C.R.O.A.C.S.

Critical Design Review

November 29th, 2021

ASEN 4018-011 Team #6

Company Sponsor:
Astroscale

Faculty Advisor:
Dr. Yu Takahashi

Presenters:
Tyler Gaston, Jake Pirnack, Jash Bhalavat, Zack Hubbard, Nicholas Herrington, Jianai Zhao

Presentation Outline

1. **Project Overview** - Tyler Gaston
2. **Design Solution** - Zack Hubbard, Jake Pirnack
3. **Critical Project Elements** - Jianai Zhao
4. **Design Requirements Satisfaction** - Jash Bhalavat, Nicholas Herrington
5. **Risk Analysis** - Zack Hubbard
6. **Verification and Validation** - Jash Bhalavat, Jake Pirnack, Nicholas Herrington
7. **Project Planning** - Tyler Gaston , Jianai Zhao

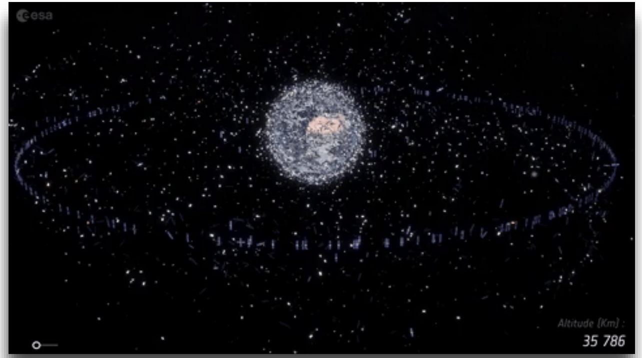
Project Overview - Purpose

Background:

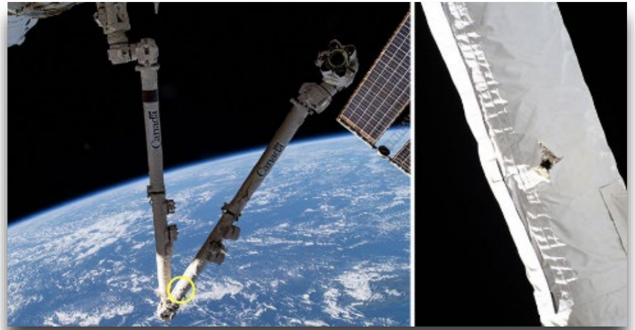
- Space Debris is growing concern, as more and more satellites are put into orbit.
- **Astroscale** is working on **end of life satellite servicing** for cooperative and noncooperative satellites.
- In order to attempt at de-orbiting debris its **dynamics must be accurately measured.**

Motivation:

- **Accuracy & Complexity:** Current ground based satellite tracking has large margins of positional error, and is ineffective at determining attitude and pointing.
- **Safety:** The servicing satellite must have a way to sense the client satellite's attitude and position without increasing the risk of a collision or creating more debris.



Space Debris Field Timeline
https://upload.wikimedia.org/wikipedia/commons/3/3d/Tough_Love_ESA19243296.gif

