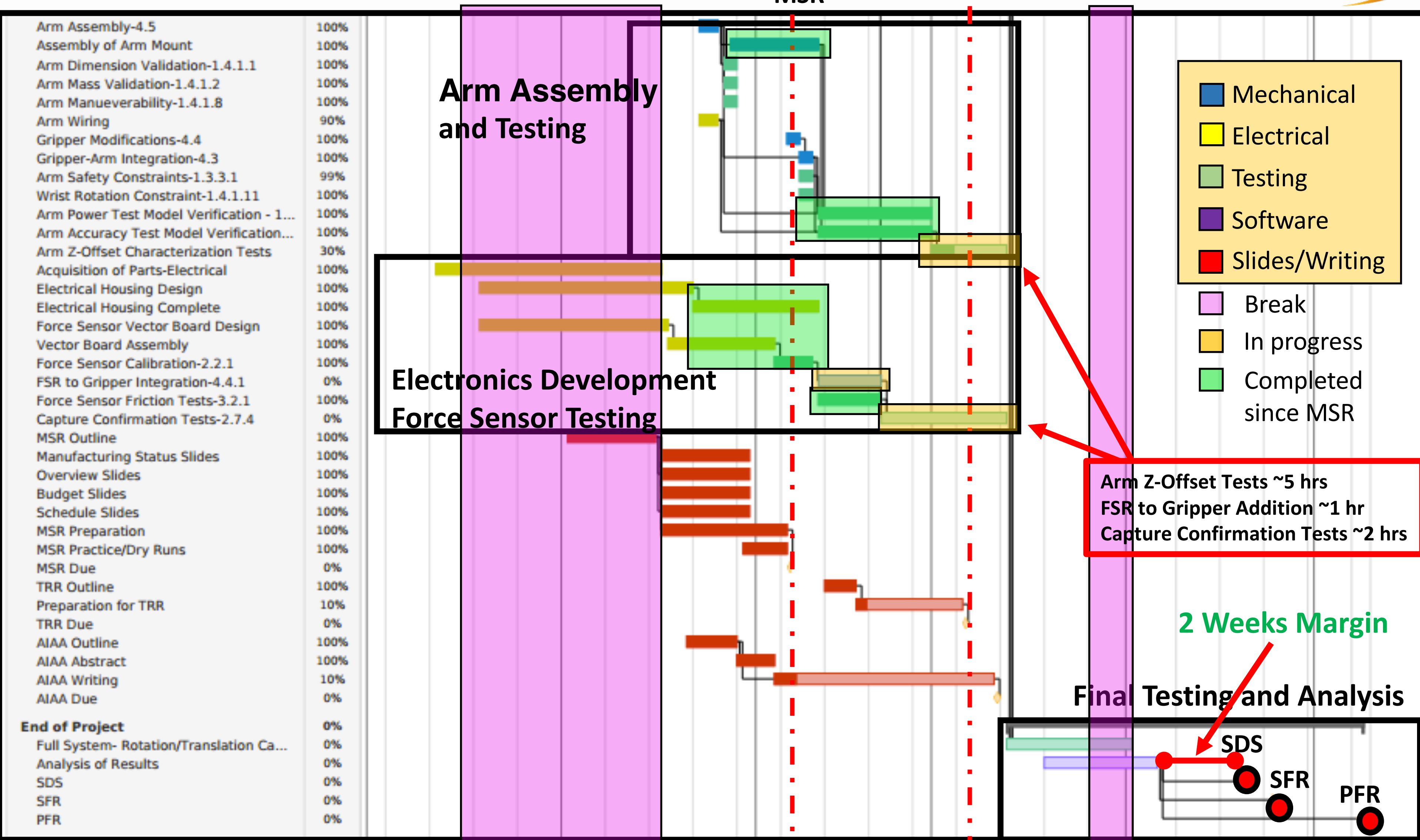
Test bed fully set up in the VICON Lab

Schedule

Schedule Overview



Schedule Overview



Summary of Tasks

Completed:

- Full Testbed Manufacturing
- Electrical Housing and wiring
- Force Sensor Calibration Tests
- AOR and Position Tests in VICON
- Arm Accuracy Testing in VICON

Behind Schedule:

- Force Sensor to Gripper Integration

Future Testing Needed…

- Arm Characterization Testing
- Confirm Capture Tests
- Closed Loop Linear Rail Tests
- Wrist Matching CubeSat Tests
- Step Checking Tests

Estimated Hours for in Progress Tasks: 50 hrs

Testing

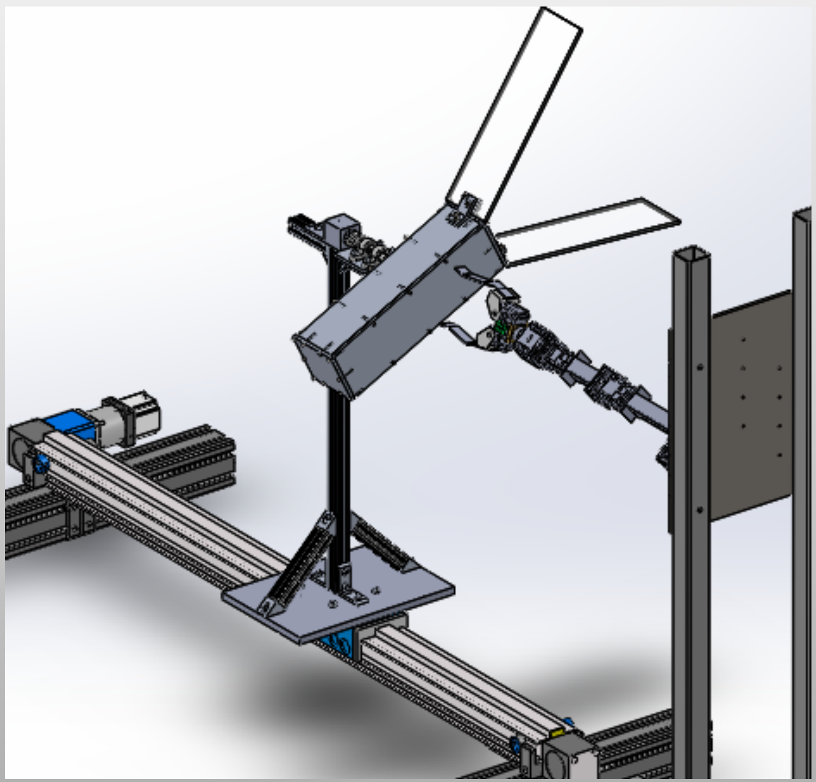
V & V Overview

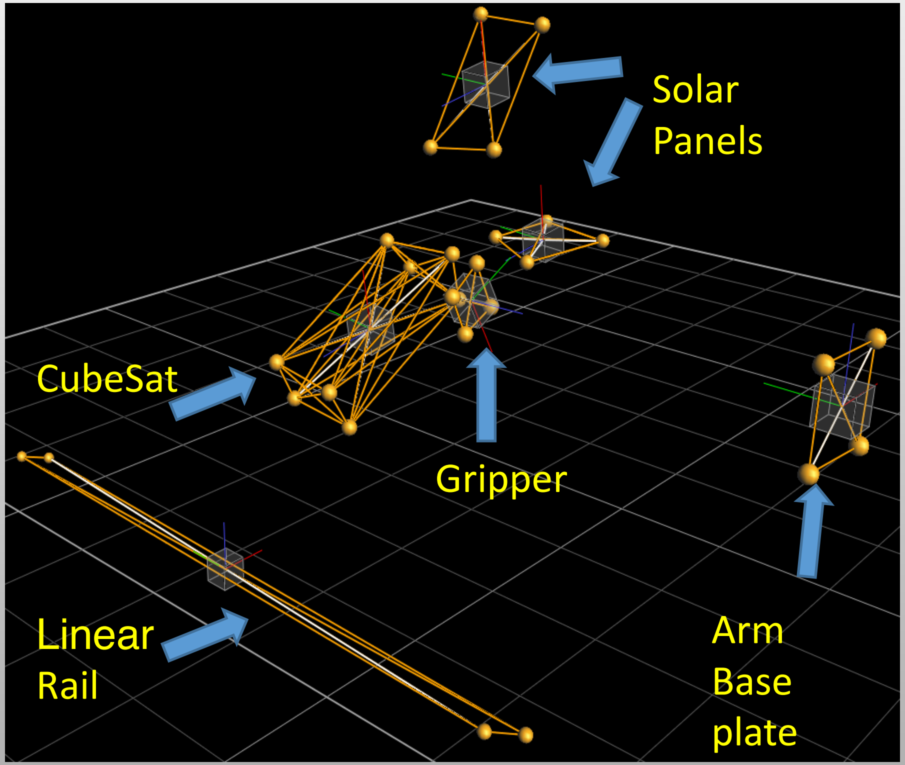
- **Major Initiatives**
  - Requirements Verification
    - Inspection
    - Test
    - Analysis
    - Demonstration
  - Model Validation
    - Arm Accuracy
    - AOR Determination
    - Phase Timing
  - Full System Integration

- **Anatomy of a Test Plan**
  - Identifier
  - Title
  - Objectives
  - Data Collection
  - Impact of Pass/Fail
  - Equipment List
  - Misc. Notes
  - Procedures
  - Results

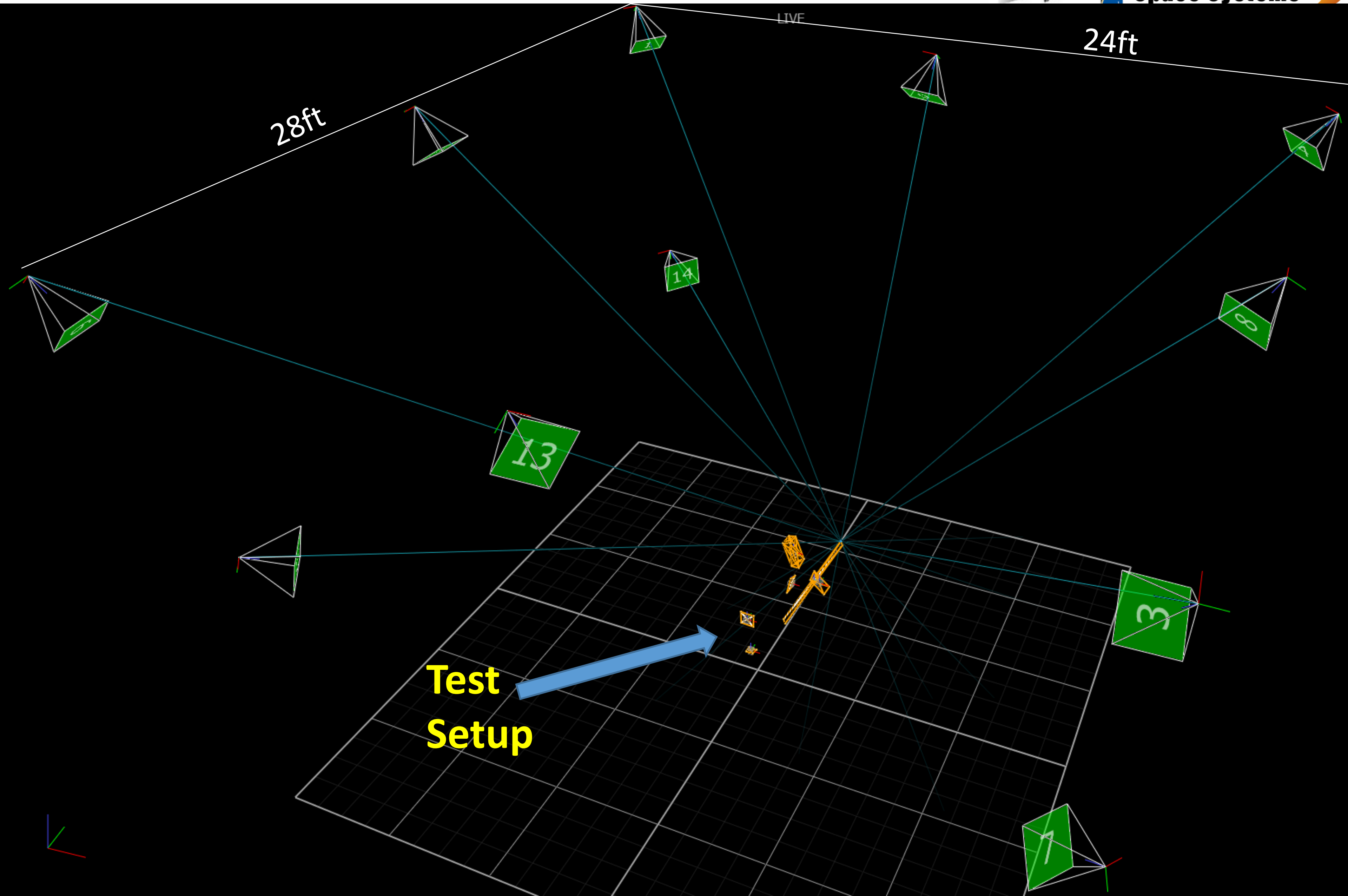
Test Fixtures and Facilities

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





VICON Camera Setup



Testing Overview

SIERRA NEVADA CORPORATION
Space Systems

Key
Functional Requirements
Model

Start: Feb 1 → Feb 15 → Mar 1 → Mar 15

Initial System Tests
- VICON
- Testbed human Commanded Control
- Arm Human Commanded Control

Subsystem Tests
- AOR Determination
- Gripper
- Control Characterization

Closed Loop Tests
- Phase Control
- Capture Confirmation
- Arm Control

Full Integration Tests
- Trans./Rot. Capture

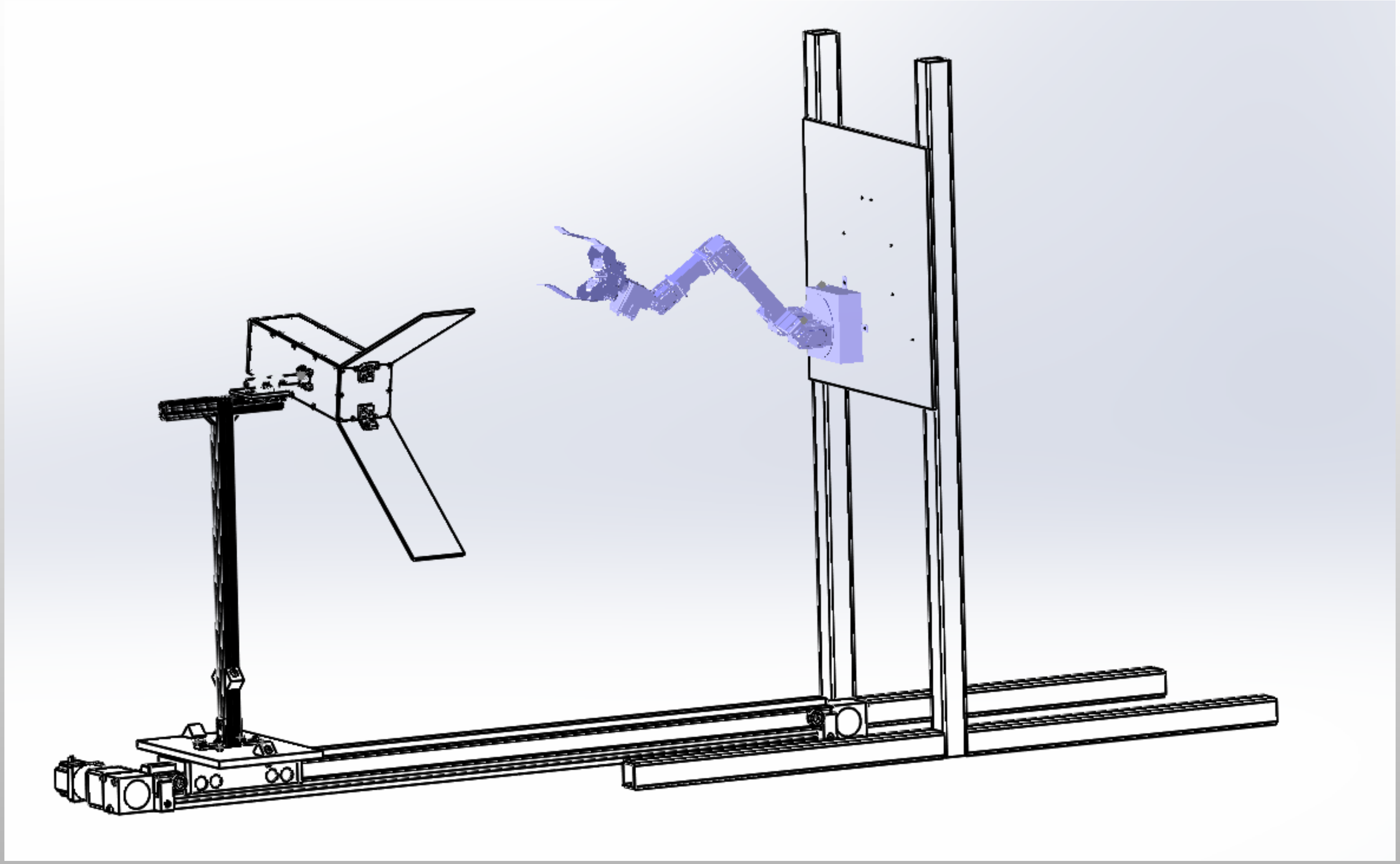
Requirement Verification Matrix

Req. #	Type	Requirement	Verification Method
1.0	FR	The CubeSat Recovery System Testbed (CRST) shall demonstrate the successful capture of a physical CubeSat model.	D
1.1	FR	The CRST shall demonstrate the motion of a CubeSat analogue during the demonstration.	D
1.1.1	DR	The CubeSat analogue shall include a physical model of a 3U CubeSat.	I
1.1.1.1	DR	The physical model of a 3U CubeSat shall have dimensions as specified in Figure 1.	I
1.1.1.2	DR	The physical model of a 3U CubeSat shall include at minimum one significant protrusion to representing solar panel(s).	I
1.1.1.3	DR	The physical model of a 3U CubeSat shall have a mass of 3 ± 0.3 kg.	I
1.1.2	DR	The CubeSat analogue shall allow for translational motion about one axis.	I
1.1.2.1	DDR	The CubeSat analogue shall employ a minimum torque of 0.51 Nm to translate the CubeSat model.	T
1.1.3	DR	The CubeSat analogue shall allow for rotational motion about one axis.	I
1.1.3.1	DR	The axis of rotation of the CubeSat model shall be about its major axis at 3 ± 0.3 deg/s.	T
1.1.3.2	DDR	The CubeSat analogue shall employ a minimum torque of 0.14 Nm to rotate the CubeSat model.	T
1.2	FR	The CRST shall determine the relative position and attitude between the CubeSat and capture device during the demonstration.	T
1.2.1	DR	The CRST shall gather positional data from each control point(servo) on the capture device.	A
1.2.2	DR	The CRST shall communicate with a vision system to sense the initial conditions and motion of the CubeSat.	T
1.2.3	DR	The CRST shall determine the axis of rotation of the CubeSat model.	T
1.2.4	DR	The CRST shall determine the relative linear position of the CubeSat model.	T
1.2.5	DR	The CRST shall calculate the desired capture location and orientation.	T
1.3	FR	The CRST shall command the motion of the capture device during the demonstration.	T
1.3.1	DR	The commands sent for capture device motion shall be within control point(servo) performance limits.	T
1.3.1.1	DDR	The CRST shall send commands to the capture device at a minimum rate of 10.5 Hz.	T
1.3.1.2	DDR	The CRST shall run its control loops at a minimum rate of 13.4 Hz.	T
1.3.2	DR	The end effector shall align with the CubeSat's spin axis, and remain aligned until the end of the capture sequence.	D
1.3.3	DR	The capture device shall not collide with the supporting structure or itself.	D
1.3.3.1	DR	The capture device shall be constrained to performed along the ranges specified in Table 1.	D

Requirement Verification Matrix – cont.

