CASCADE

Cubesat Active Systematic CApture DEvice

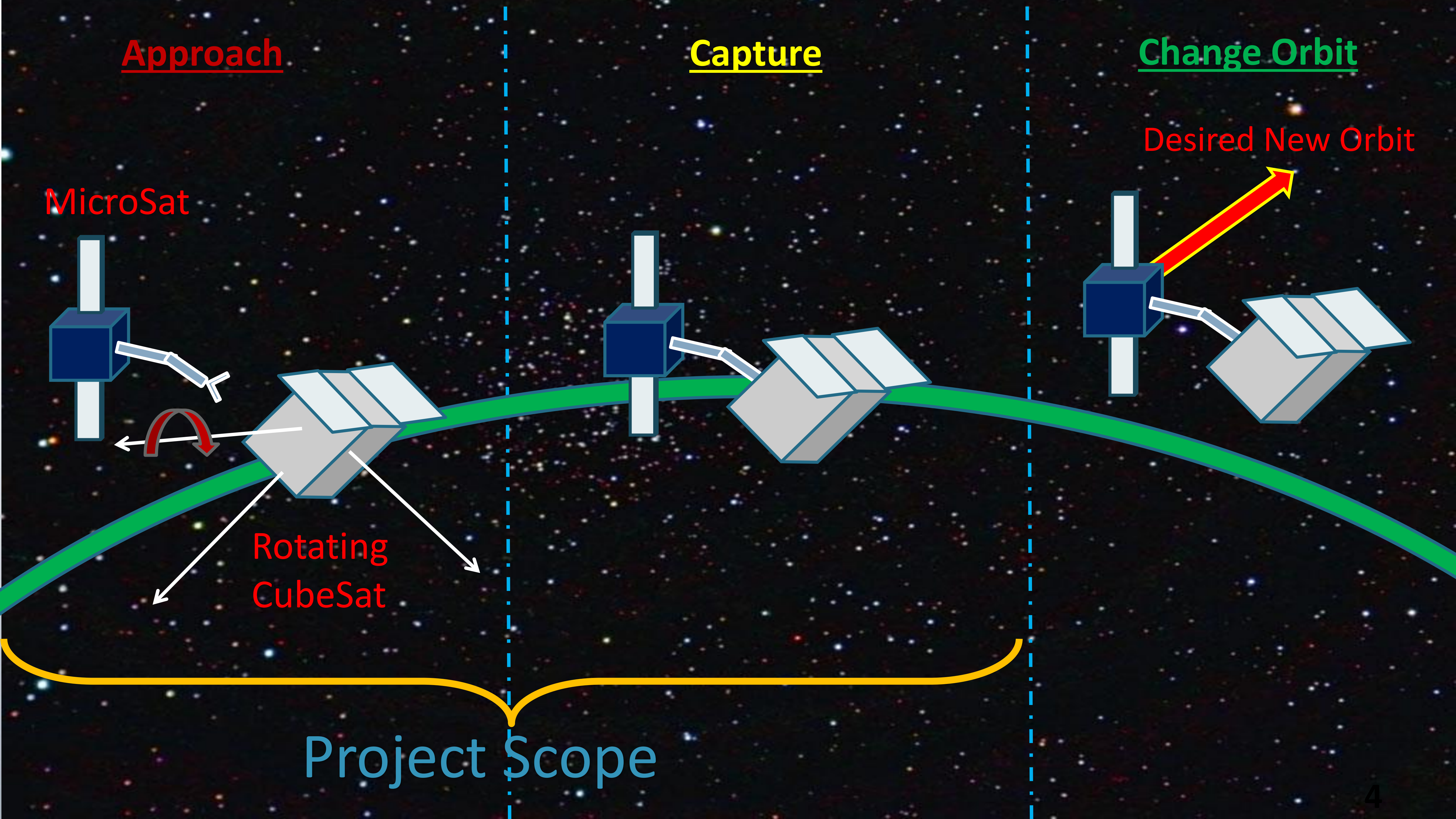
Preliminary Design Review
October 12th 2016

Project Overview

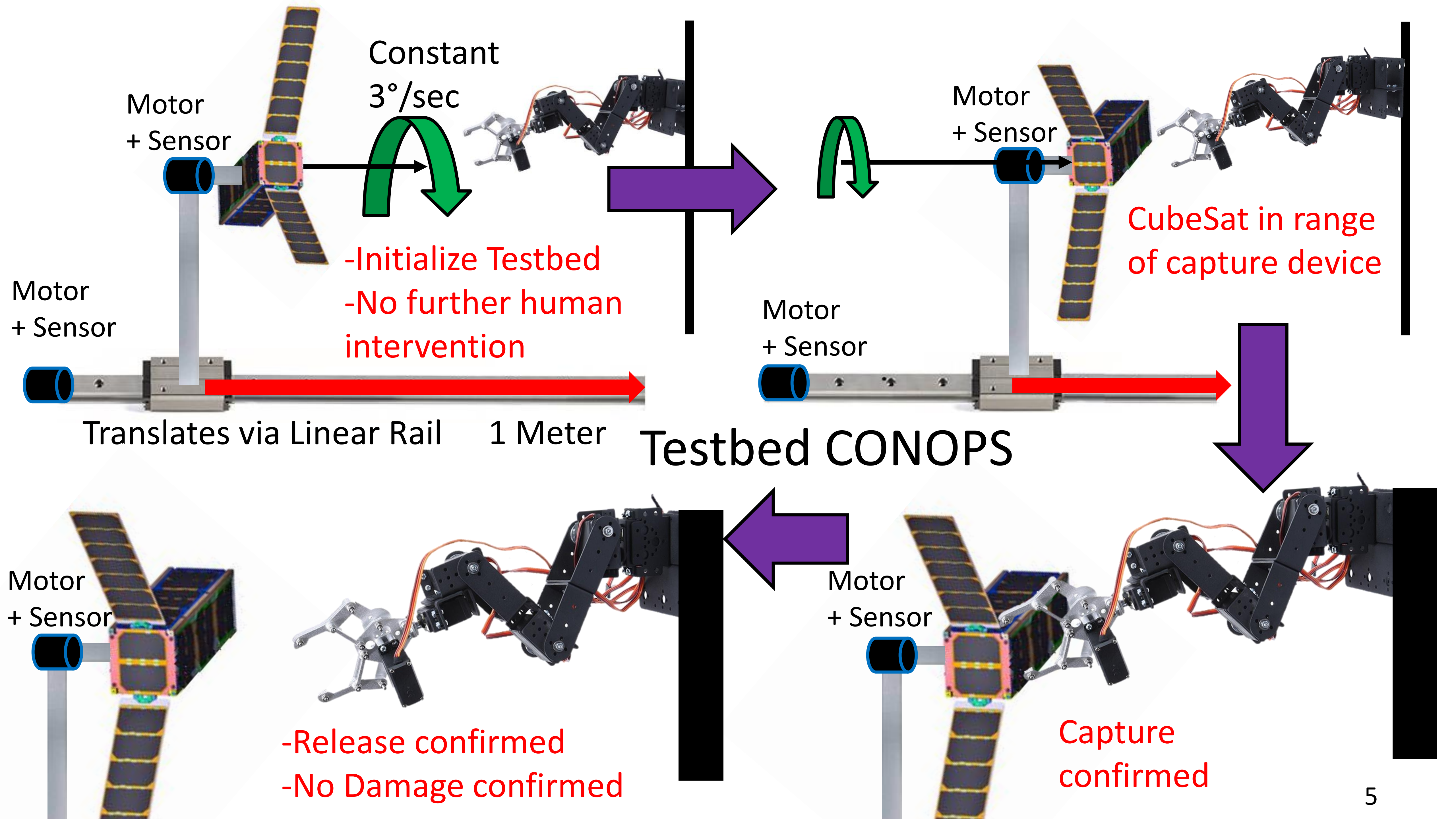
Project Statement

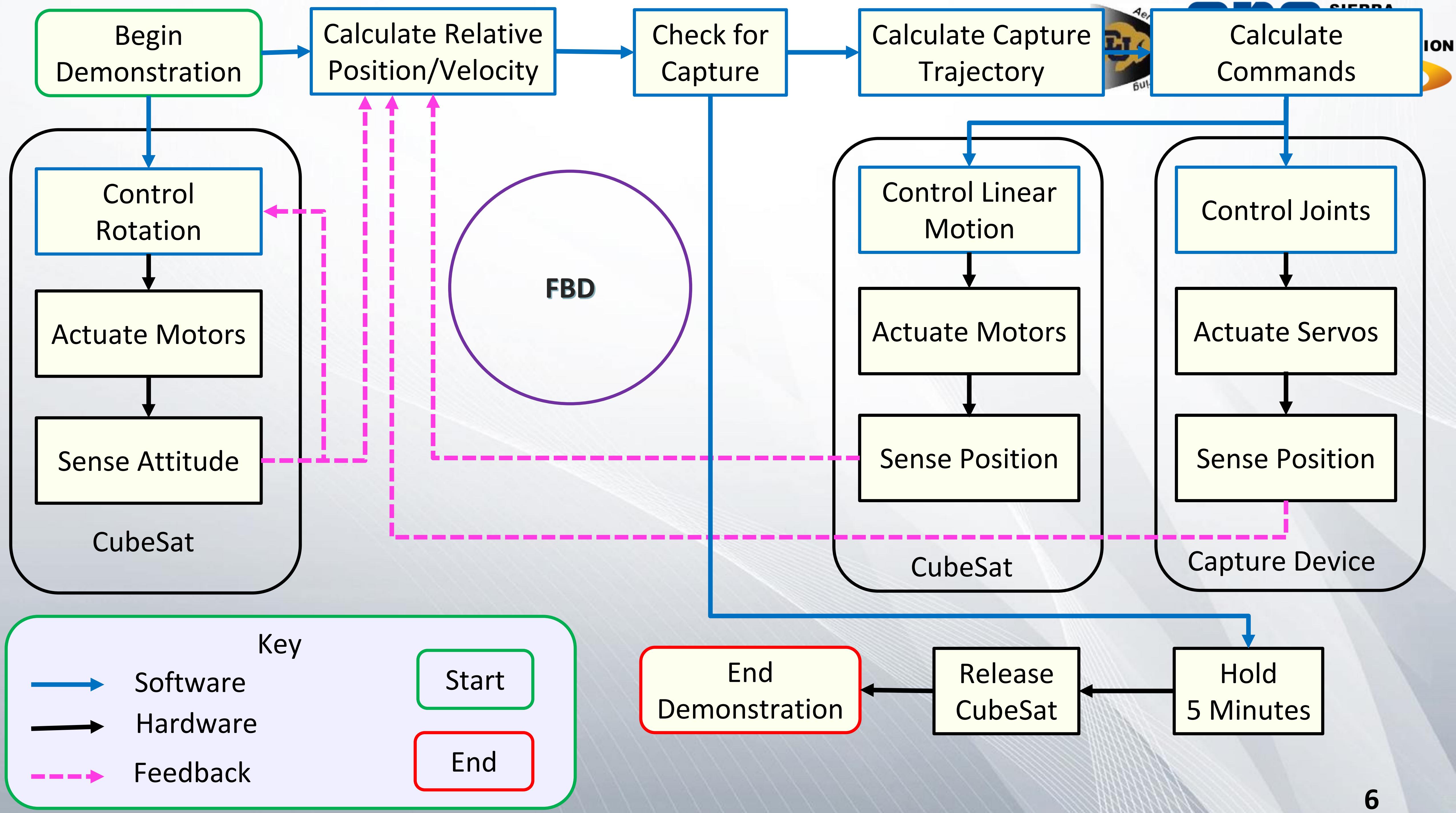
Team CASCADE will demonstrate the implementation of an algorithm to autonomously capture a rotating 3U CubeSat model.

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.


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

Testbed CONOPS




Begin Demonstration
Calculate Relative Position/Velocity
Check for Capture
Calculate Capture Trajectory
Calculate Commands
Control Rotation
Actuate Motors
Sense Attitude
CubeSat
FBD
Control Linear Motion
Actuate Motors
Sense Position
CubeSat
Control Joints
Actuate Servos
Sense Position
Capture Device
Key
Software
Hardware
Feedback
Start
End
End Demonstration
Release CubeSat
Hold 5 Minutes

Functional Requirements

- The **CRST** shall demonstrate the successful capture of a physical CubeSat model.

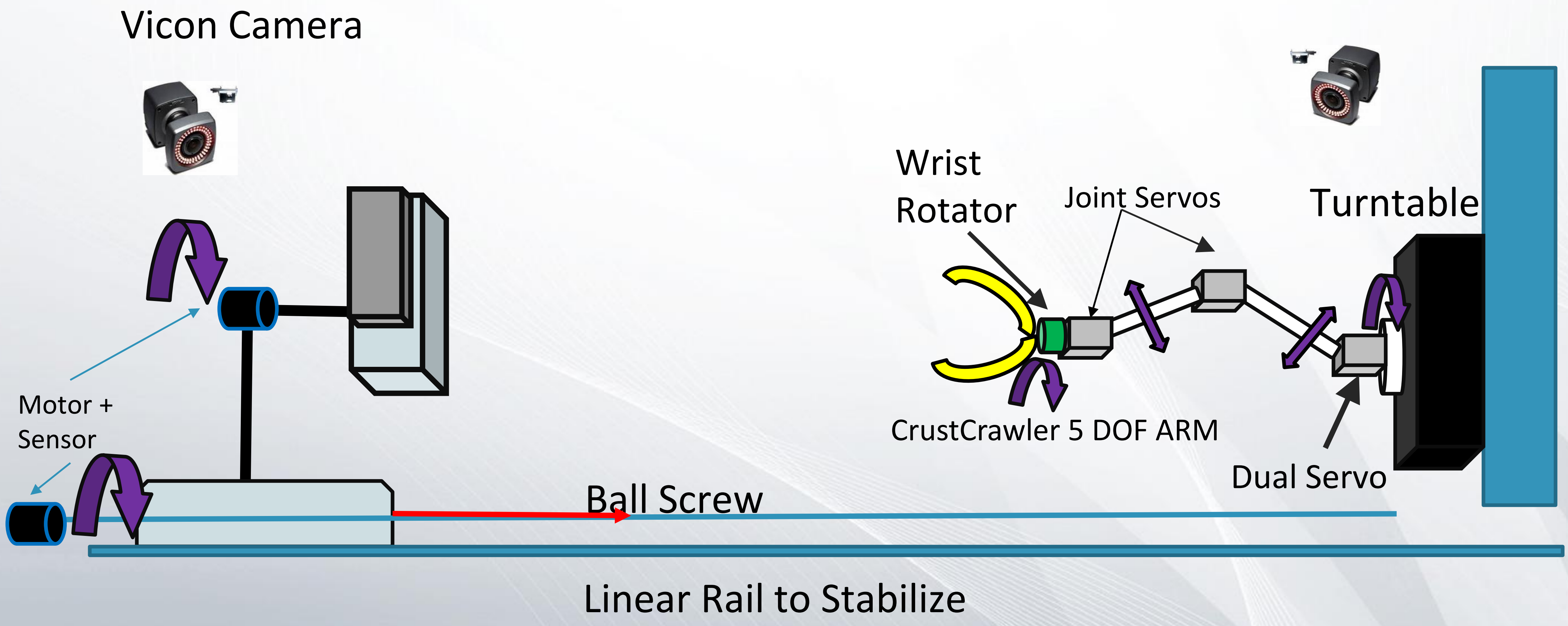
  - The CRST shall demonstrate the motion of the CubeSat analogue.
  - The CRST shall determine the relative position and attitude of the CubeSat.
  - The CRST shall calculate a capture trajectory to be used with the capture device.
  - The CRST shall command the relative motion between the CubeSat and the capture device based on the calculated capture trajectory.
  - The CRST shall execute capture of the physical CubeSat model by the capture device.

Levels of Success

Success Levels	Testbed Demonstration	Capture Device Control
Level 1	1 DOF Translation	Commanded Trajectory (open loop)
Level 2	1 DOF Rotation	Compare closed-loop data to open loop commands to validate algorithm
Level 3	1 DOF Translation and 1 DOF Rotation	Implement closed-loop algorithm (autonomy)

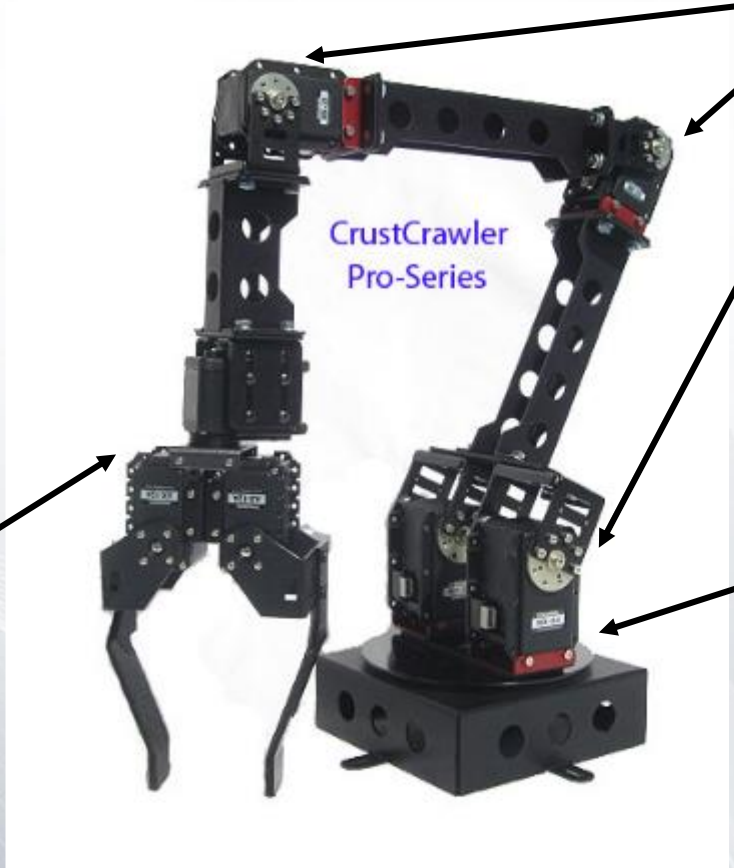
Baseline Design

Baseline Design



Capture Mechanism

- 5 Degree of Freedom Robotic Arm
  - CrustCrawler Pro Series
  - Customizable modular assembly
  - Compatible with complete line of Robotis servos for specific performance needs



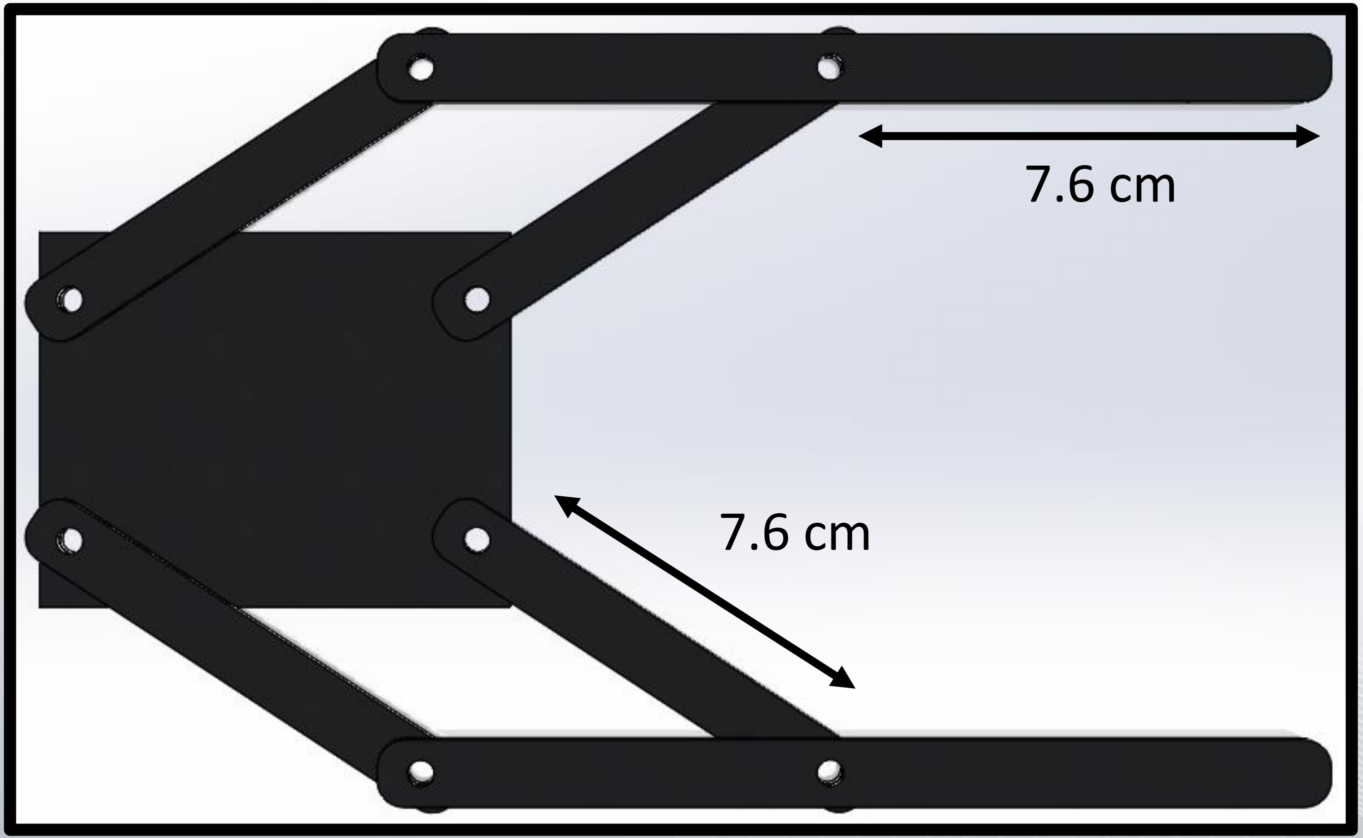
Robotis MX64 servos for joint rotation: 3 DOF

Wrist Rotate: 1 DOF

Robotis MX106 servo for turntable: 1 DOF

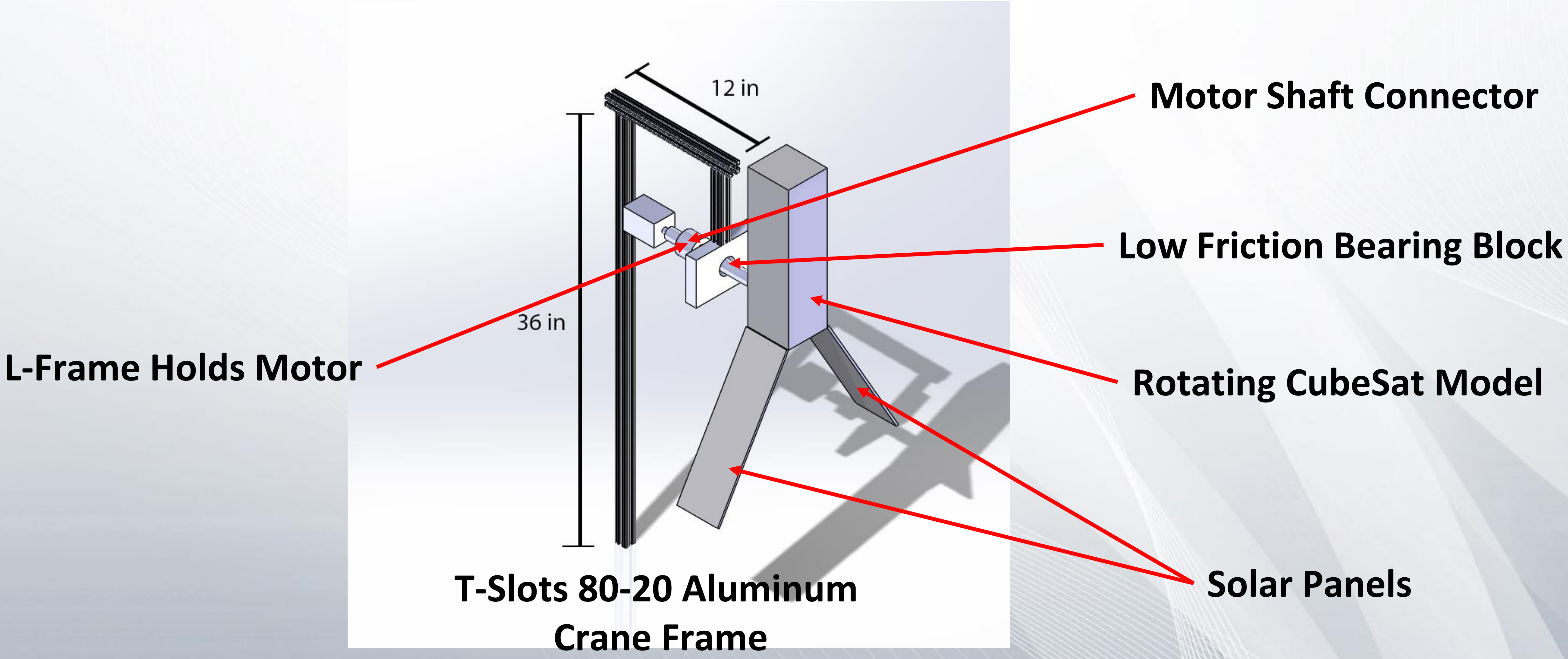
Claw Design: Claw Specifications

Four Bar Parallel Linkage



Max Opening: 15.2cm
Min Opening: 9.5 cm

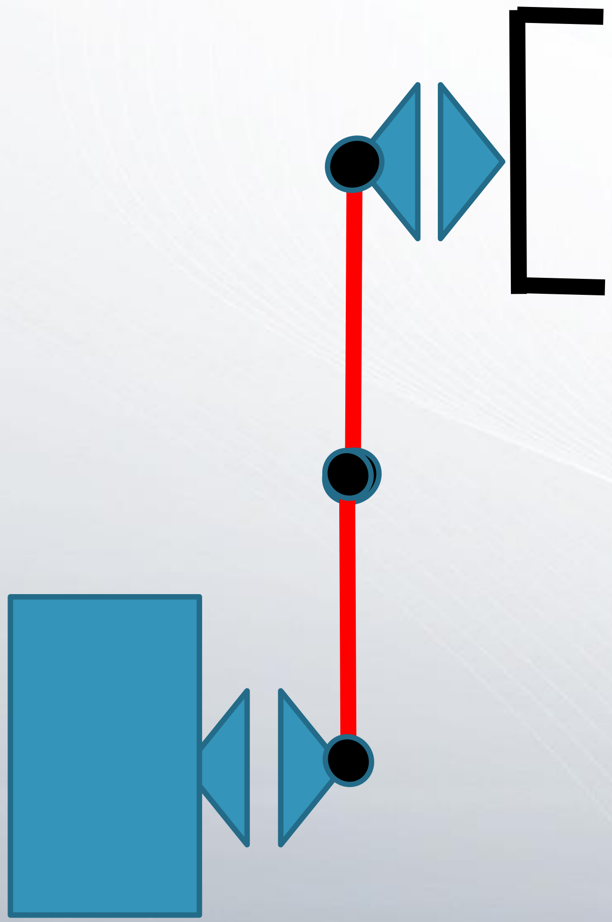
TestBed Integration: Rotation



Baseline Design: Sensors

Device	Sensing Parameters	Primary Sensor	Secondary Sensor
Robotic Arm	Angular Position	MX-series Contactless Absolute Encoder	RECUV Motion Detection Lab
	Angular Velocity	MX-series Contactless Absolute Encoder.	RECUV Motion Detection Lab
End Effectors	Angular Position	Futaba Servo with position feedback	RECUV Motion Detection Lab
	Angular Velocity	Futaba Servo with position feedback	RECUV Motion Detection Lab
	Tactile	Square FSR pressure sensor	
CubeSat	Translational Position and velocity	HEDS-5640 Optical Encoder	RECUV Motion Detection Lab
	Angular Position and Velocity	HEDS-5640 Optical Encoder	RECUV Motion Detection Lab

Baseline Algorithm



1: Align End effector with axis of rotation
2: Rotate end effector to match CubeSat rotation rate
3: Linear Translation of CubeSat to reach position
4: Command Arm to grab position
5: Command End effector to grasp CubeSat

Feasibility Analysis

Critical Project Elements

All CPEs

Hardware
Capture device end effectors
Capture device arm
Linear translation system
Rotational system
Testbed Integration