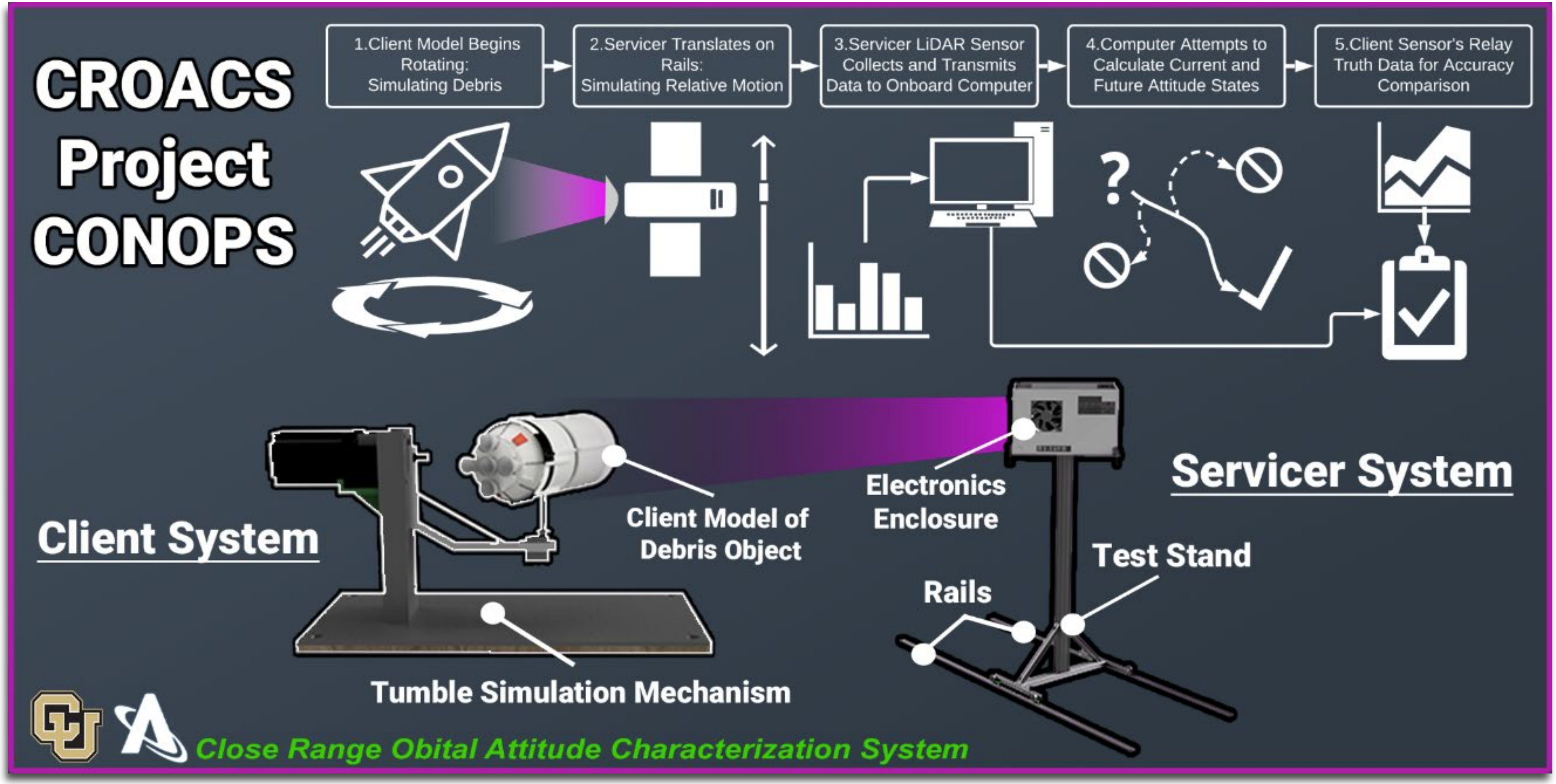


ISS Space Debris Damage https://spacenews.com/wp-content/uploads/2021/06/canadarm-debris-2021.png

Project Overview - Specific Objectives

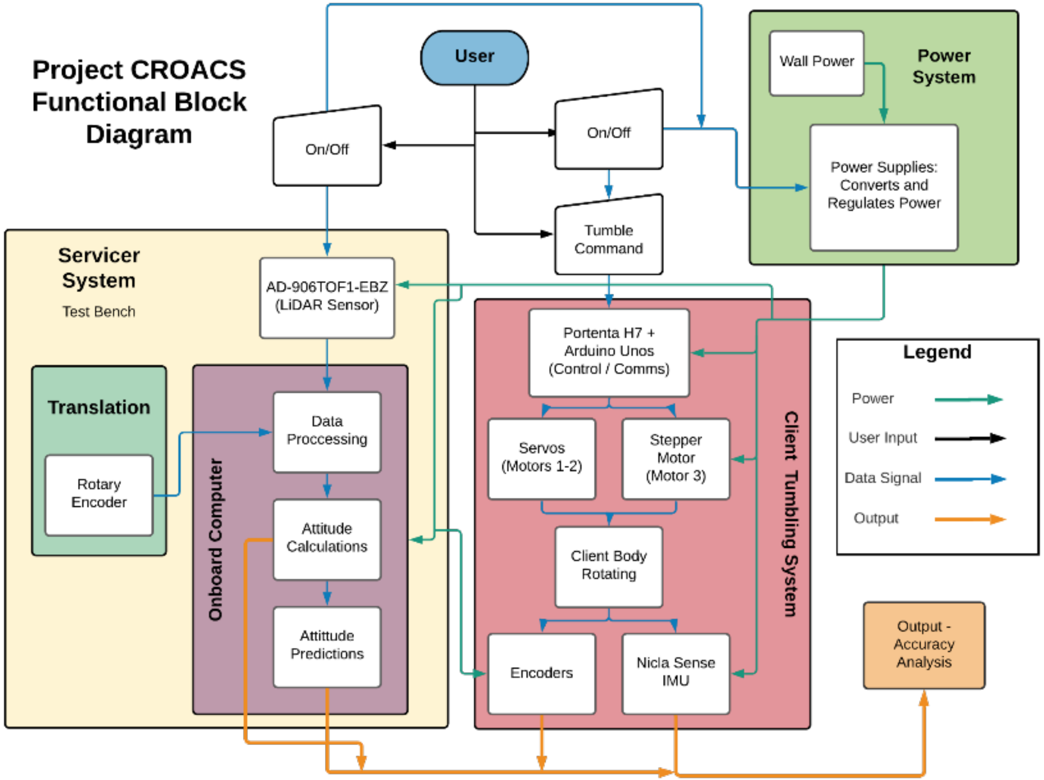
- ❑ **Remotely sense** attitude, position, angular velocity, and translational velocity of a client satellite
- ❑ **Predict future dynamics** of a client satellite based on remotely sensed data
- ❑ **Simulate 3D motion** of an uncooperative, known satellite for testing