Req. #	Type	Requirement	Verification Method
1.4	FR	The CRST shall execute capture of the physical CubeSat model autonomously during the demonstration.	T
1.4.1	DR	The CRST shall include a physical capture device used to capture the physical CubeSat model.	I
1.4.1.1	DR	The capture device shall occupy no more volume than the payload bay shown in Figure 2.	I
1.4.1.2	DR	The capture device shall have a mass budget of 15kg.	I
1.4.1.3	DR	The capture device shall have an average power of no more than 100W.	T
1.4.1.4	DR	The capture device shall have a peak power of no more than 168W.	T
1.4.1.5	DR	The capture device shall have a peak current draw of no more than 10A.	T
1.4.1.6	DR	The capture device shall have a peak voltage draw of no more than 28V ± 6V unregulated.	T
1.4.1.7	DDR	The end effector of the capture device shall have a minimum grip strength of 8.9 N.	T
1.4.1.8	DR	The end effector of the capture device shall be capable of movement in 3D space.	D
1.4.1.9	DR	The capture device shall be able to release from the CubeSat after capture without human intervention.	I
1.4.1.10	DR	The capture device shall be able to confirm the capture of the CubeSat with tactile feedback without human intervention.	T
1.4.2	DR	The demonstration shall begin at a minimum distance of 1m between the physical CubeSat model and the capture device.	I
1.4.3	DR	The CRST shall capture the CubeSat with the capture device in less than 30 minutes.	D
1.4.4	DR	The CRST shall capture the CubeSat without visible damage to the CubeSat nor the capture device.	I
1.4.5	DR	The CRST shall allow for five repeated demonstrations.	D
1.4.6	DR	The CRST shall hold the CubeSat with the capture device for a minimum of five minutes after capture confirmation.	I
1.4.7	DR	The demonstration shall begin at a measurable horizontal distance offset between the base of the capture device and the translation axis of the CubeSat model.	I
1.4.8	DR	The demonstration shall begin at a measurable vertical distance offset between the base of the capture device and the translation axis of the CubeSat model.	I

Capture Device Testing



Arm Control Accuracy Test

Objectives

- Ensure that robotic arm can be commanded within allowable position error during phases 1 and 4 of capture sequence
- Validate robotic arm control model

Key Requirements

- FR 1.3 – CRST shall command the motion of the capture device during the demonstration
- DDR 1.3.1.1 – CRST shall send commands to capture device at a minimum of 10.5 Hz

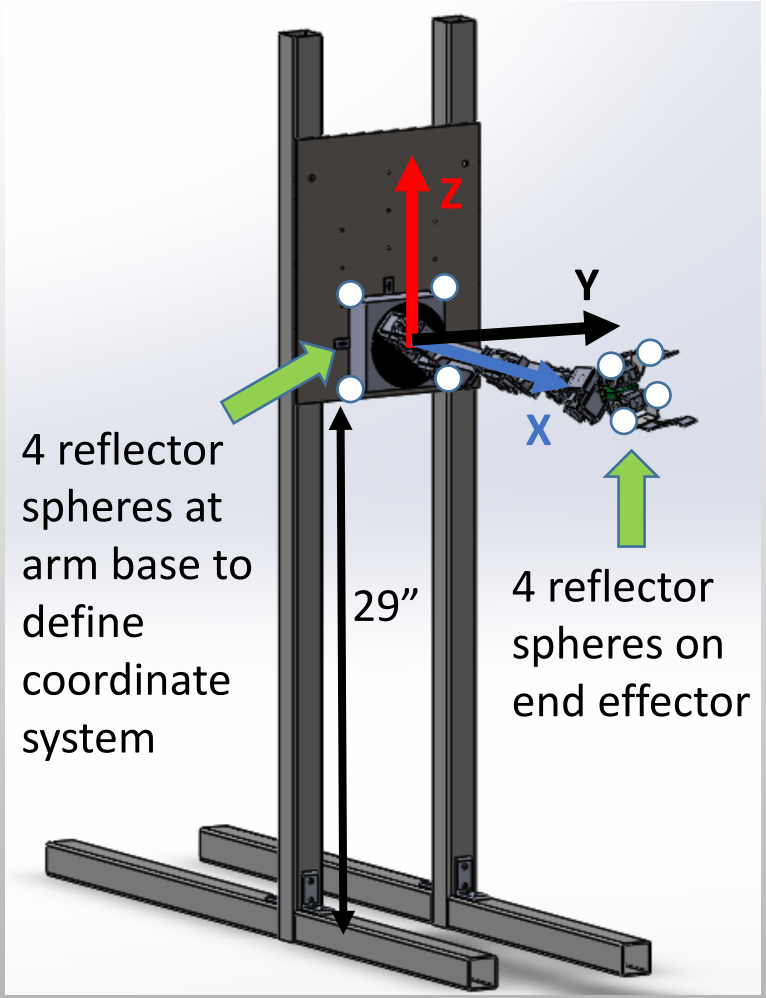
How it Reduces Risk

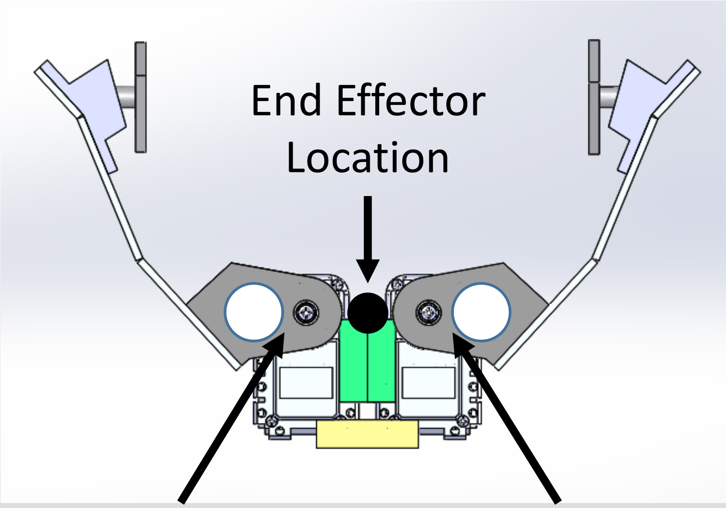
- Shows that the arm can move to a commanded position within error limits that will keep it from crashing into CubeSat or itself

Associated Model: Arm Control Model

Arm Accuracy Test Setup

Location: RECUV Motion Capture Lab

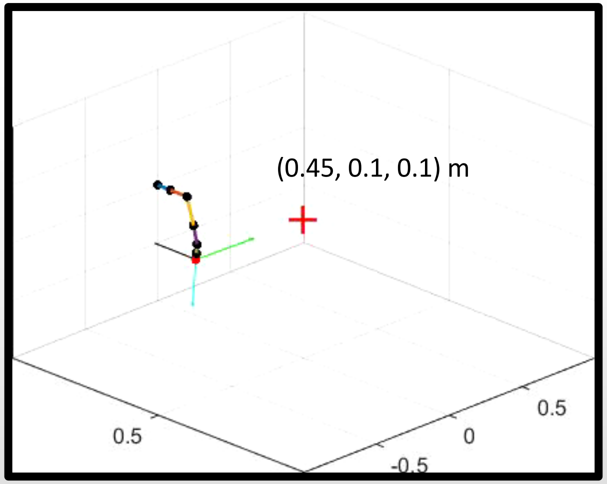


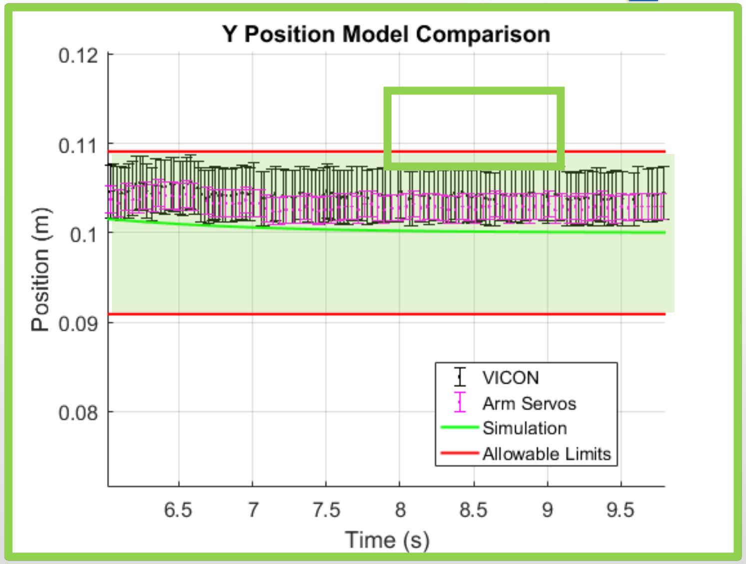


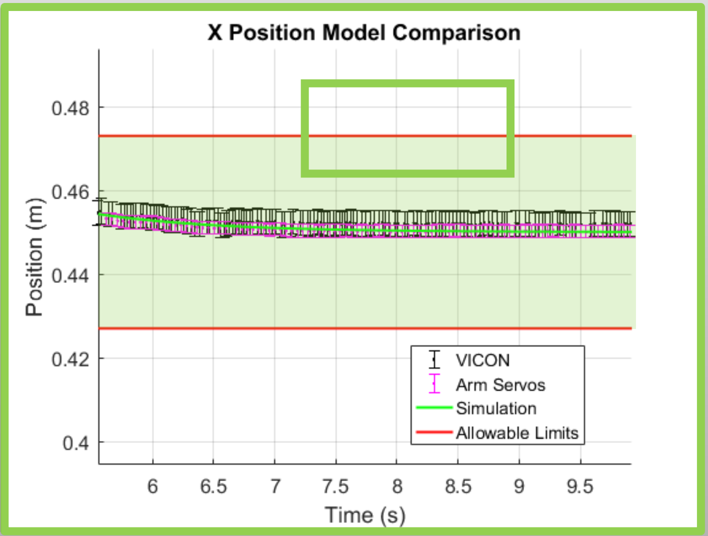
Spheres placed so that screws were used as reference between model and physical testing

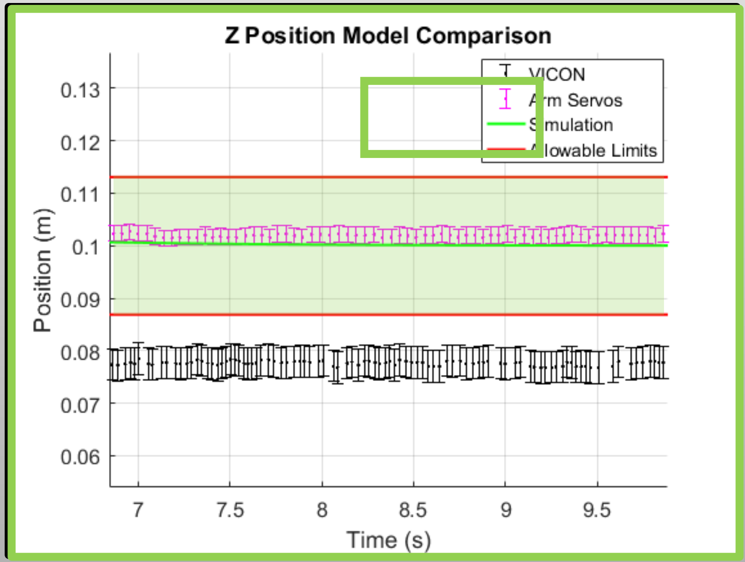
Data Sources	Sampling Rate	Data Collected
VICON Camera System	~85 Hz	End effector position: (X,Y,Z)
Arm Joint Angle Forward Kinematics	~18 Hz	

Arm Accuracy Test: Phase 1 Results









Arm Control Characterizing

Cause of Error in Z Position

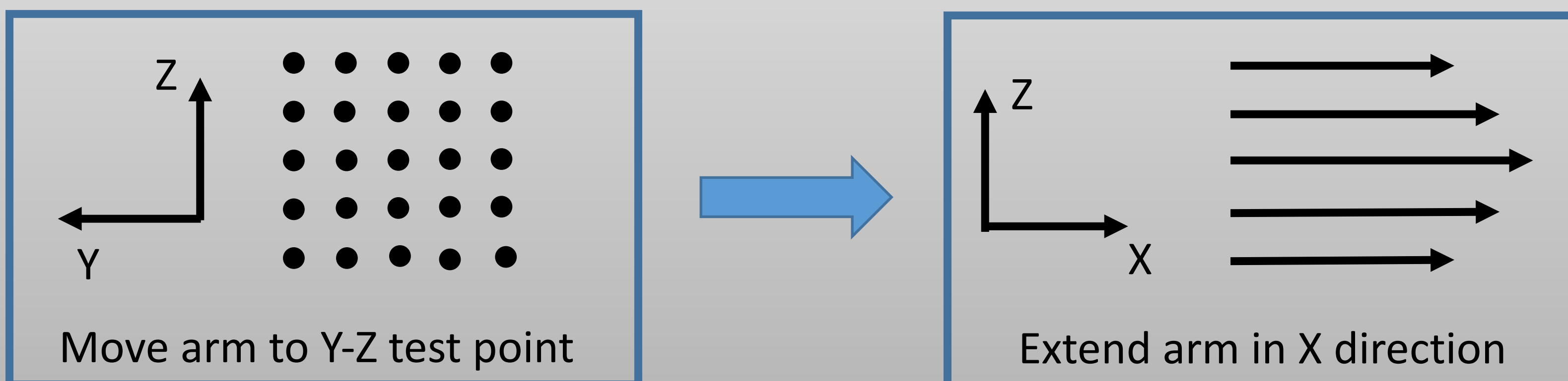
- Force of gravity acting on arm is causing slop in the turntable and joint servos, forcing the end effector to droop down in the Z direction
- Forward kinematics does not account for this, so the arm “thinks” it is in the right place

Mitigation Plan

- Characterize Z position error as a function of (X,Y,Z) position through empirical testing
- Use this characterization to offset arm control commands in software

Test Procedure

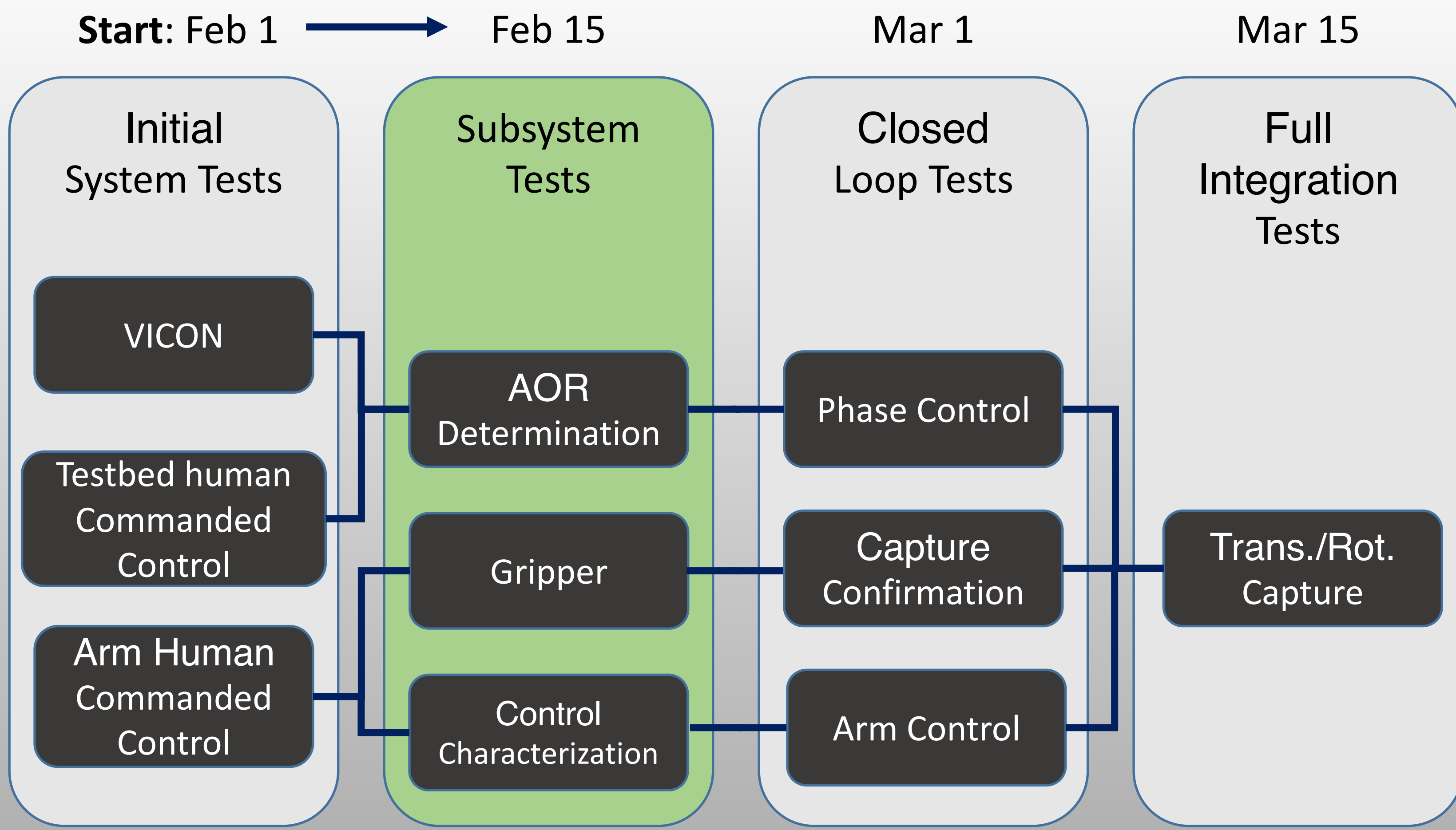
- Same setup and data collection as arm accuracy test using VICON
- Test end effector position while extending along X axis at varying Y and Z positions



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

Subsystem Testing

Objective: Validate subsystems and characterize control of arm



CubeSat AOR Position

Objectives

1. Verify CubeSat AOR position determination algorithm
   - Functionality
   - Calculation Completion Time
   - Characterize error and standard deviation
2. Characterize behaviors of VICON (dynamic noise, unexpected behaviors)

Key Requirements

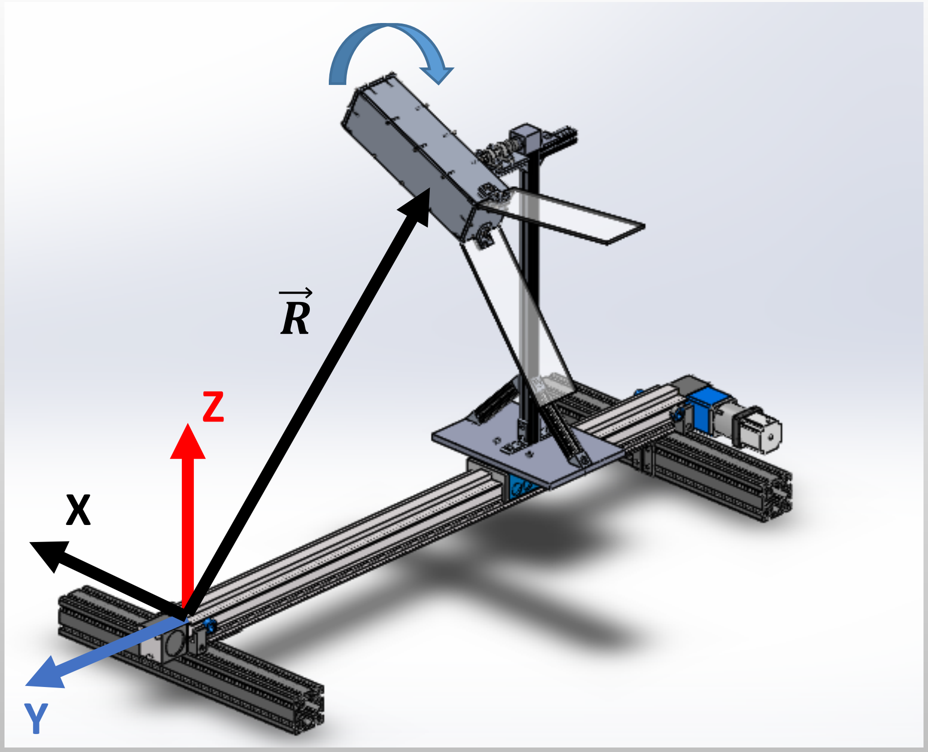
- FR 1.2 – The CRST shall determine the relative position and attitude between the CubeSat and capture device during the demonstration.
- DR 1.2.1 - The CRST shall gather positional data from each control point on the CubeSat.
- DR 1.2.4 – The CRST shall determine the relative linear position of the CubeSat model.