Software
Approach and capture algorithm

Testing
Autonomous Guidance System
CubeSat Capture

Rationale
Criticality
Familiarity
Complexity

Focus for PDR

Hardware
Capture device end effectors
Capture device arm

Software
Approach and capture algorithm

Critical Project Elements

CPE 1

Capture Device

Degrees of Freedom

Motor Selection
Finding minimum torque necessary for capture

Determine how to confirm capture

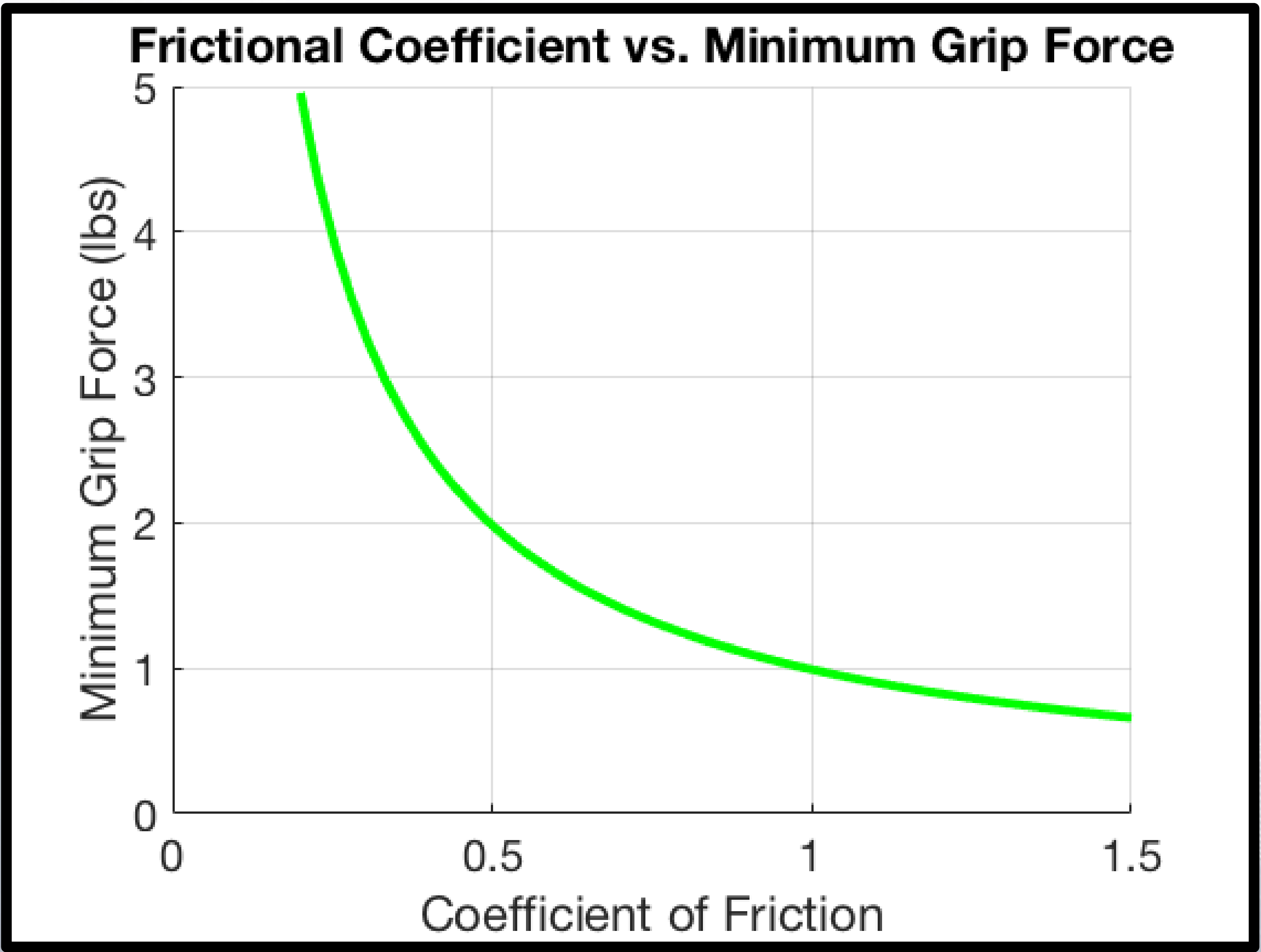
CPE 2

Algorithm

Demonstrate computing power feasibility

Show that solutions for capture exist

Claw Design: Friction Sensitivity



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

$I = 0.08$ kg-m^2

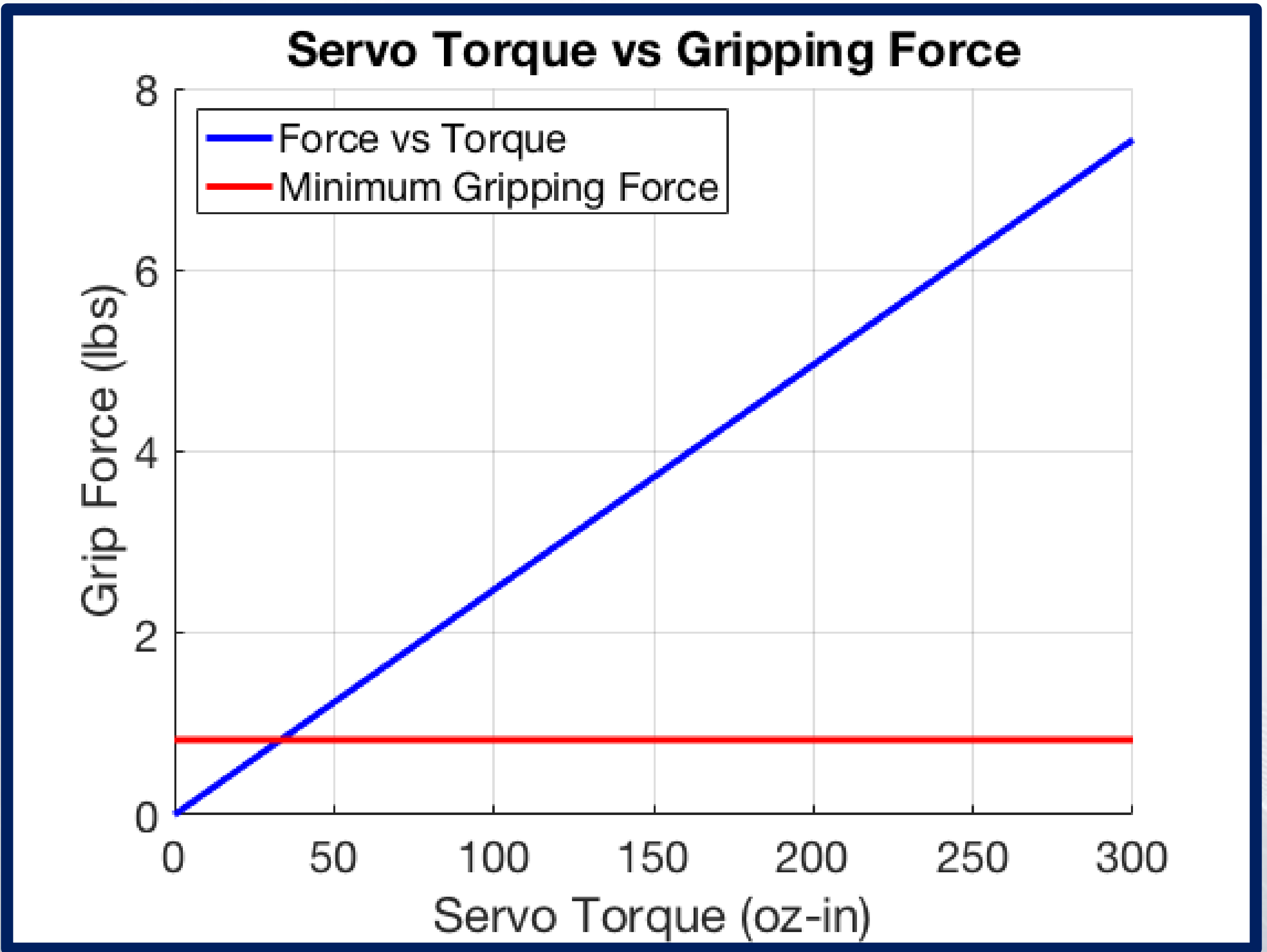
$\delta\omega = 3$ deg/s

$\delta t = 0.01$ s

$d = 4.75$ cm

FR 1.7 Execute Capture

Claw Design: Min. Servo Torque



→ $F_g = 2T/L \cos(\alpha)$

Aluminum-Aluminum

$\mu = 1.2$

$F_{min} = 0.8260$ lbs

$T_{min} = 26.07$ oz-in

Aluminum-Steel

$\mu = 0.62$

$F_{min} = 1.62$ lbs

$T_{min} = 33.02$ oz-in

FR 1.7 Execute Capture

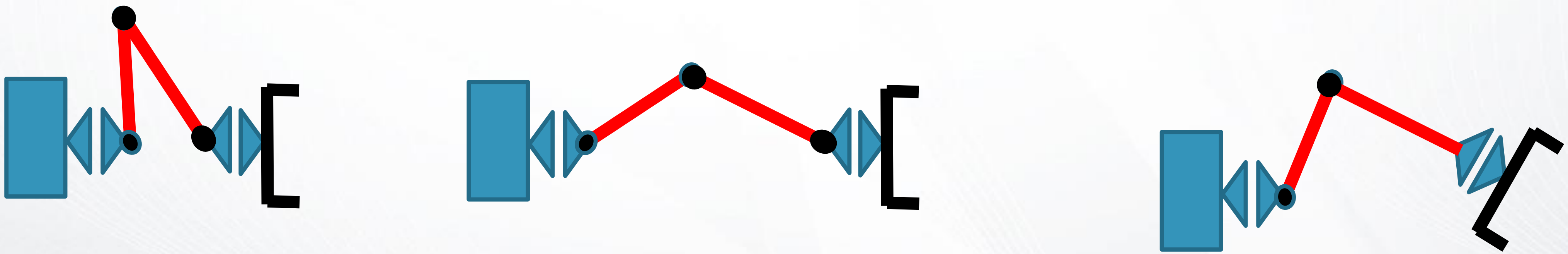
Claw Design: Closing Force Sensor

Start Closing Command → Claw Actuates → CubeSat Surface Reached → Sense force → Required Grip Force Reached?

- **Yes** → **Stop Closing Command**
- **No** → Sense force

FR 1.7 Execute Capture

Capture Deployment

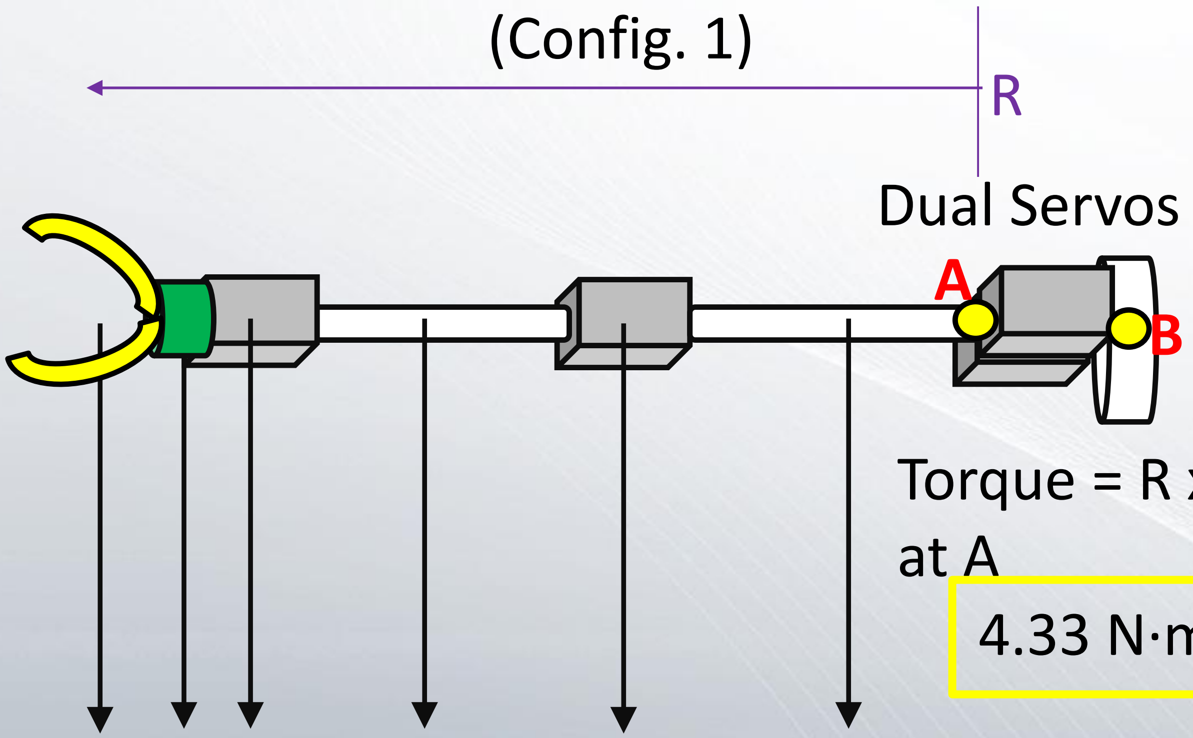


- 3 linked servos allow arm to extend out along straight path while holding end effector orientation
- 1 Turn table allows arm to reach in and out of the page
- 1 wrist rotator allows arm to match CubeSat rotation for capture
- **Total = 5 DOF**

- With only 2 linked servos, the end effector orientation cannot stay fixed as arm extends

Capture Deployment

Base Servos
(Config. 1)



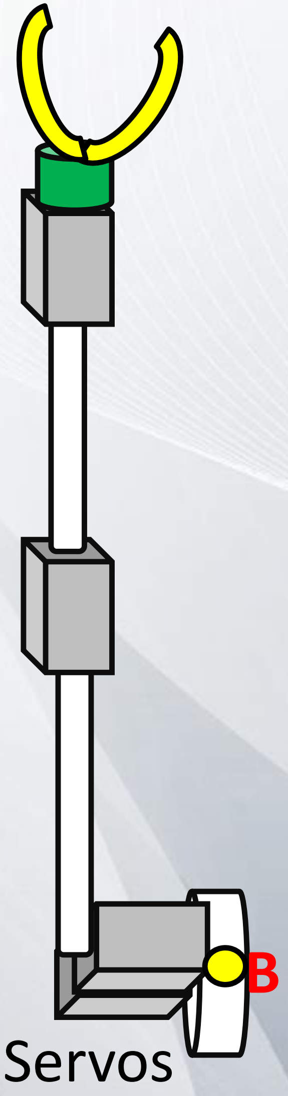
Torque = R x F at A

4.33 N·m

Weight at C.G.

Assuming:
- Homogenous pieces with CG at midpoint (except claw)

Turntable
(Config. 2)



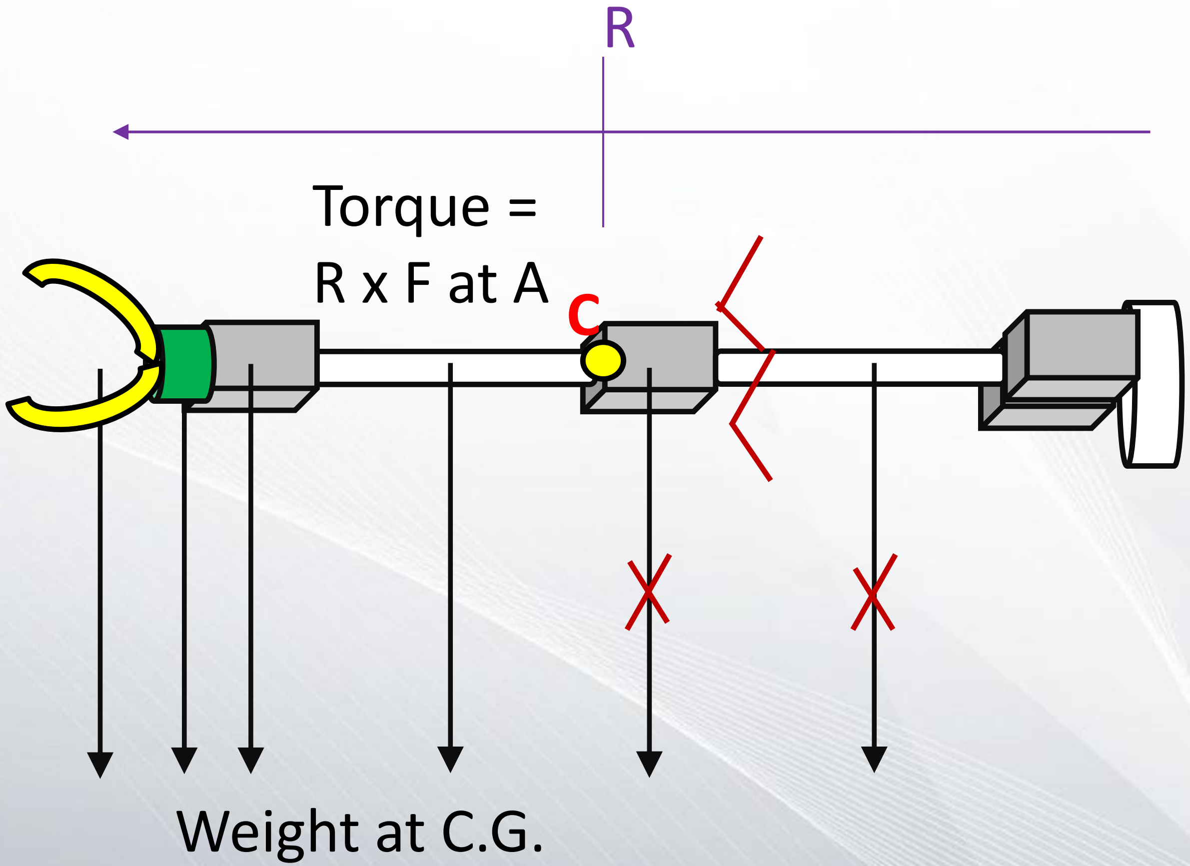
Torque at B: Arm into or out of board

4.33 N·m

Results in same torque!

FR 1.7 Execute Capture

Capture Deployment



$\boxed{1.85\ N \cdot m}$

FR 1.7
Execute
Capture

Capture Deployment

MX-64 Servo	Torque	Power
Static Condition 1	2.17 N·m	24 W
Maximum Operating Range	3 N·m	36.8 W
MX-106 Servo	**Torque**	**Power**
Static Condition 2	4.33 N·m	32.4 W
Maximum Operating Range	6 N·m	62 W

- Dual Axis Base divides torque in half: 4.33/2 = 2.17 Nm per servo
- Power = Voltage X Current
- Operation Voltage 10-14.8V(12V Recommended)
- Current Proportional to Torque

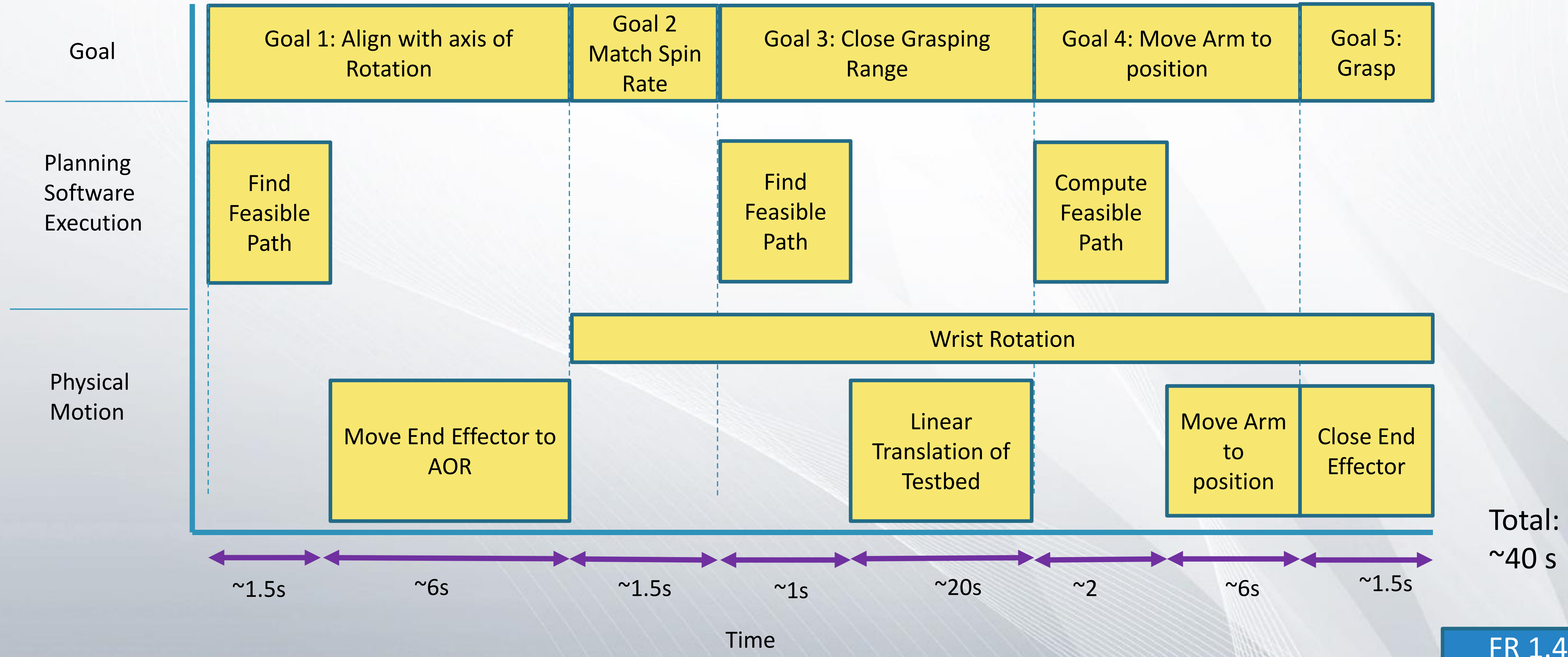
FR 1.7 Execute Capture

Capture Deployment

Peak Power: 168W

	Config. 1 Estimate(W)	Maximum(W)	Config. 2 Estimate(W)	Maximum(W)
Turntable	--	--	20.4	62
Base Servos(2)	48	73.6	--	--
Joint Servo	19.2	36.8	19.2	36.8
Joint Servo	6	36.8	6	36.8
Wrist Rotator	<4	36.8	<4	36.8
Claw Servo	<4	<10	<4	<10
Total	81.2	184	53.6	182.4
Margin	**52%**	**-10%**	**68%**	**-9%**

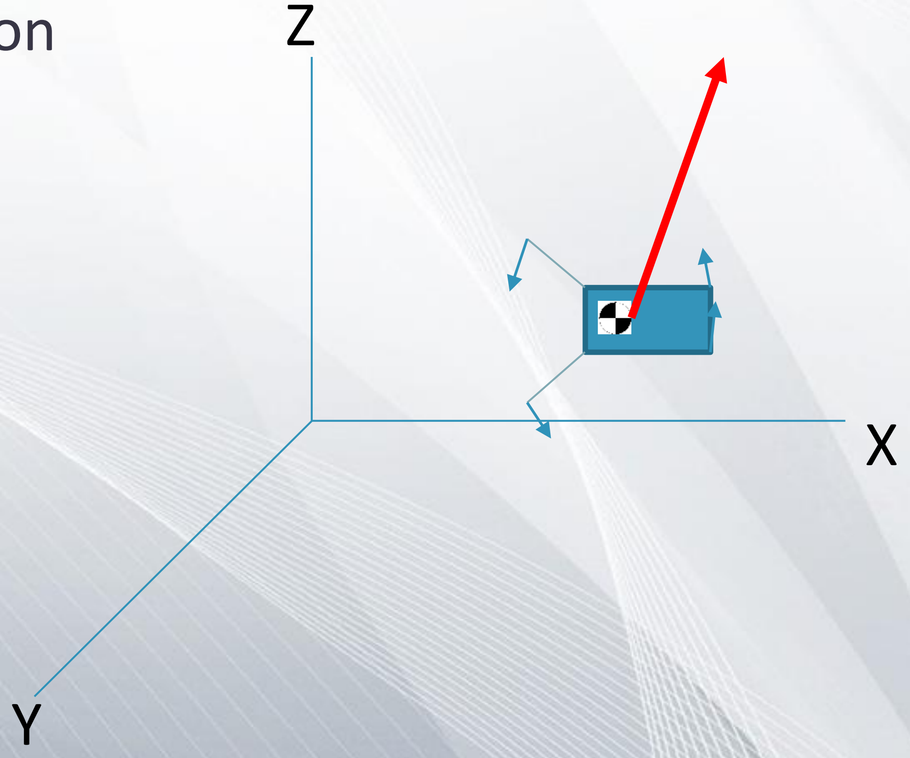
Execution Timeline



FR 1.4 Calculate Trajectory

Determine Axis of Rotation

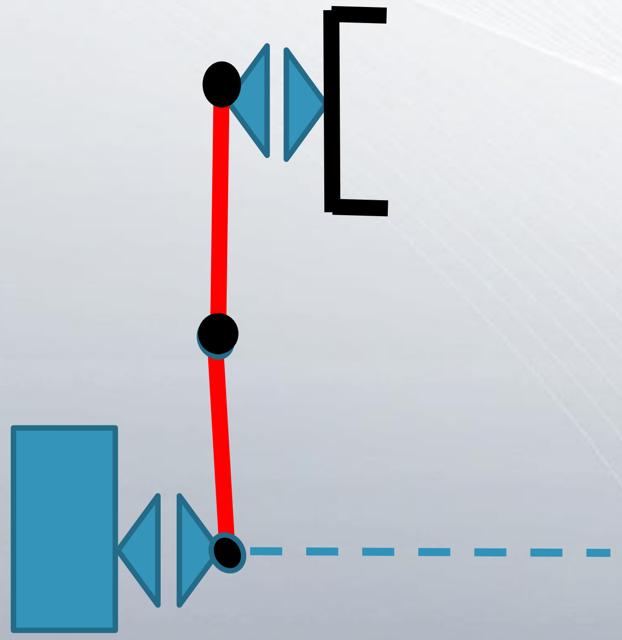
- Using VICON data
- Need to find the location of the axis of rotation in an inertial frame
- Tracking the CubeSat's rotation and translation
- Based on the sampled positions and points
- Determine the axis of rotation and vector



FR 1.4
Calculate
Trajectory

Goal 1: Align With Axis of Rotation

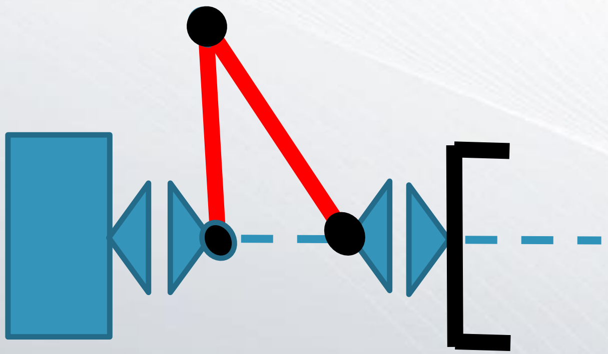
Read Sensor Data → Calculate Relative Velocity and position between End effector and CubeSat → Find Axis of Rotation → Solve IK problem for final position → Determine trajectory of each joint → Smooth out path for each subposition → Determine Commands for each position to match planned trajectory



FR 1.4
Calculate Trajectory

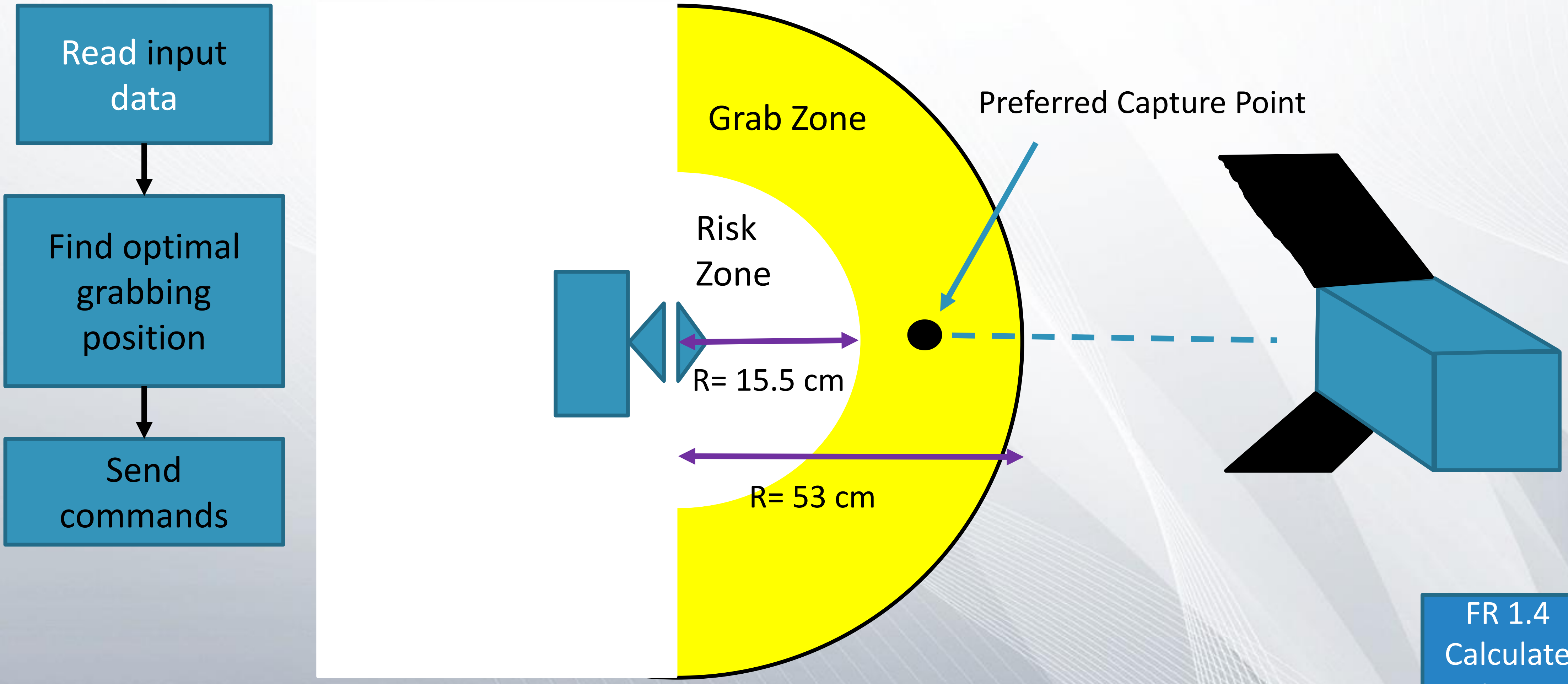
Goal 2: Match Spin Rate

Read Sensor Data → Calculate Relative Angular Position → Command $\Delta\theta_{desired}$ to zero → Controller



FR 1.4 Calculate Trajectory

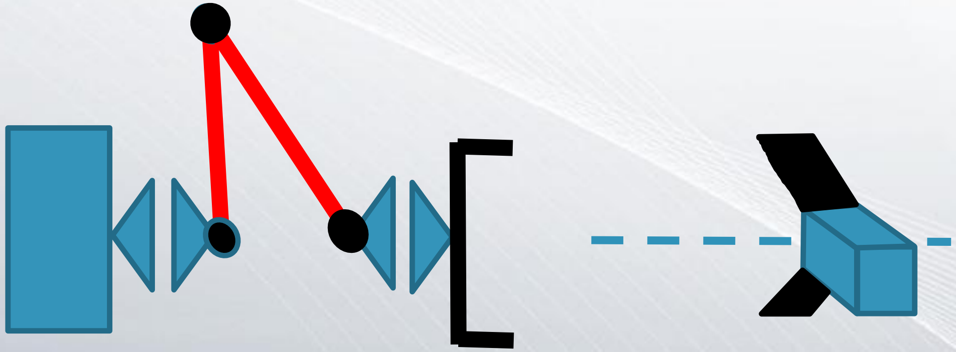
Goal 3: Linear Translation



FR 1.4 Calculate Trajectory

Goal 4: Move to Grasp Location

Read Sensor Data → Calculate Relative Velocity and position between End effector and Cubesat → Solve IK problem for final position → Find Trajectory of each joint to reach final position → Smooth out path for each subposition → Send Commands for each position to match planned trajectory

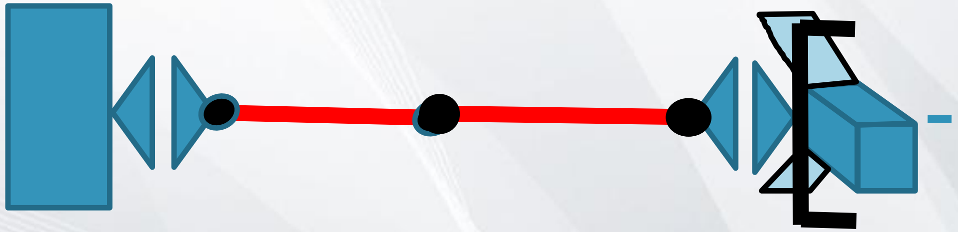


FR 1.4 Calculate Trajectory

Goal 5: Grab It!