Concept of Operations



Design Solution

Functional Block Diagram



Design Progress: PDR → CDR

CROACS

Electronics

Servicer
- LiDAR sensor selection
- Onboard computer selection
- Wheel encoder for servicer position

Client
- Motor selection
- Truth data collection redesign
- BLE components for wireless comms

Hardware

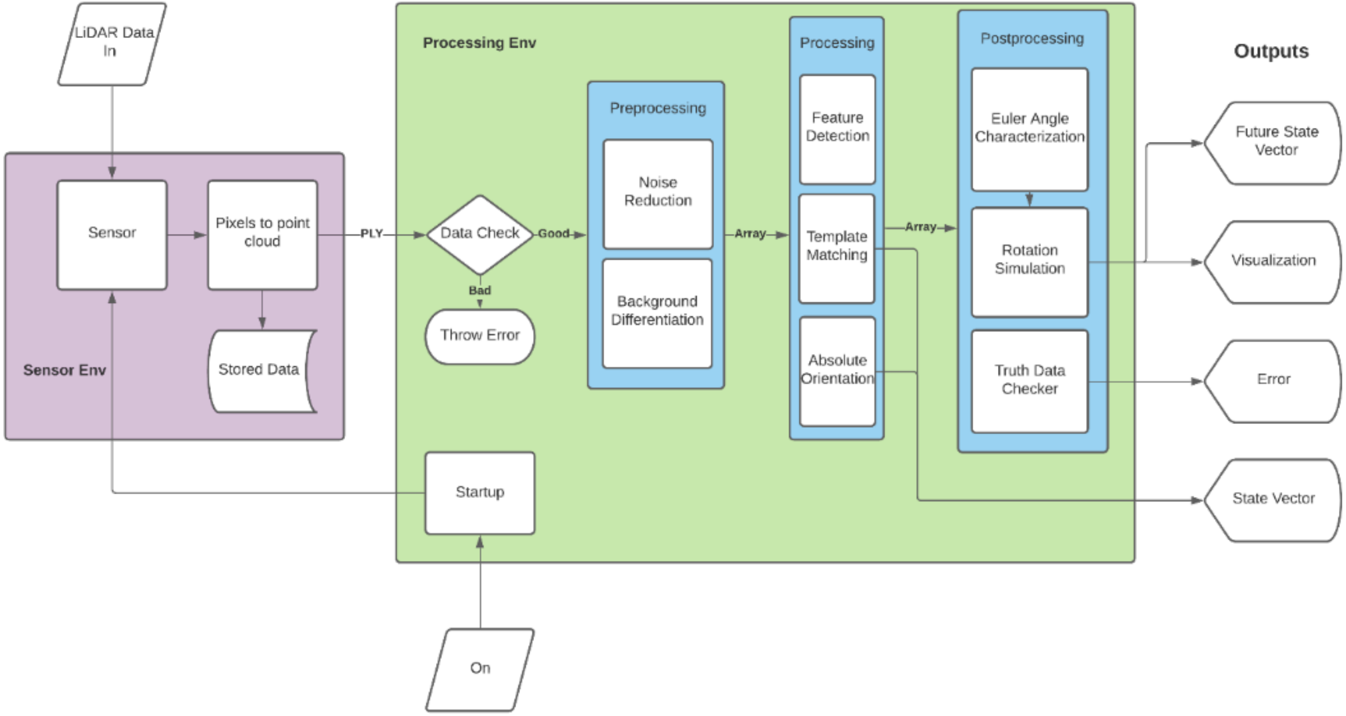
Servicer
- Finalized enclosure dimensions
- Materials and final part designs
- Simplified test stand design

Client
- Motor integration design
- Electronics integration design
- Material and part design
- Higher fidelity booster model