How it Reduces Risk

- Proves that the algorithm calculates an accurate and safe prediction of the CubeSat's position for capture during phases 1 and 4

VICON AOR Position Setup

Location: RECUV Motion Capture Lab
Duration: 2 Hour Test



Objective: Verify determination algorithm
- Functionality
- Completion Time (x1)
- Characterize error & standard deviation

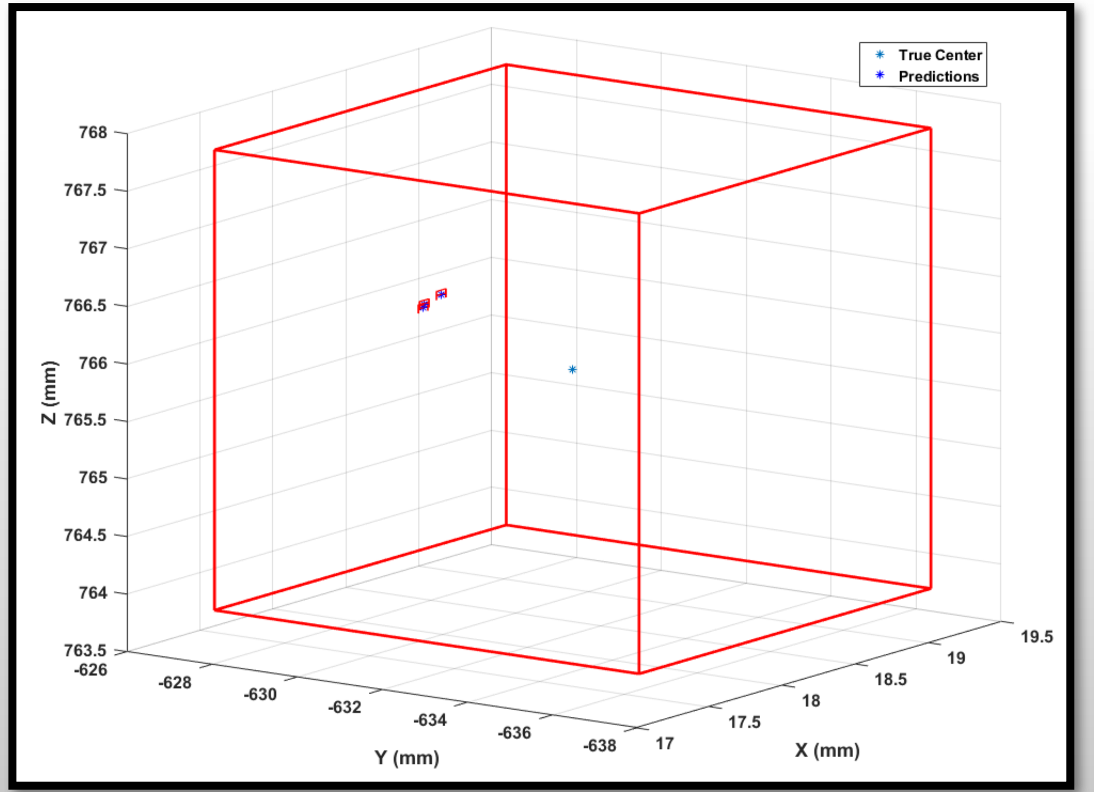
Assumption: Position is the CubeSat's C.G.
Stationary CubeSat

Data to be Collected	Data Source
Determined Position (x,y,z)	VICON
True Position (x,y,z)	VICON

Equipment: Rotation Testbed, 20 IR spheres

CubeSat Translation Testing

VICON Position Results - Calculations



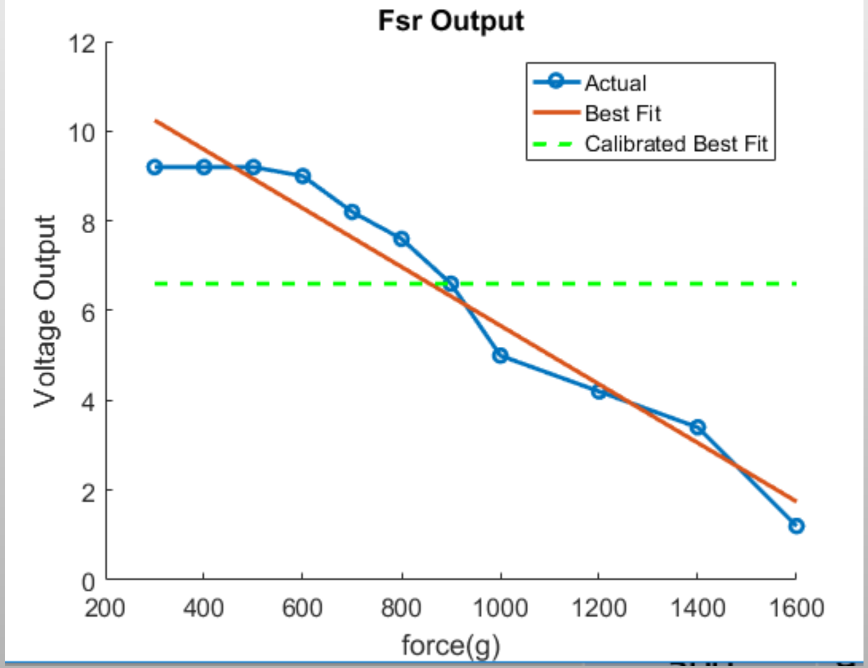
Three Predictions of CubeSat's Position

1. **All predictions contain an error bound**
2. **All predictions are within the maximum error tolerance**

Maximum Differences			
	X (mm)	Y (mm)	Z (mm)
$\Delta x, y, z$	**0.37**	**2.25**	**0.62**
Error Margin	62.94 %	55.00 %	68.96%

Force Sensor Calibration Test

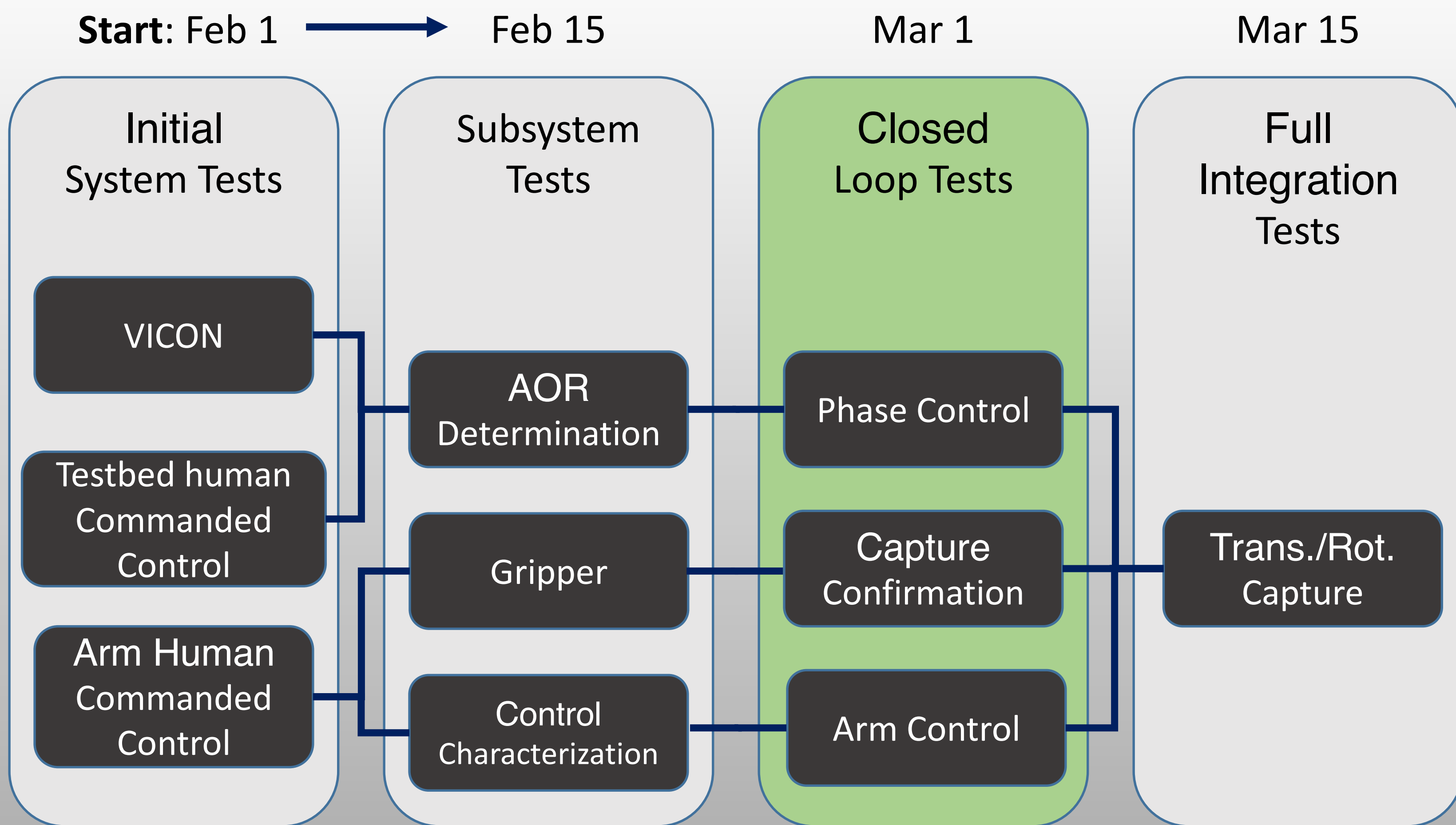
- *As Seen By the Oscilloscope scope*
- $\mathbf{Vout} = -\mathbf{0.0065} * \boldsymbol{force} + \mathbf{12.20}$
- *When Calibrated 1.2V = 9.2V and 9.2 = 0V giving us a range of 8V*
- Coefficient of Variation = 0.94



Force (grams)	Vo
300	9.2
400	9.2
500	9.2
600	9.0
700	8.2
800	7.6
900	**6.6**
1000	5
1200	4.2
1400	3.4
1600	1.2

Closed-loop Testing

Objective: Establish closed-loop control



Capture Confirmation Test

Objectives

- Use the calculated force required to act as the threshold for shutdown of the gripper servos
- Confirm that servos stop when reaching the force threshold at aligned and offset positions
- Confirm that the gripper has a 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 1.4.6 - The CRST shall hold the CubeSat with the capture device for a minimum of five minutes after capture confirmation

How it Reduces Risk

- Testing the shutoff of the servos at the appropriate force and the grip on the CubeSat ensures that the capture will not result in damage to the capture device and that the capture device will successfully maintain a hold on the CubeSat

Associated Model: Minimum Grip Force

Capture Confirmation Test: Setup

Location: RECUV Motion Capture Lab

Testing Procedure:

1.

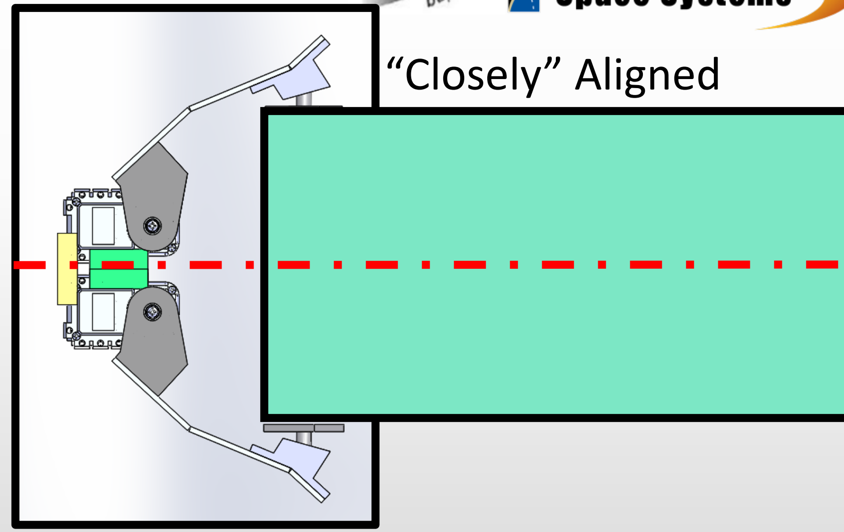
- Line up the gripper to be as close to the center of the CubeSat as possible
- Ensure that the servos shut off when the appropriate force is reaches by reading the force sensor data

2.

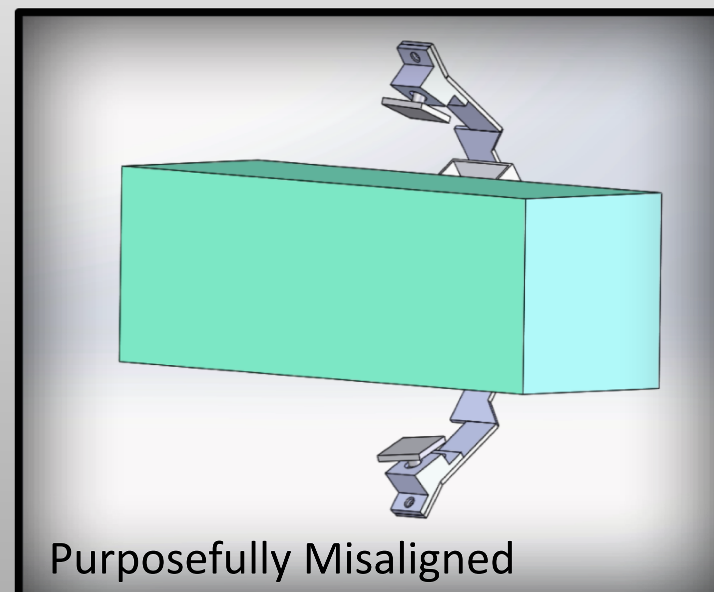
- Test with the gripper purposefully misaligned and show that the servos shut off at different times

Data Sources	Sampling Rate	Data Collected
LabVIEW	~ 100 Hz	Force Generated Voltage (V)
Force Sensor		
Dynamixel Gripper Servos	~28 Hz	Joint Angle Torque

1.)

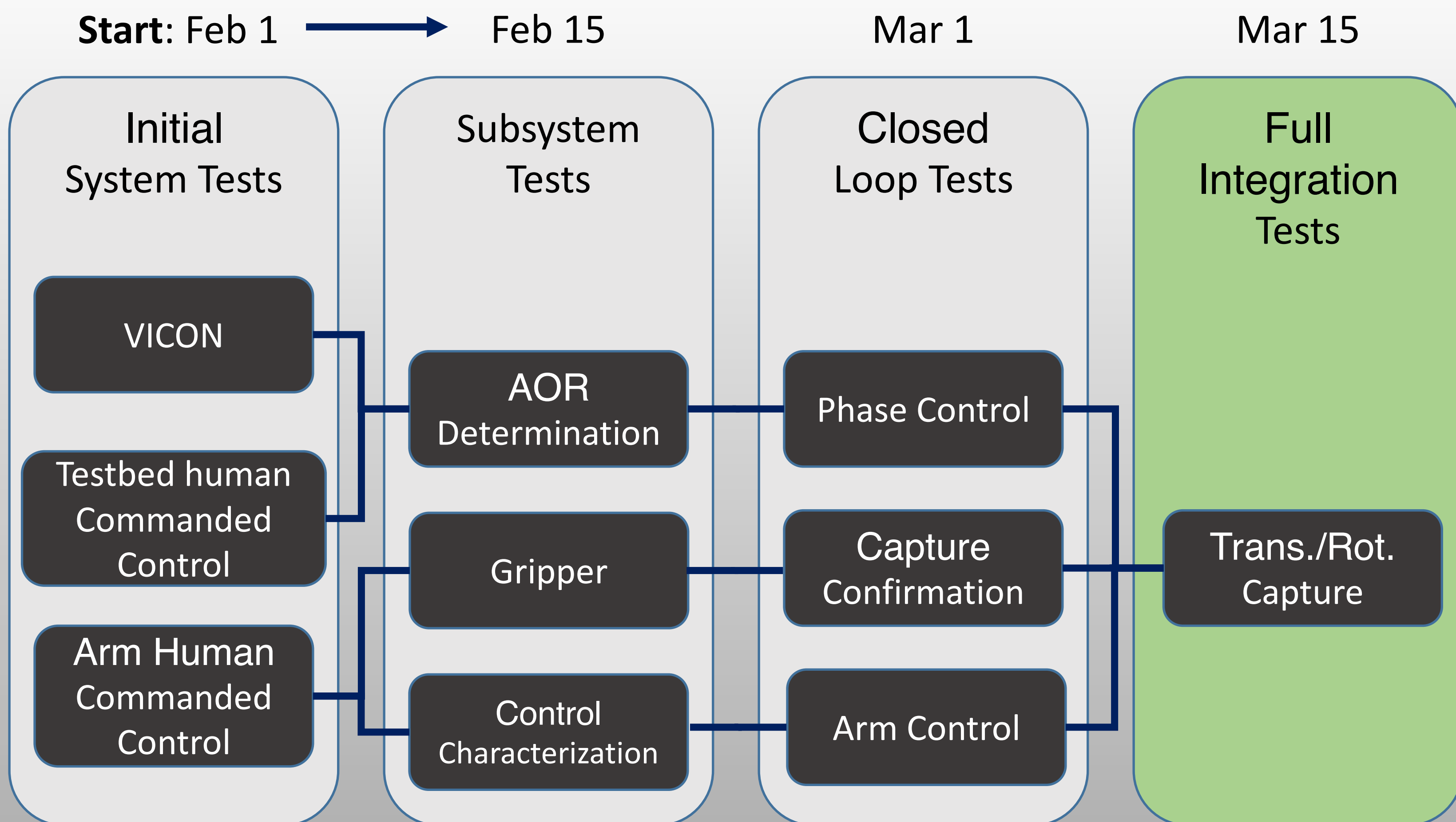


2.)



Full Integration Testing

Objective: Integration leading up to final demonstration – **Highest level of success**



Phase Checks/ Commands Testing

Objectives:
- Verify functionality of autonomous algorithm
- Verify each loop runs at least the required rate.