Read Sensor Data → Force grip greater than 0.82 lbf → If Grip force less than Value → Command to close slightly more

Force grip greater than 0.82 lbf → Stop closing end effector



FR 1.4 Calculate Trajectory

Resources

MPK-Motion Planning Kit

C++ library for motion planning

OpenRAVE Software

- Provides an environment for testing, developing, and deploying motion planning algorithms in real-world robotics applications
- IK_Fast

Trajectory Planning

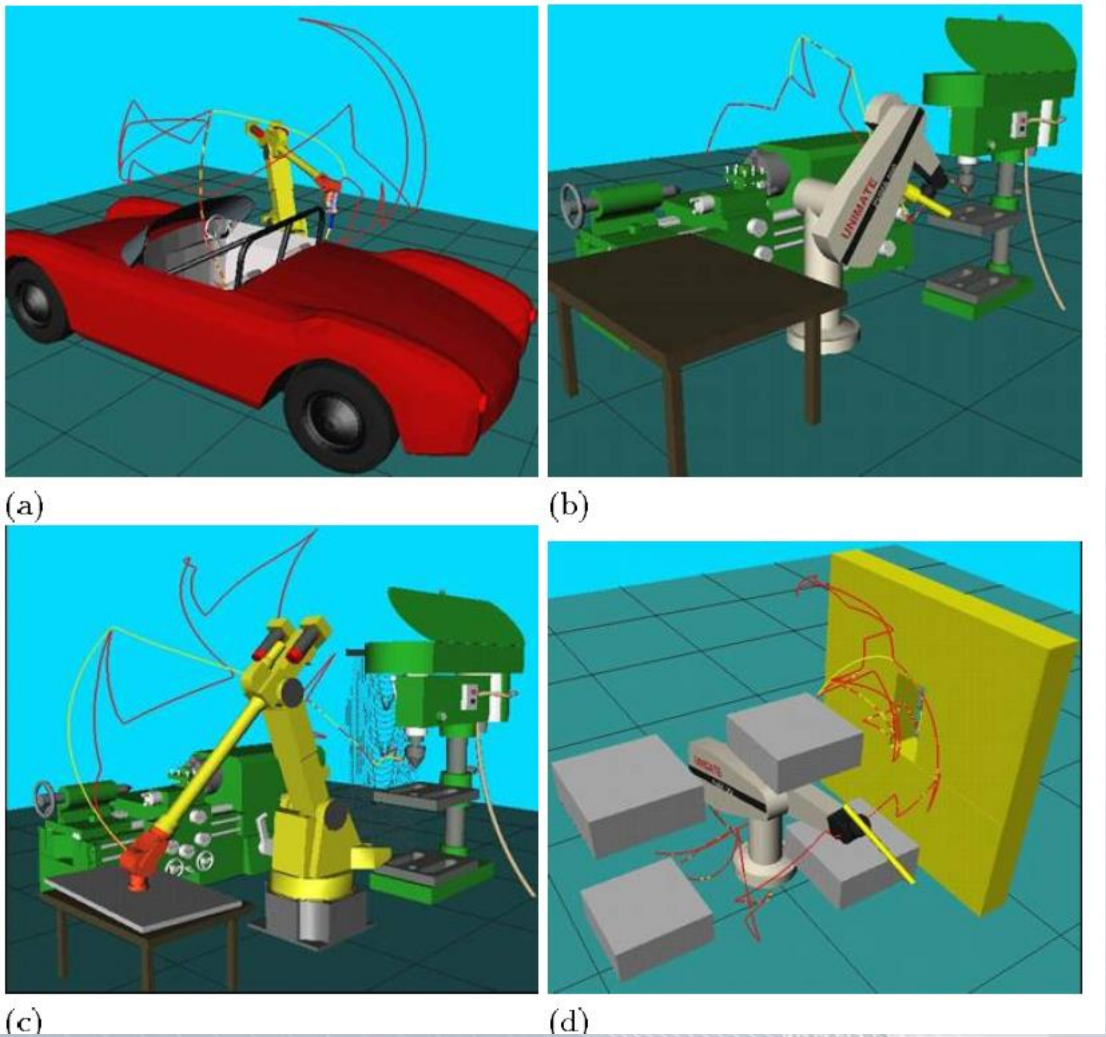
FR 1.4
Calculate Trajectory

Feasibility: Computing Power

- MPK: 1GHz Pentium 3 Processor
- 3.4 Gflops

Situation	DOF	Time to compute solution [sec]
A	4	0.6
B	5	0.17
C	5	4.42
D	5	6.99

- Varies depending on complexity of obstacle space



FR 1.4 Calculate Trajectory

Feasibility: Computing Power

For this project:

Not many obstacles

5 DOF arm

Safe to say: Less than a minute to compute a solution for each goal

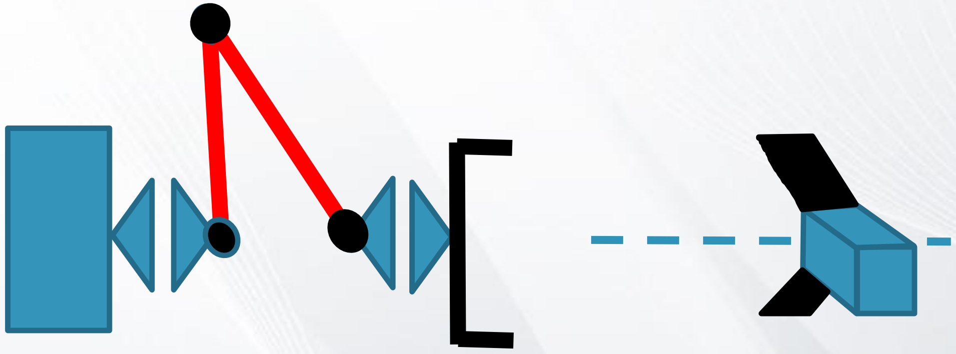
Much more powerful processors (x25 power)

But:

Must read information from sensors

Interpret the data

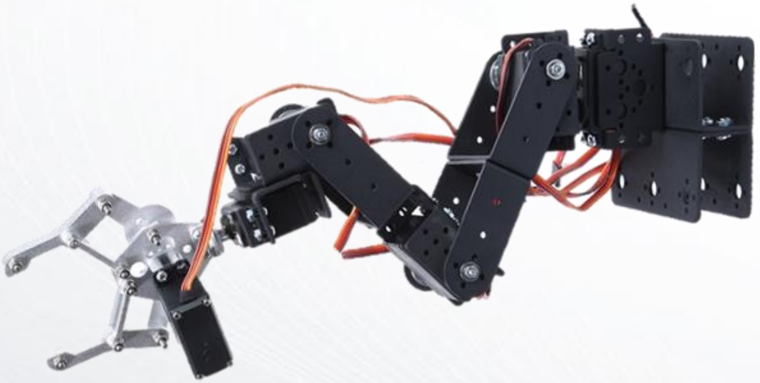
Then solve the trajectory



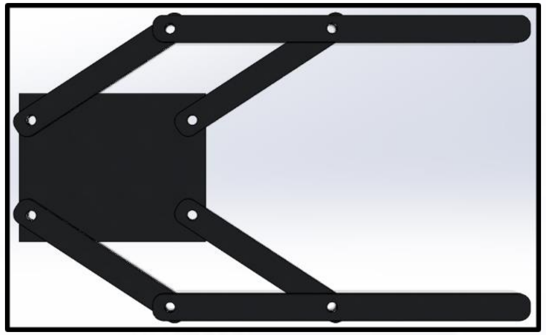
FR 1.4 Calculate Trajectory

Project Summary

Design Recap



- Degrees of freedom satisfy solution space
- Capture device arm remains in power budget



- Claw provides sufficient gripping force to maintain capture of the CubeSat without inflicting damage

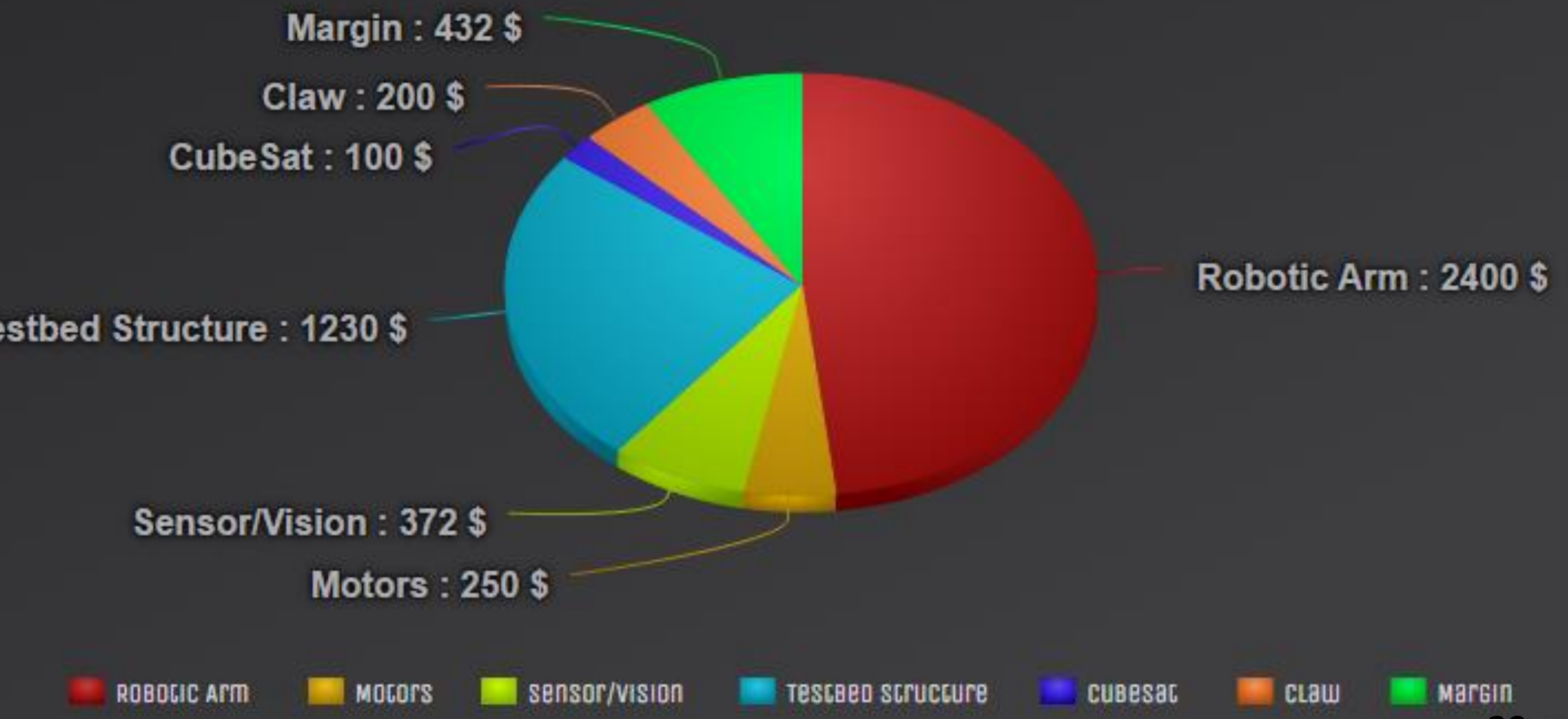
Algorithm

- Capture algorithm can solve IK problem within a successful time

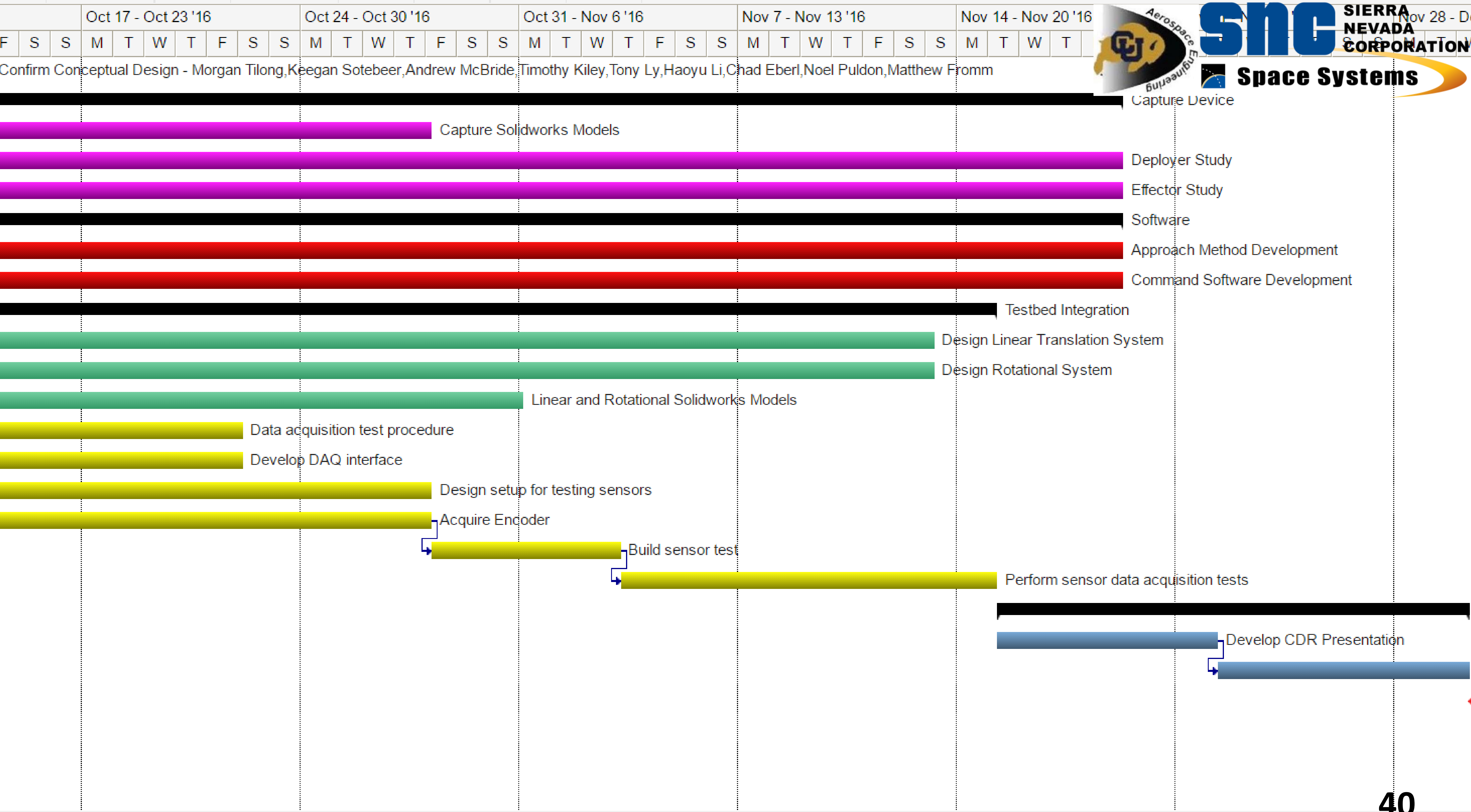
TestBed

- Sensors provide the position and velocity data necessary to calculate the variables for capture algorithm

COST BUDGET

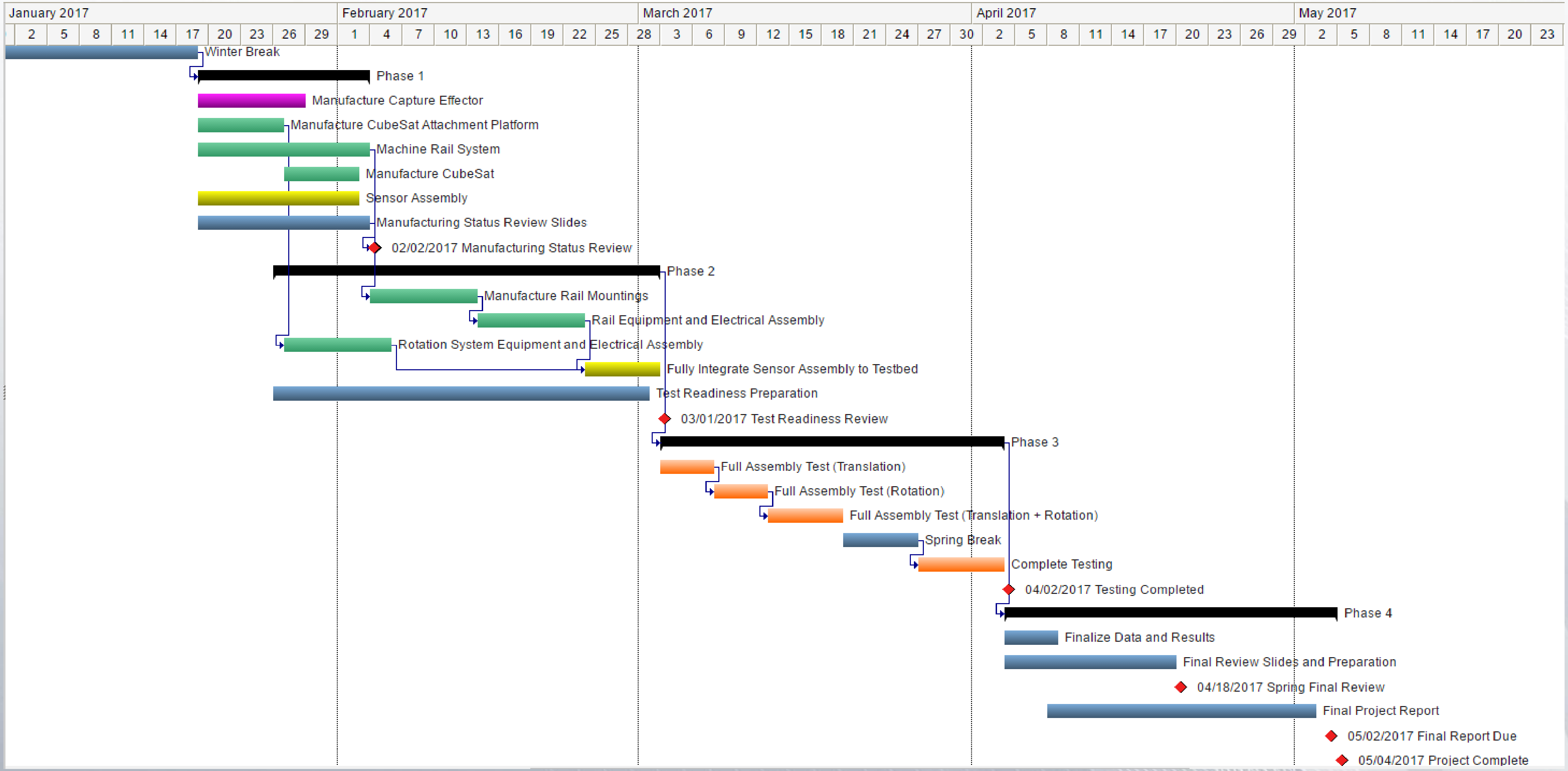


Margin : 432 $
Claw : 200 $
CubeSat : 100 $
estbed Structure : 1230 $
Sensor/Vision : 372 $
Motors : 250 $
Robotic Arm : 2400 $
Robotic Arm
Motors
Sensor/Vision
Testbed Structure
Cubesat
Claw
Margin



SIERRA NEVADA CORPORATION Space Systems

Schedule



January 2017
February 2017
March 2017
April 2017
May 2017
Winter Break
Phase 1
Manufacture Capture Effector
Manufacture CubeSat Attachment Platform
Machine Rail System
Manufacture CubeSat
Sensor Assembly
Manufacturing Status Review Slides
02/02/2017 Manufacturing Status Review
Phase 2
Manufacture Rail Mountings
Rail Equipment and Electrical Assembly
Rotation System Equipment and Electrical Assembly
Fully Integrate Sensor Assembly to Testbed
Test Readiness Preparation
03/01/2017 Test Readiness Review
Phase 3
Full Assembly Test (Translation)
Full Assembly Test (Rotation)
Full Assembly Test (Translation + Rotation)
Spring Break
Complete Testing
04/02/2017 Testing Completed
Phase 4
Finalize Data and Results
Final Review Slides and Preparation
04/18/2017 Spring Final Review
Final Project Report
05/02/2017 Final Report Due
05/04/2017 Project Complete

Acknowledgements

Team CASCADE would like to acknowledge PAB members Professor Jackson and Professor Nabity for their continued assistance as we work to understand and develop solutions for this project. Also, we would like to acknowledge AES faculty staff Trudy Schwartz, Matt Rhode, and Bobby Hodgkinson.

References

- Sánchez, Gildardo, and Jean-Claude Latombe. "A Single-Query Bi-Directional Probabilistic Roadmap Planner with Lazy Collision Checking." *Springer Tracts in Advanced Robotics Robotics Research* (n.d.): 403-17. Web.

- LaValle, Steven Michael. *Planning Algorithms*. Cambridge: Cambridge UP, 2006. Print.
- Proud, Ryan W. ,Hart Jeremy J., Mrozinksi, RichardB."Methods for Determining the Levels of Autonomy to Design into a Human Spaceflight Vehicle: A function of Specific Approach" NASA Johnson Space Center (n.d):Web.
- *Ball Bearing Frictional Torque*. SMB Bearings, n.d. Web. 5 Oct. 2016. <http://www.smbbearings.com/technical/bearing-frictional-torque.html>.

- *INCH SERIES CERAMIC BALL BEARINGS*. MicroBlue Bearings, n.d. Web. 3 Oct. 2016. <http://www.microbluebearings.com/categories/CERAMIC-BALL-BEARINGS/INCH-SERIES-CERAMIC-BALL-BEARINGS/>.

- *ClearPath*. Teknic, n.d. Web. 29 Sept. 2016. <https://www.teknic.com/products/clearpath-brushless-dc-servo-motors/>.

- *Intro 101: Building with 80/20*. 80/20 Inc., n.d. Web. 8 Oct. 2016. <https://www.8020.net/university-product-basics>.

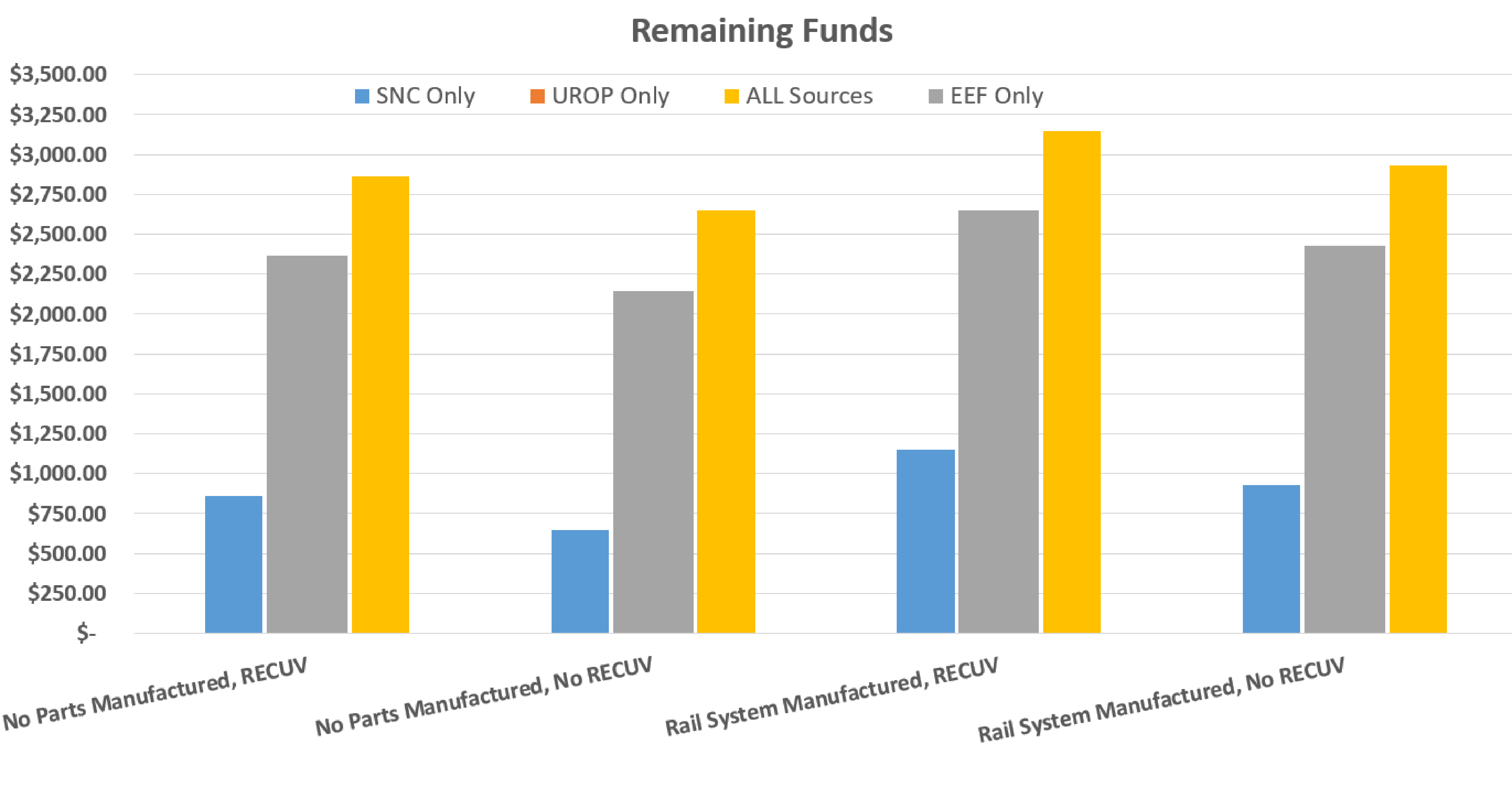
Thank you from Team CASCADE!

Matt Fromm	PM
Noel Puldon	Systems
Tim Kiley	Software
Andrew McBride	Testbed
Tony Ly	Algorithm
Haoyu Li	Dynamics
Chad Eberl	Mechanical
Keegan Sotebeer	Controls
Morgan Tilong	CFO & Instrumentation

Budget

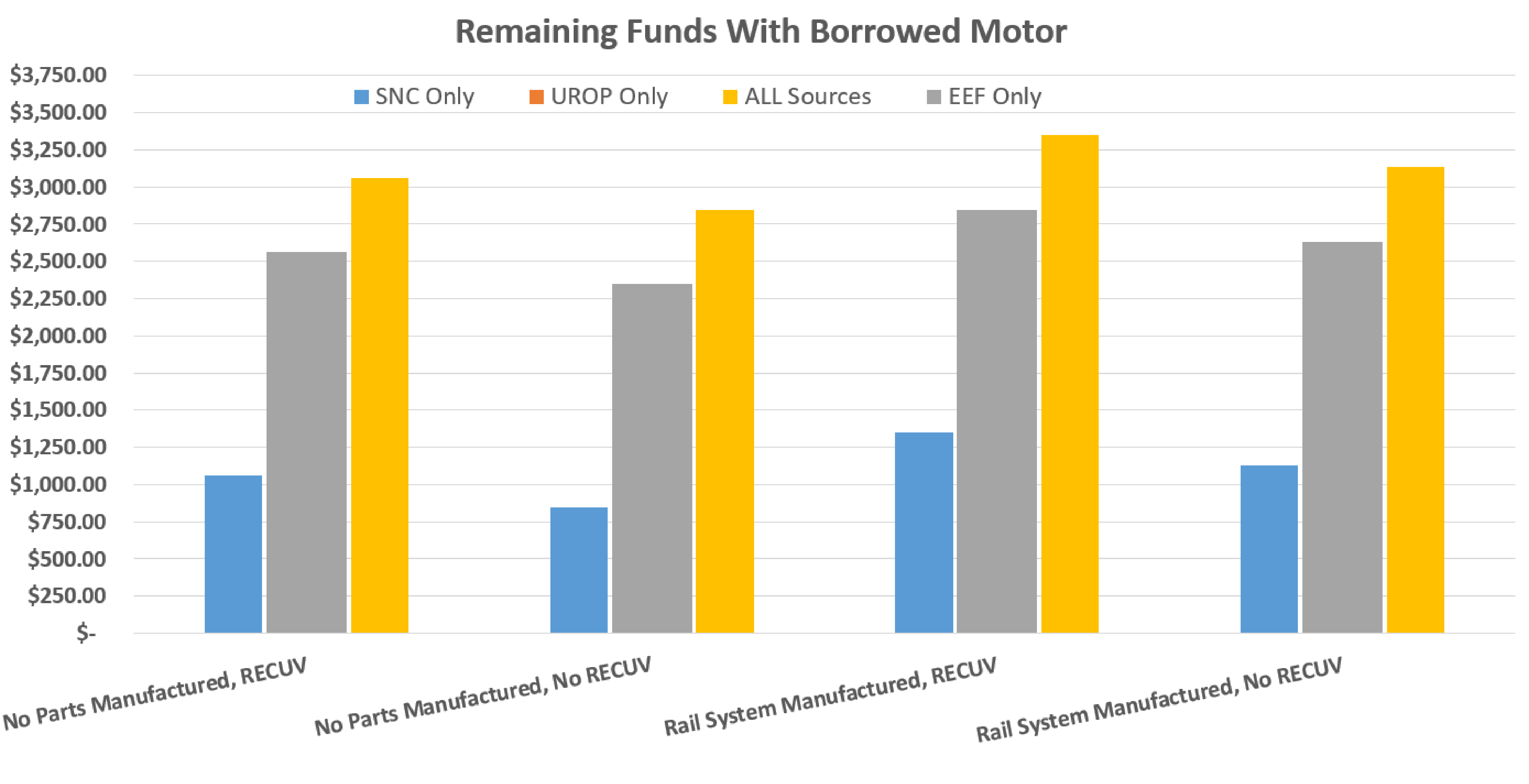
Item	Item Type	Cost	Supplier	Quantity	Total Amount	Manufacturing Coefficient	Total (Manufactured)
Hardware							
4 DOF arm	arm	$2,401.90	CrustCrawler	1	$2,401.90	1	$2,401.90
Ball Screw	Ball Screw	$200.00	McMaster	1	$200.00	0.7	$140.00
Ball Screw Nut	Ball Screw Nut	$250.00	McMaster	1	$250.00	0.7	$175.00
End Mounting Block	end mounting block	$500.00	McMaster	1	$500.00	0.7	$350.00
Stepper Motor	Motor	$50.00	Pololu	1	$50.00	1	$50.00
Gripper Servo	Servo	$100.00		1	$100.00	1	$100.00
Brushless DC Motor	Motor	$200.00	Potentially Borrowed	1	$200.00	1	$200.00
Linear Rails	linear rails	$50.00		2	$100.00	1	$100.00
Low Friction Bearing	Bearing	$100.00	MicroBlue Bearings	1	$100.00	1	$100.00
T-Slots 80-20	linear rails	$60.00	80/20 Inc.	1	$60.00	1	$60.00
Fasteners	Fasteners	$20.00	80/20 Inc.	1	$20.00	1	$20.00
Electronics							
Encoders		$40.00		2	$80.00	1	$80.00
Pressure Sensor		$20.00		2	$40.00	1	$40.00
Rangefinder		$35.00		1	$35.00	1	$35.00
CMU cam		$67.00	Robotshop	1	$67.00	1	$67.00
Lidar-lite-v3		$150	sparqfun	1	$150.00	1	$150.00
SNC Contribution	$5,000			Total Cost	$4,353.90		$4,068.90
EEF Contribution	$1,500						
UROP Contribution	$500						
		No Parts Manufactured, RECUV Utilized		**Motor Borrowed**	**Rail System Manufactured, RECUV Utilized**		**Motor Borrowed**
		Margin (no additional funding)	$863.10	$1,063.10	Margin (no additional funding)	$1,148.10	$1,348.10
		Margin (EEF approved)	$2,363.10	$2,563.10	Margin (EEF approved)	$2,648.10	$2,848.10
		Margin (UROP approved)	$1,363.10	$1,563.10	Margin (UROP approved)	$1,648.10	$1,848.10
		Margin (all sources included)	$2,863.10	$3,063.10	Margin (all sources included)	$3,148.10	$3,348.10
		No Parts Manufactured, RECUV Not Utilized		**Motor Borrowed**	**Rail System Manufactured, RECUV Not Utilized**		**Motor Borrowed**
		Margin (no additional funding)	$646.10	$846.10	Margin (no additional funding)	$931.10	$1,131.10
		Margin (EEF approved)	$2,146.10	$2,346.10	Margin (EEF approved)	$2,431.10	$2,631.10
		Margin (UROP approved)	$1,146.10	$1,346.10	Margin (UROP approved)	$1,431.10	$1,631.10
		Margin (all sources included)	$2,646.10	$2,846.10	Margin (all sources included)	$2,931.10	$3,131.10

Budget



Remaining Funds
SNC Only
UROP Only
ALL Sources
EEF Only
$3,500.00
$3,250.00
$3,000.00
$2,750.00
$2,500.00
$2,250.00
$2,000.00
$1,750.00
$1,500.00
$1,250.00
$1,000.00
$750.00
$500.00
$250.00
$-
No Parts Manufactured, RECUV
No Parts Manufactured, No RECUV
Rail System Manufactured, RECUV
Rail System Manufactured, No RECUV