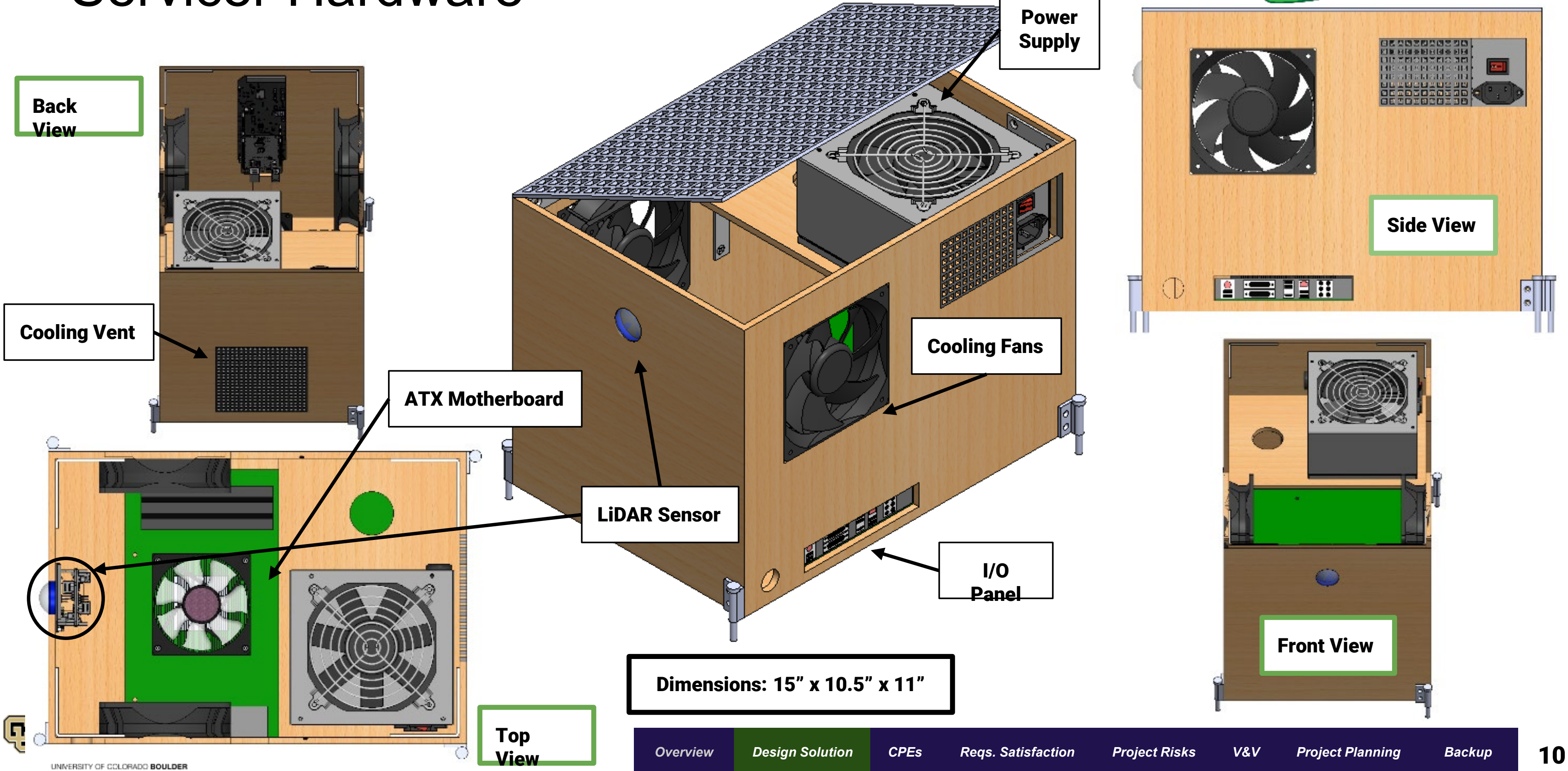
Software

Servicer
- Decreased template matching time
- Motion characterization
- Prediction modules
- Established servicer environment