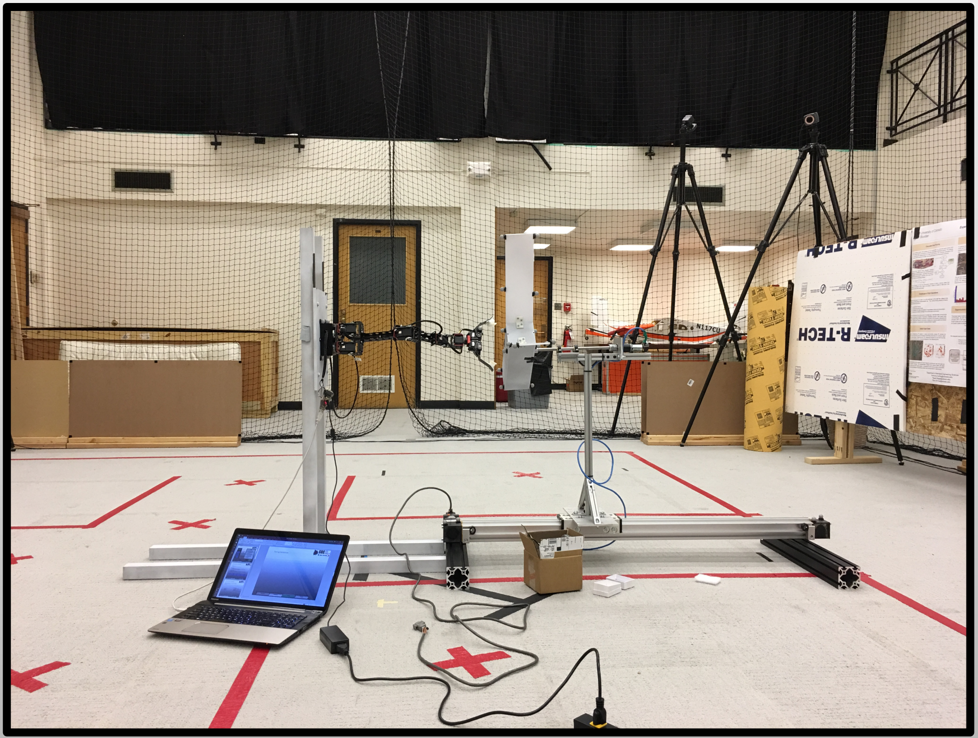
Requirements:
- 1.4--The CRST shall execute capture of the physical CubeSat model autonomously during the demonstration.
- 1.3.1.1: CRST shall send commands to the capture device at a minimum rate of 10.5 Hz
- 1.3.1.2 CRST shall run its control loops at a minimum rate of 13.4 Hz

How it Reduces Risk
- Validates that each step of capture sequence can be performed autonomously
- Increases confidence for final integration

Step 1: Align with AOR → Step 2: Translate CubeSat → Step 3: Spin End Effector → Step 4: Extend to Grab Position → Step 5: Close End Effector

Phase Checks/ Commands

Objectives: Verify functionality of autonomous algorithm
Location: RECUV vision lab
Duration: 8 Hr



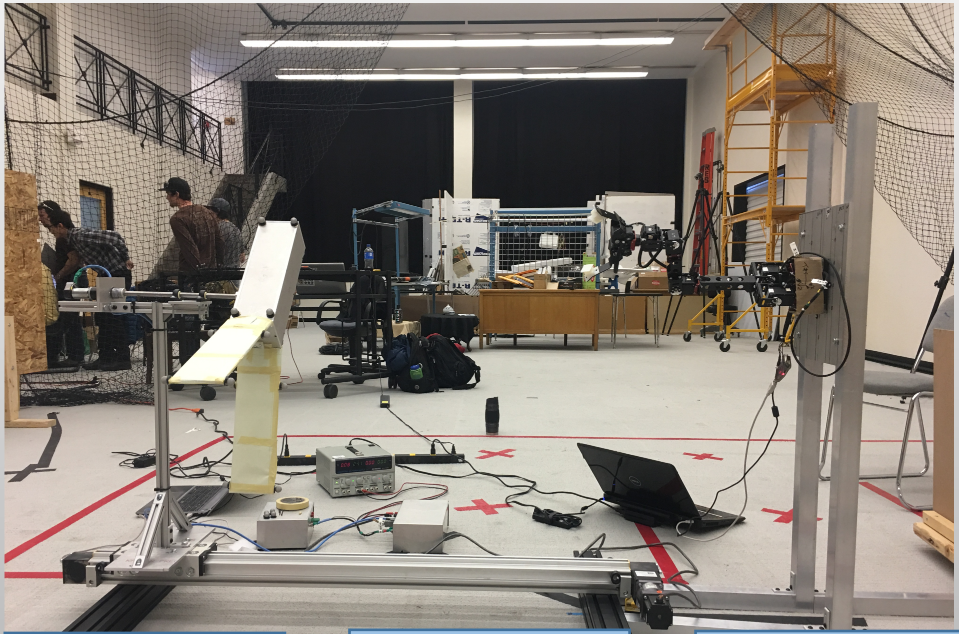
Test Procedure:

1. Start program for phase 1
2. Once phase 1 completes, compare to phase check results(i.e. desired command vs actual result)
3. Check loop rates
4. Continue for remaining 4 phases.

Loop	Predicted Rate	Requirement
VICON	100 Hz	10.5 Hz
Arm	28 Hz	13.4 Hz
TestBed	~100 Hz	13.4 Hz

Final Test

Objective: Verify integration of subsystems for the final Demonstration
Requirements: 1.0--The CubeSat Recovery System Testbed (CRST) shall demonstrate the successful capture of a physical CubeSat model.
Location: VICON Lab



Procedure:

1. Calibration of VICON system
2. Setup Testbed
3. Run the Demonstration

Data Collection:

- CubeSat Position / Orientation
- Arm Position
- Force Sensor Measured Voltage

Step 1: Align with AOR → Step 2: Translate CubeSat → Step 3: Spin End Effector → Step 4: Extend to Grab Position → Step 5: Close End Effector

Budget

Budget Update

Additional Procurements since MSR:

Extra Force Sensing Resistors: Delivered

3D Printed Ball Joints and Hinges: Delivered

Vicon Reflective Spheres: Delivered

Estimating Spending at MSR: $4,437.77
Total Spending: $4,460.64 (11% Margin at TRR)

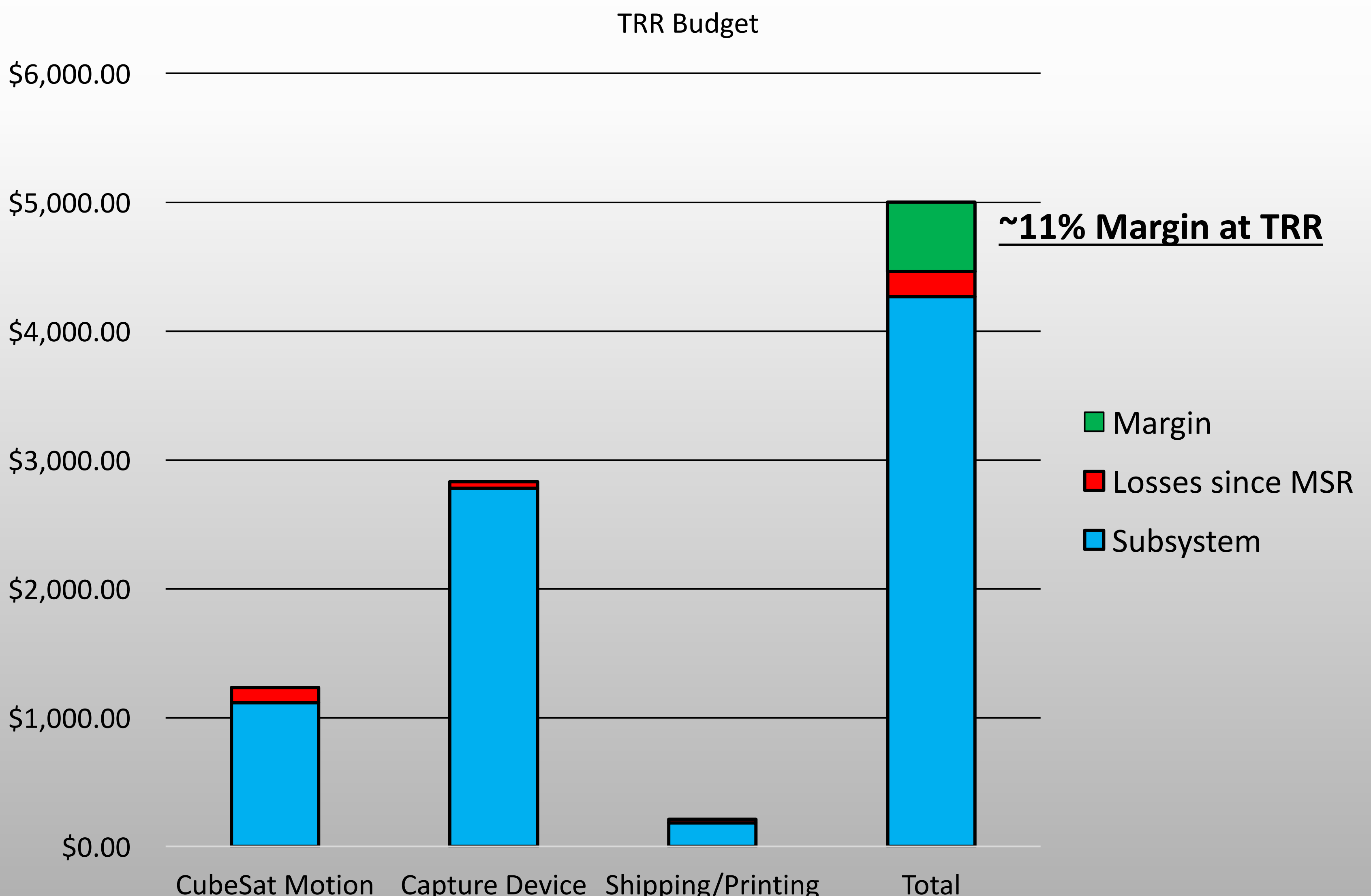
Future Procurements

$173.85 allotted for printing

Updated Budget Estimate

$4634.49 → **~7.3% End of Year Margin**

Budget Status



Conclusion

Thanks for your time!

Acknowledgments:

Our Customer

Henry “Lad” Curtis

Sierra Nevada Corporation

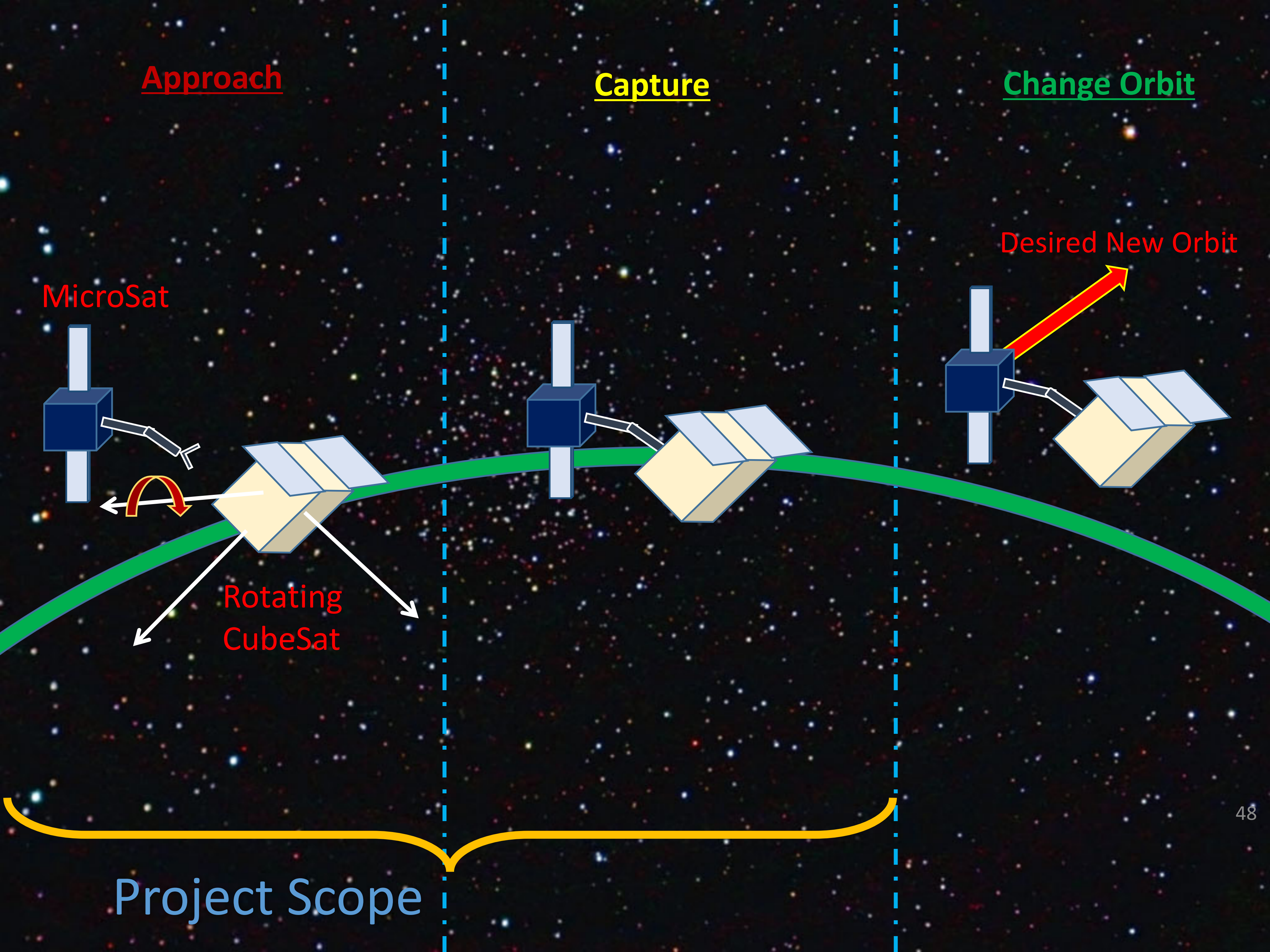
Faculty Advisor: Jelliffe Jackson

Robotics Help: Nikolaus Correll

CU Faculty and Staff

Budget Status

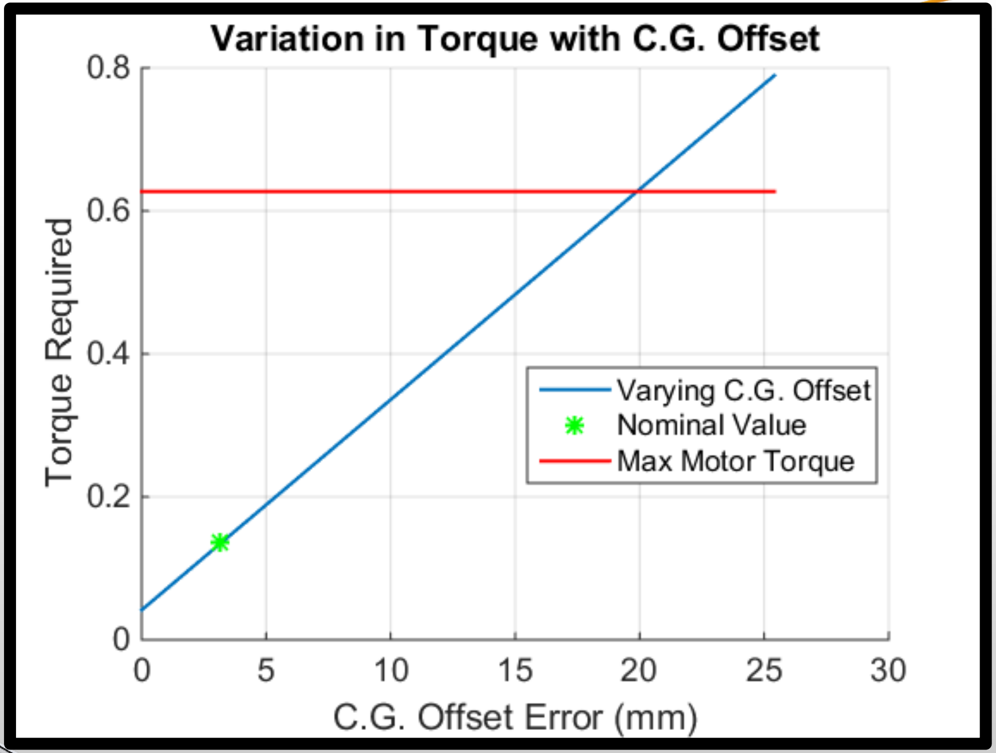
Component	Cost at MSR	Actual Cost	Projected Cost	Difference
CubeSat Model	$101.68	$133.53	$0.00	**-$31.85**
CS Rotation Frame	$192.26	$208.60	$0.00	**-$16.34**
CS Rotation Motor	$695.01	$695.01	$0.00	**$0.00**
CS Translation Frame	$124.92	$124.92	$0.00	**$0.00**
Arm Mount	$64.42	$70.07	$0.00	**-$5.65**
Pro Series Arm	$2492.60	$2492.60	$0.00	**$0.00**
Gripper and FSR circuit	$243.30	$217.20	$0.00	**$26.10**
Vicon Reflective Spheres	$0.00	$140.00	$0.00	**-$140.00**
Shipping	$182.63	$211.61	$0.00	**-$28.98**
Printing	$341	$167.15	$173.85	**$0.00**
Total:	$4437.77	$4460.64	$173.85	**-$196.72**

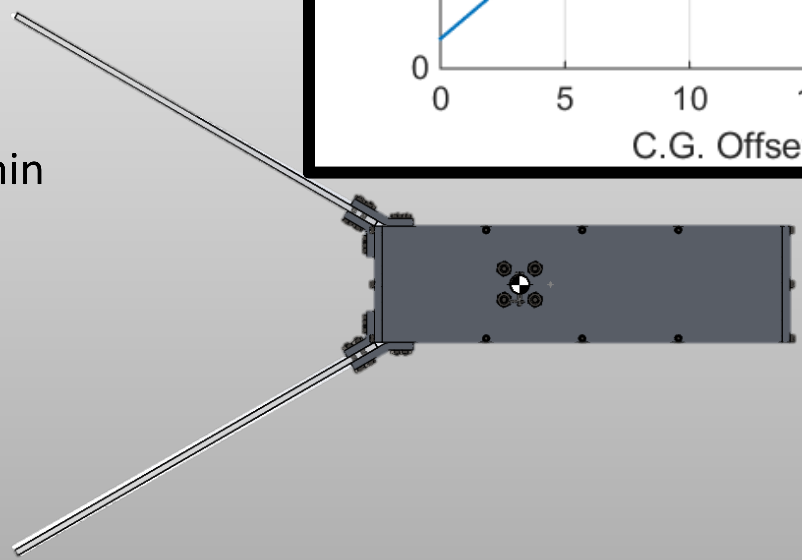


Approach
Capture
Change Orbit
Desired New Orbit
MicroSat
Rotating
CubeSat
Project Scope

CubeSat Ballasting

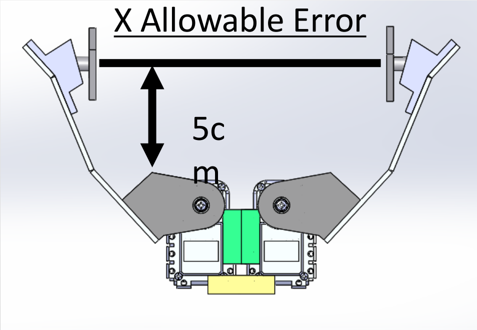
- Inspection: CubeSat C.G. within tolerable limits and no ballasting is needed
- Have not quantified to a degree of accuracy what the C.G. offset is
- A test would consist of sweeping through focal points to find C.G. and measuring offset to within ± .01”