Budget

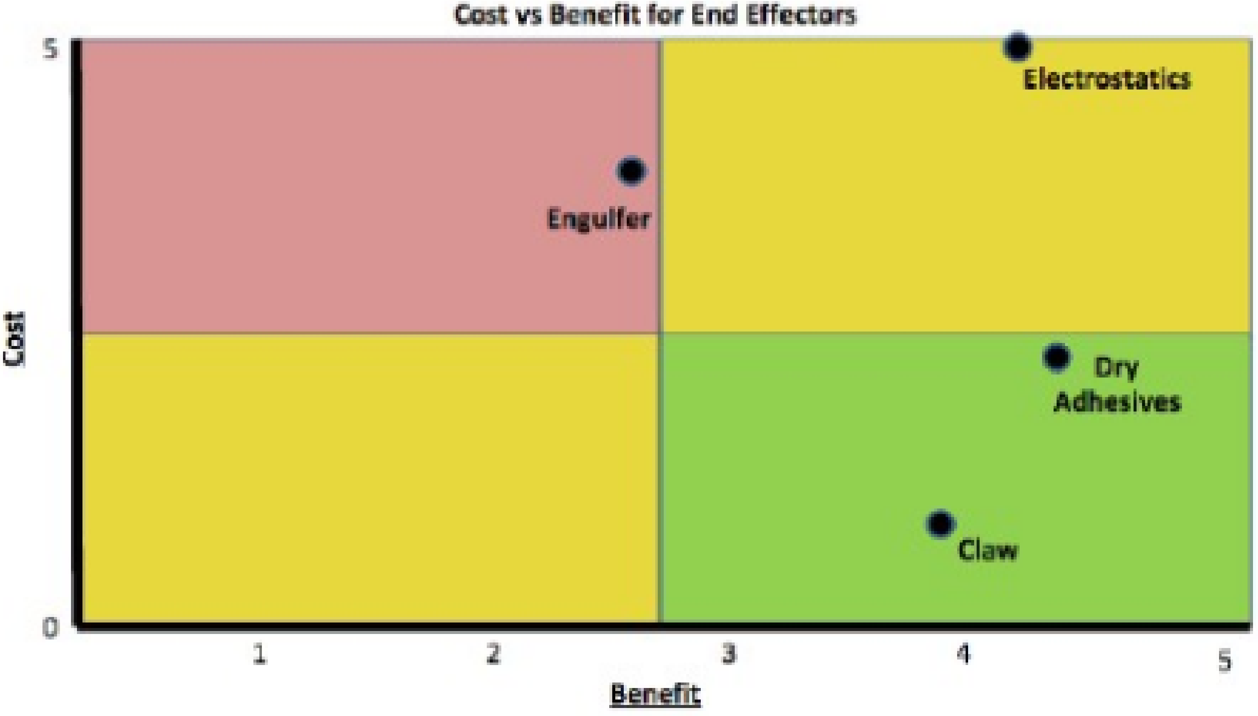


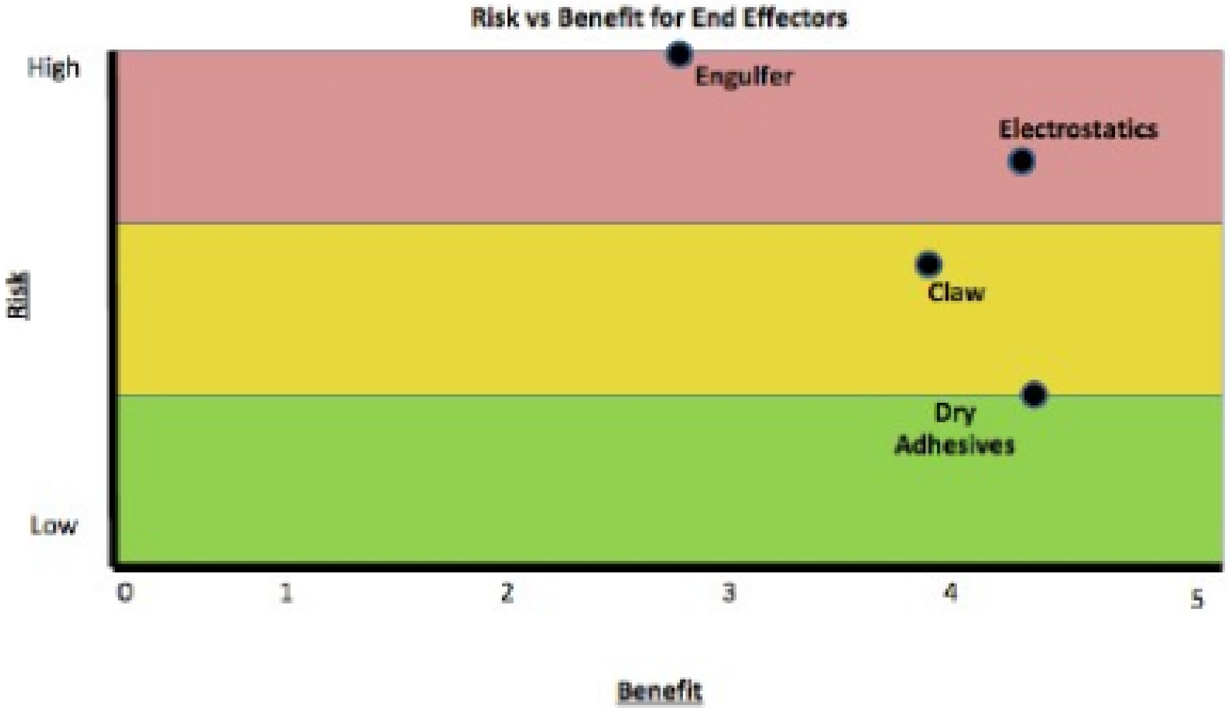
Remaining Funds With Borrowed Motor
SNC Only
UROP Only
ALL Sources
EEF Only
$3,750.00
$3,500.00
$3,250.00
$3,000.00
$2,750.00
$2,500.00
$2,250.00
$2,000.00
$1,750.00
$1,500.00
$1,250.00
$1,000.00
$750.00
$500.00
$250.00
$-
No Parts Manufactured, RECUV
No Parts Manufactured, No RECUV
Rail System Manufactured, RECUV
Rail System Manufactured, No RECUV

End Effector Trade

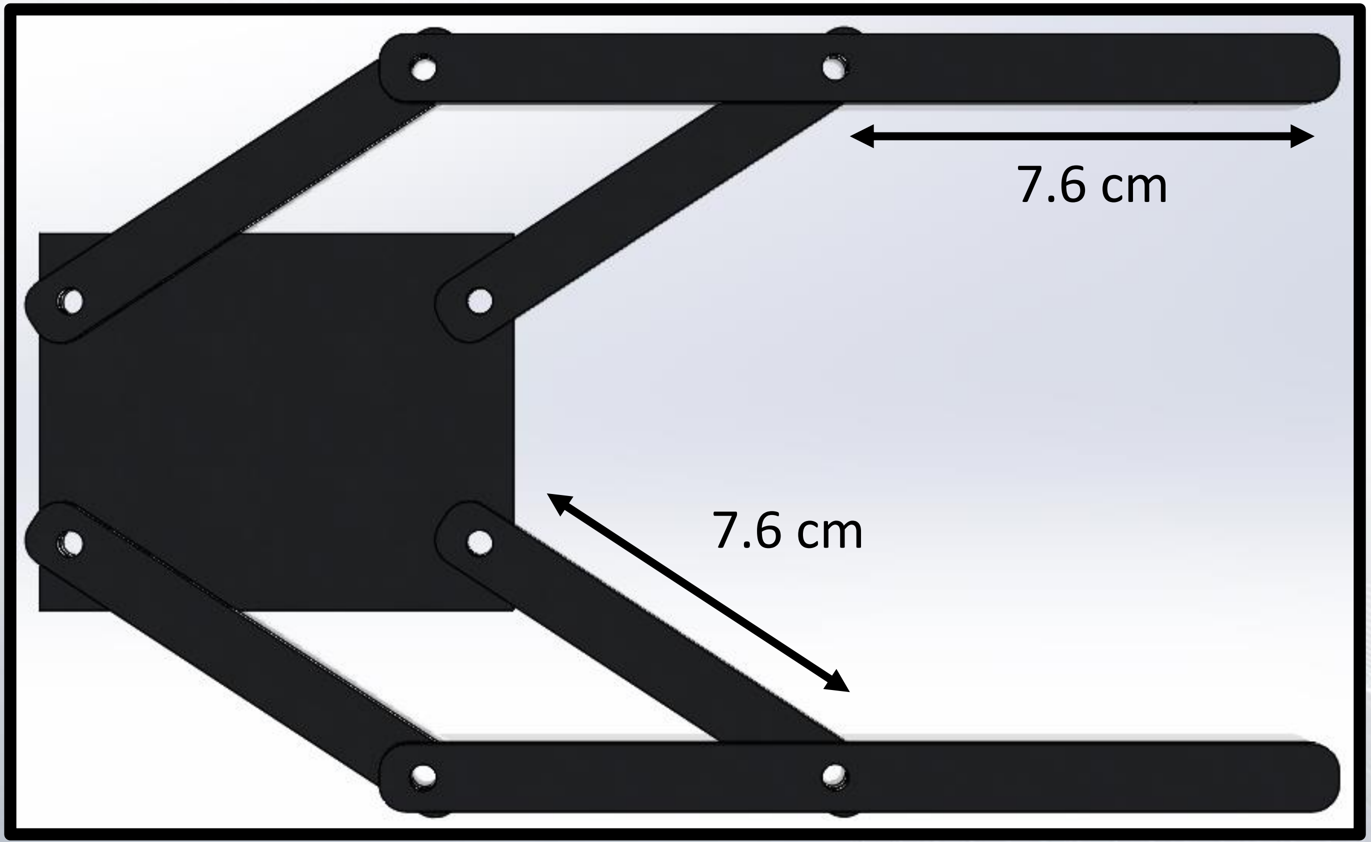
End Effector Trade		Claw		Dry Adhesive		Engulfer		Electrostatics	
Criteria	%	Raw	W	Raw	W	Raw	W	Raw	W
Mass	0.1	5	0.5	4	0.4	4	0.4	3	0.3
Volume	0.1	4	0.4	3	0.3	5	0.5	3	0.3
Release Ability	0.3	5	1.5	5	1.5	1	0.3	5	1.5
Approach Difficulty	0.3	3	0.9	4	1.2	5	1.5	4	1.2
Reliability	0.2	3	0.6	5	1	1	0.2	5	1
TOTAL			3.9		4.4		2.9		4.3

End Effector Trade





Claw Design: Claw Specifications



Total Volume: 96 cm^3

Material	Mass (grams)	Cost ($)
1060 Aluminum	**260**	$6.81
Carbon Fiber	**170**	$19.20
ABS Plastic	**98**	$4.51

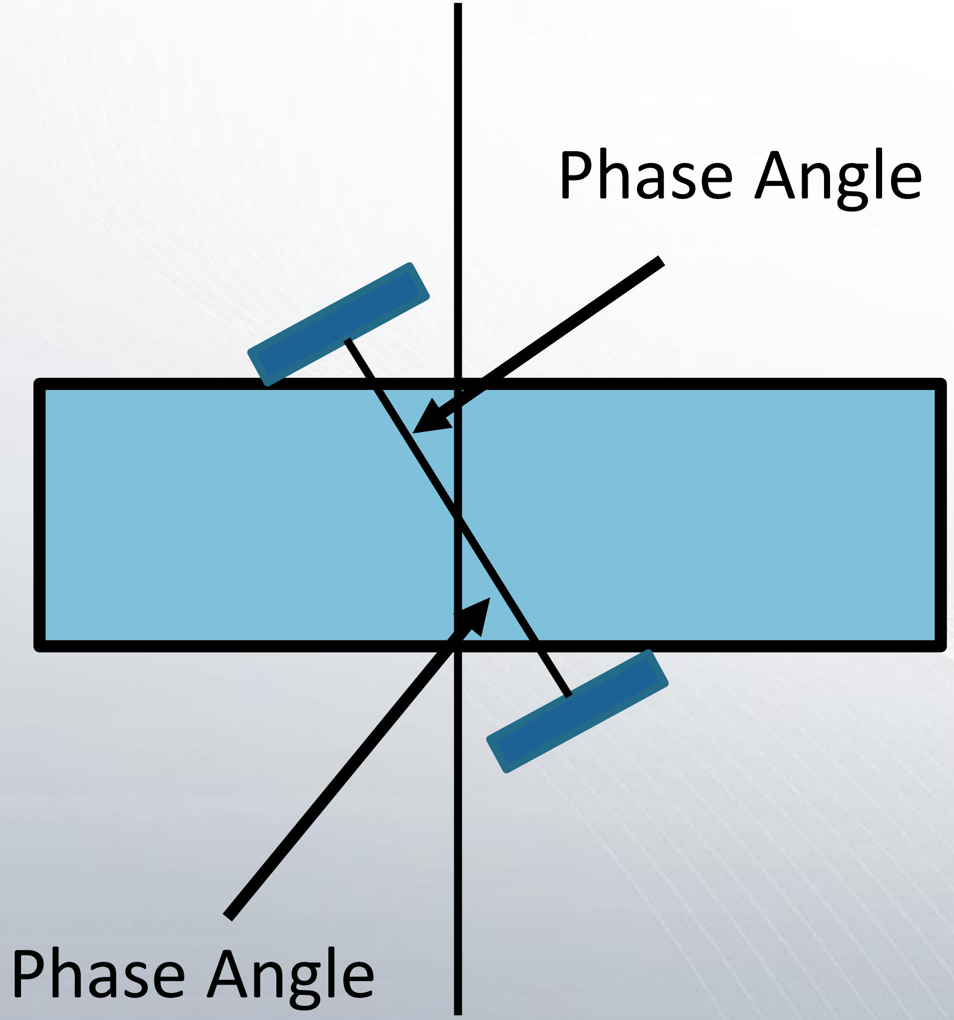
Required Servo: ~26 oz-in torque

Cost: ~$60

Total Cost: ~$70

Claw Design

Phase Error



For an opening of 15.2 cm and a claw width of 4.6 cm the maximum allowable phase angle is <u>36.4 degrees.</u>

<u>Rotation Constraints</u>

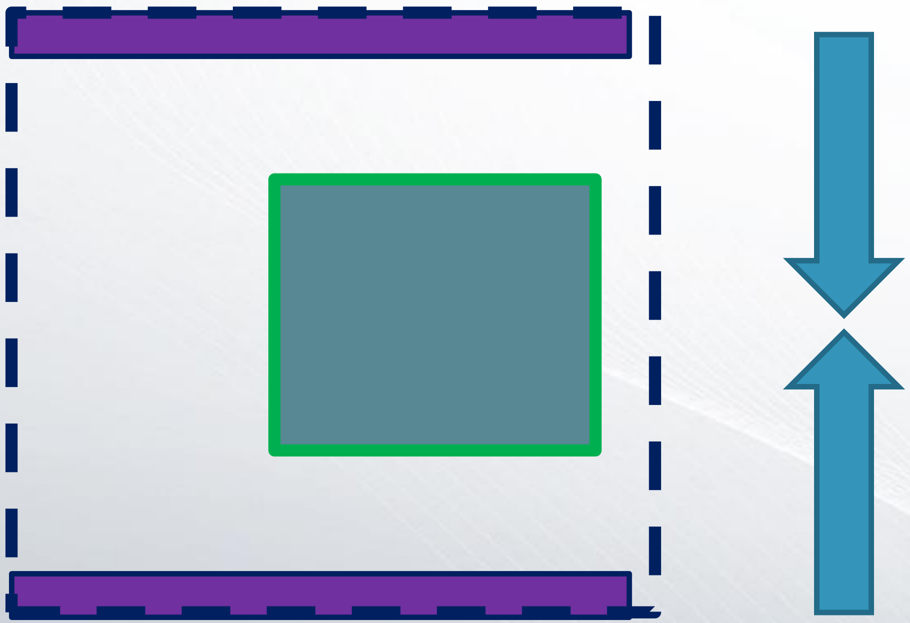
- Wrist Servo Minimum = 0.114 RPM
- Wrist Servo Maximum = 63 RPM
- <u>CubeSat Rotation = 0.5 RPM</u>

<u>Error</u>

- CubeSat Max Encoder Error = +/- 0.6667°

Design Options: End Effector

Parallel Closing:

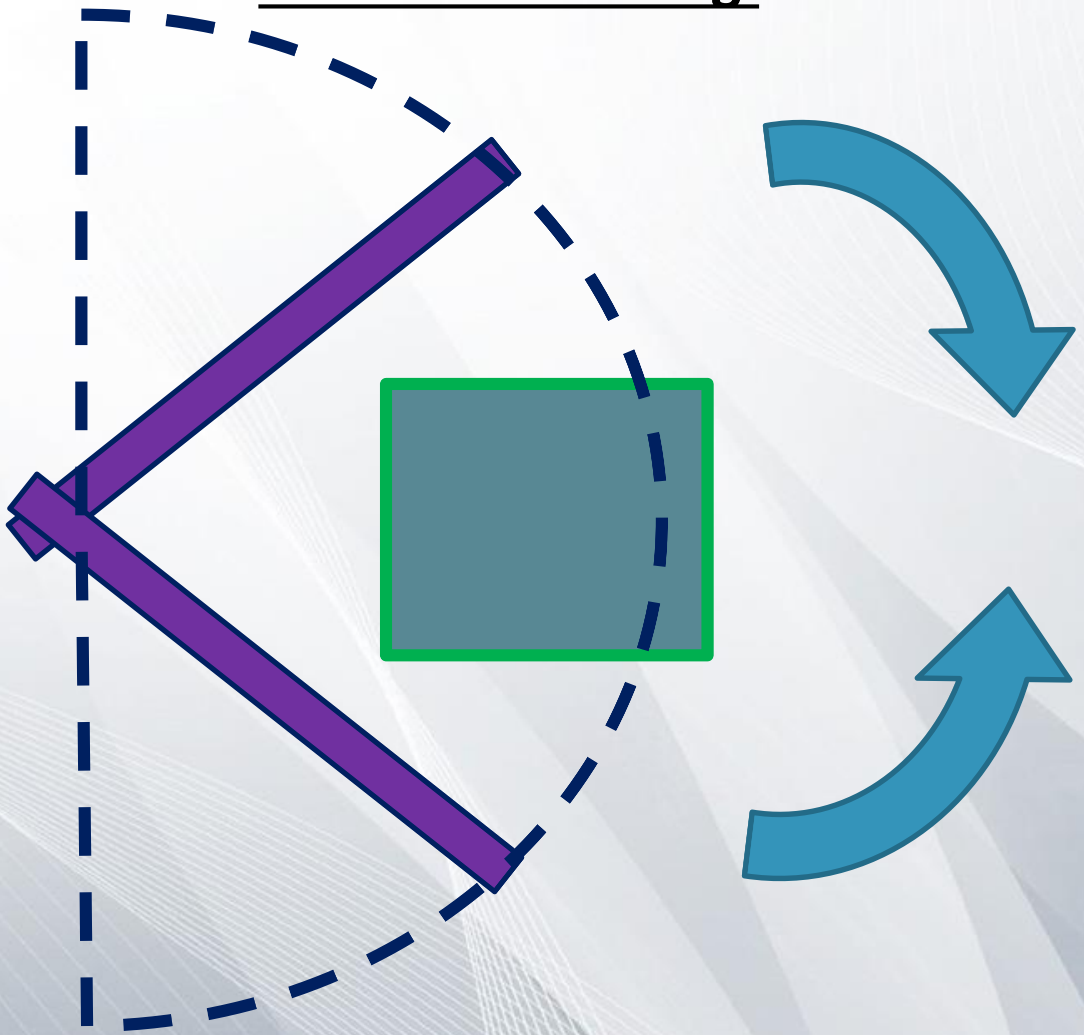


Pros:

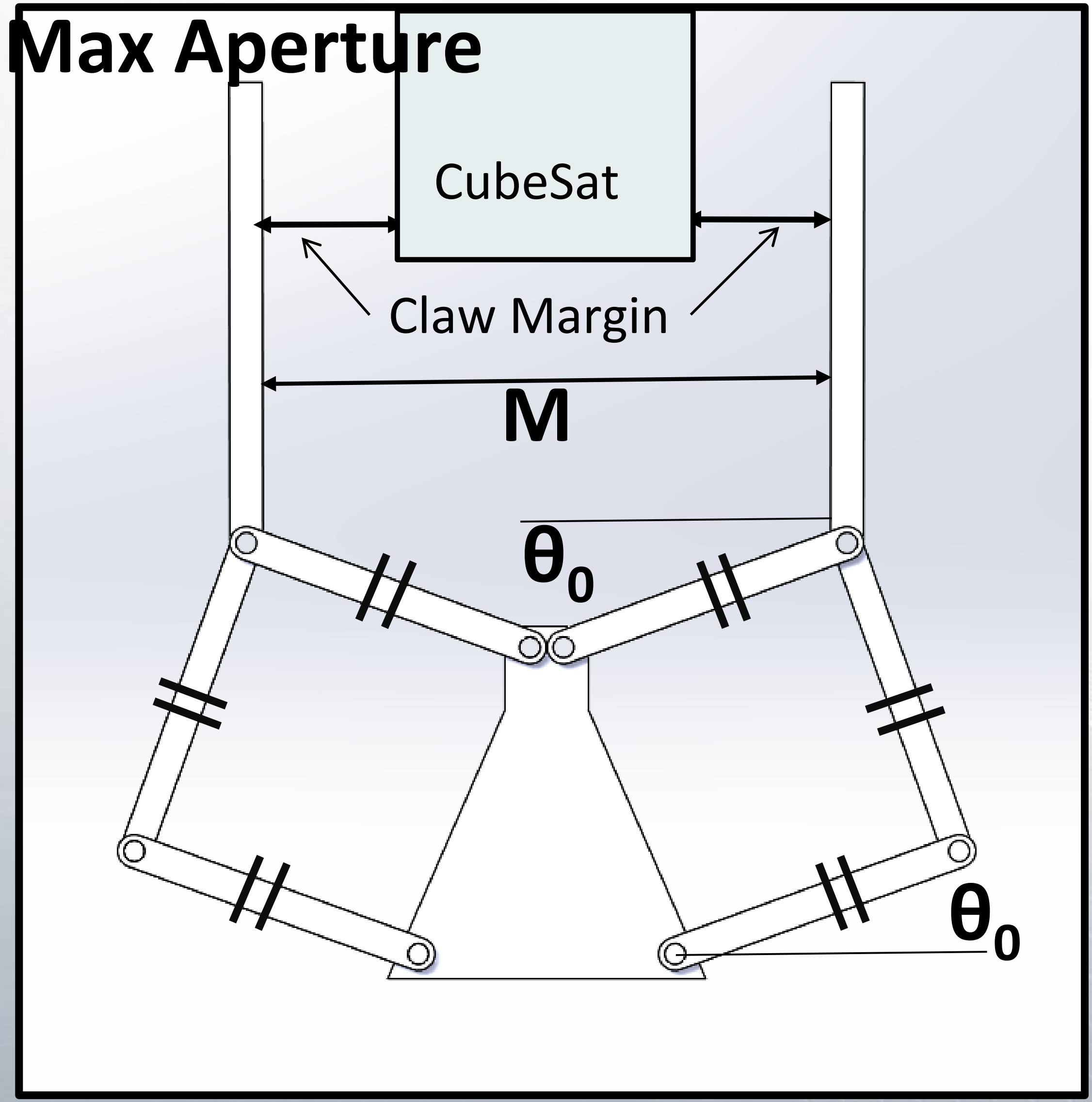
Multiple Gripping Widths

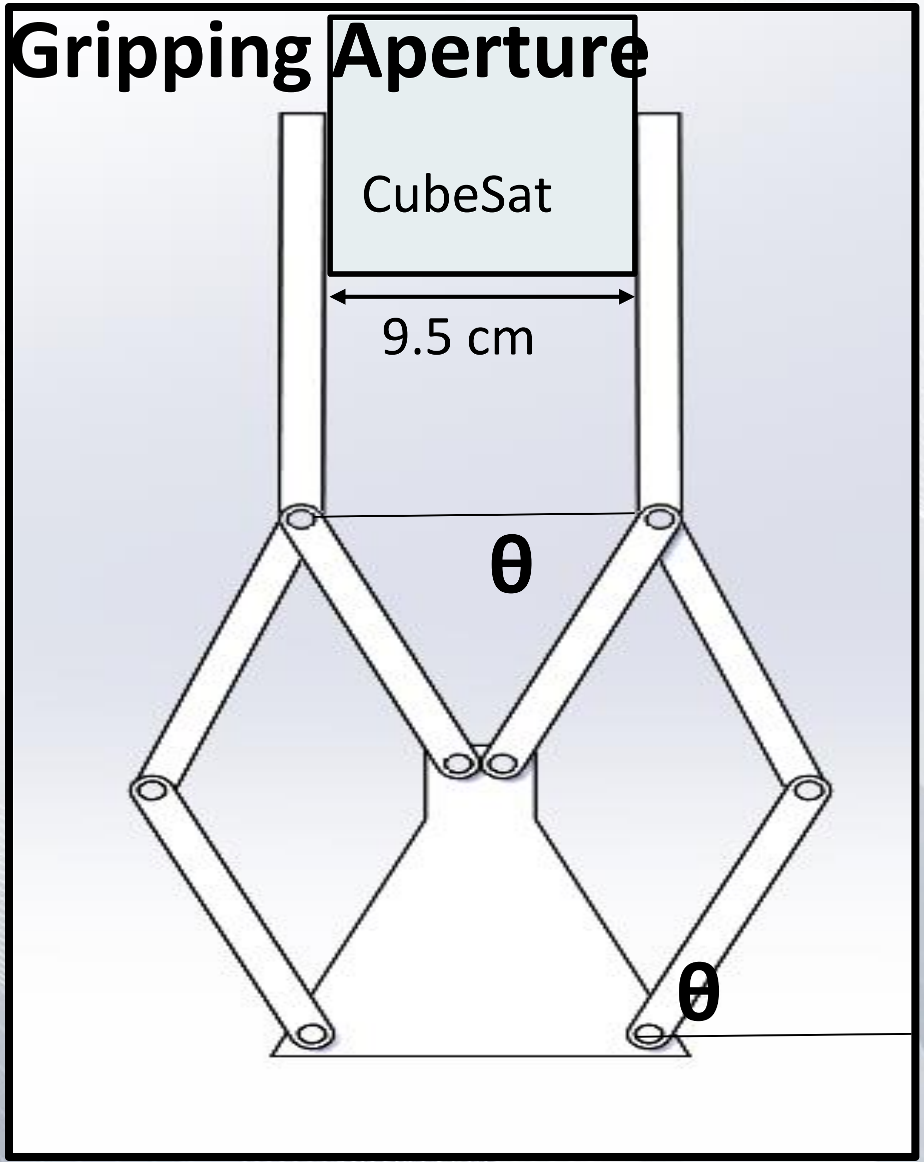
Larger Contact Area

Rotational Closing:

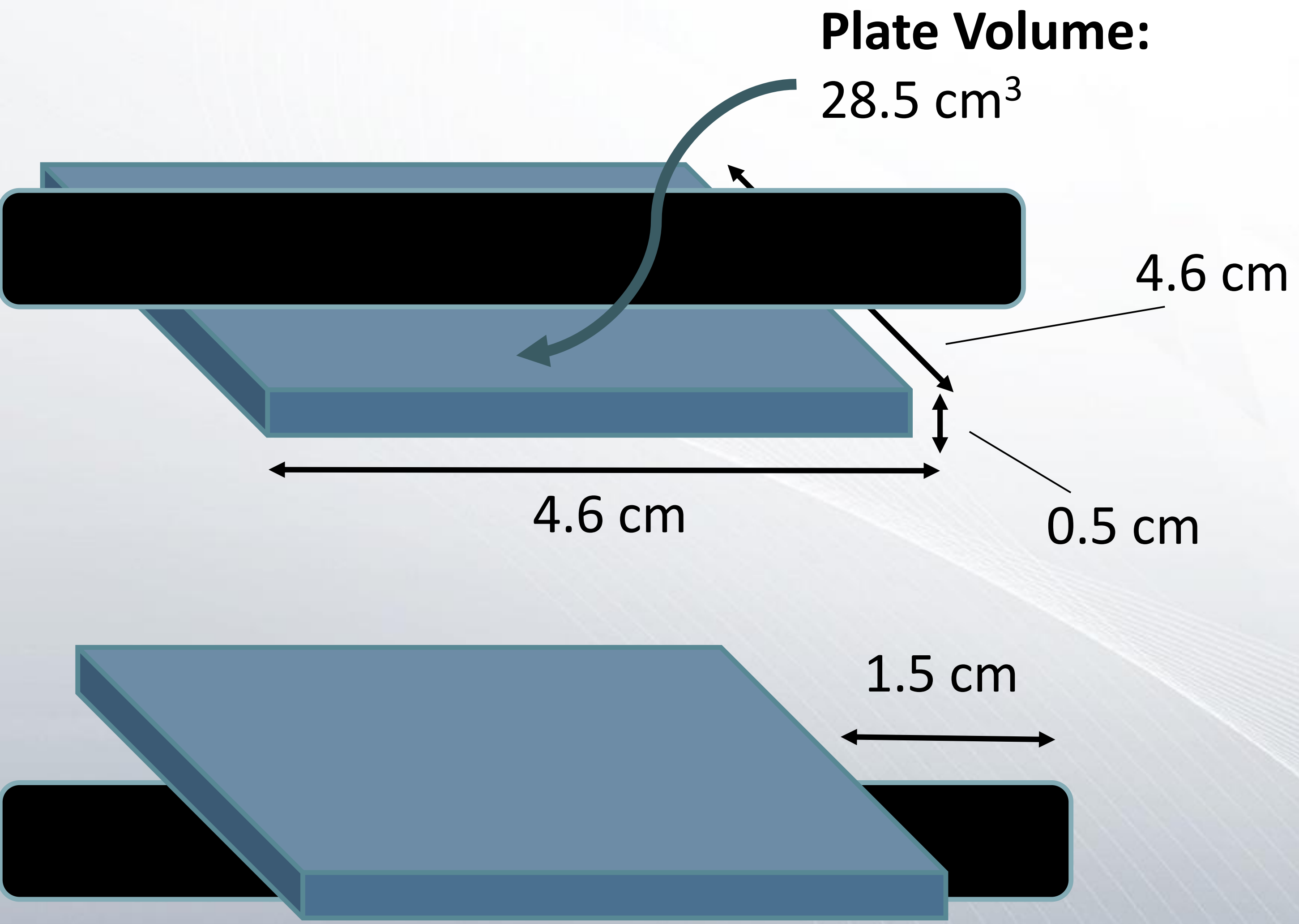


Claw Design: 4 Bar Parallel Linkage





Claw Design: Gripping Plates



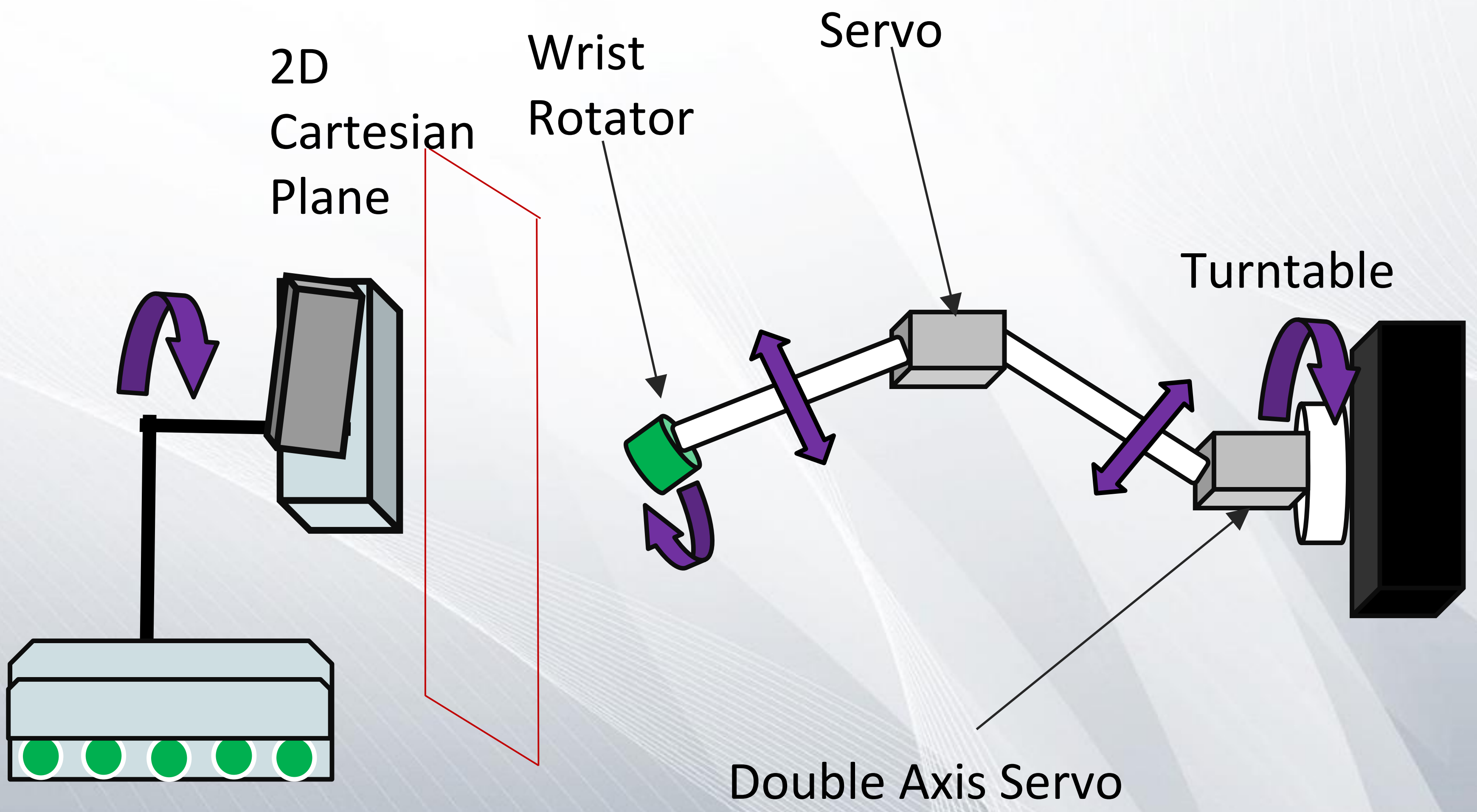
Material	Coefficient of Friction	Density (g/cm^3)
Aluminum 1060	1.2	2.7
Steel	0.61	8
Copper	0.57	8.96