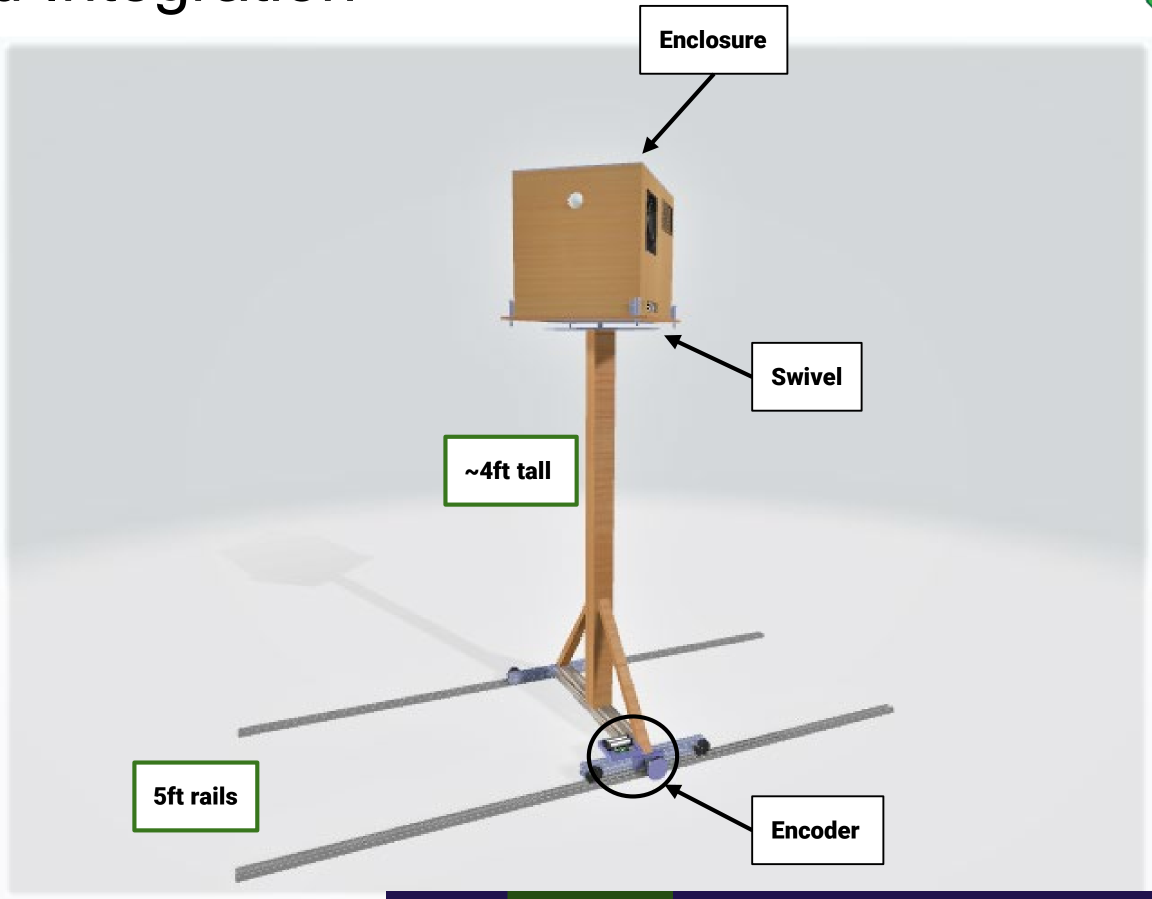
Servicer Software - Flowchart Overview



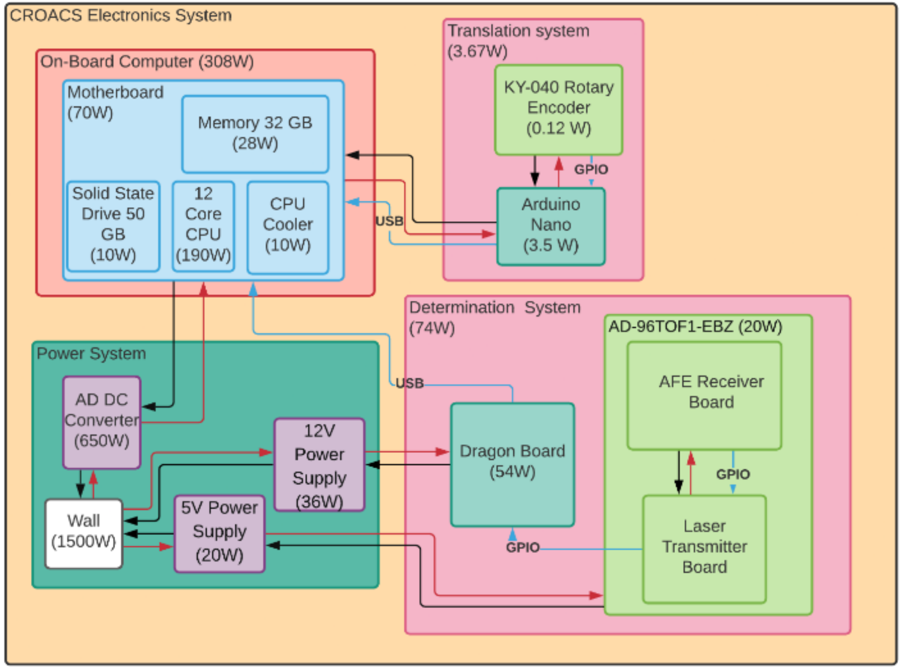
Servicer Hardware

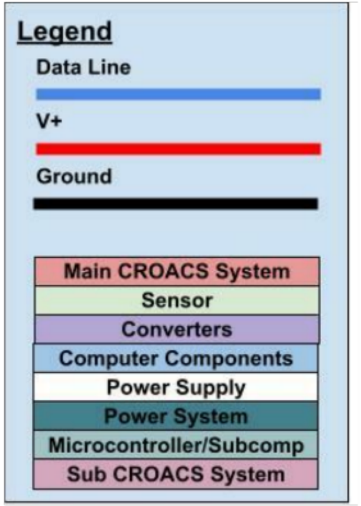


Test Stand Integration



Servicer Electrical Design





AD-96TOF1-EBZ
Lidar Sensor

Client Design Animation

Client Hardware Design: Motor Interfacing

Motor 1 (continuous rotation servo)