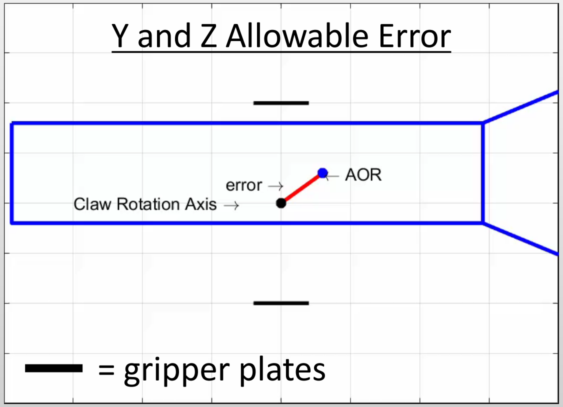




Arm Accuracy Error

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

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

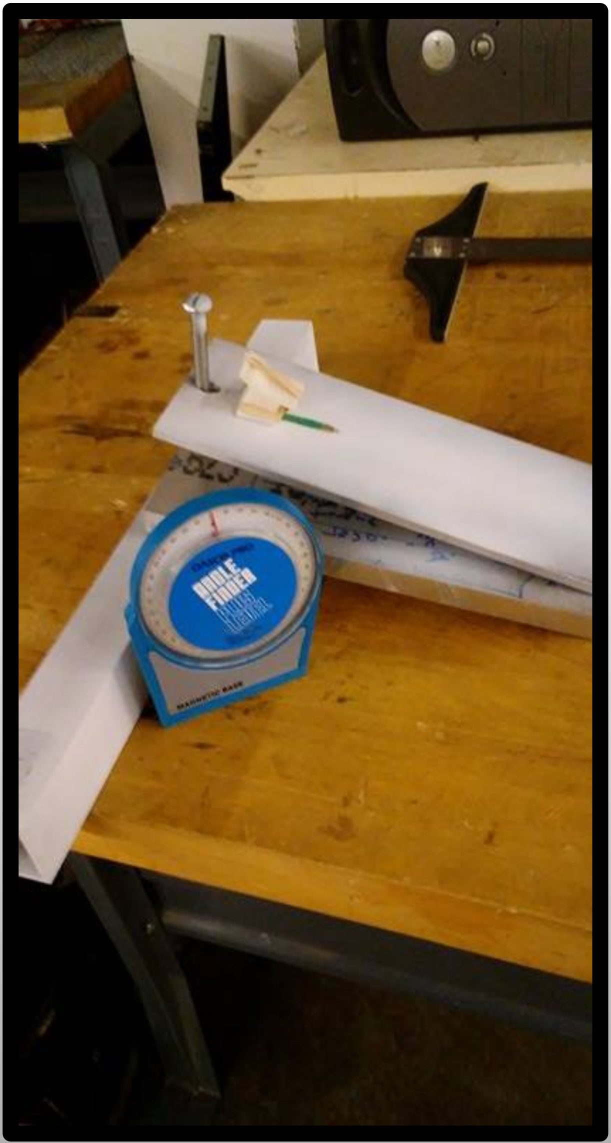
- FR 1.4 - The CRST shall execute capture of the physical CubeSat model autonomously during the demonstration.
- DR 1.4.1.10 - The capture device shall be able to confirm the capture of the CubeSat with tactile feedback without human intervention.
- DR 1.4.1.7 – The end effector of the capture device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

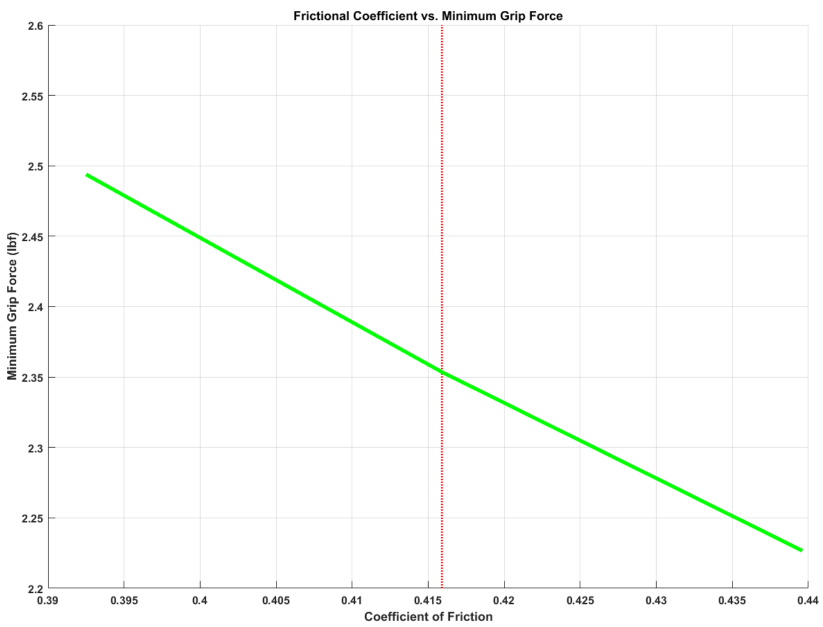
- Force sensor on ball-joint is placed on CubeSat face analog
- The face analog is raised in elevation until the force sensor slides down
- 25 tests are conducted to find the mean and standard deviation
- Tangent of the angle of repose gives static friction coefficient

Mean: 22.58°

Standard Deviation: 1.15°

Coefficient of Friction $\mu = \mathrm{Tan}(\theta)$ 0.4159 ± 0.0201

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

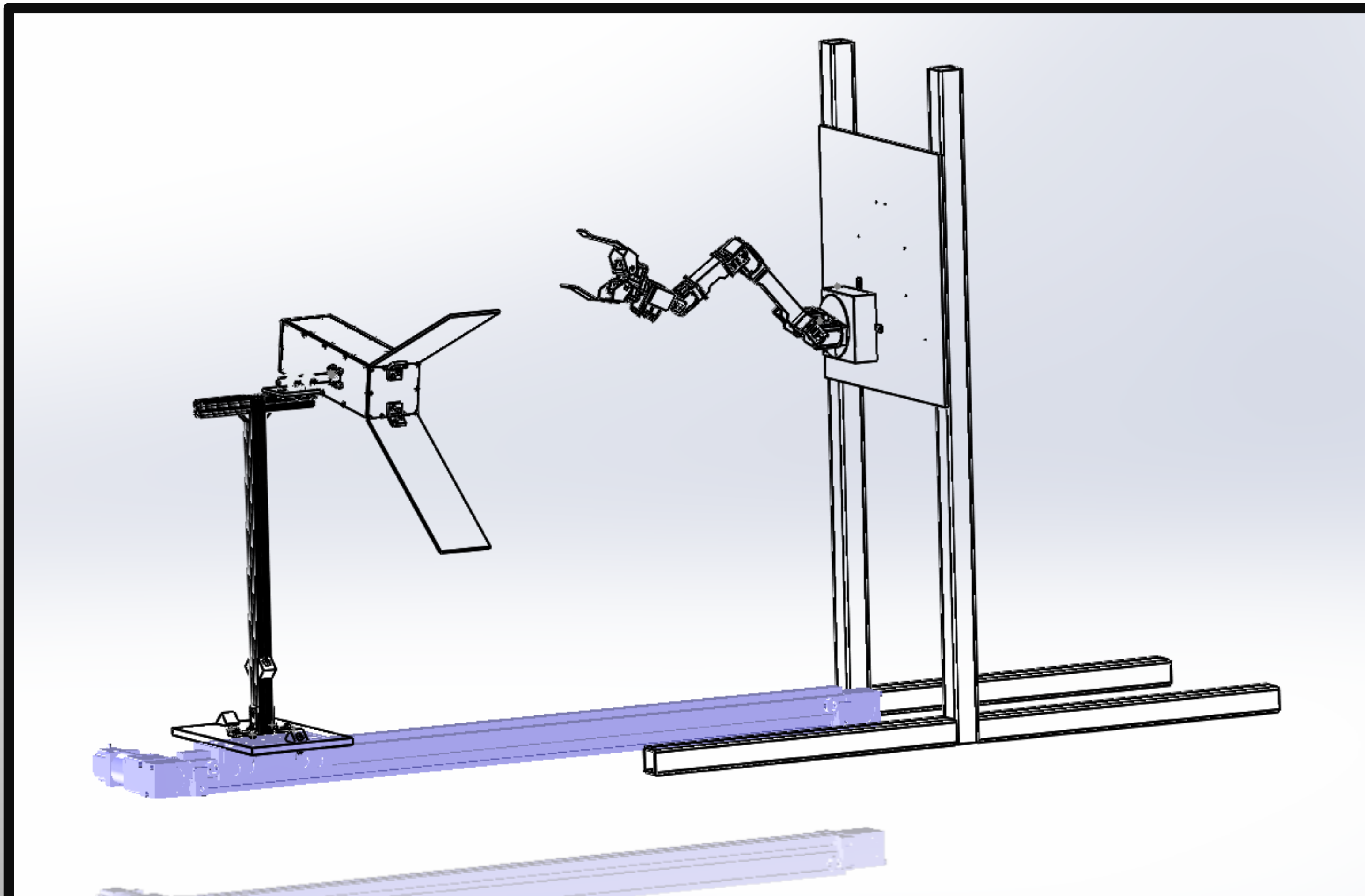
2.227 lbf

Maximum Force Required

2.494 lbf

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

CubeSat Translation Testing



CubeSat Stationary Position Failure

Unexpected Results & Conflicts

1. VICON dynamic data was too noisy for the algorithm
   - Numerical differentiation is an unstable method
   - Shorter time intervals leads to instability
2. LabVIEW's Matlab Script node decreases loop time

Key Requirements Affected

- 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 gather positional data from each control point on the CubeSat.
- DR 1.2.4 – The CRST shall determine the relative linear position of the CubeSat model.

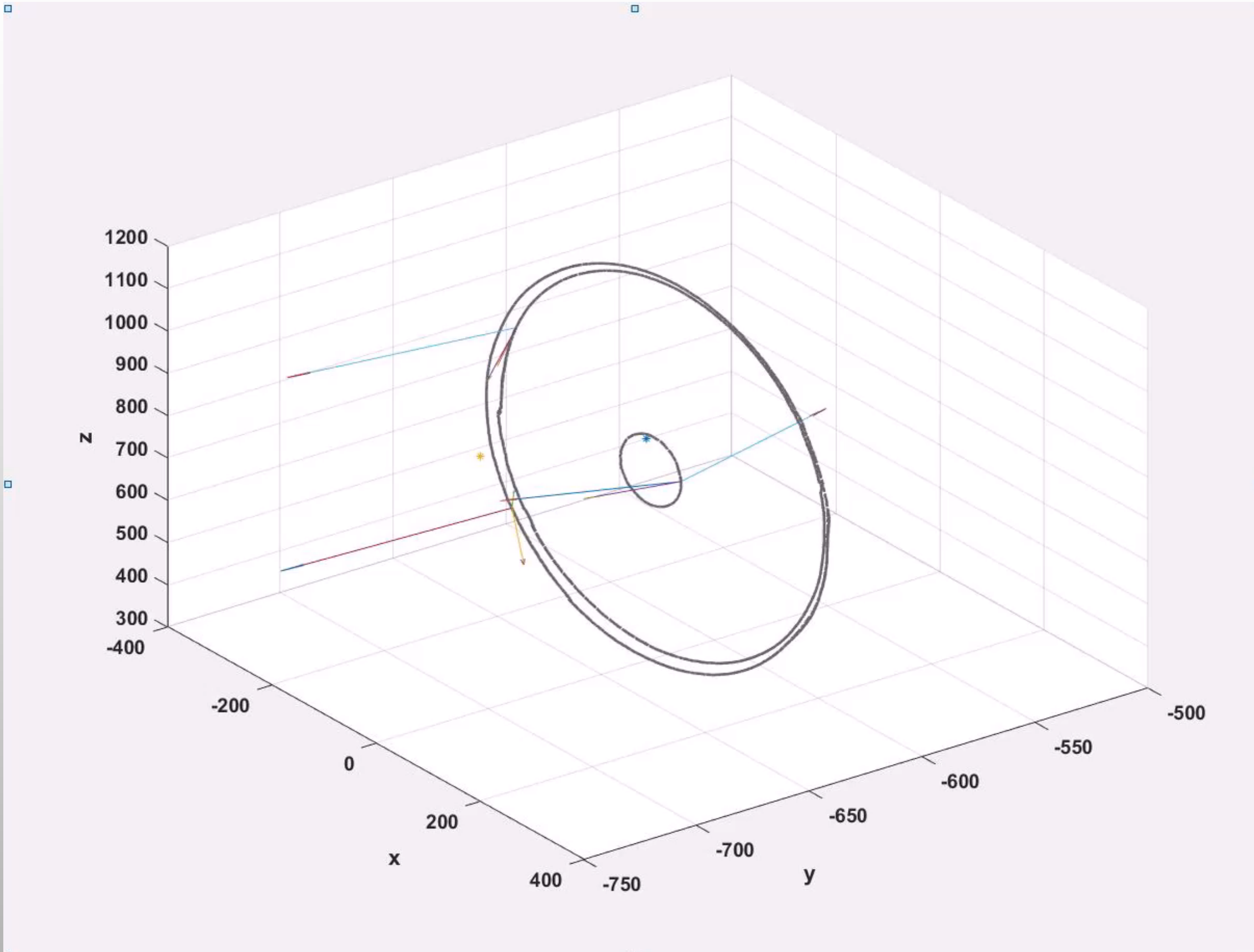
Impact

- Algorithm cannot handle dynamic data that contains high frequency noise at 100 Hz
  - A modified or new algorithm must be developed

Solution Attempts

1. Ensuring correct data stream, ensuring algorithm functionality within model
2. Increasing loop speed
3. Applying a digital filter to eliminate high frequency noise
   - Slow and not smooth enough
4. Utilizing different numerical differential methods
5. Modified TNB frame development strategy, but not developed

CubeSat Stationary Position Failure



- TNB Frame Instability
- Closest Intersection Prediction Inaccurate
- A.O.R. prediction not successful

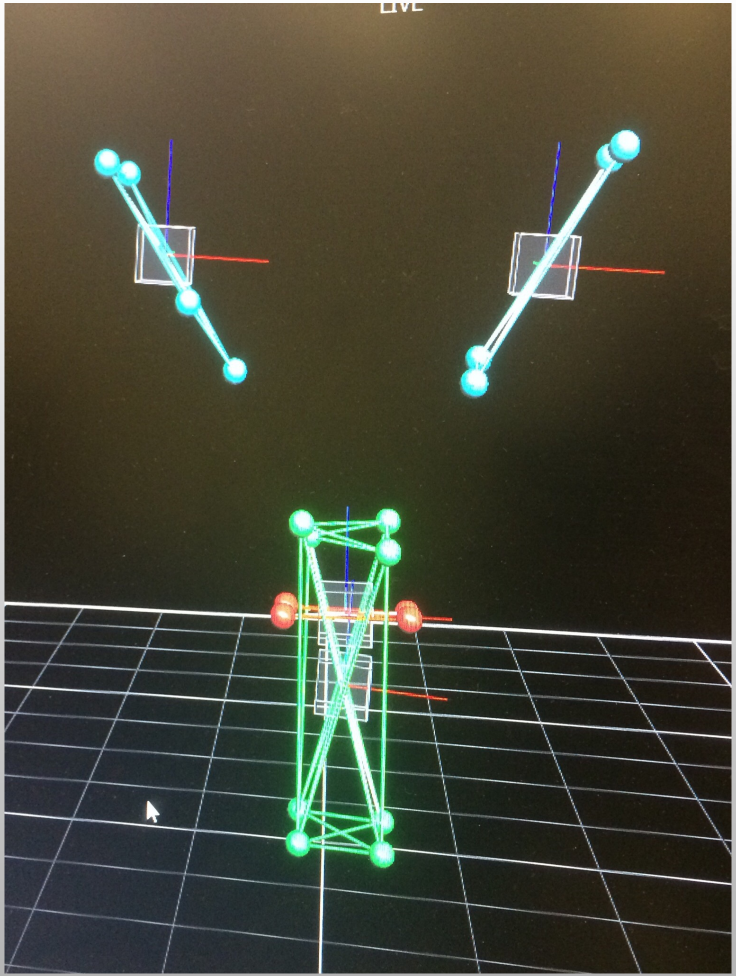
VICON Position Error Tolerance

- Similar to Arm Accuracy Test

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

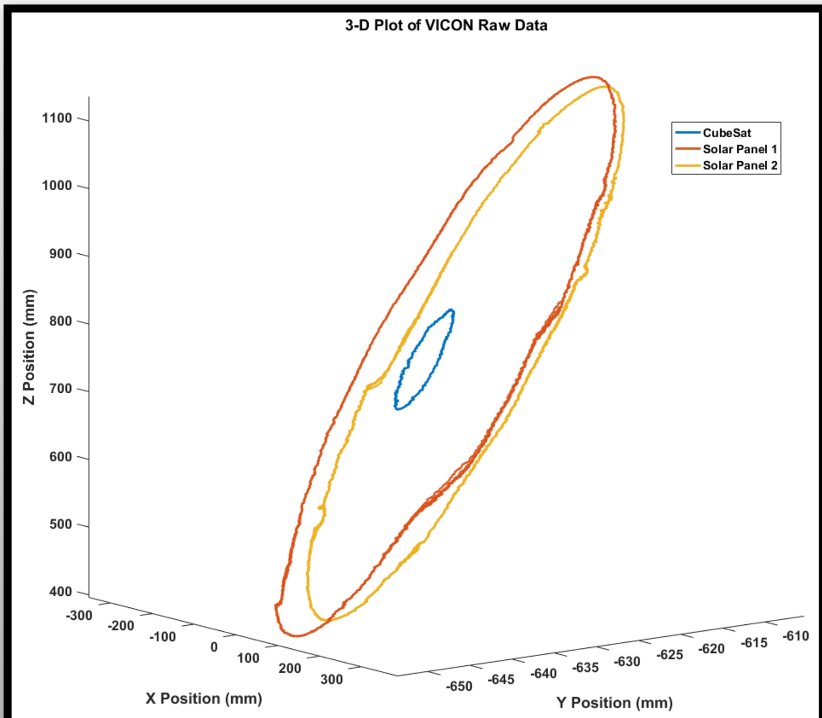
Measurement Error Bars	
VICON Camera System	±3mm (VICON noise + sphere placement error)

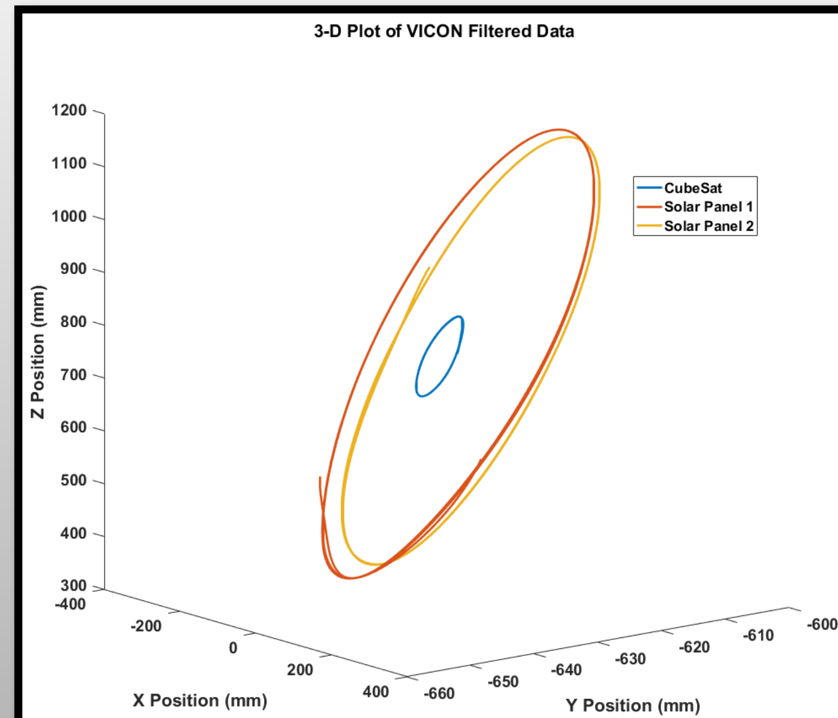
VICON Position Results – Physical Setup



VICON Position Results
Butterworth Filter

Info	X (mm)	Y (mm)	Z (mm)
Raw Noise	~ 0.2	~ 0.3	~ 0.15
R.M.S.	0.1459	0.1849	0.5557





CubeSat Stationary Orientation Test

Objectives

1. Verify the A.O.R. & Orientation algorithm
    - Functionality
    - Calculation Completion Time
    - Characterize error and standard deviation

Key Requirements

- FR 1.2 – The CRST shall determine the relative position and attitude between the CubeSat and capture device during the demonstration.
- DR 1.2.2 – The CRST shall communicate with a vision system to sense the initial conditions and motion of the CubeSat.
- DR 1.2.3 - The CRST shall determine the axis of rotation of the CubeSat model.