→ Aluminum Plate Grippers

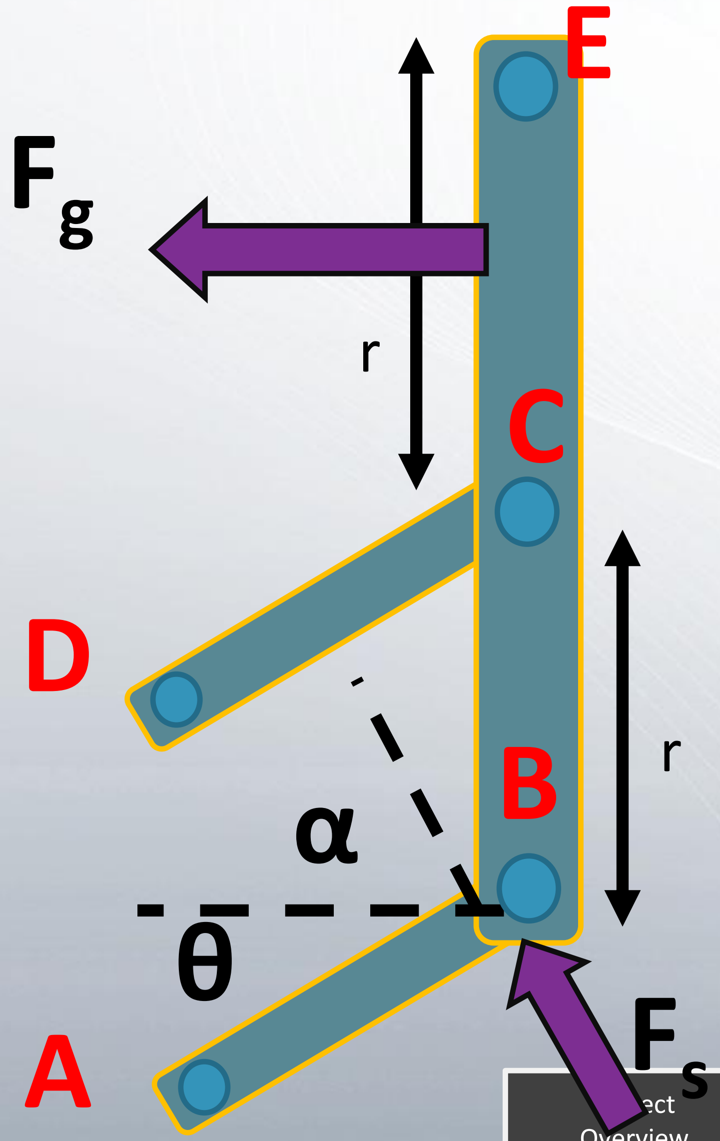
Cost: $2.30

Capture Deployment

- 2D-Cartesian plane accessible with 4 DOF
- Wrist matches CubeSat rotation rate
- Middle joint makes claw orthogonal to CubeSat



Claw Design: Gripping Force



Assumptions:

1.) No deformation or elongation in bars

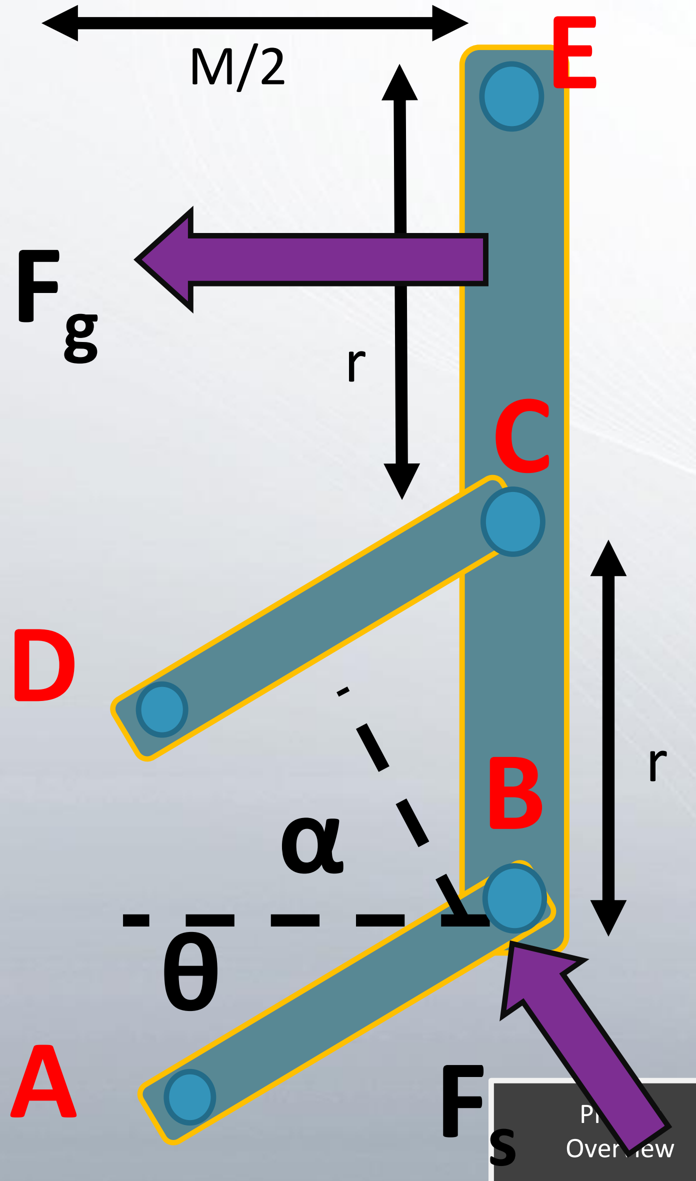
2.) Massless bars

4.) Homogenous Material

5.) Bar Thickness Negligible

6.) Joint AB is driven by servo and gear which exerts force to gripping frame BCE.

Claw Design: Gripping Force



Geometric Variables

$$\alpha = 90 - \theta$$

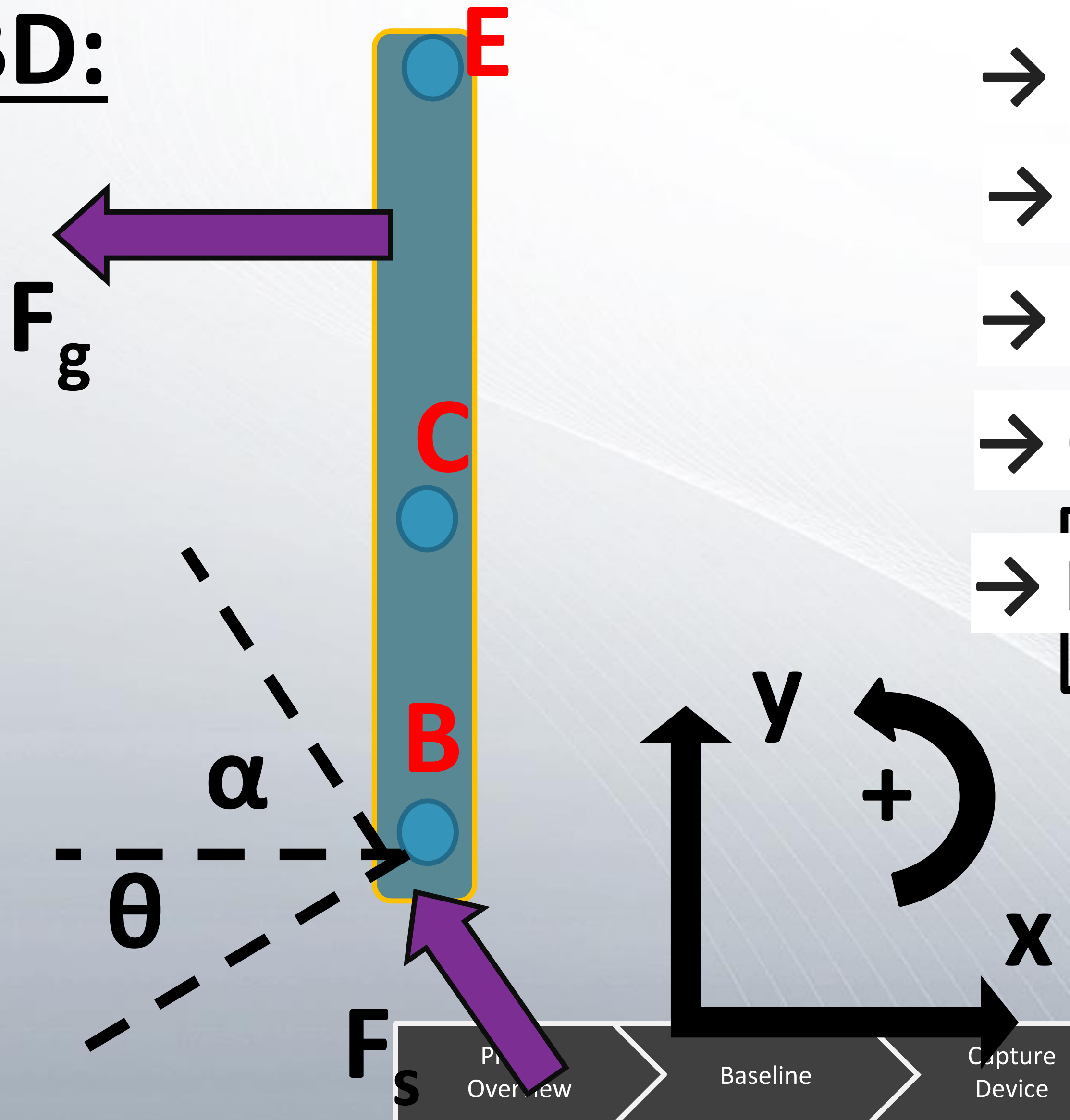
$$r = 7.6 \text{ cm}$$

At Gripping Aperture

$$\rightarrow \theta = \cos^{-1}(M/2r)$$

Claw Design: Gripping Force

FBD:



$\rightarrow \sum M_C = 0$

$\rightarrow 0 = F_g\, L/2 - F_s\, r \cos(\alpha)$

$\rightarrow F_s = T/r$

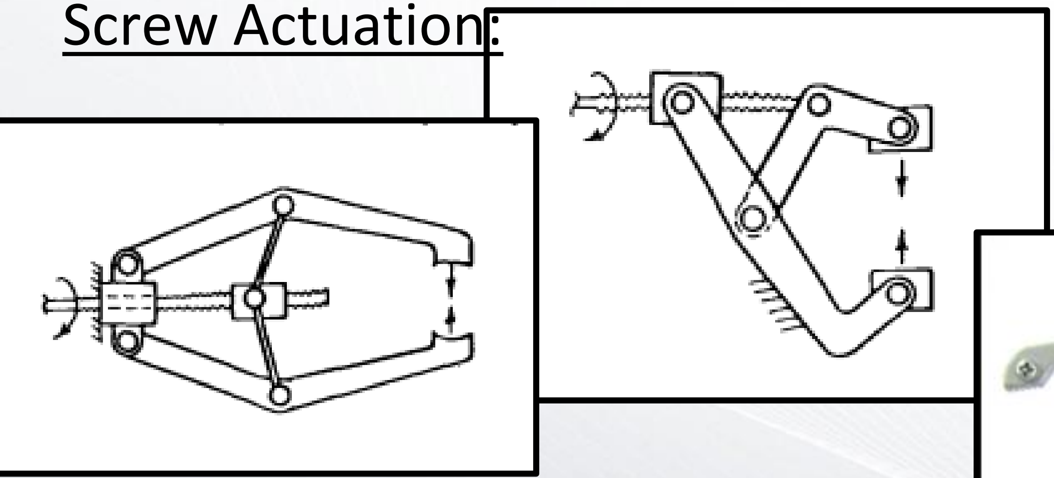
$\rightarrow 0 = F_g\, L/2 - T \cos(\alpha)$

$\rightarrow \boxed{F_g = 2T/L \cos(\alpha)}$

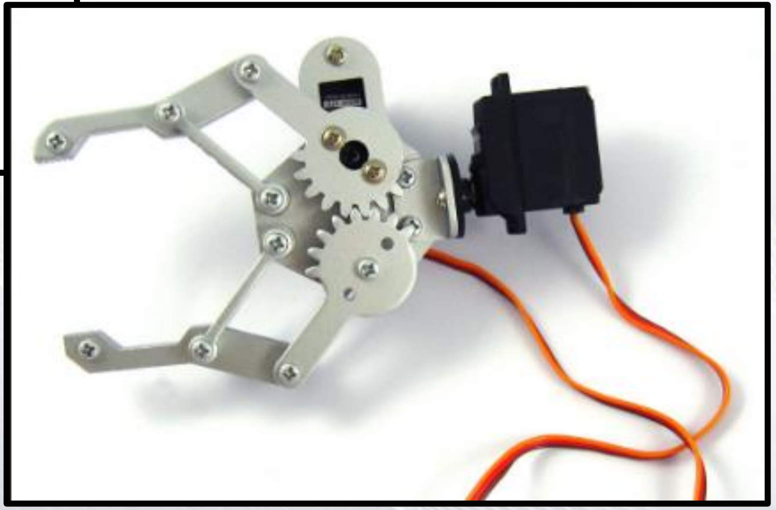
Design Options: Claw End Effector

Parallel Grippers:

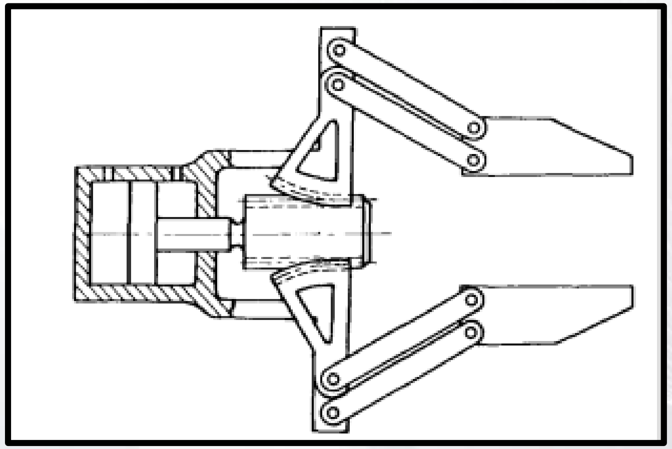
Screw Actuation:



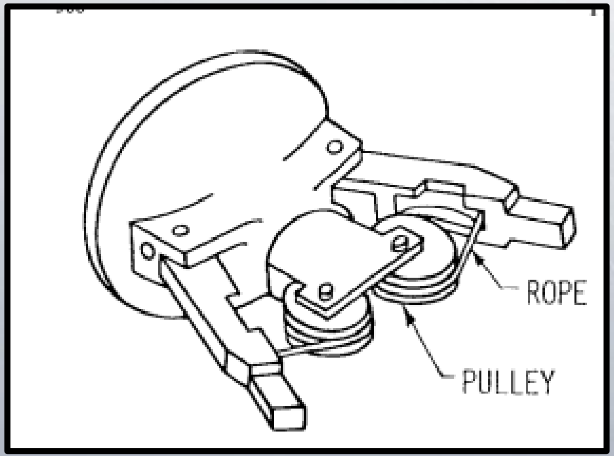
Servo Mechanism:



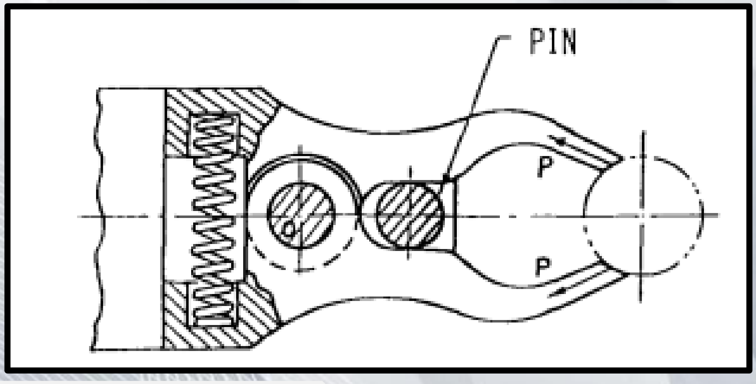
Gear and Rack:



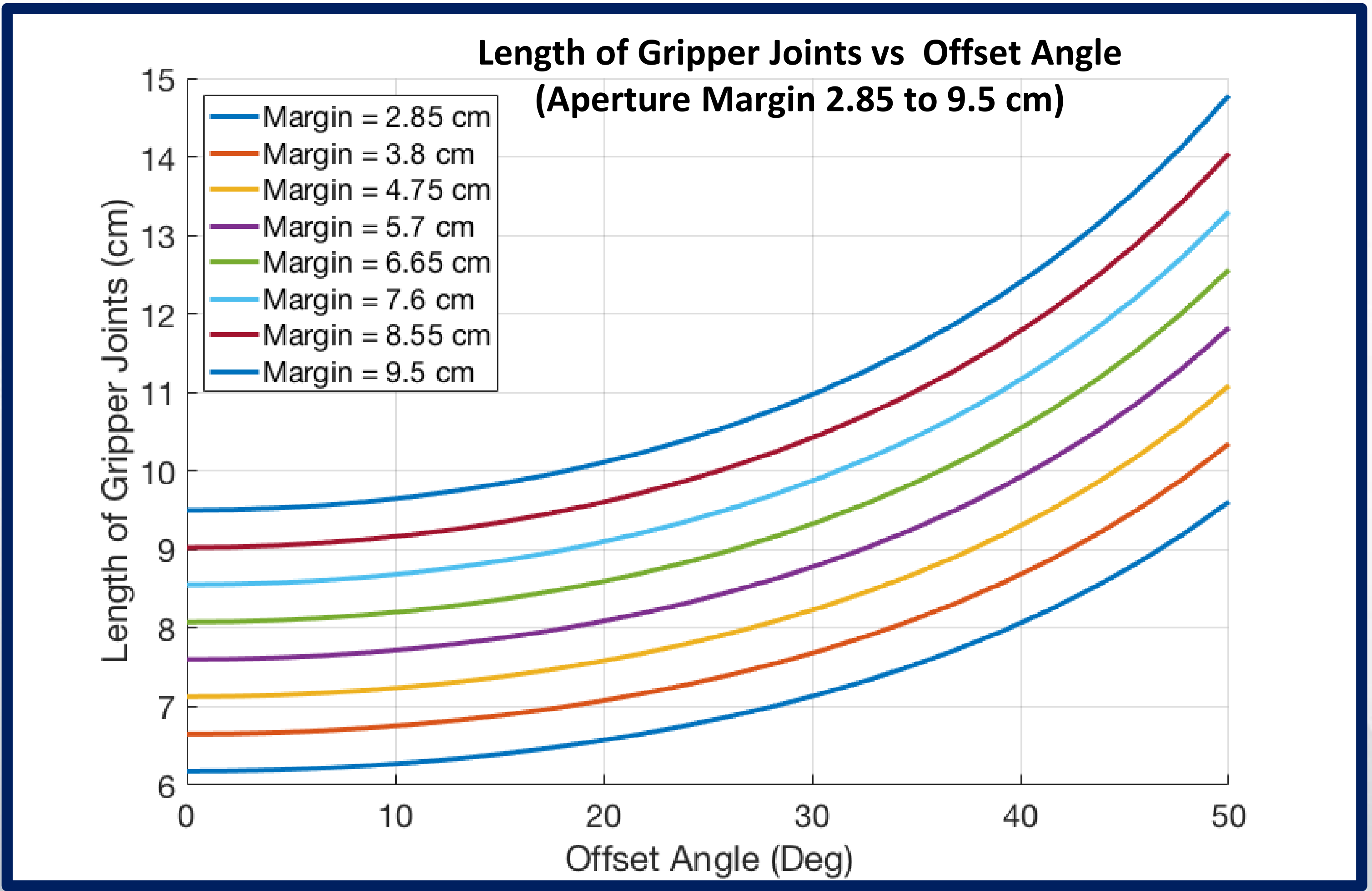
Rope and Pulley:



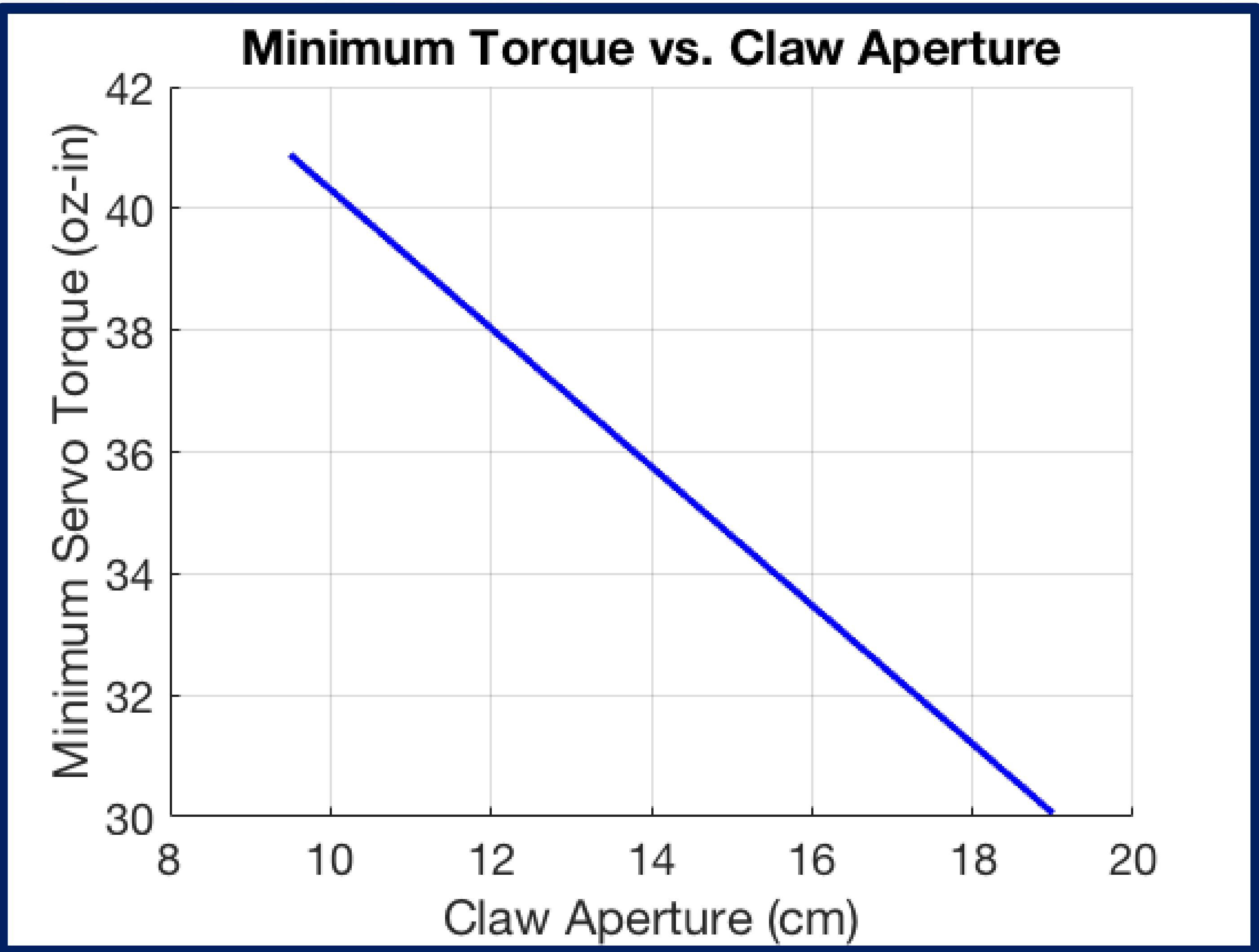
Spring Loaded:



Claw: Gripper Configuration



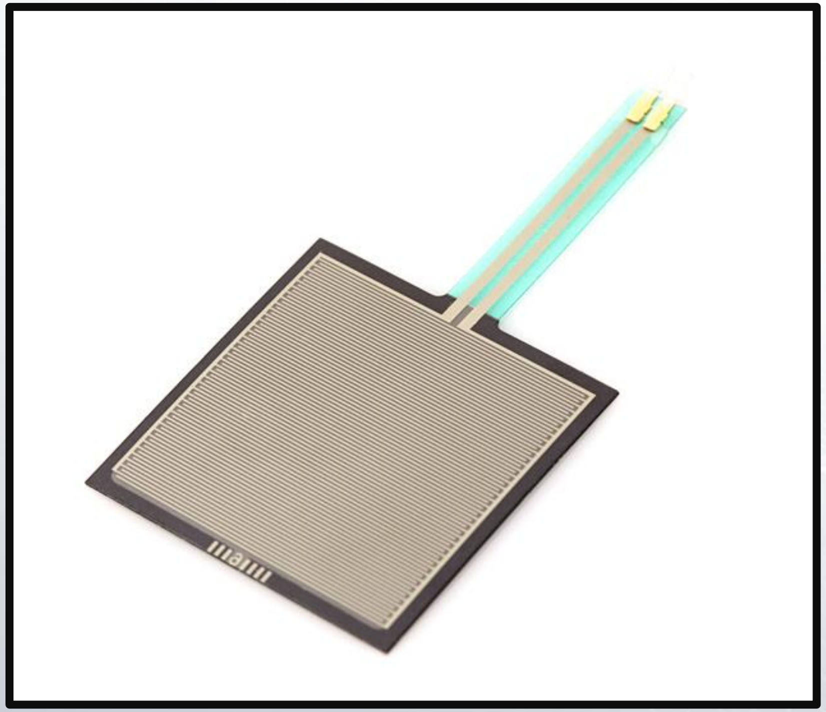
Claw Design: Min. Servo Torque

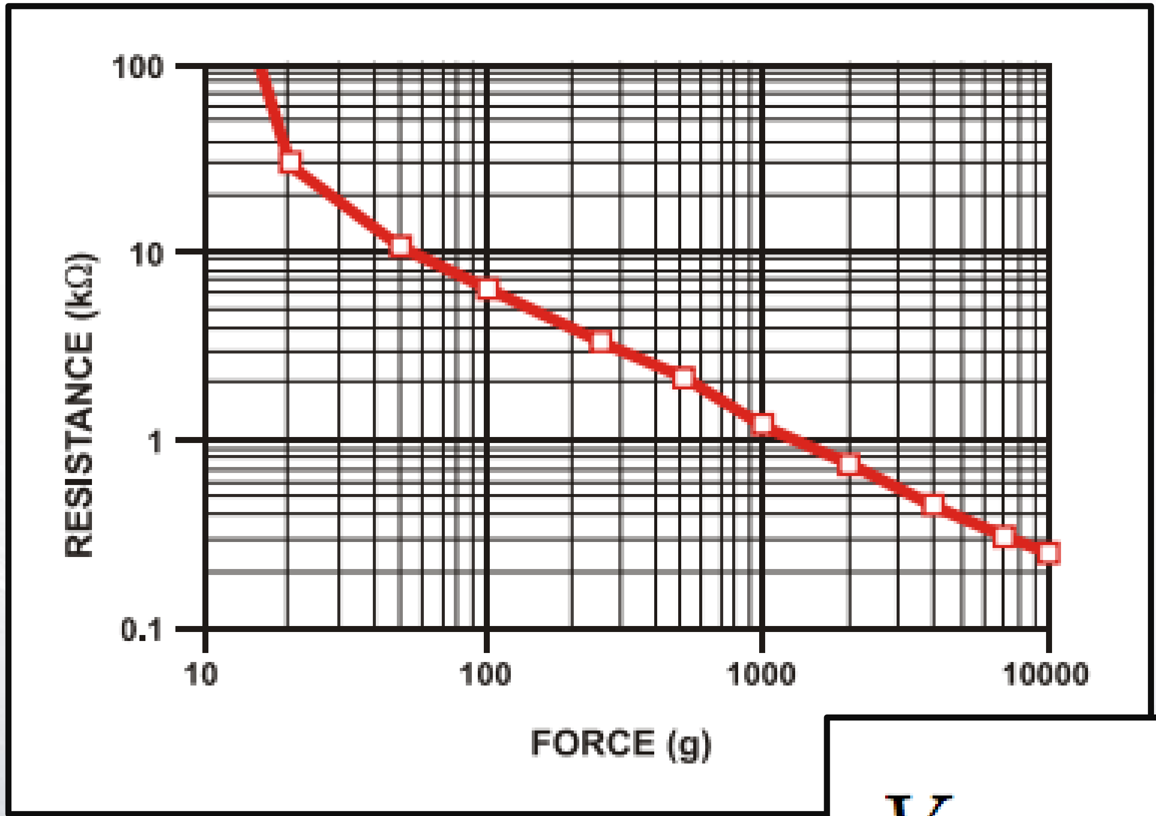


<u>Conclusion:</u>

Minimum Torque not affected much by maximum claw aperture. (~ 10 oz-in margin)

Claw Design: Force Sensor Calibration

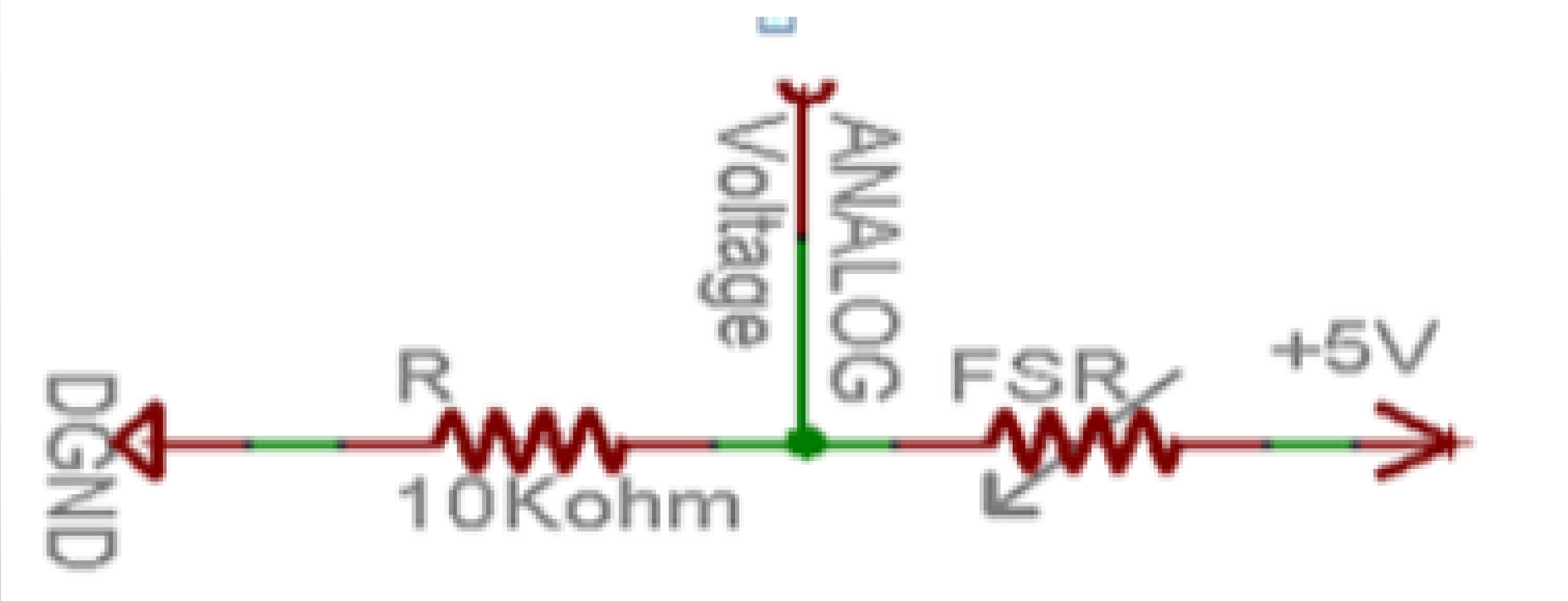




$$V_{out} = V_{cc}\frac{R}{R+FSR}$$

Apply Known Weights → Measure Voltage → Calculate FSR → Fit to Datasheet Resistance

Claw Design: Force Sensor Calibration



$$V_{out} = V_{cc}\frac{R}{R+FSR}$$

Apply Known Weights → Measure Voltage → Calculate FSR → Fit to Datasheet Resistance

Claw Manufacturing Feasibility

<u>Machining Resources</u>:

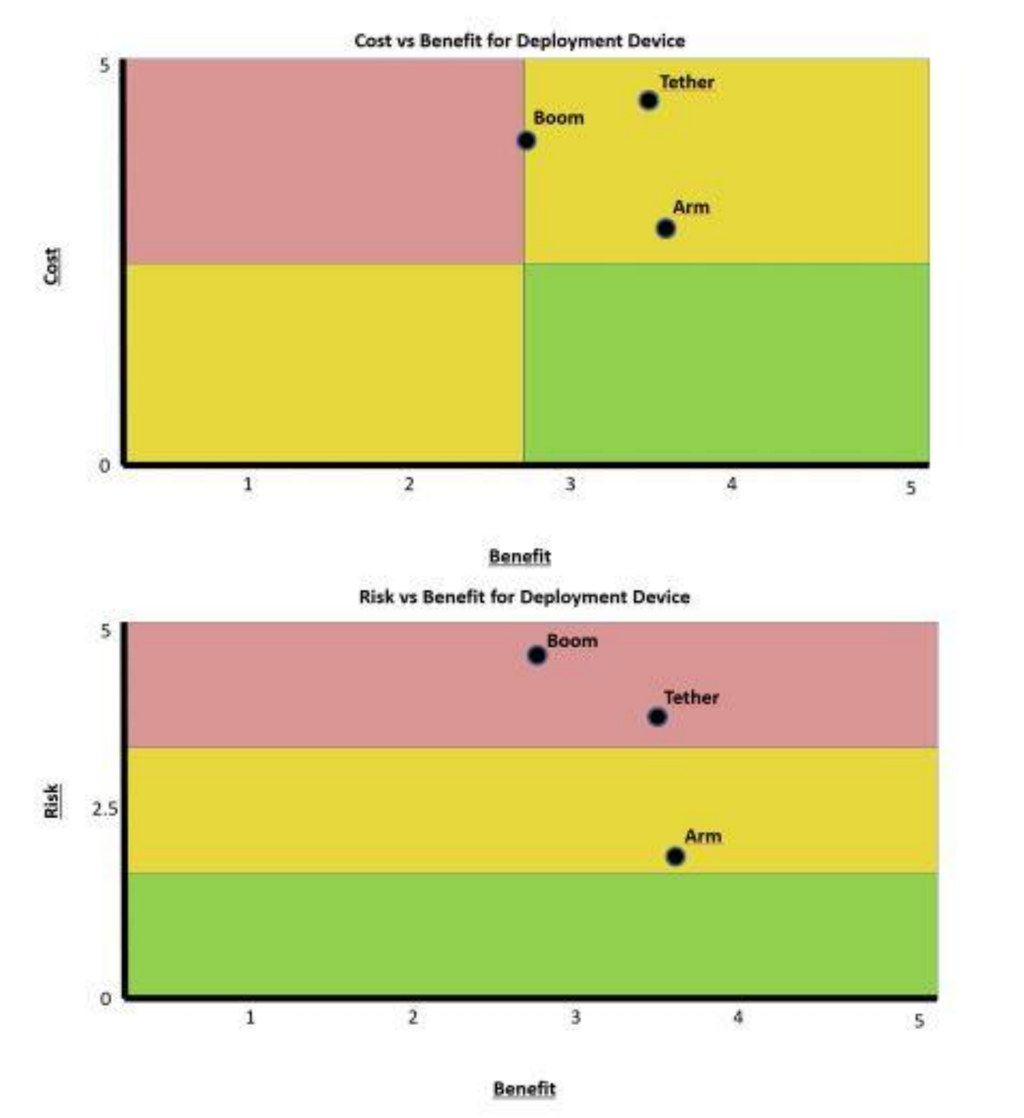
Physics Machine Shop
Aerospace Machine Shop
ITLL Machine Shop

+/- 0.005 inch available Machining Tolerance good enough for machining 7.6 cm bars.