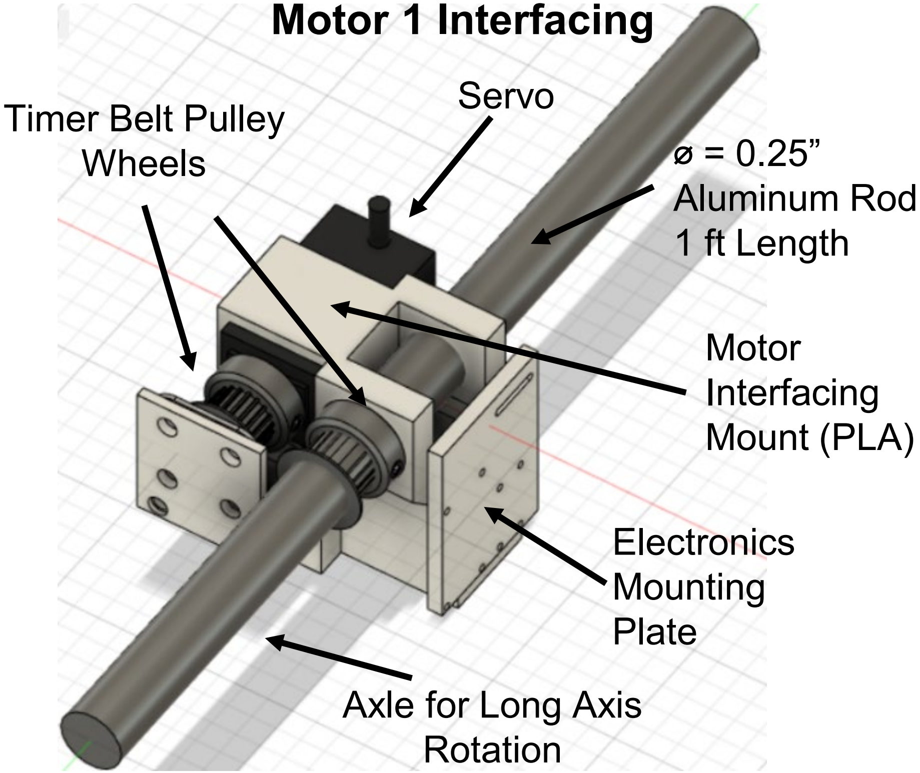
- **Sits inside debris model**, mounted with driving electronics
- Drives model using toothed belt

Motor 2 (continuous rotation servo)

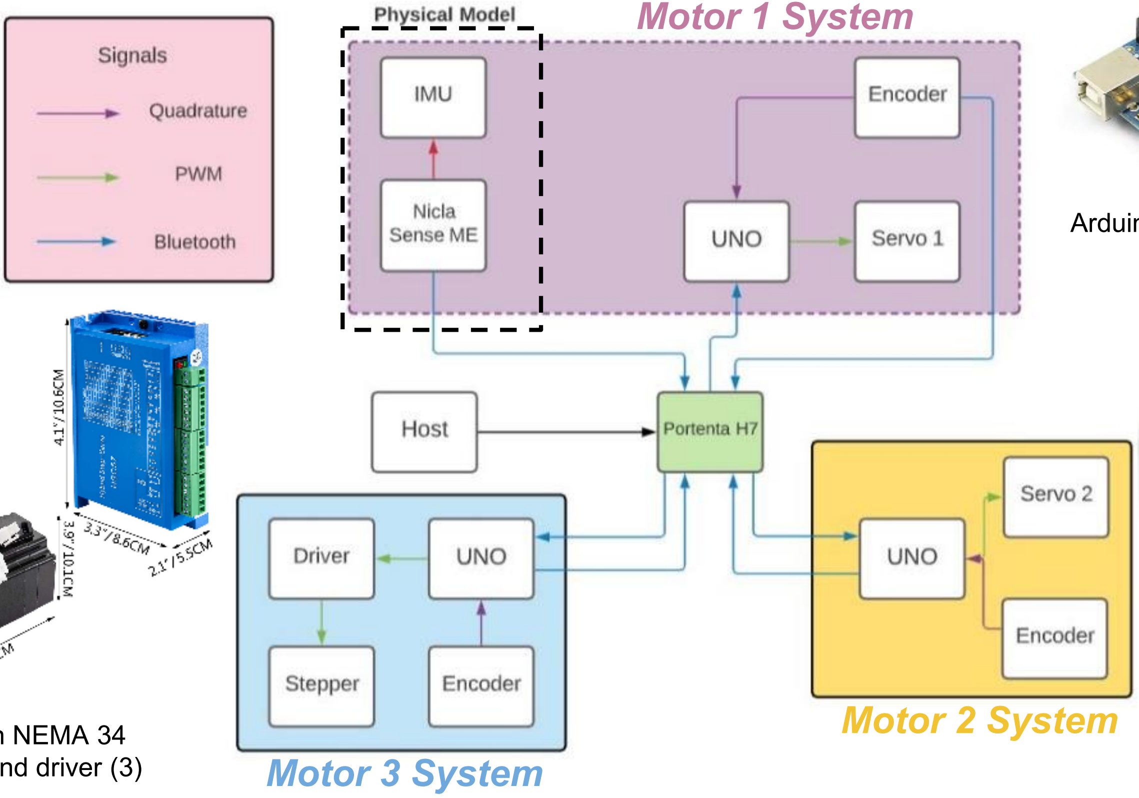
- Mounted to rotation axis is perpendicular to L-arm, drives rotation directly

Motor 3 (stepper motor)