How it Reduces Risk

- Proves that the algorithm calculates an accurate and safe prediction of the CubeSat's axis of rotation and orientation for capture during phases 1 and 4.
    - Minimizing alignment error of end effector
    - Minimizing phase error of wrist rotator

Closed Loop Position Control Testing

Objectives

- Ensure that the translation system is capable of moving a commanded distance using position feedback from VICON system

Key Requirements

- DR 1.1.2 – The CubeSat analogue shall allow for translational motion along one axis
- DR 1.2.3 – The CRST shall determine the relative linear position of the CubeSat model

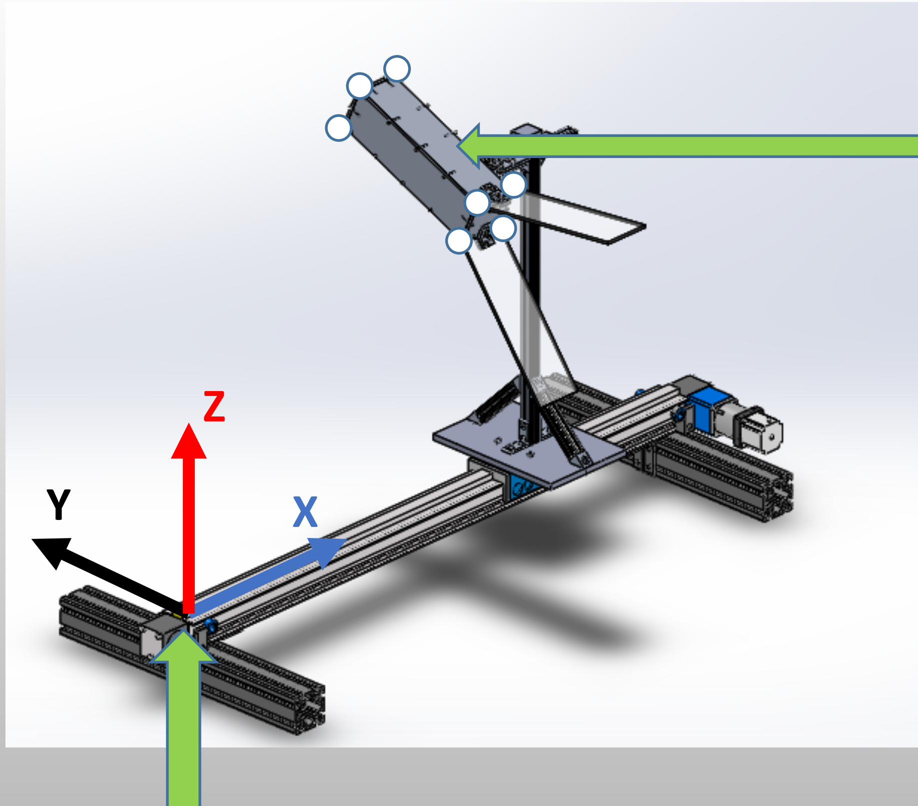
How it Reduces Risk

- Ensures that the CubeSat will reach the commanded position along the linear rail and is not in danger of crashing into the arm during final integration

Associated Models: CubeSat translation control model

Closed Loop Position Control Testing Setup

Location: RECUV Motion Capture Lab



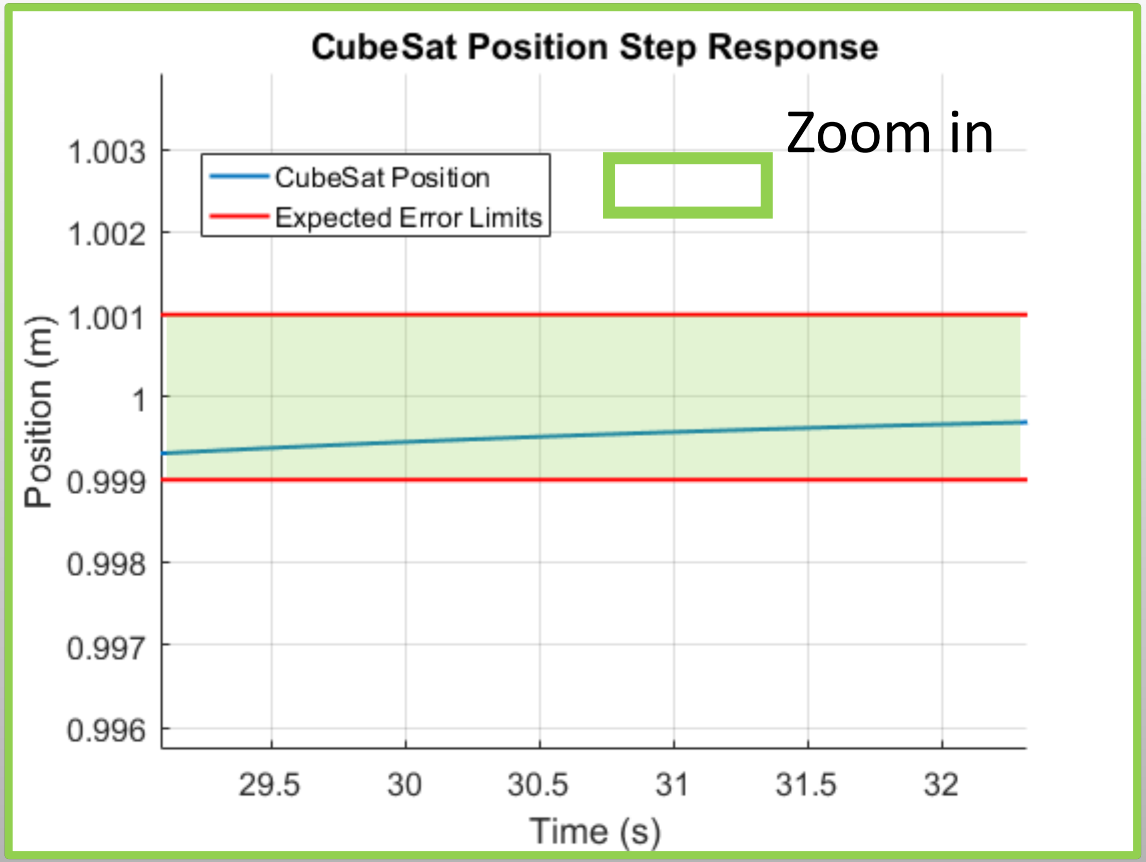
8x Reflector Spheres for CubeSat position feedback from VICON

Origin set with VICON calibration wand

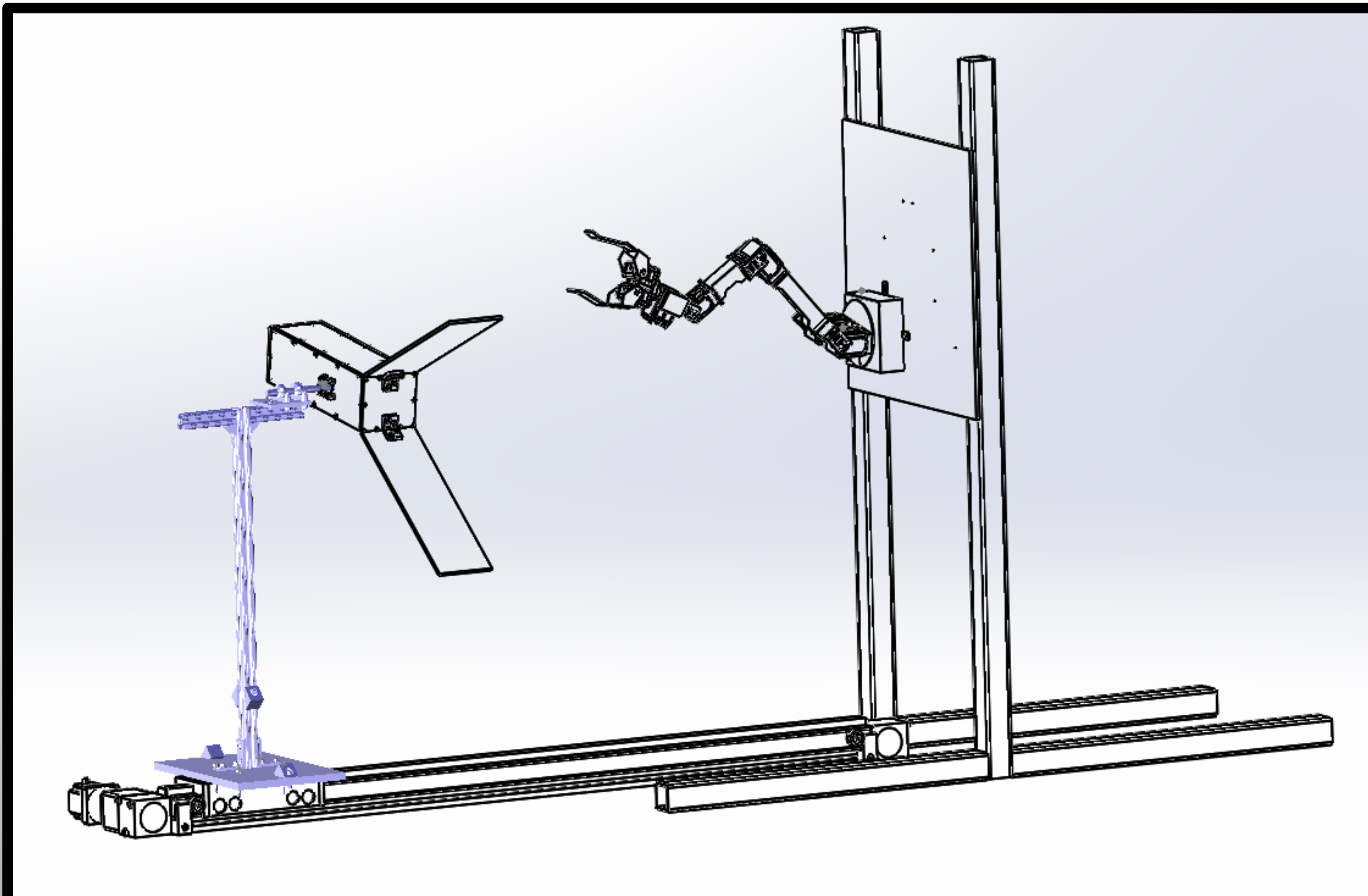
Input Command	Data to be Collected	Data Source	Sampling Frequency
Change in X position	CubeSat position (X,Y,Z)	VICON	~85 Hz

Closed Loop Expected Results

- Input: 1 meter step command
- Expected accuracy: ±1 mm due to noise in VICON system
- Expected loop rate: 166 Hz

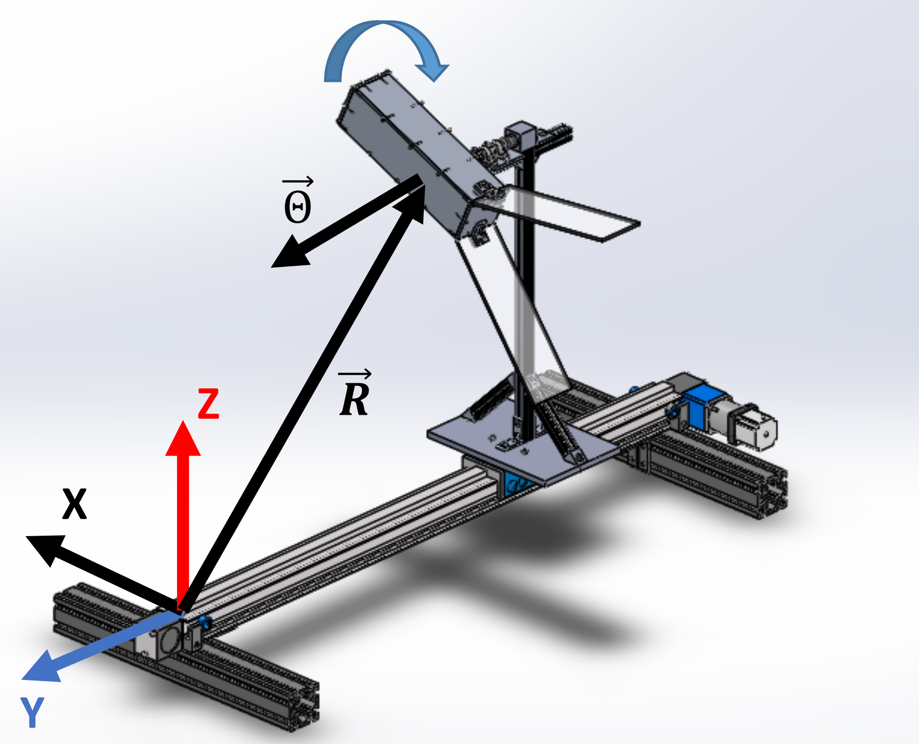


CubeSat Rotation Testing



CubeSat A.O.R. & Orientation Testing Setup

Location: RECUV Motion Capture Lab
Duration: 3.5 hour Test



Objective: Verify the A.O.R. & Orientation algorithm

- Functionality
- Calculation Completion Time
- Characterize error and standard deviation

Assumption: Stationary CubeSat

Data to be Collected	Data Source
Determined Position (x,y,z)	VICON
Euler Angles (Ψ, Θ, Φ)	VICON
Sampling Time	LabVIEW

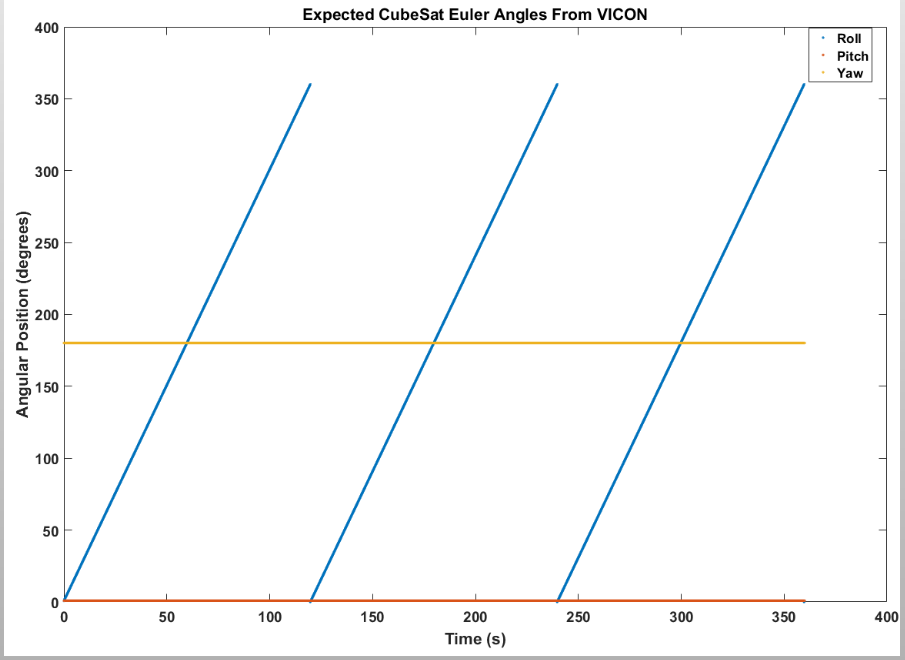
Equipment: Rotation Testbed, 20 IR Spheres

CubeSat A.O.R. & Orientation Expected Results

Input: VICON data

Expected Output:

1. Continuous prediction of CubeSat's relative orientation
   - 1 angle: Rotation angle
2. Prediction of CubeSat's axis of rotation
   - 2 angles: Azimuth, elevation



A.O.R. Expected Results	
Expected	Value
X,Y,Z	[$0.\overline{9}$, 1.4e-4, 2.24e-4]
Azimuth, Elevation	1.398e-4, 2.241e-4
Completion Time	5.448 ms

CubeSat Rotation Rate Test

Objectives

1. Verify that the CubeSat analogue spins at the desired rotation rate

Key Requirements

- FR 1.1 – The CRST shall demonstrate the motion of a CubeSat analogue during the demonstration.
- DR 1.1.3 – The CubeSat analogue shall allow for rotational motion about one axis.
- 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.

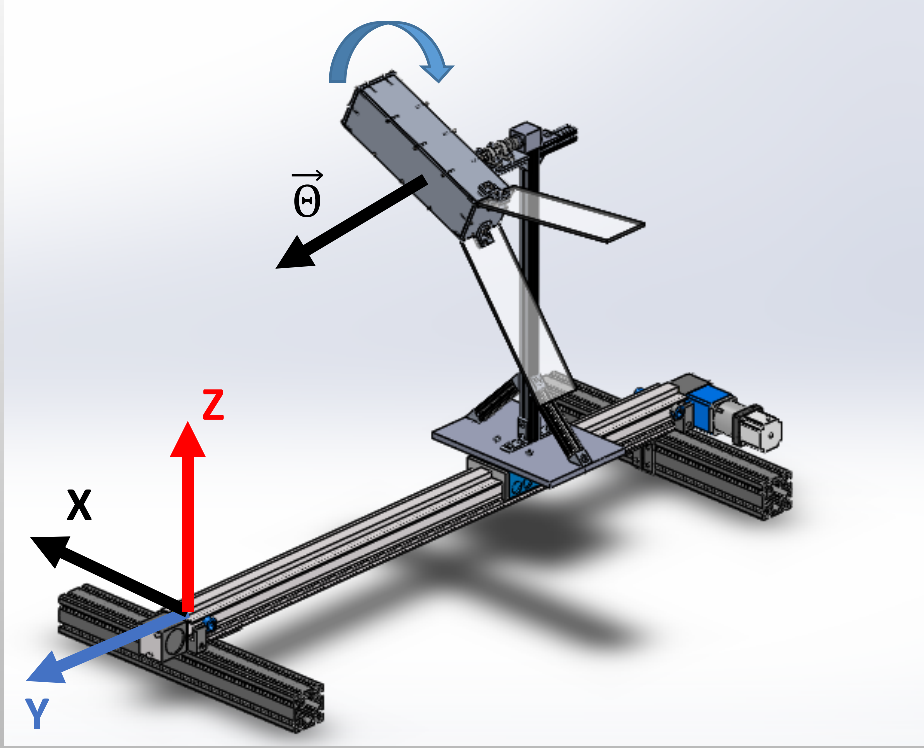
How it Reduces Risk

- Ensures that the CubeSat rotates at the desired rotation rate and precisely to limit the possibility of phase error during capture.