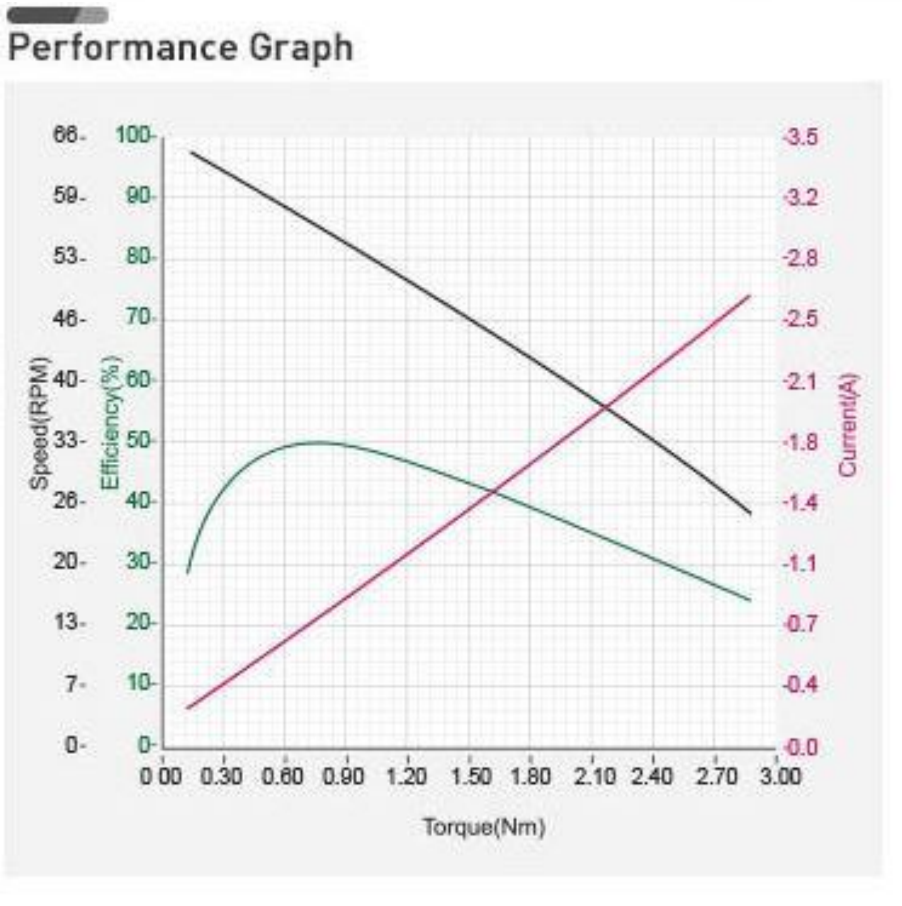
Capture Deployment

Table 30. Results of Deployment Device Trade Study

Capture Mechanism Trade		Robotic Arm		Boom		Tether	
Criteria	%	Raw	W	Raw	W	Raw	W
Mass	0.1	4	0.4	3	0.3	5	0.5
Volume	0.1	4	0.4	3	0.3	4	0.4
Power	0.1	1	0.1	2	0.2	4	0.4
Control	0.3	5	1.5	2	0.6	2	0.6
Implementation	0.2	2	0.4	4	0.8	4	0.8
Reliability	0.2	4	0.8	3	0.6	4	0.8
TOTAL			3.6		2.8		3.5



Capture Deployment

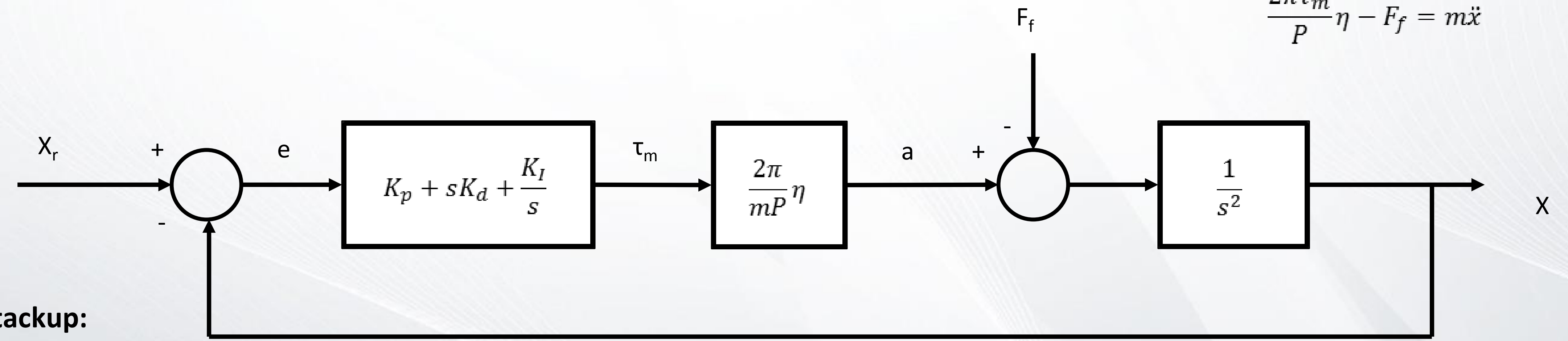


http://support.robotis.com/en/product/dynamixel/mx_series/mx-64.htm

Testbed Integration:Translation

Fundamental Equation:

$$\frac{2\pi\tau_m}{P}\eta - F_f = m\ddot{x}$$



Uncertainty Stackup:

- Stepper Motor Error = ±1.8° = .005*P
- Encoder Error = ±0.352° = .000978*P
- **Total = .005978*P**
- <u>**>1 mm positional accuracy**</u>

Control Assumptions:

- No motor friction of back EMF
- No drag
- No sensor noise disturbance

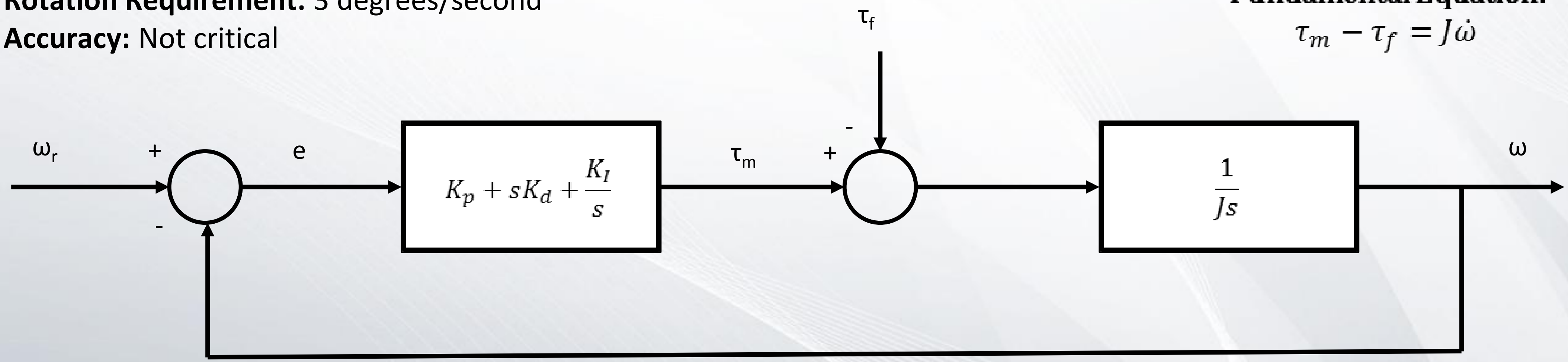
X_r = Reference position determined by algorithm
X = Measured position
η = Lead screw efficiency
e = Error
τ_m = Motor torque
F_f = Force of friction
m = Mass
P = Screw lead (linear distance/revolution)
J = CubeSat moment of inertia

Testbed Integration:Rotation

- **Rotation Requirement:** 3 degrees/second
- **Accuracy:** Not critical

Fundamental Equation:

$$\tau_m - \tau_f = J\dot{\omega}$$



Assumptions:
No back EMF in motor
No drag
No sensor noise disturbance

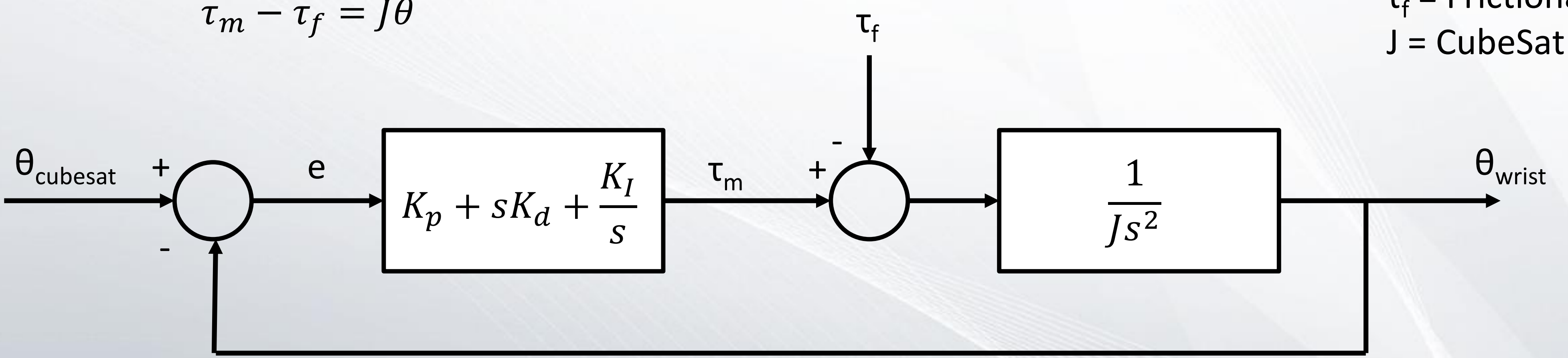
ω_r = Reference angular velocity
ω = Measured angular velocity
e = Error
τ_m = Motor torque
τ_f = Frictional torque
J = CubeSat moment of inertia

Wrist Rotation Control (backup)

θ_r = Reference angular position
θ = Measured angular position
e = Error
τ_m = Motor torque
τ_f = Frictional torque
J = CubeSat moment of inertia

Fundamental Equation:

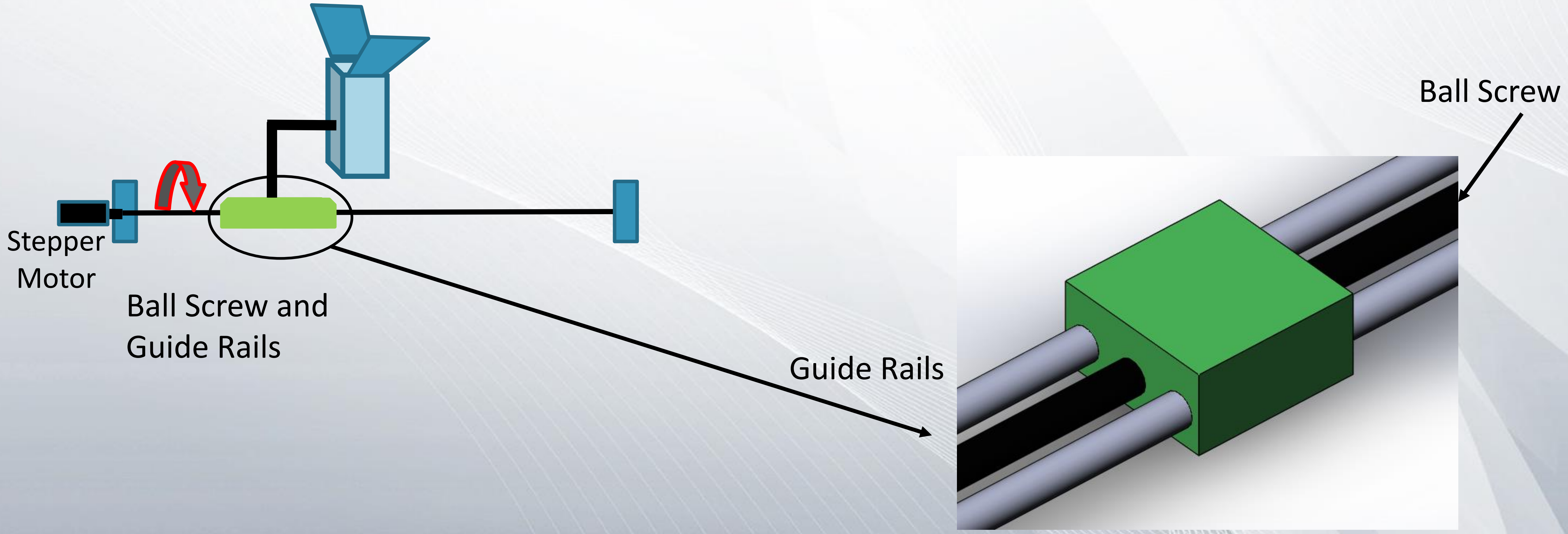
$$\tau_m - \tau_f = J\ddot{\theta}$$



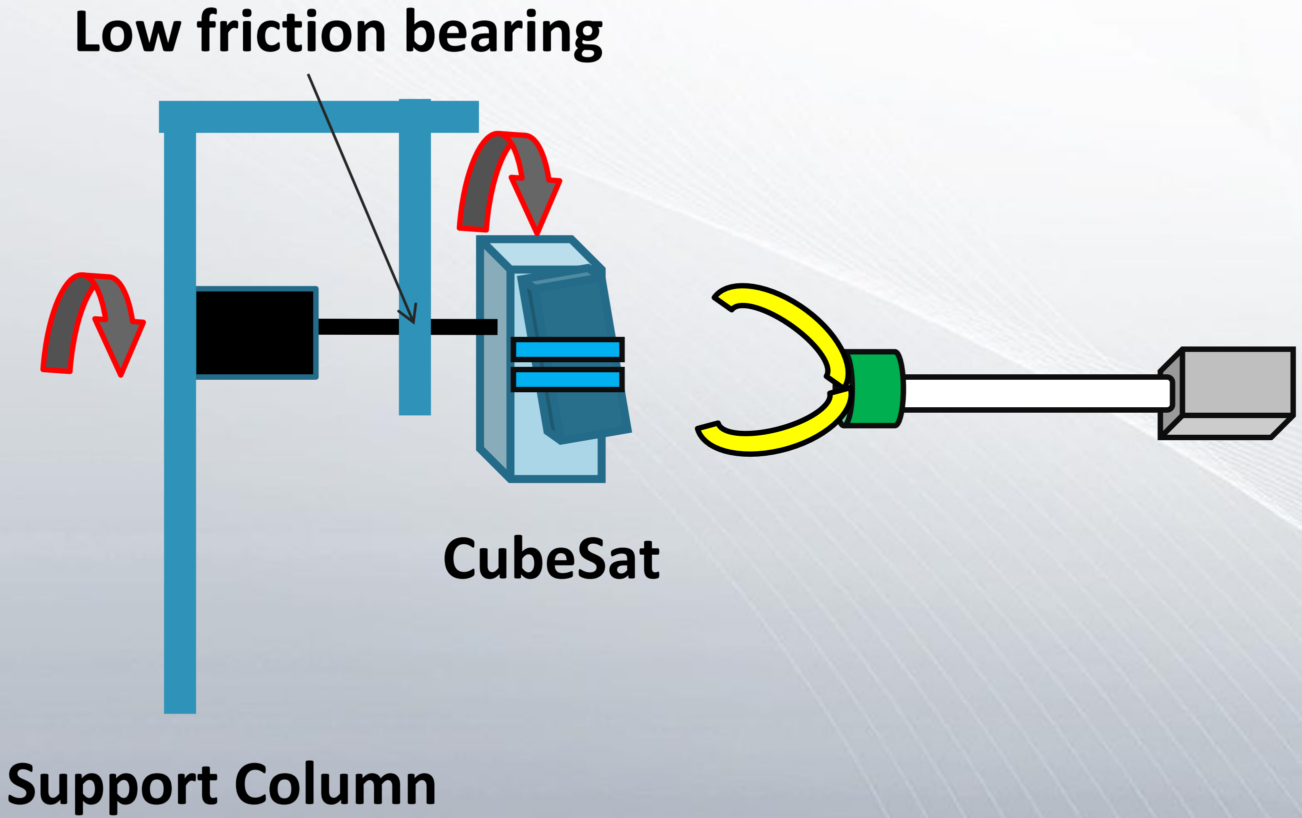
Uncertainty Stackup
- CubeSat encoder sensor error = ±0.352° (based on 1024 P/R encoder)
- Wrist actuation error = ±0.088° (based on Dynamixel MX-28R)
- Command delay time error = negligible (3 Mbps baud rate)
- **Total = ±0.88° with FOS of 2**

Assumptions:
No back EMF in motor
No drag
No sensor noise disturbance

TestBed Integration: Linear Translation Overview



TestBed Integration: Rotation



Process

1. Motor spins up the CubeSat to 3 deg/s at a chosen angular acceleration rate
2. Motor maintains the angular speed
3. After successful capture, motor turns off and acts as a bearing

Testbed Integration: Torque

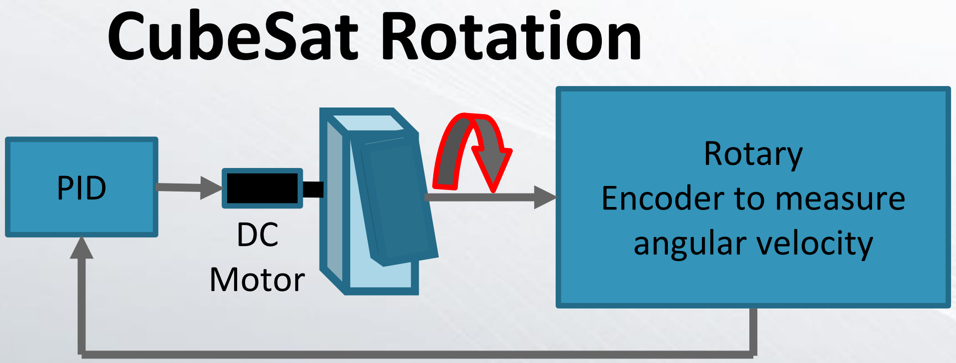
$$\tau_{required} = \tau_{offset} + \tau_{friction} + \tau_{acceleration}$$

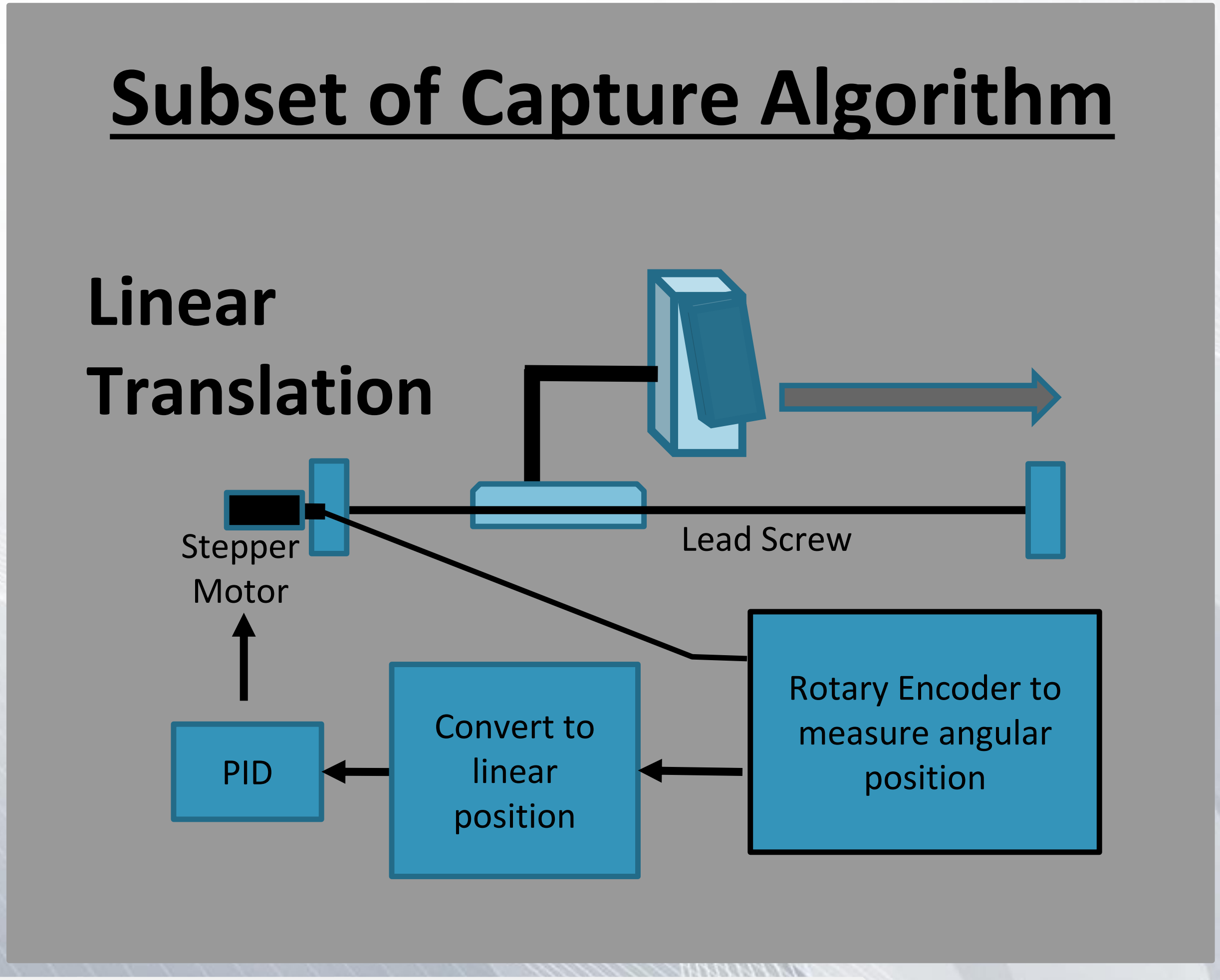
τ_{offset} : Torque due to gravitational force

$\tau_{friction}$: Torque due to motor and bearing friction

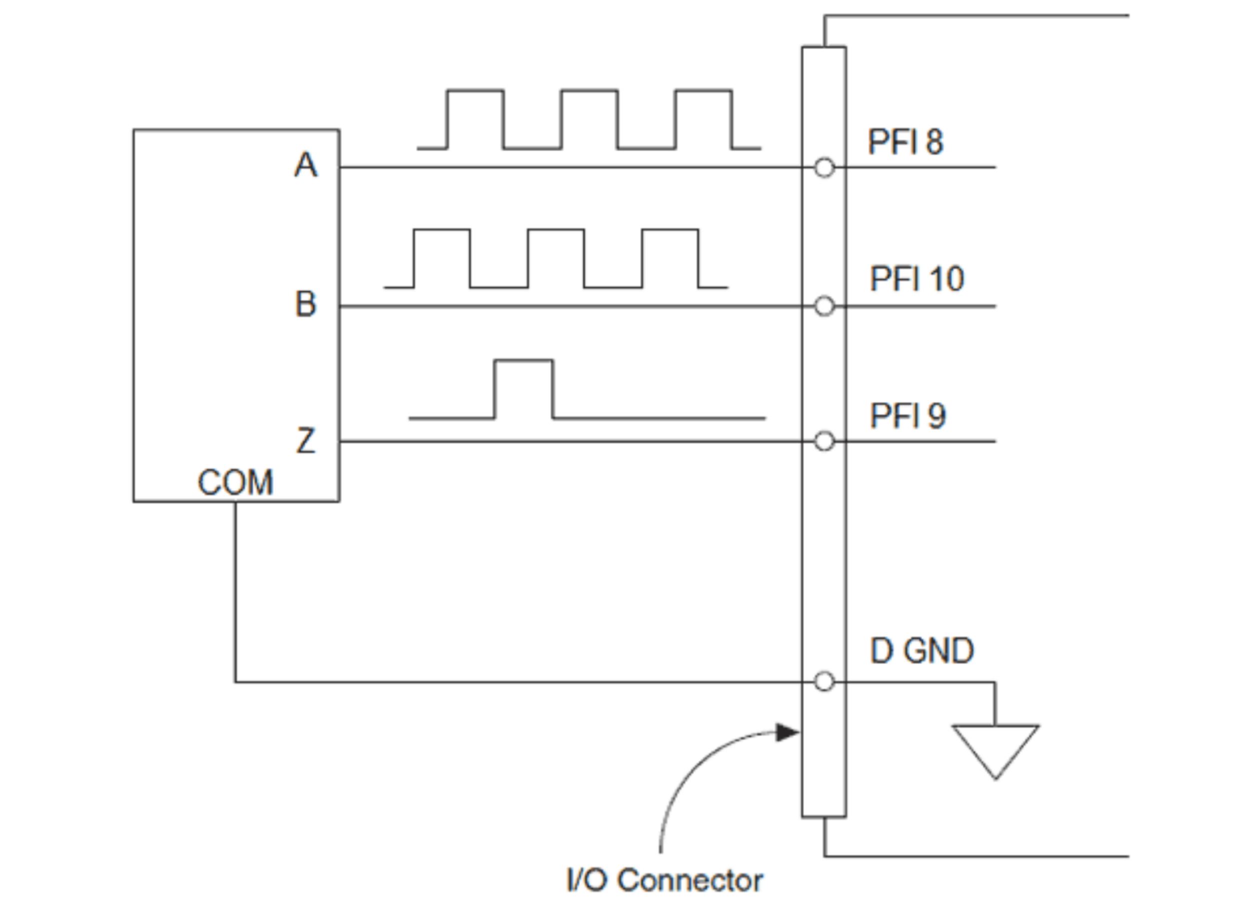
$\tau_{acceleration}$: Torque for angular acceleration

TestBed Integration: Control





Connection of Encoder to DAQ



- DAQ Functionality: Simultaneously samples readings form a rotary or linear position encoder with an analogue input signal enabling sensor signals to be measured against position or velocity.