- Drives planetary gearbox which directly drives rotation of L-arm



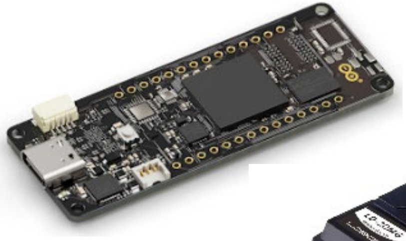
Client Electrical Design (Command & Data)



Mophorn NEMA 34
Stepper and driver (3)

Arduino UNO WiFi Rev 2

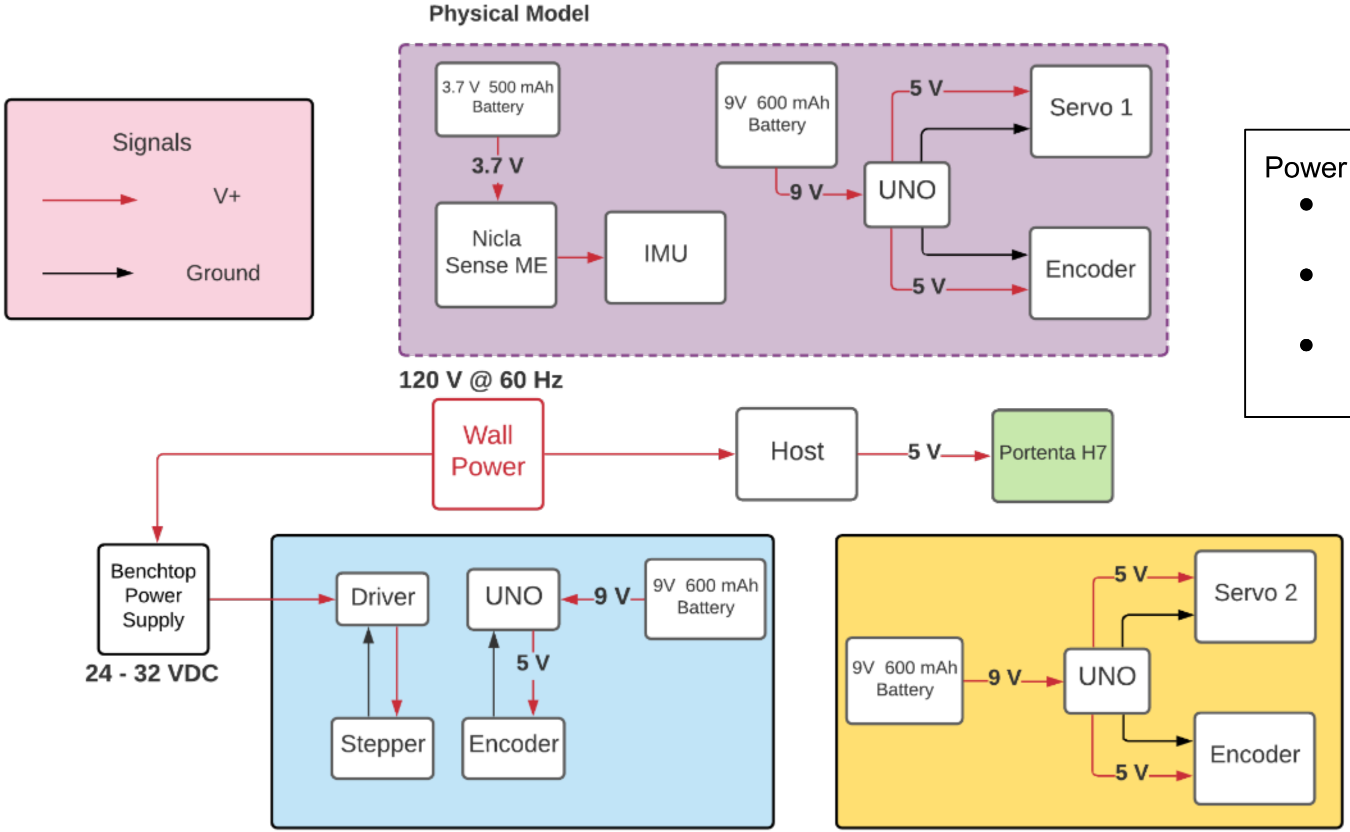
Nicla Sense ME



Portenta H7

JX Servo (1)

Client Electrical Design (Power)



Power Budget (run times):

- IMU subsystem
  - 2hrs
- Motor 1 Subsystem
  - 1.55 hrs *(minimum)*
- Motor 2 Subsystem
  - **0.79 hrs *(minimum)***