Associated Models: CubeSat rotation control model

CubeSat Rotation Rate Testing Setup

Location: RECUV Motion Capture Lab
Duration: 1 hour Test



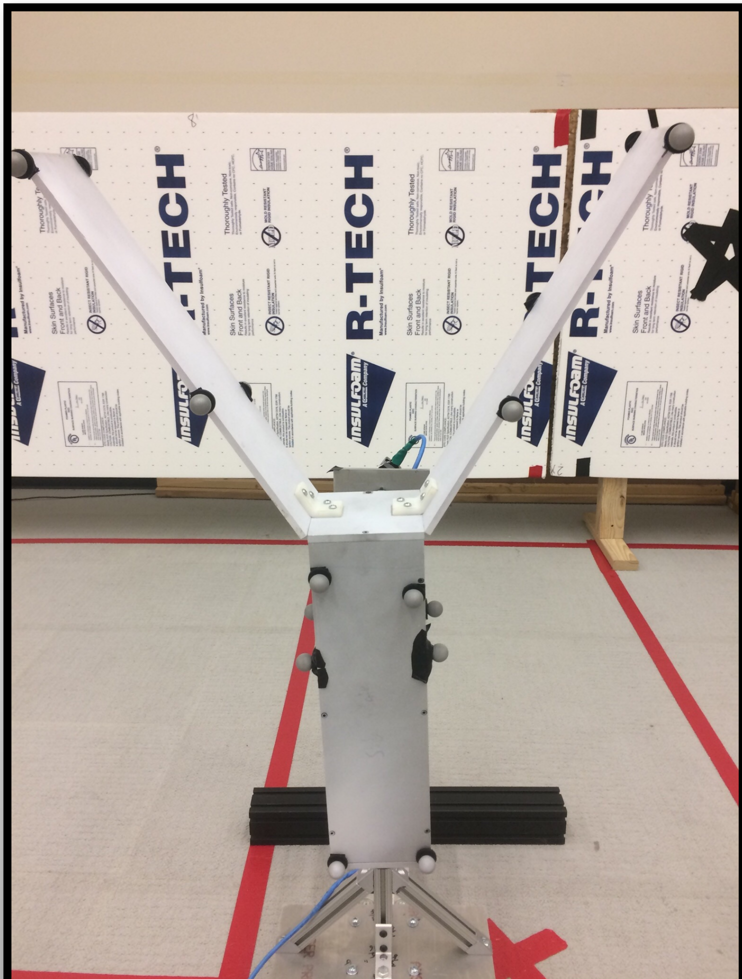
Objective: Verify CubeSat's rotation rate
- Ensure 3 deg/s Characterize standard deviation

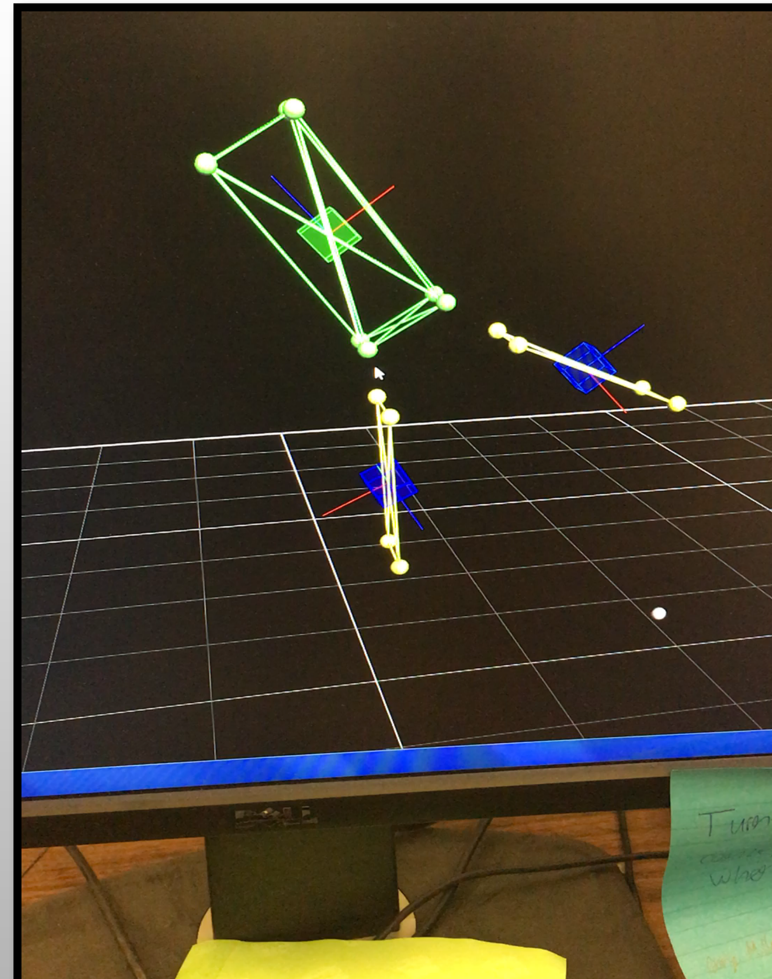
Assumption: Stationary CubeSat

Data to be Collected	Data Source
Euler Angles (Ψ, Θ, Φ)	VICON
Sampling Time	LabVIEW

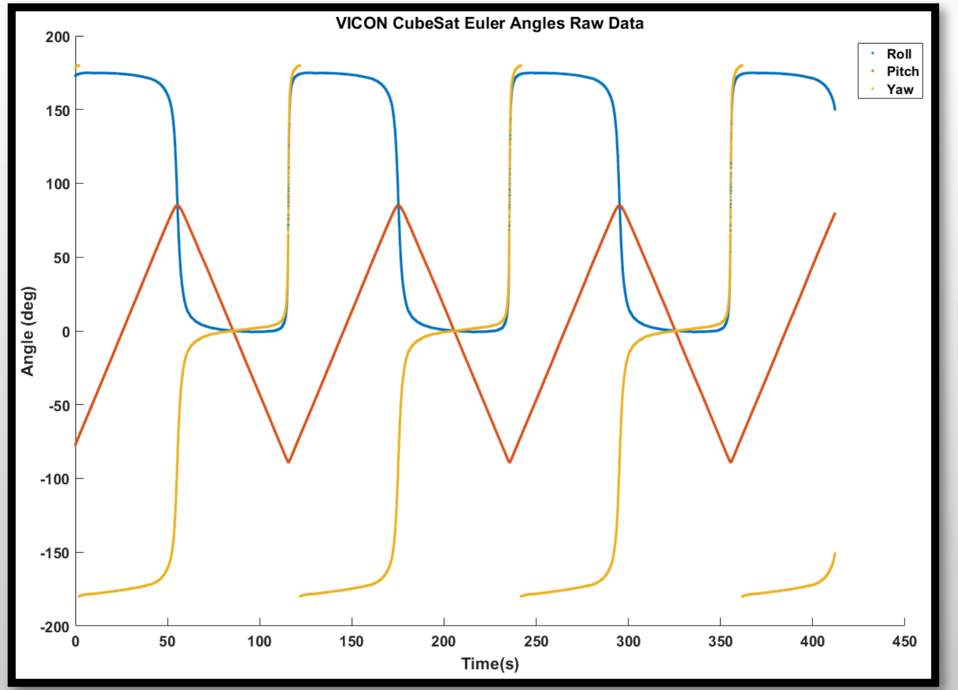
Equipment: Rotation Testbed, 8 IR Spheres

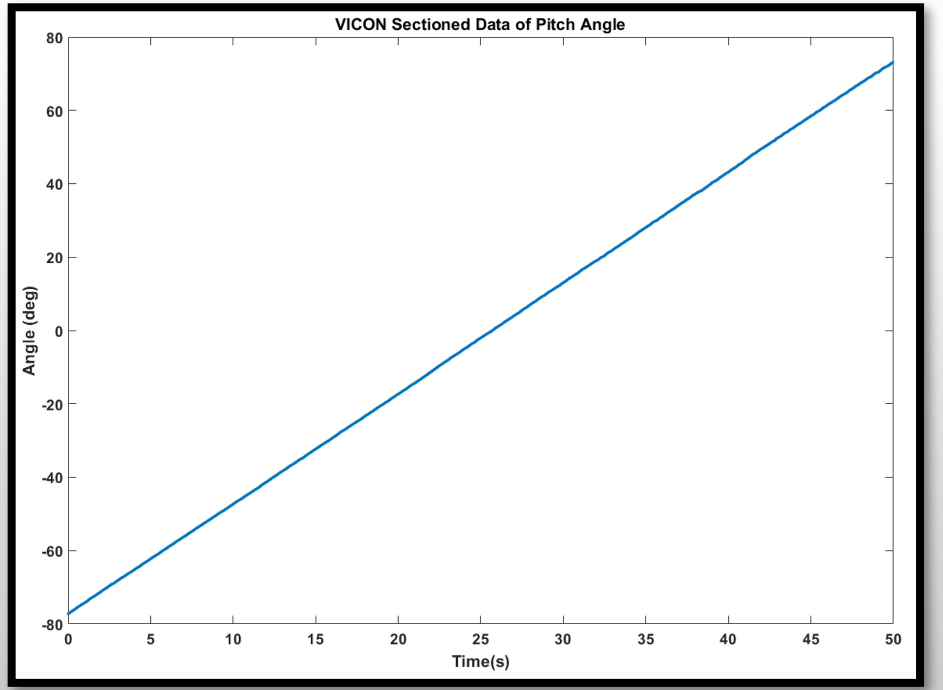
VICON Rotation Results – Physical Setup





VICON Rotation Test Results





Notes:

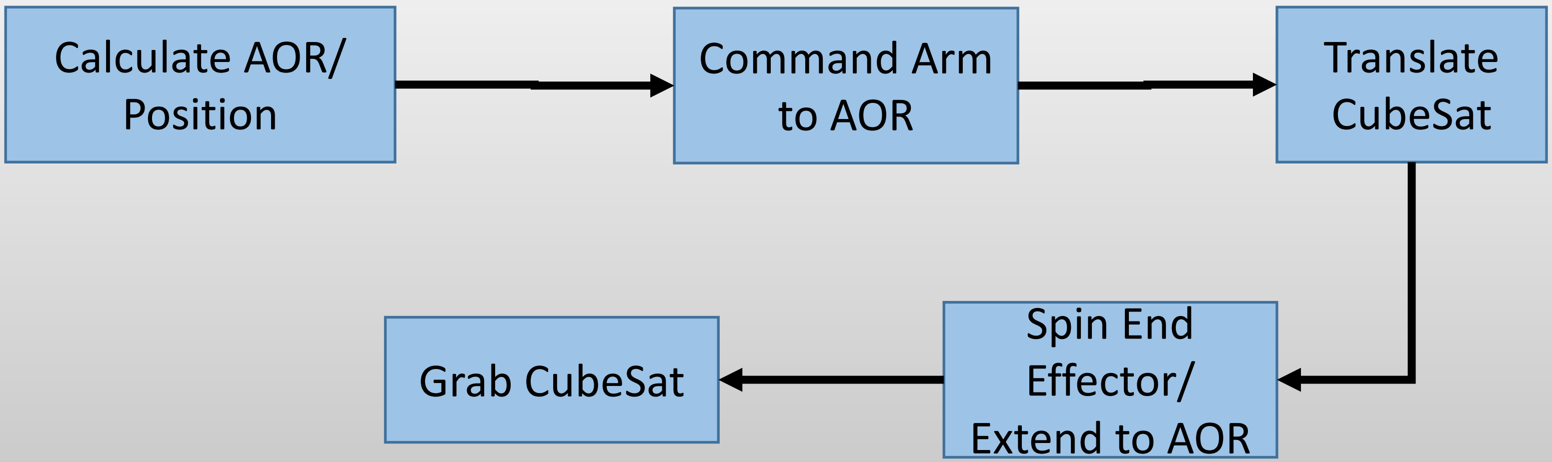
- VICON body coordinate frames flip occasionally
  - Cause: Roll axis flips 180°
  - Mitigation: IR Sphere Arrangement to Lock In Coordinate Frame

VICON Rotation Test Results

Allowable Maximum Error	
10 % of Desired Rotation : 0.3 deg/s	
Calculated Pitch Angular Rate	
Slope #	**$\dot{\Theta}$ (deg/s)**
1	3.0094
2	2.9889
3	2.9833
Standard Dev.	0.0137
Desired Angular Rate	
Requirement	**3**
Maximum Differences	
$\Delta\dot{\Theta}$	**0.0167**
% Tolerance	**5.567 %**

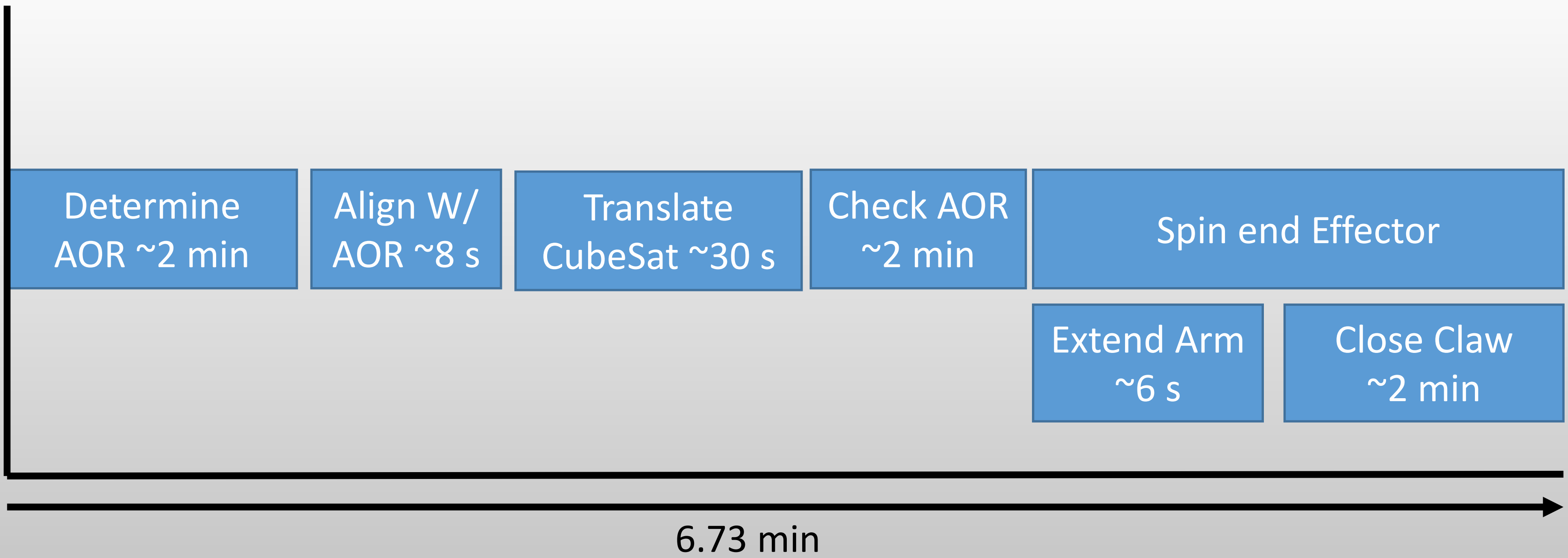
Potential Software Offramp

- In the event parallel while loops don't work
- Utilize loops in sequential order for phases