➔ Quadrature encoder Input

➔ On board programmable gain amplifier

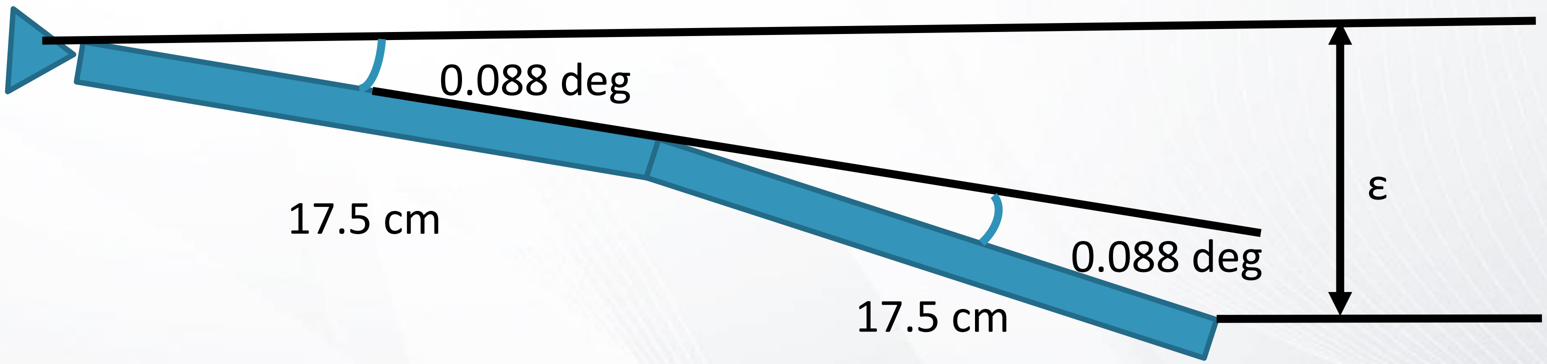
➔ High speed analogue to digital converter

Arm Resolution

Assume rigid bars

0.8 mm end deflection

Used Resolution of servo



Capture Deployment

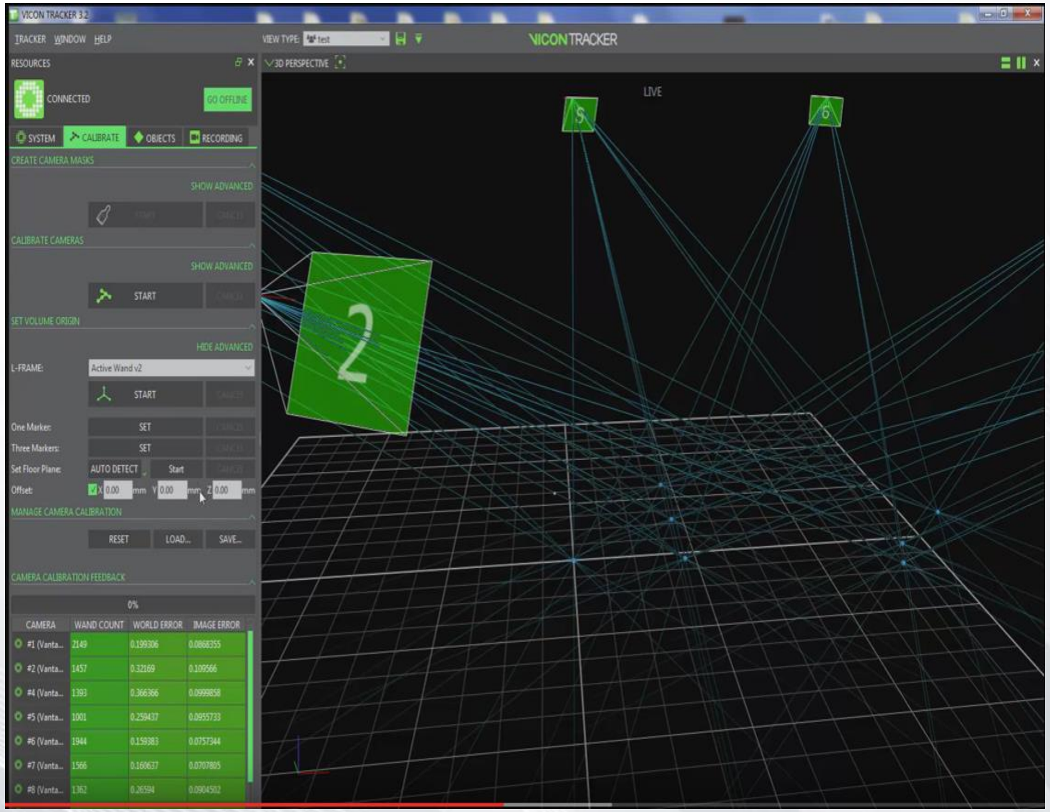
Item	Mass	
MX-64 Servo(3)	510g	170g/ea
WristRotate64	190g	
MX64 Turn Table	126g	
Claw	200g	
5in Girder(2)	74g	37g/ea
Total	1.1kg	
Margin	**93%**	

15kg allowable payload mass

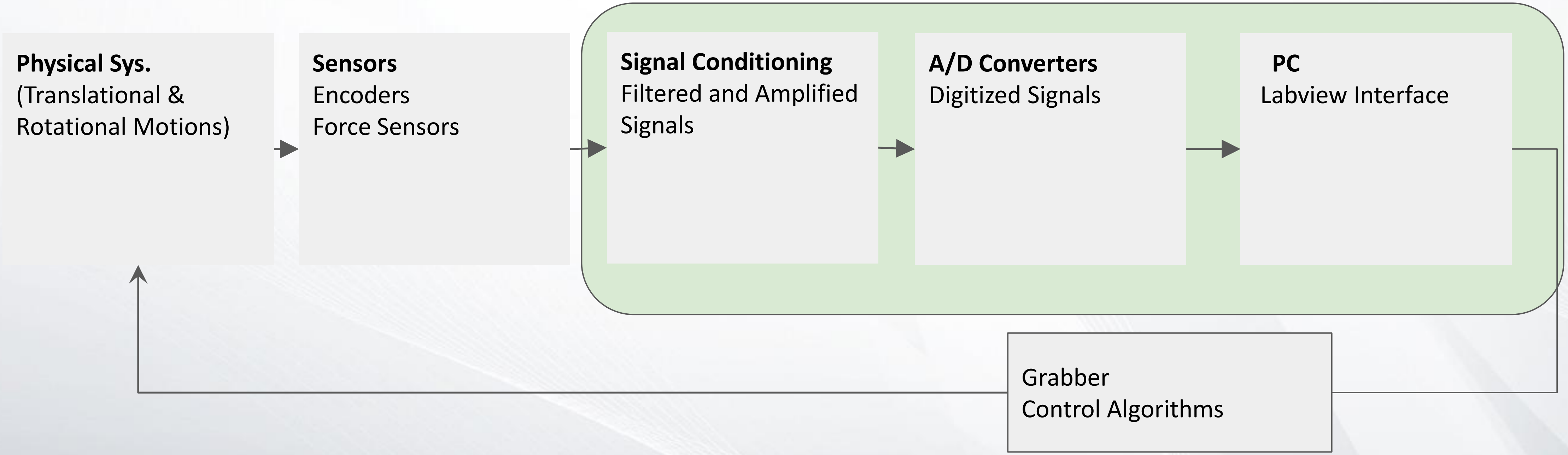
Testbed Integration Sensors

- VICON System from RECUV
- System protocol software uses infrared reflector balls attached to system to sense and measure motion in a 3D virtual space.
- Gives Position to 1mm of accuracy at 100 Hz collection rate
- From Position Data-Determine Linear Rates
- Also able to determine Angular Rates

- Resources:
  - Steve McGuire
  - Straight Forward Program to Use



Data Acquisition System

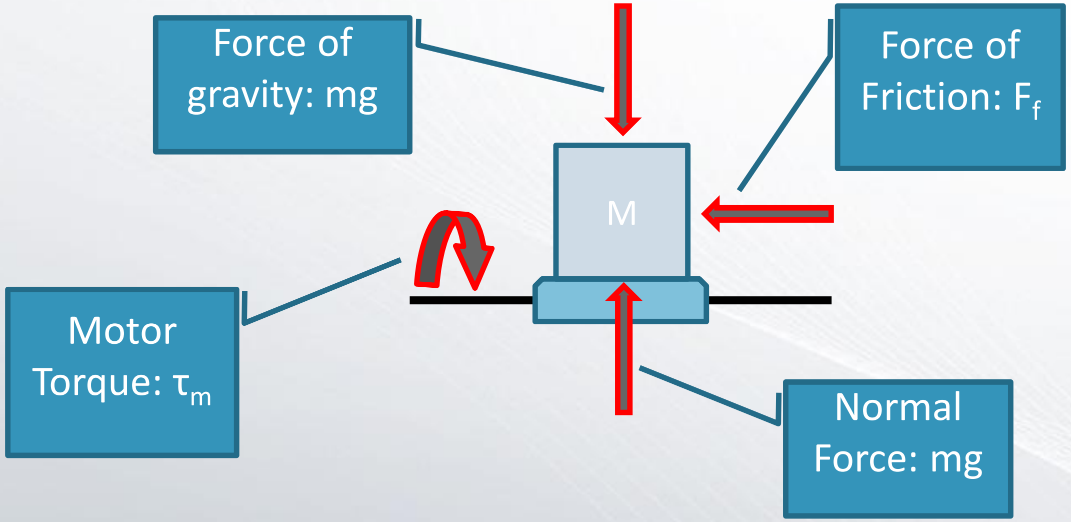


- **Goal is to match the angular motion of the end effector to the angular motion of the CubeSat.**
- **Rotation Requirement:** 3 degrees/second
- **Translation Requirement:** Track position within 1mm.

Data Resources

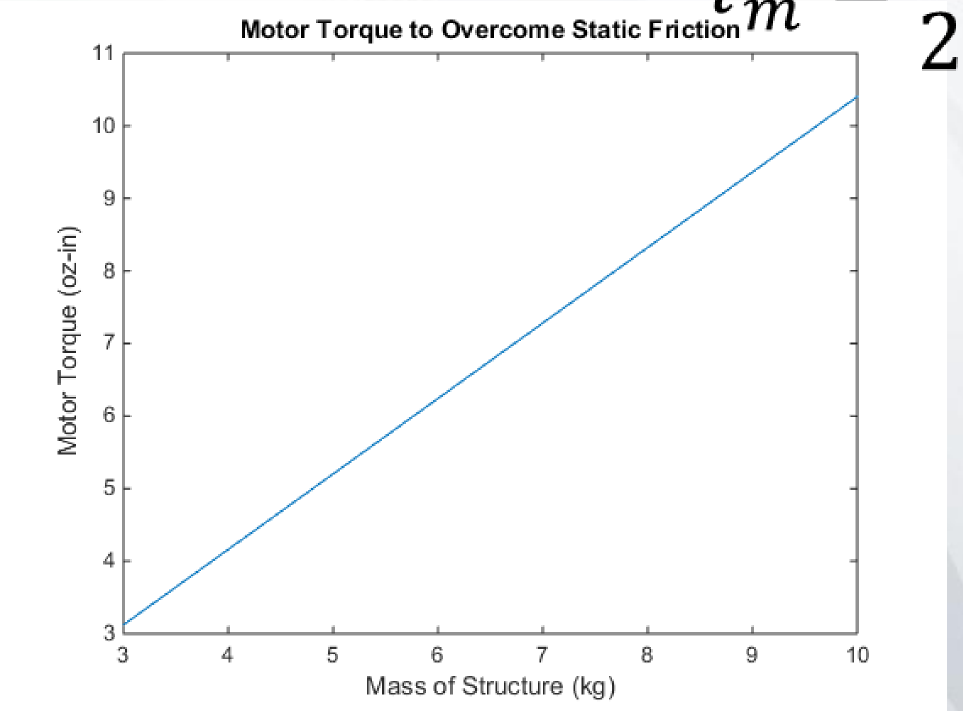
- LabVIEW
- National Instruments Website-Contains Numerous Tutorials/ Help
- AES Faculty: Trudy Schwartz and Bobby Hodgkinson
- ITLL Faculty:
- Dan Godrick—National Instruments hardware and LabVIEW
- Christine Buckler—Equipment Sensors

Testbed Integration: Translation



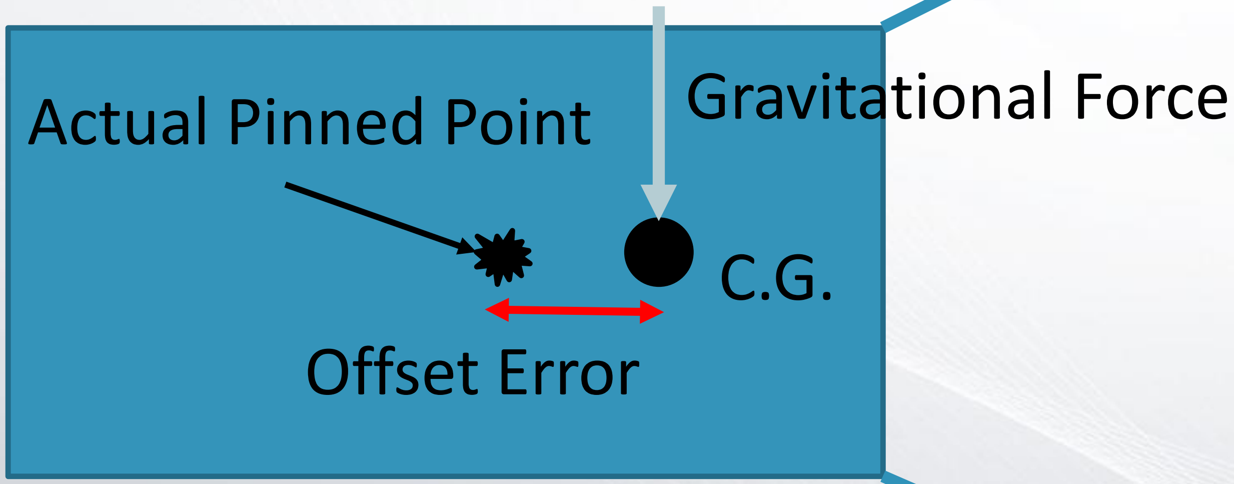
$$\tau_m = \frac{P}{2\pi\eta}\mu_s mg$$

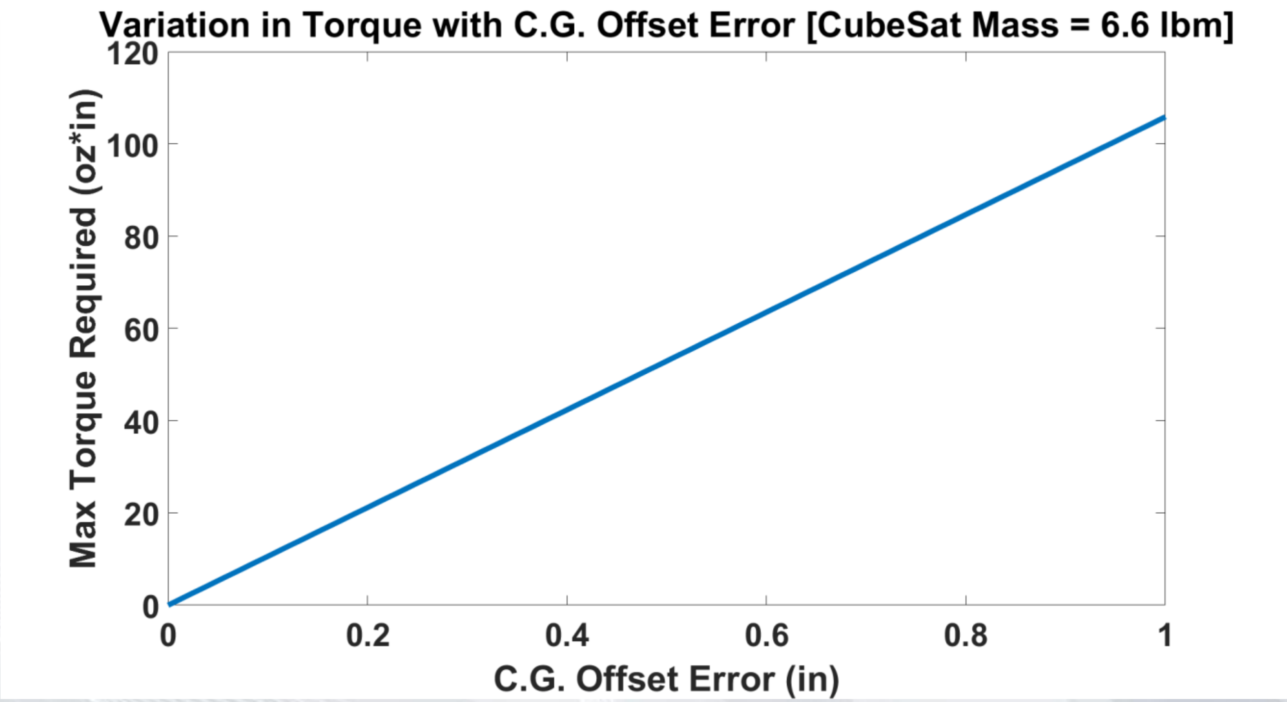
- 125 oz-in torque stepper motor: $40



Testbed Integration: Torque

Free Body Diagram





$$\tau = F_g \delta L$$

Testbed Integration: Torque

$$\tau_{friction} = \frac{1}{2}\mu_f F_g d \qquad \tau_{acceleration} = I\alpha_{desired}$$

Approximations	
Offset Torque (0.5 in error)	52.1788 oz-in
Frictional Torque	10.4191 oz-in
Acceleration Torque (3 deg/s^2)	0.6073 oz-in
Total	63.2052 oz-in

Testbed Integration: Components

Electric Brushless Motor

- Precise Motion Control
- Low Friction

Low Friction Bearing

- Low Coefficient of Friction (~0.2)
- Several Size Options

T-Slots 80-20 Aluminum

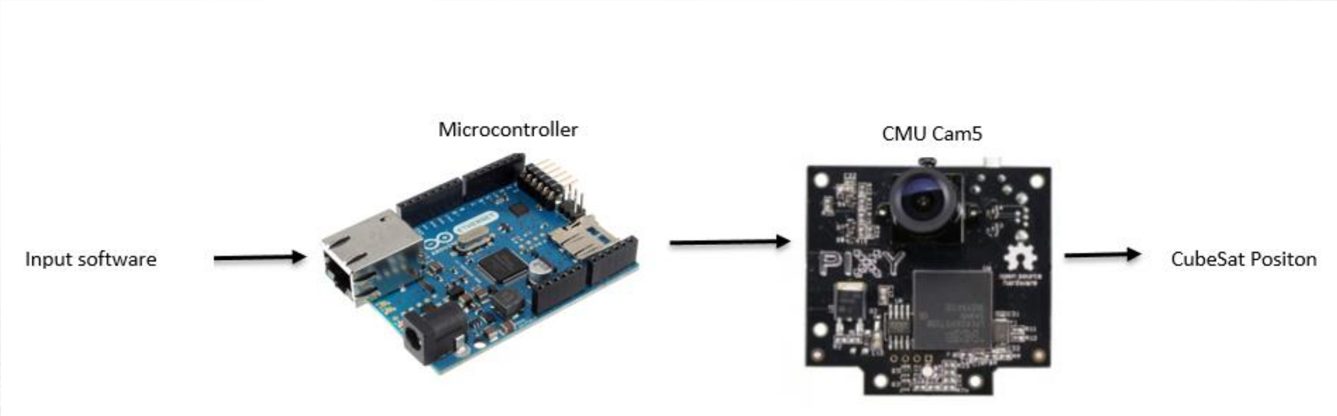
- Flexible Configuration
- Internal/External fasteners

Testbed Integration: Switch From Reaction Wheel

- Reaction wheel's complexity was underestimated
- Frictional torque due to spinning inertia was not considered
- Electric brushless stepper motor can provide same precision & accuracy

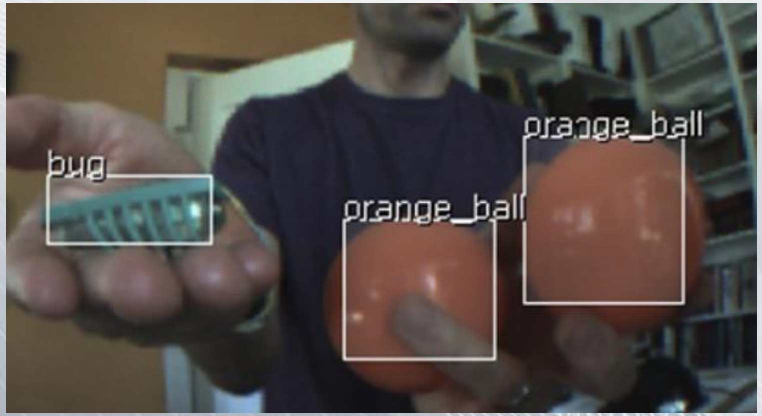
Testbed Integration (back up slide):
External CubeSat Tracking Using CMUcam5 Pixy

- The CMUcam5 vision sensor is capable of motion tracking and finding objects
- The image processor is capable of tracking:
  - Object signature
  - X,Y,Z location of object
  - Angle of the object
  - Will print object information to serial port.



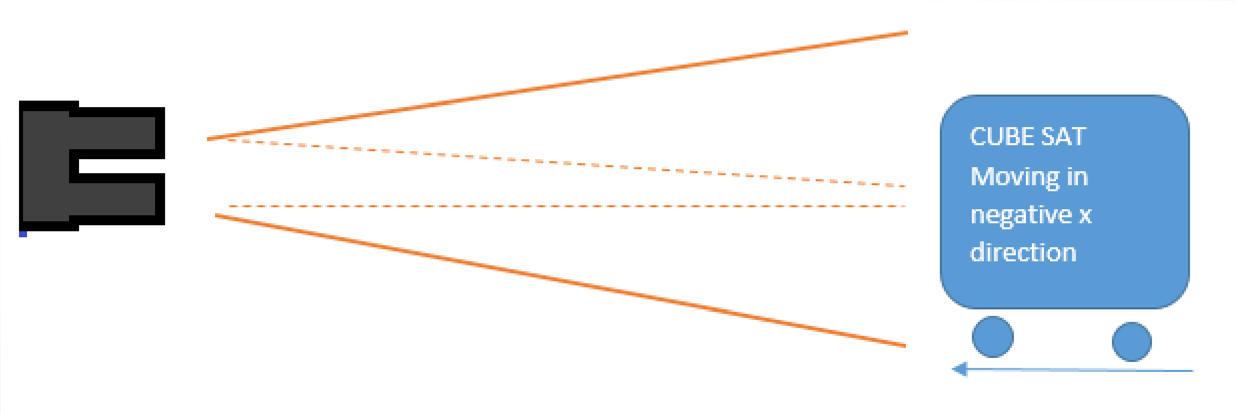
- The Arduino function library:
- #include <spi.h>
- #include <Pixy.h>

Arduino pixy camera call is pixy.blocks[i].
(signature,x,y,z,width,angle, etc.)



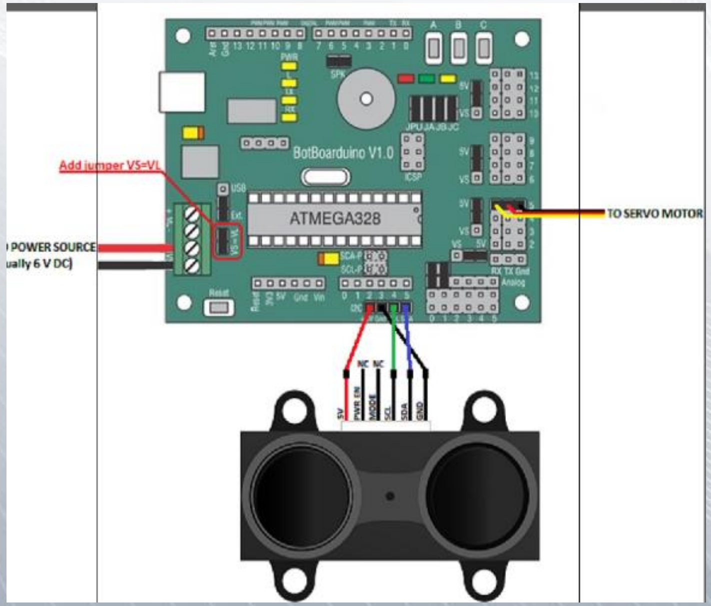
Testbed Integration:
External CubeSat Tracking Using Lidar-Lite-v3

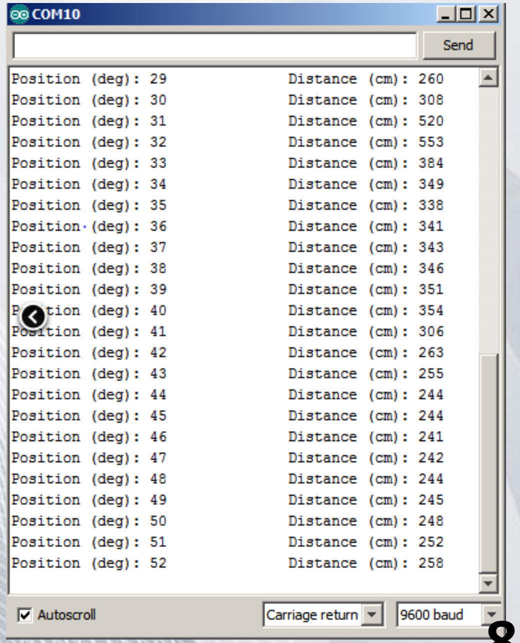
- Range finding and can sense the distance between the CubeSat and the capture device.
- The LIDAR sensor can measure angle in the case that the CubeSat moves from the line of site of the LIDAR.



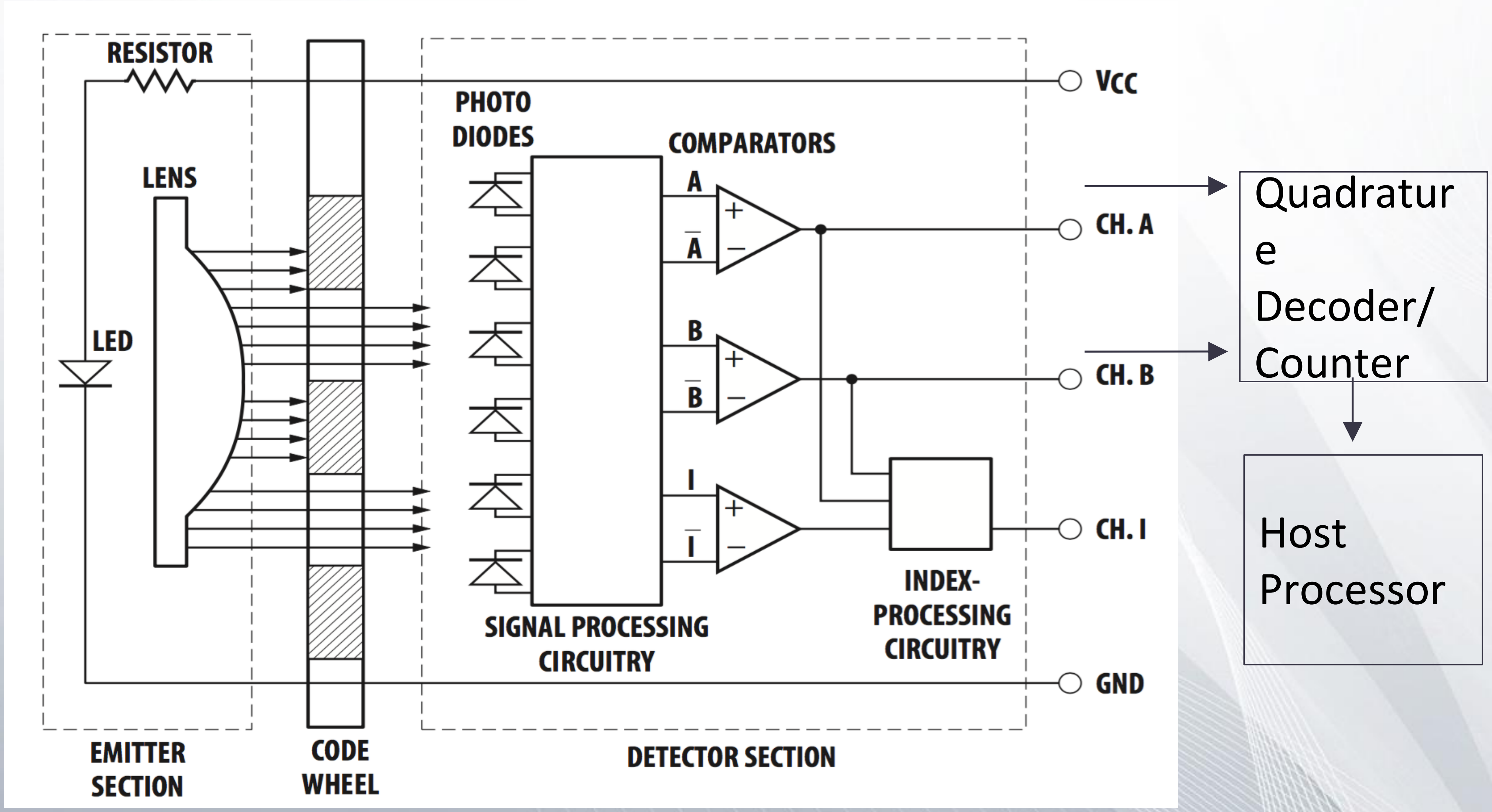
Features:

- Range: 0-40m Laser Emitter
- Accuracy: +/- 2.5cm at distances greater than 1m
- Power: 4.75–5V DC; 6V Max
- Current Consumption: 105ma idle; 130ma continuous
- Rep Rate: 1–500Hz
- Laser Wave Length/Peak Power: 905nm/1.3 watts
- Beam Divergence: 4 m Radian x 2 m Radian
- Optical Aperture: 12.5mm
- Interface: I^2C or PWM





Block Diagram of HEDS-5640 Encoder



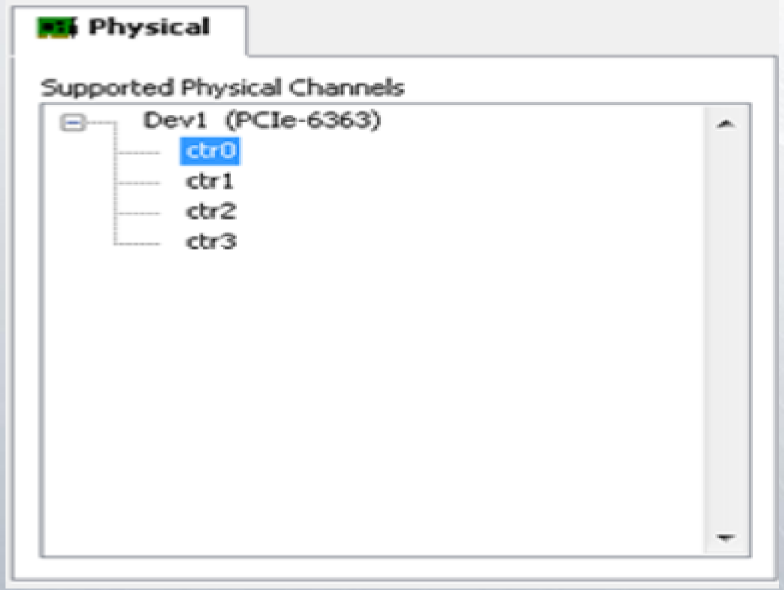
Testbed Integration:

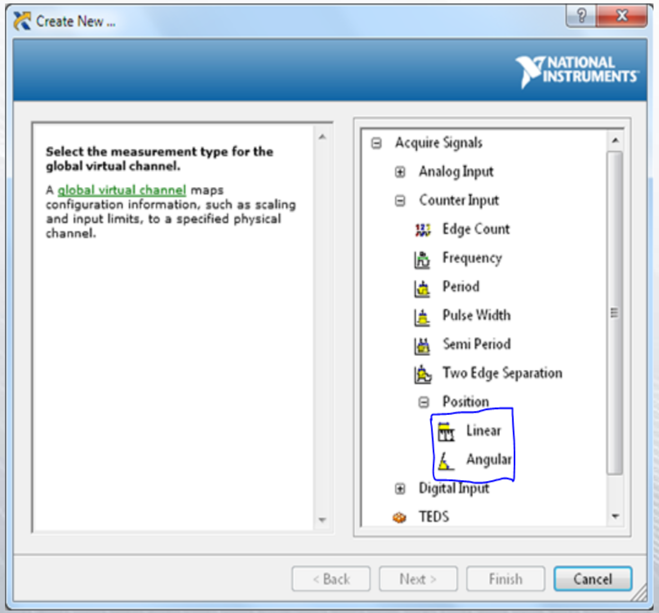
Encoder Data Acquisition.

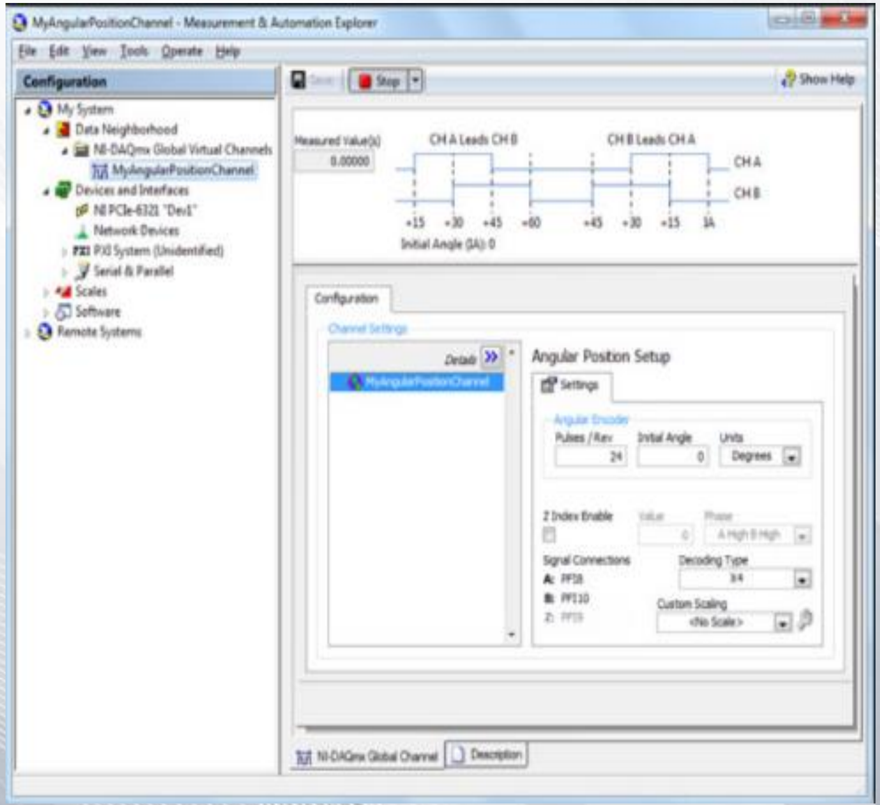
Channel A&B will determine direction (CCW, CW), Channel Z: resets the counter.

Selection of signal acquisition from DAQ

Channel input select.