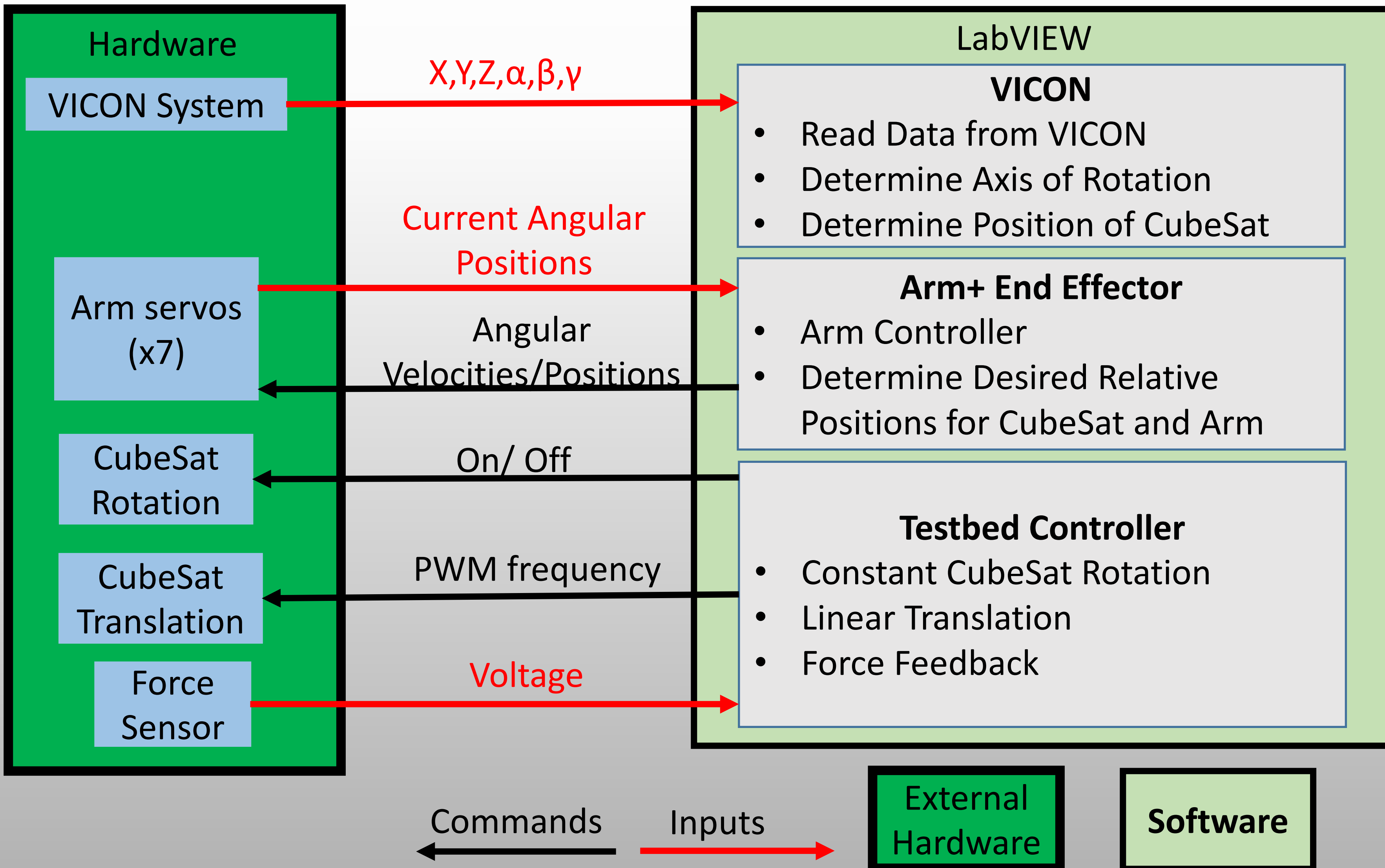


Still allows for highest level of success

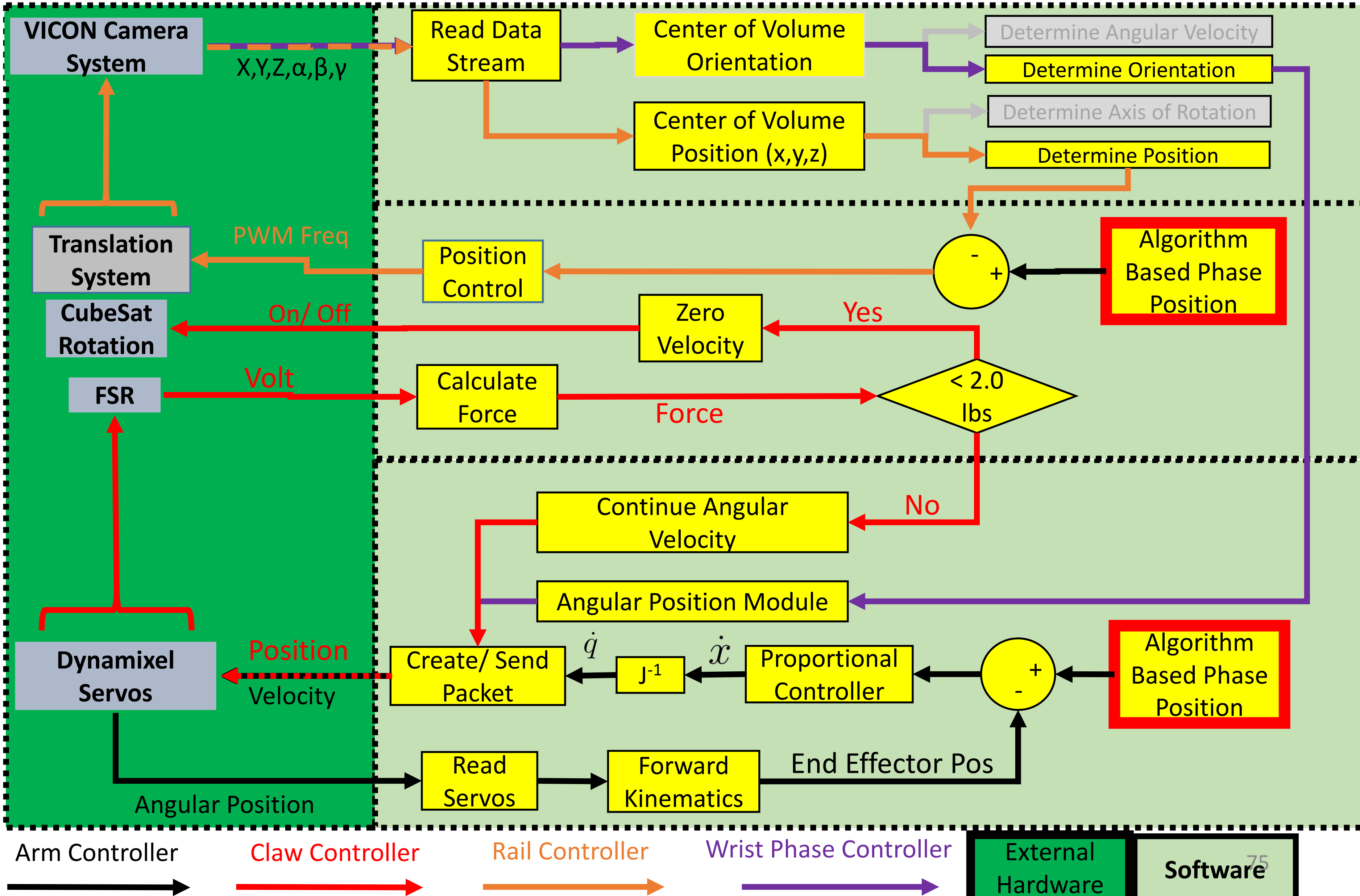
Software Timing—5 Steps



Software I/O


Hardware
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: Controllers



Software's Five Phases To Capture

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

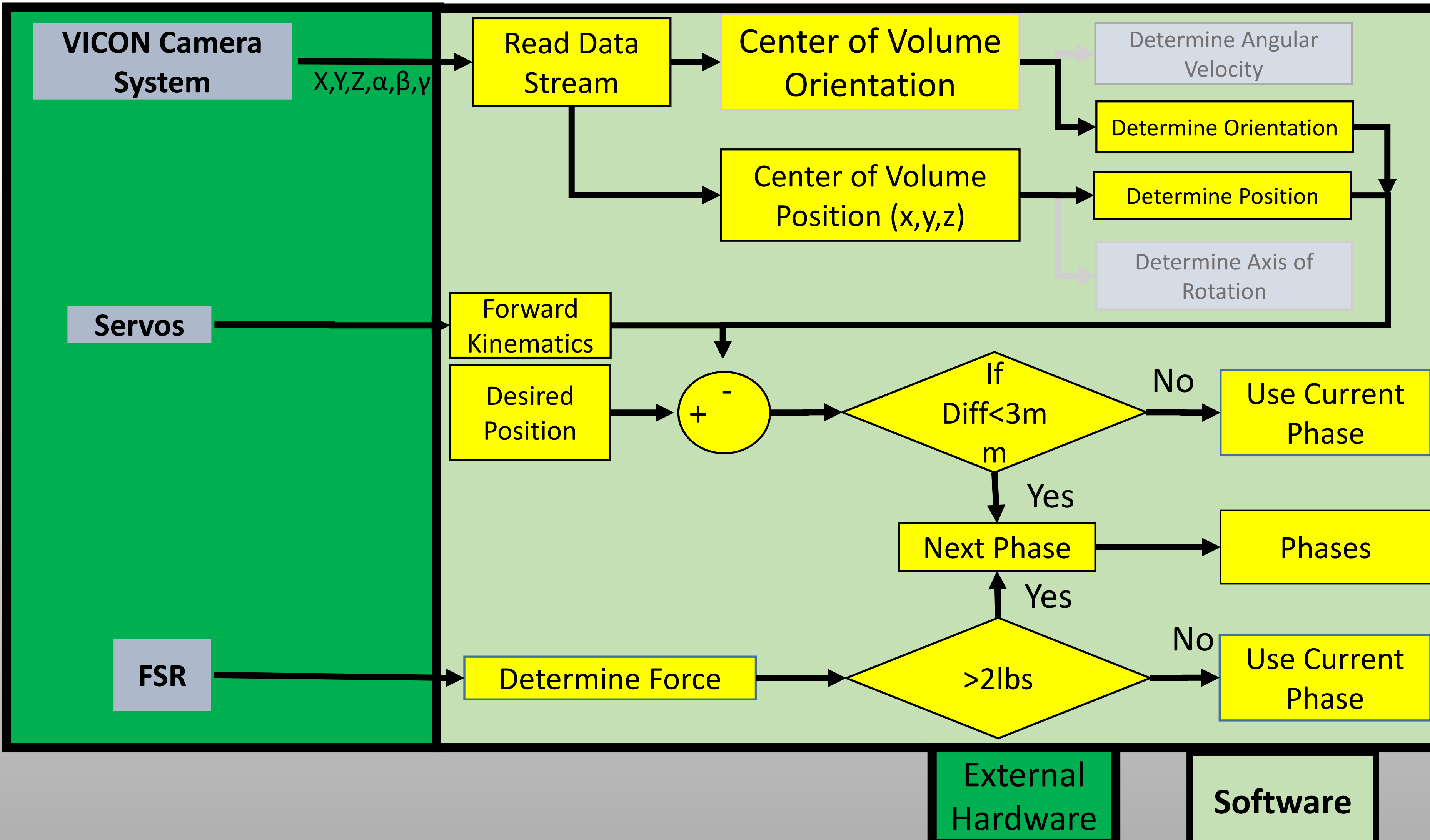
2: Translate CubeSat to Gripping Position → Position on Rail Based on 75% of Full Extension

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



Wrist Rotation Test

Objective:

- Verify functionality of End effector--CubeSat orientation matching

Requirements:

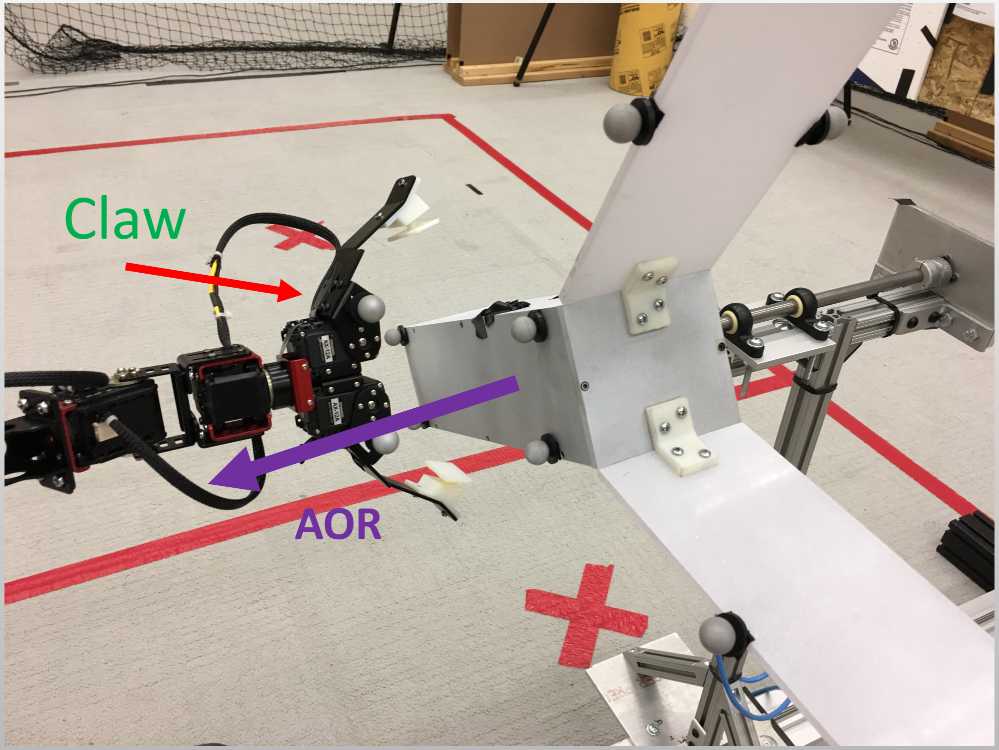
- 1.3.2--The end effector shall align with the CubeSat's spin axis and remain aligned until the end of the capture sequence

How it Reduces Risk:

- Highest probably of success since risk of collision is low

Wrist Rotation Tests

Objectives: Verify functionality of End effector--CubeSat orientation matching
Location: RECUV vision lab
Duration: 3 Hr

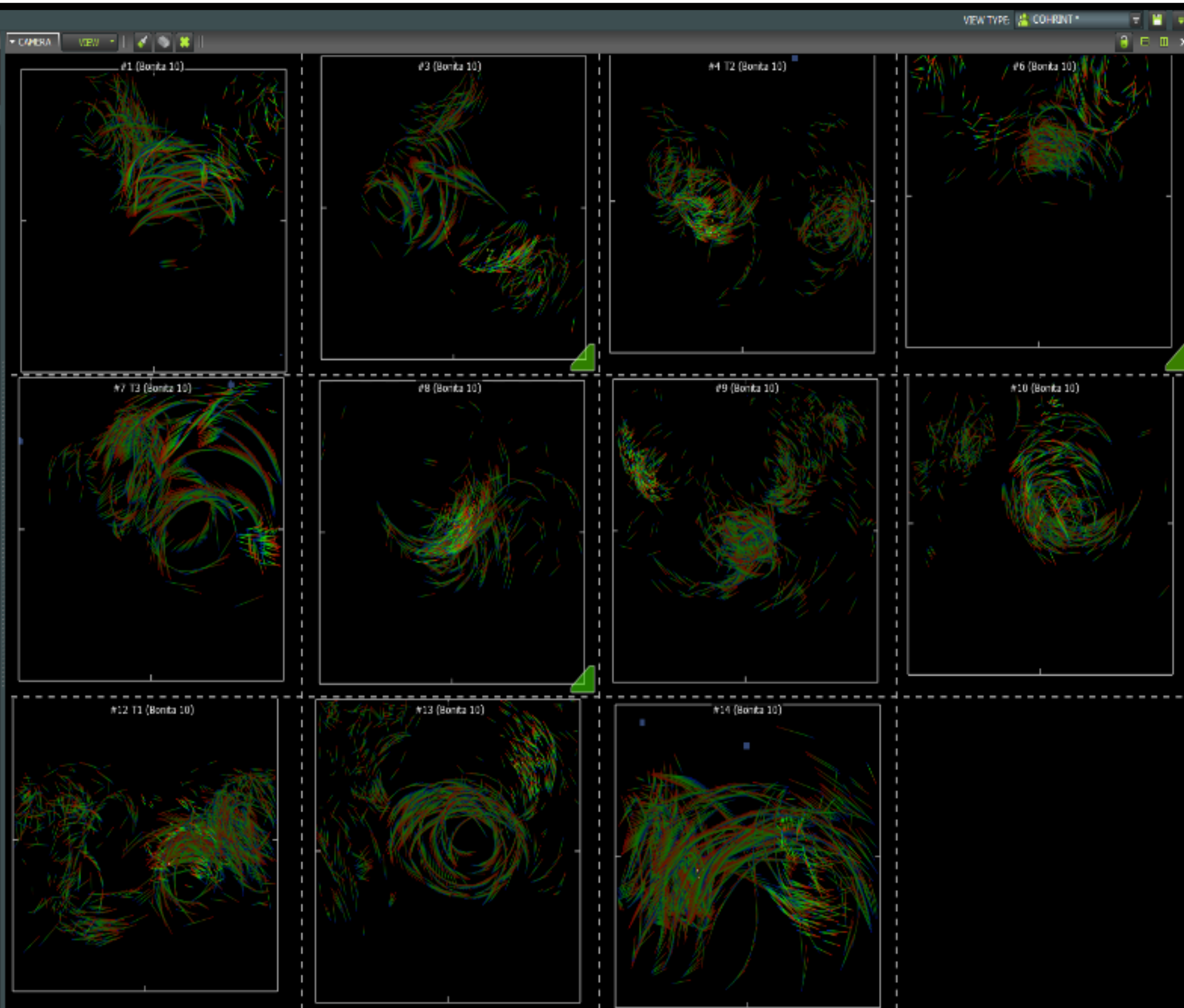


Test Procedure:

1. Rotate CubeSat
2. Collect data on orientation of end effector and CubeSat

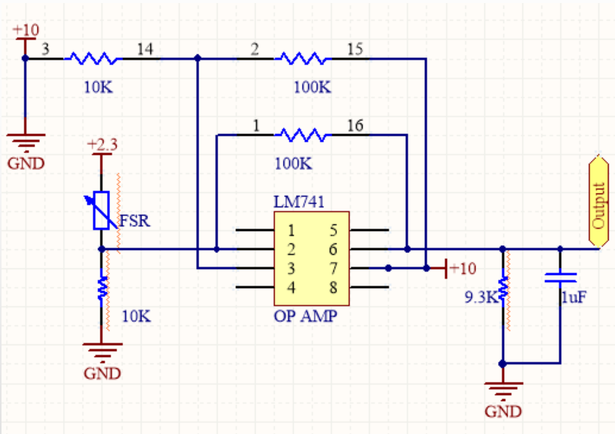
Difference in Orientation
~0.15 ± 0.03 degrees

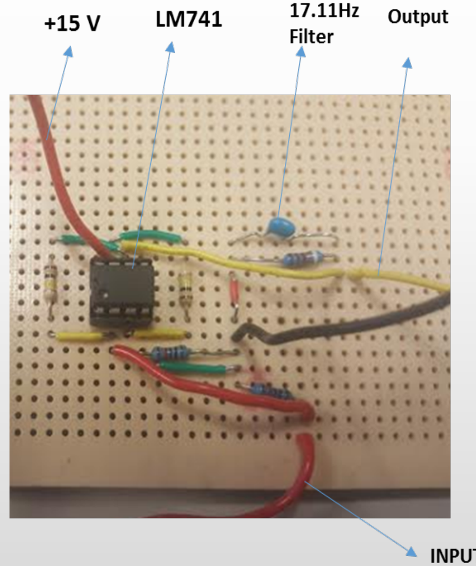
VICON Calibration

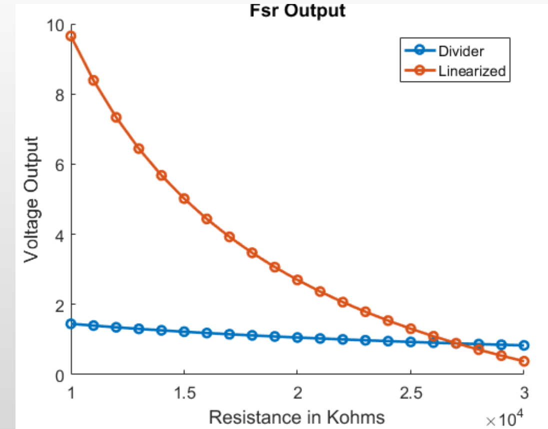


- Calibration uses specialized objects with known dimension and relative marker position to calculate relative position and orientation of VICON cameras to correct for lens distortion.
- Volume origin set using Tracker- measures position of Calibration object and uses the information to define a global coordinate system.
- Image error (RMS distance in camera pixels) shows accuracy of marker position reconstruction: difference between 2D image and 3D reconstruction dependent on camera type, size of capture volume, lens type

FSR Updated Design



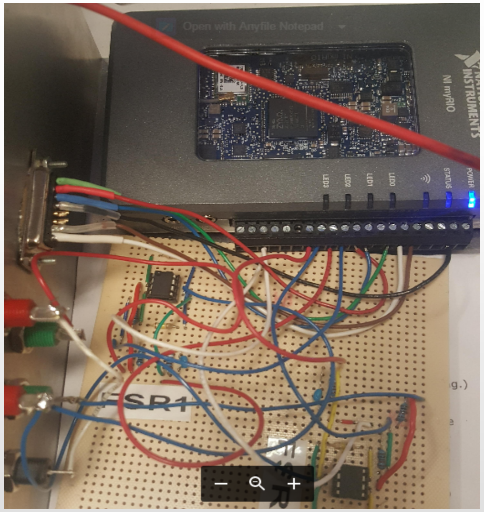




$$Vout = V_{thev}\left(\frac{R_2}{R_{thev}}\right) - V_2\left(\frac{R_4}{R_3 + R_4}\right)\left(\frac{R_2 + R_{thev}}{R_2}\right)$$

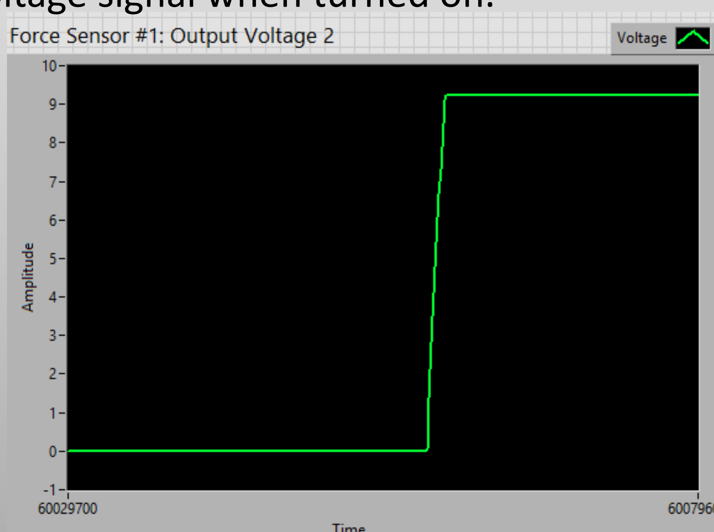
- Operating at an FSR resistance of 10KΩ to 30KΩ
- V_{thev} = Voltage divider output as a function of Fsr.
- R_{thev} =FSR in parallel with 10KΩ

Integrating the FSR and MyRio

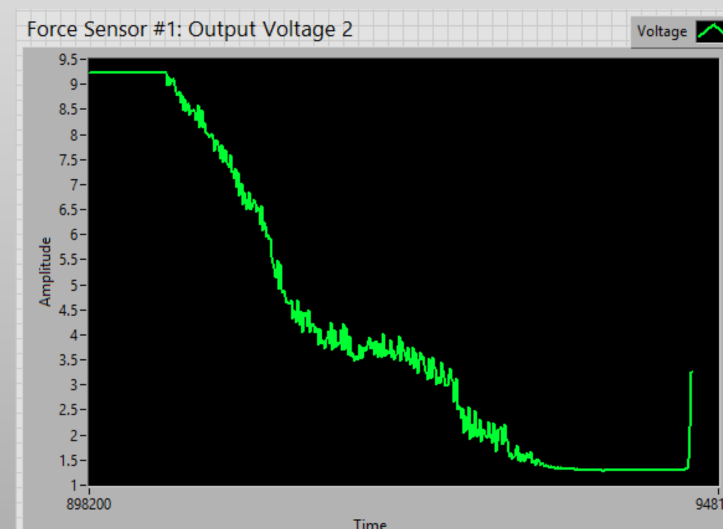


- The MyRio will read the FSR voltage signal at 500mHz at ±0.005V
- When the Voltage goes below a predefined voltage which we will set at 6.6V an alarm will go off signifying confirm Capture.

The MyRio will read an inverted voltage signal when turned on.



The voltage signal will decrease with an increase in force over time.



APPENDIX

Overview	CPEs	Schedule	Testing	Subsystem Testing	Closed-loop Testing	Full Integration Testing	Budget	Backup
CONOPs			Fixtures & Facilities	AOR	Capture Confirmation	Phase Checks		Arm Accuracy Error
FBD			Overview	Translation				Friction Test
HBD			Requirement Verification	FSR				Stationary Position Error
			Arm					VICON Position Error
								Position Control
								AOR & Orientation
								VICON Rotation Results
								Software I/O
								VICON Calibration