Autonomy

Numerous Levels of Autonomy

According to NASA:

Capable of gathering and filtering data with out displaying to human (LV. 8)

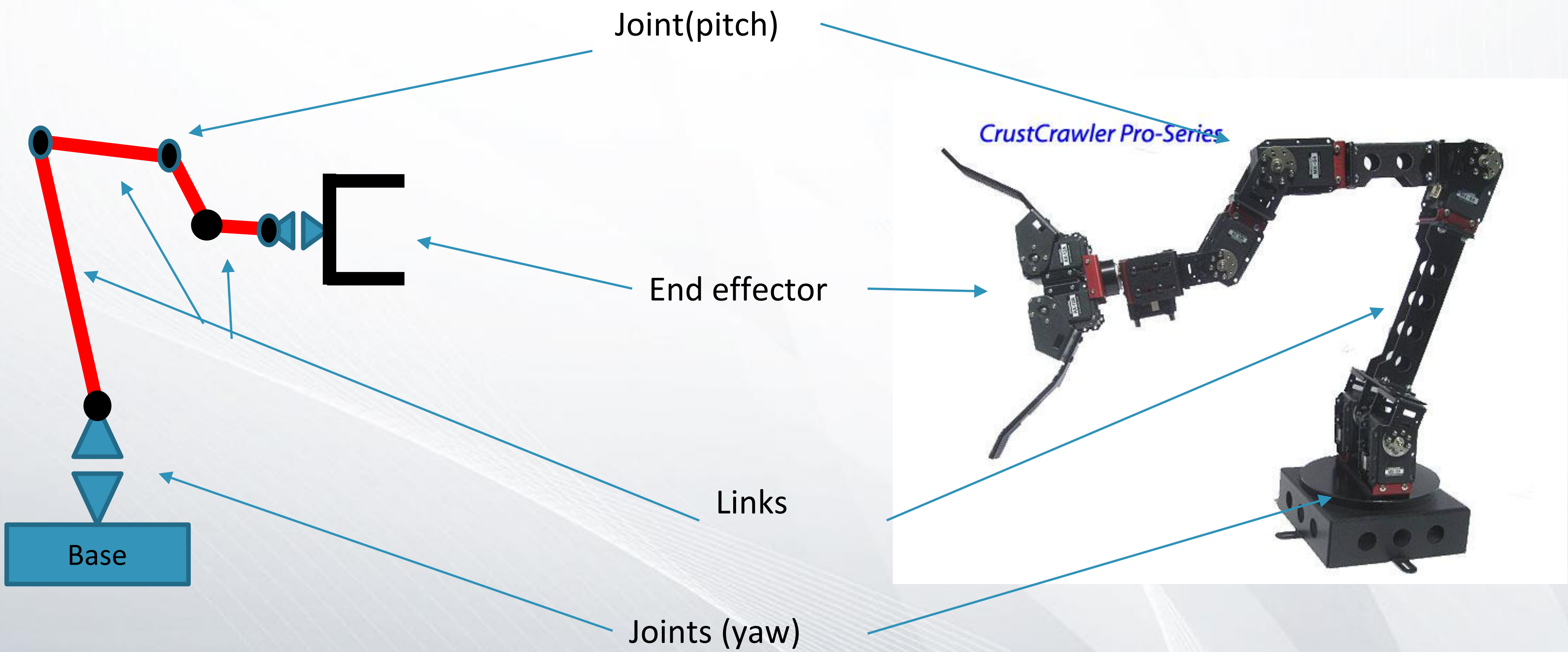
Overlays prediction with analysis and interprets data for result with out displaying to human (LV. 7)

Computer decides final ranking of decisions and displays result to human (LV.7)

Computer executes decision with override capability from human (LV. 7)

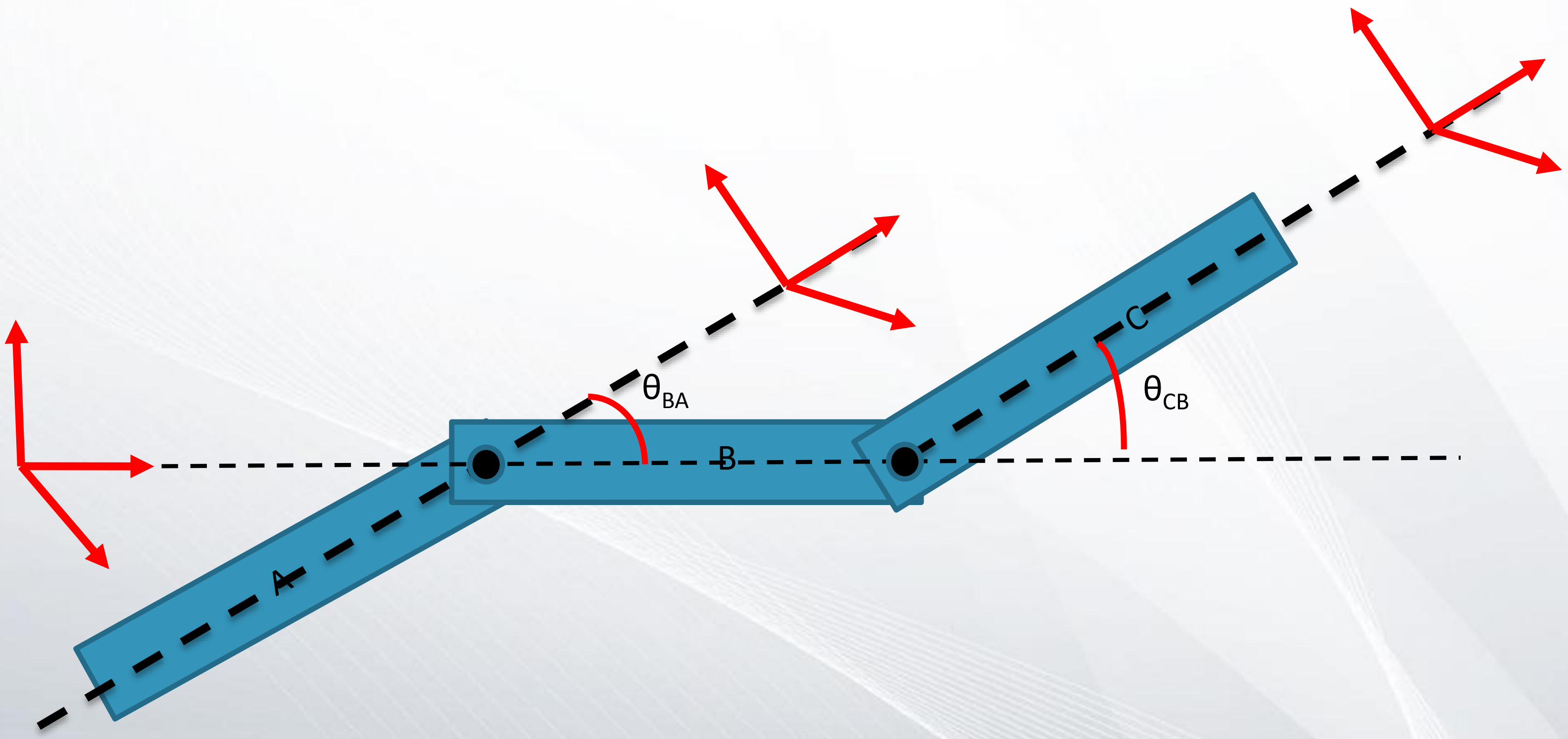
Level	Observe	Orient	Decide	[illegible]
8	The computer is responsible for gathering and filtering data without displaying any information to the human.	The computer overlays predictions with analysis and interprets data for a result that is not displayed to the human.	The computer performs the final rankin[illegible] task, and does not display the result to t[illegible] human.	[illegible] on and [illegible]
7	[illegible] gathering and filtering data without displaying any information to the human. Though, a "program status indicator" is displayed.	[illegible] analysis and interprets data for a result which is only displayed to the human if result fits programmed context (context dependant summaries).	[illegible] task and displays a reduced set of ranked options without displaying "why" the decision was made to the human.	[illegible] only informs the human if required by context. The human is given override ability after execution when physically possible.
6	The computer is responsible for gathering, filtering, and prioritizing information displayed to the human.	The computer overlays predictions with analysis and interprets the data. The human is shown all results for potential override.	The computer performs the ranking task and displays a reduced set of ranked options while displaying "why" the decision was made to the human.	The computer executes the decision, informs the human, and allows for override ability after execution when physically possible. In the event of a contingency, the human can independently execute the decision.
5	The computer is responsible for gathering and displaying unprioritized information to the human. The computer filters out the unhighlighted data displayed to the human.	The computer overlays predictions with analysis and interprets data. The human is the backup for interpreting data.	The computer performs the ranking task. All results, including "why" the decision was made, are displayed to the human.	The computer allows the human a context-dependant time-to-veto before executing the decision. In the event of a contingency, the human can independently execute the decision.
4	The computer is responsible for gathering and displaying unfiltered, unprioritized information to the human. The computer highlights the relevant non-prioritized information displayed to the human.	The computer is the prime source for analyzing data and making predictions as a trusted calculator. The human is the prime source for interpreting data.	Both the human and the computer perform the ranking task, the results from the computer are considered prime.	The computer allows the human a pre-programmed time-to-veto before executing the decision. In the event of a contingency, the human can independently execute the decision.
3	The computer is responsible for gathering and displaying unfiltered, unhighlighted, and unprioritized information to the human. The human is responsible for filtering and prioritizing the data, with computer backup.	The computer is the prime source for analyzing data and making predictions with human checks of the calculations. The human is the only source for interpreting data.	Both the human and the computer perform the ranking task, the results from the human are considered prime.	The computer executes the decision after human grants authority-to-proceed. In the event of a contingency, the human can independently execute the decision.
2	The human is the prime source for gathering, filtering, and prioritizing data, with computer backup.	The human is the prime source for analyzing data and making predictions, with computer verification when needed. The human is the only source for interpreting data.	The human is the only source for performing the ranking task, but the computer can be used as a tool for assistance.	The human is the prime source for executing the decision, with computer backup for contingencies (e.g. deconditioned humans).
1	The human is the only source for gathering, filtering, and prioritizing data.	The human is the only source for analyzing data, making predictions, and [illegible]	The human is the only source for performing the ranking task [illegible]	The human is the only source for executing the decision.

Forward Kinematics

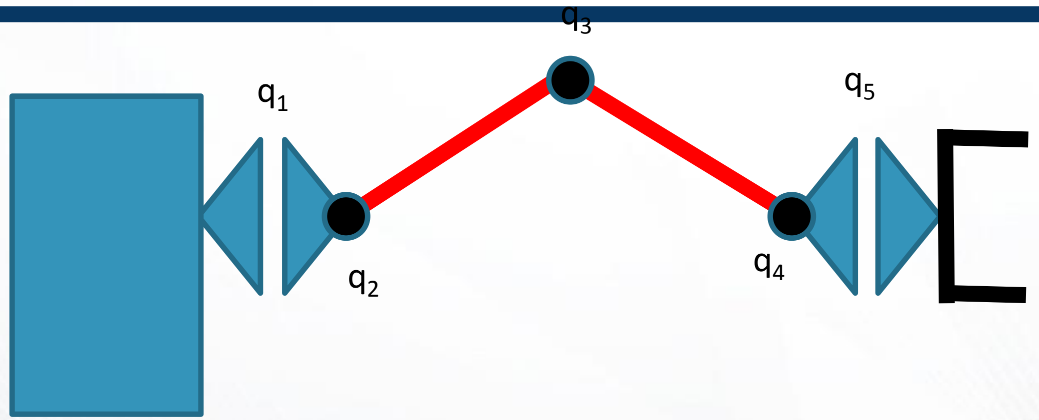


- How does one define the state of the arm?

Forward Kinematics



Answer: Euler Angles/ Quaternions

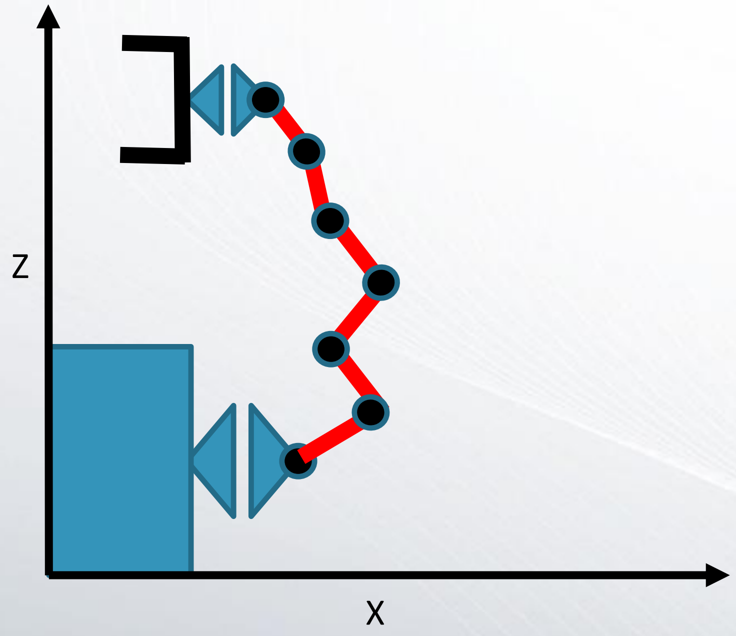


$$q_i = [\phi_i, \theta_i, \psi_i]$$

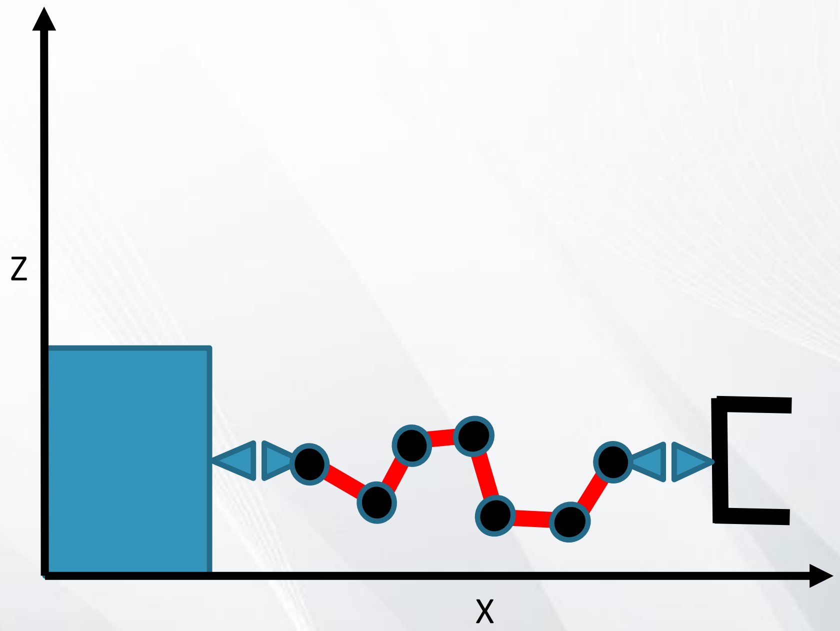
$$\vec{P}_{endeffector} = f(q_1, q_2, q_3, q_4, q_5)$$

Inverse Kinematics(IK problem)

End Effector Initial State



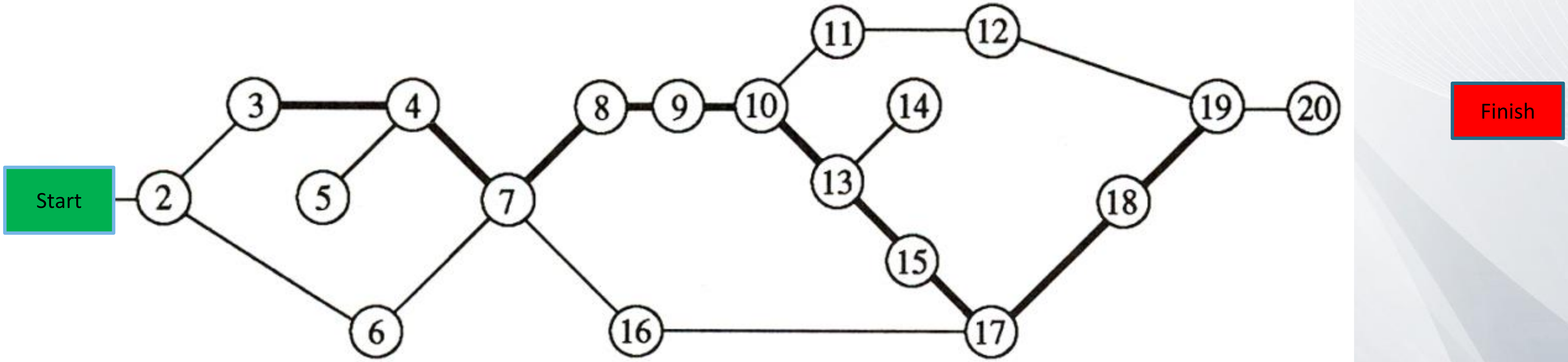
End Effector Position Goal



$$f^{-1}(\vec{P}_{endeffector}) = [q_1, q_2, q_3, q_4, q_5]$$

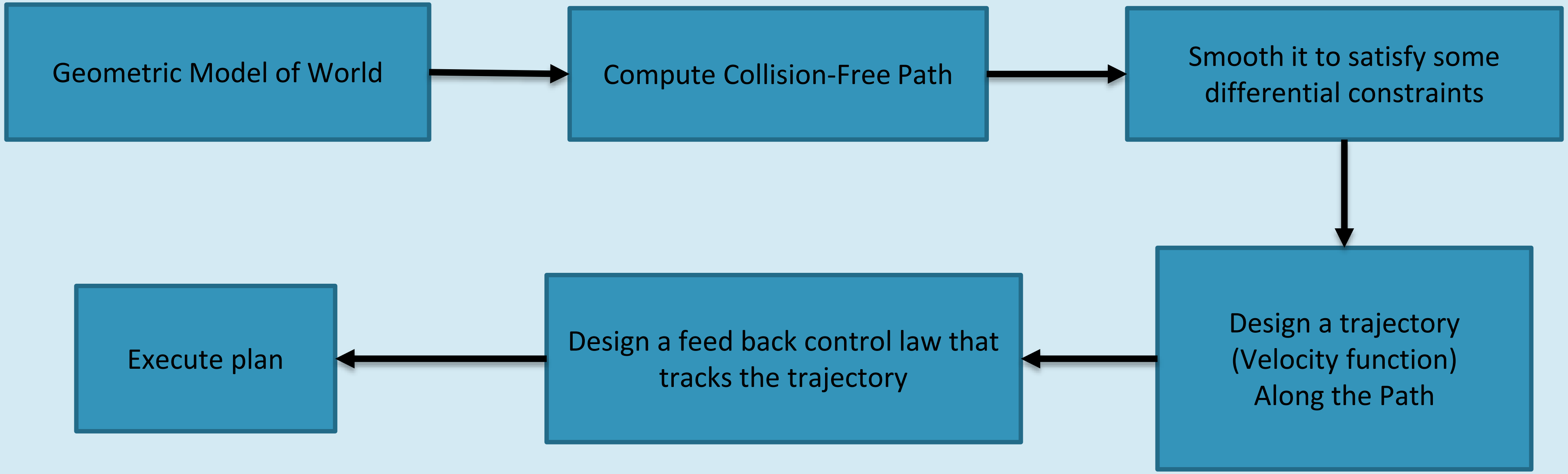
Compute the vector of angles that will cause end effector to reach some desired state.

Search Graph



Trajectory Planning: Methodology

Trajectory Planning Algorithm (Motion Planning)



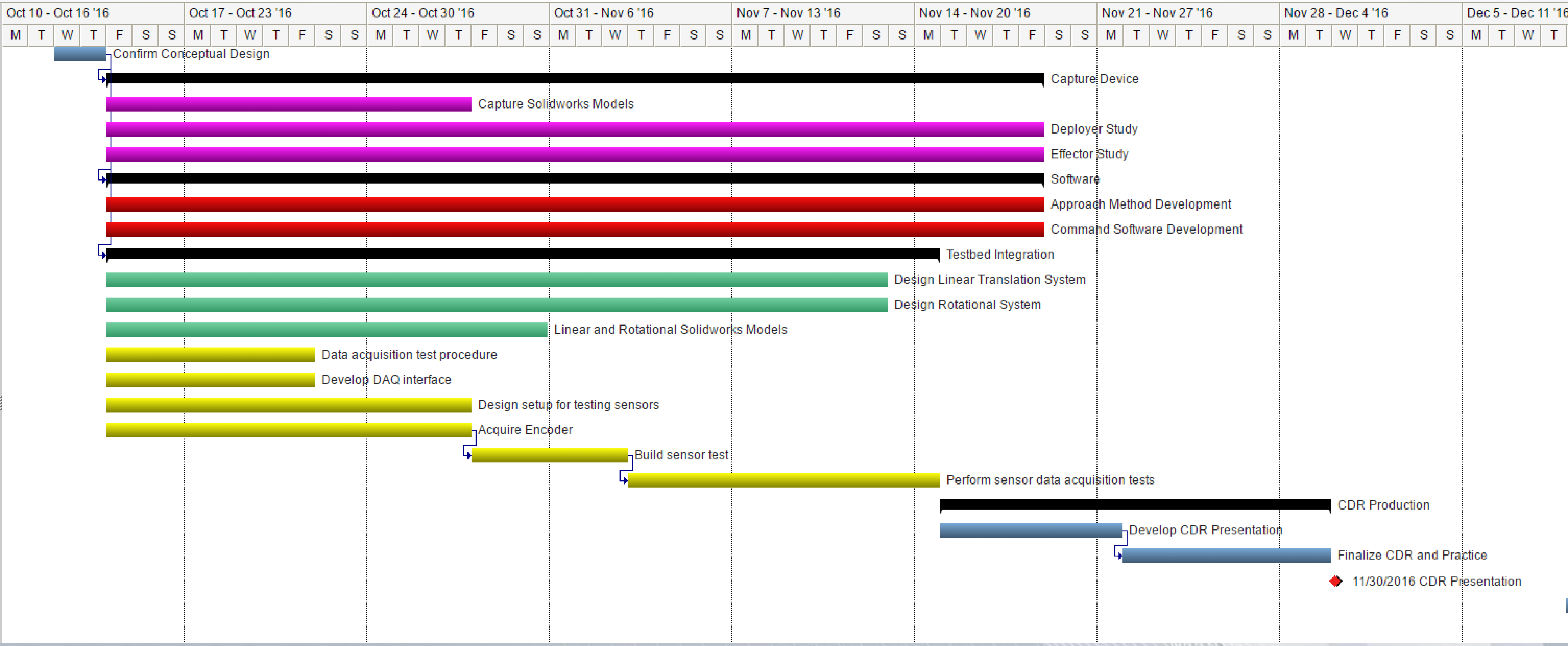
MPK details

Uses a probabilistic roadmap planner

Samples the configuration space to find milestones (ie. possible configurations)

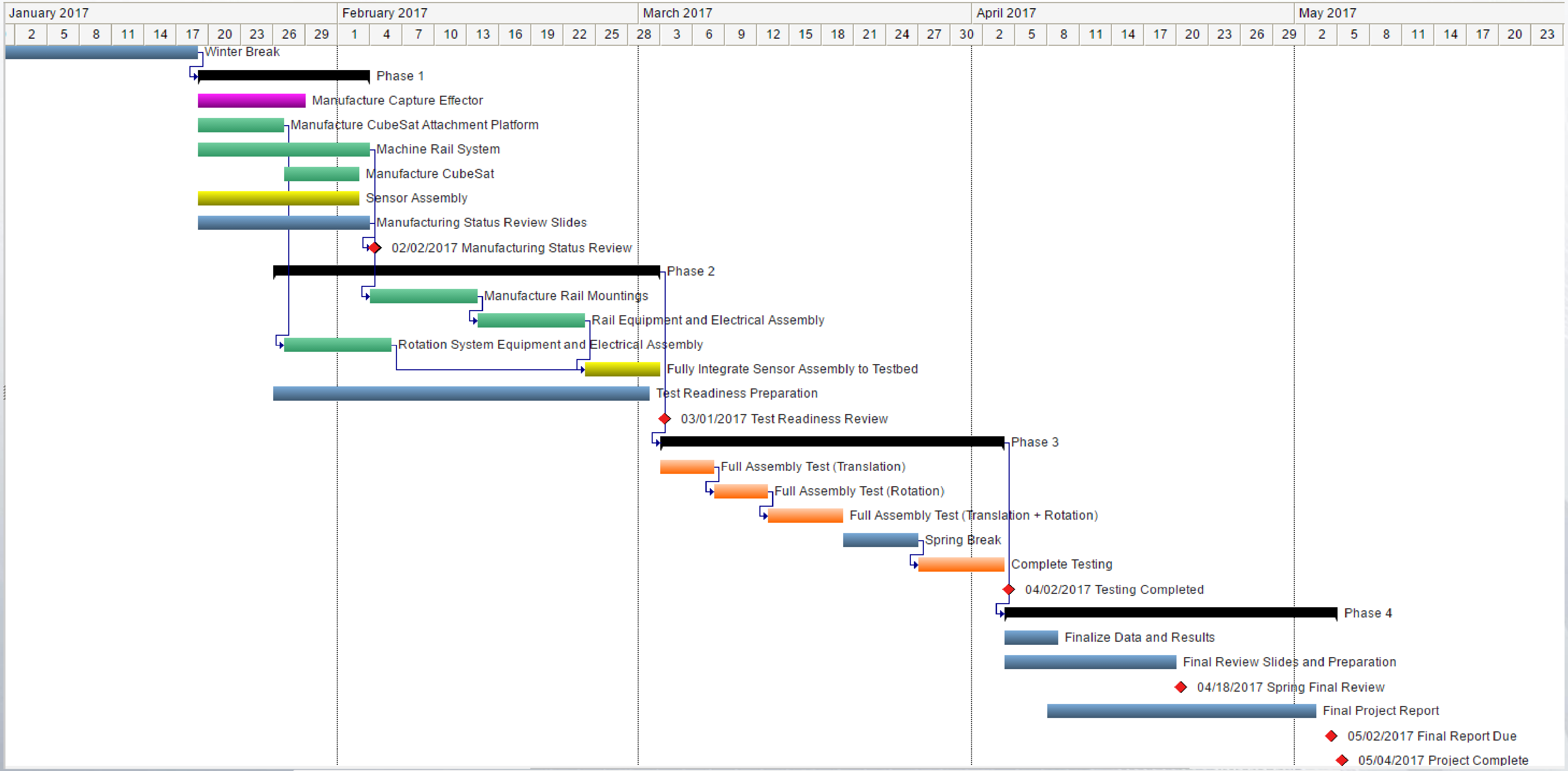
Connects the milestones to create a trajectory

Schedule



Oct 10 - Oct 16 '16
Oct 17 - Oct 23 '16
Oct 24 - Oct 30 '16
Oct 31 - Nov 6 '16
Nov 7 - Nov 13 '16
Nov 14 - Nov 20 '16
Nov 21 - Nov 27 '16
Nov 28 - Dec 4 '16
Dec 5 - Dec 11 '16
M T W T F S S
Confirm Conceptual Design
Capture Device
Capture Solidworks Models
Deployer Study
Effector Study
Software
Approach Method Development
Command Software Development
Testbed Integration
Design Linear Translation System
Design Rotational System
Linear and Rotational Solidworks Models
Data acquisition test procedure
Develop DAQ interface
Design setup for testing sensors
Acquire Encoder
Build sensor test
Perform sensor data acquisition tests
CDR Production
Develop CDR Presentation
Finalize CDR and Practice
11/30/2016 CDR Presentation

Schedule



January 2017
February 2017
March 2017
April 2017
May 2017
2 5 8 11 14 17 20 23 26 29 1 4 7 10 13 16 19 22 25 28 3 6 9 12 15 18 21 24 27 30 2 5 8 11 14 17 20 23 26 29 2 5 8 11 14 17 20 23
Winter Break
Phase 1
Manufacture Capture Effector
Manufacture CubeSat Attachment Platform
Machine Rail System
Manufacture CubeSat
Sensor Assembly
Manufacturing Status Review Slides
02/02/2017 Manufacturing Status Review
Phase 2
Manufacture Rail Mountings
Rail Equipment and Electrical Assembly
Rotation System Equipment and Electrical Assembly
Fully Integrate Sensor Assembly to Testbed
Test Readiness Preparation
03/01/2017 Test Readiness Review
Phase 3
Full Assembly Test (Translation)
Full Assembly Test (Rotation)
Full Assembly Test (Translation + Rotation)
Spring Break
Complete Testing
04/02/2017 Testing Completed
Phase 4
Finalize Data and Results
Final Review Slides and Preparation
04/18/2017 Spring Final Review
Final Project Report
05/02/2017 Final Report Due
05/04/2017 Project Complete

Design Requirements

Req. #	Parent	Type	Requirement
1.1	1	FR	The CRST shall demonstrate the motion of a CubeSat analogue during the demonstration.
1.1.1	1.1	DR	The CubeSat analogue shall include a physical model of a 3U CubeSat with dimensions specified in Figure 2
1.1.1.1	1.1.1	DR	The physical model of a 3U CubeSat shall include at minimum one significant protrusion to represent solar panel(s).
1.1.2	1.1	DR	The CubeSat analogue shall allow for translational motion about only one axis.
1.1.3	1.1	DR	The CubeSat analogue shall allow for rotational motion about only one axis, the same as the translational axis.
1.2	1	FR	The CRST shall determine the relative position and attitude of the CubeSat and capture device during the demonstration.
1.2.1	1.2	DR	The CRST shall employ sensors to gather data at each control point of all moving bodies during the demonstration.
1.3	1	FR	The CRST shall determine the relative position and attitude rates of the CubeSat and capture device during the demonstration.
1.3.1	1.3	DR	The CRST shall employ sensors to gather data at each control point of all moving bodies during the demonstration.
1.4	1	FR	The CRST shall calculate a capture trajectory capable of capturing the CubeSat during the demonstration.
1.4.1	1.4	DR	The CRST shall employ software to calculate a capture trajectory capable of capturing the CubeSat during the demonstration.
1.5	1	FR	The CRST shall command the relative linear motion between the CubeSat and the capture device based on the calculated captur
1.5.1	1.5	DR	The relative linear translation between the CubeSat and the capture device shall be within motor performance tolerances.
1.6	1	FR	The CRST shall command the motion of the capture device based on the calculated capture trajectory during the demonstration
1.6.1	1.6	DR	The commands sent for capture device motion shall be within joint servos performance tolerances.
1.7	1	FR	The CRST shall execute capture of the physical CubeSat model by a capture device during the demonstration.
1.7.1	1.7	DR	The CRST shall include a physical capture device used to capture the physical CubeSat model.
1.7.1.1	1.7.1	DR	The capture device shall occupy no more volume than the pay-load bay shown in Figure 1.
1.7.1.2	1.7.1	DR	The capture device shall have a mass budget of 15kg.
1.7.1.3	1.7.1	DR	The capture device shall have an average power of no more than 100W
1.7.1.4	1.7.1	DR	The capture device shall have an peak power of no more than 168W
1.7.1.5	1.7.1	DR	The capture device shall have an peak current draw of no more than 10A
1.7.1.6	1.7.1	DR	The capture device shall have an peak voltage draw of no more than 28V ± 6V unregulated
1.7.2	1.7	DR	The demonstration shall begin at a minimum distance of 1m between the physical CubeSat model and the capture device.
1.7.3	1.7	DR	Control of the demonstration after initiation shall be autonomous (closed-loop) in nature.
1.7.4	1.7	DR	The CRST shall capture the CubeSat with the capture device in less than 30 minutes.
1.7.5	1.7	DR	The CRST shall capture the CubeSat with the capture device without visible damage to the CubeSat nor the capture device
1.7.6	1.7	DR	The CRST shall allow for five repeated demonstrations.
1.7.6.1	1.7.6	DR	The capture device shall be able to release and back away from the CubeSat after capture without human intervention.
1.7.7	1.7	DR	The CRST shall hold the CubeSat with the capture device for a minimum of 5 minutes after capture during the demonstration.

Presentation Appendix

Project Def.	Baseline Design	Feasibility	Project Status

Overview	Baseline	Capture Device	Software	Software	Summary
Project Statement	Rail System	Friction	Timeline	Computing power	Design Recap
CONOPS	Capture Arm	Servo Torque	Axis of Rotation	Computing power 2	Cost Budget
FBD	Capture Claw	Closing Sensor	Match Spin Rate		Schedule
Functional Requirements	Rotation System	Arm	Linear Translation		
Levels of Success	Sensors	Torque sheet	Move to grasp		
	Algorithm	Power Budget	Resources		

Backup Appendix

Project Def.	Baseline Design	Feasibility	Project Status

Overview	Testbed	Testbed	Software	Effector	Effector	Deployer	Schedule	Sensors
Design Requirements	Translation Control	Rotation Torque	Forward Kinematics	End Effector Trade	Gripping Plates	Deployment Trade	Budget Backup Excel	VICON
	Rotation Control	Rotation Components	Inverse Kinematics	Effector Trade 2	Gripping Force		Budget Backup Bars	LIDAR
	Wrist Control	Switch from RW	Search Graph	Claw Specifications	Gripping Force2		Budget Backup Borrow	ENCODER
	Linear Rail		Trajectory Methodology	Claw Design	Gripping Force3			
	Rotation			Phase Error	Design Options			
	System Control			Effector Visual	Gripper Config			
	DAQ			Parallel Linkage	Force Sensor			