Critical Project Elements

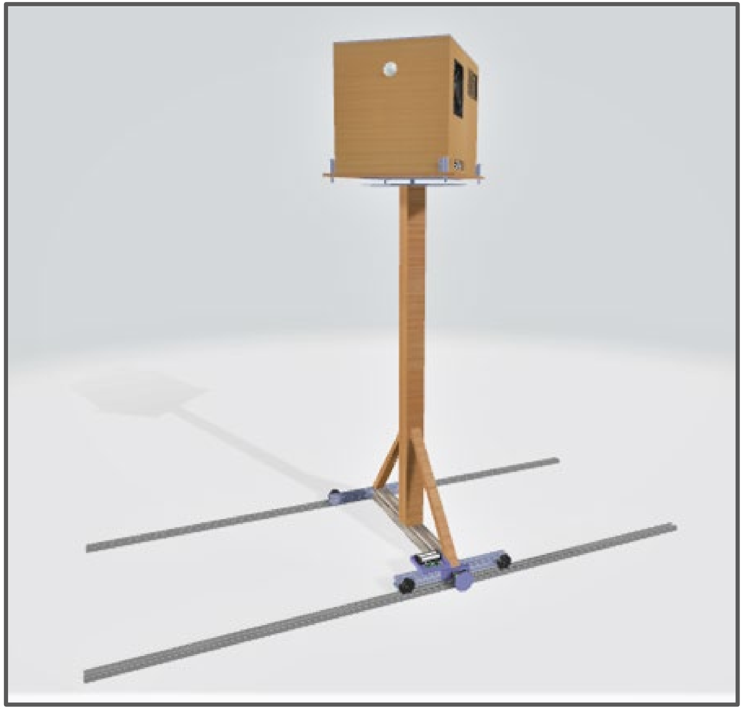
Critical Project Elements

CPE	Description	FR
[E1] Servicer Infrastructure	-Physical enclosure to **house all electronics and sensors** of the servicer. -Capable of **translation** during testing.	**[FR4]**
[E2] Client Model	-**Physical model** of space debris with **three axes of motorized rotation.** -Onboard sensors **report truth data**.	**[FR5]**
[E3] Data Processing	-Imaging sensor **collects and transmits** usable data to **on-board processor** -On-board processor meets specifications to run software **close to real time**	**[FR1]** **[FR3]**
[E4] State Determination	-Software **differentiates client from background**. -Software calculations **match truth data to a <10% margin of error**.	**[FR2]**
[E5] State Prediction	-Software is **capable of characterizing steady state dynamics** of client to a 95% confidence interval in order to predict future states.	**[FR2]**

Design Requirements & Satisfaction

Servicer Infrastructure (FR4)

DR 4.3: The servicer shall be capable of at least 3 ft of translation in at least 1 direction



- Aluminum 8020 Ground Track
  - 5 feet of track allowing 4 feet of translational motion.
  - Encoder on servicer wheels to monitor translational speed.

Design Requirement	Satisfaction
DR 4.2, 4.3	Yes

Client Model (FR5)

DR 5.1: The client shall record measurement data about its position, orientation, and angular velocity.
DR 5.2: The client shall be able to spin about three different axes at a rate of at least 10 deg/sec.

- IMU, Encoders, and Vicon System
  - Each record truth data to compare with software predictions
    - Devices verify each other.
  - Able to detect rotation speeds up to 10 deg/sec
- Continuous rotation servos
  - Smooth rotation at low speeds
  - Both servos meet torque requirements
- Stepper motor
  - Planetary gearbox used to step down speed so that rotation is smooth
  - Mitigates “jitter” at low speeds

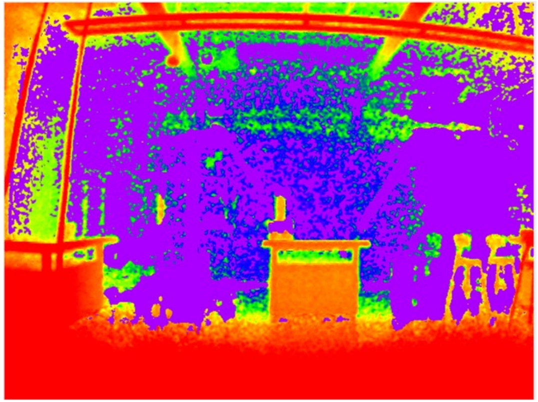
Motor	Torque Requirements *For 10 deg/sec*	Selected Motor Torque Rating
1 (Servo)	≈ 1 [N cm]	20 [kg cm] or 1.96[N m]
2 (Servo)	≈ 1 [N cm]	35 [kg cm] or 2.94[N m]
3 (Stepper Motor)	8 [N m]	9 [N m]

Design Requirement	Satisfaction
DR 5.1, 5.2	Yes

Data Processing (FR1)

DR 1.1: The servicer shall sample data at a rate suitable for a client spinning at a rate of, at most, 10 deg/sec.
DR 1.3: The servicer shall be able to gather data from the client at a range of at least 3m.

- LiDAR Sensor: AD-906TOF1-EBZ
- Minimum Required Data Rate: 20 fps
  - For 1 degree accuracy at a Nyquist signal speed of 20 deg/sec
  - Max Data Rate of LiDAR Sensor: 30 fps
- 3 Sensing Modes:
  - Near: 25 - 80 cm
  - Medium: 30 cm - 4.5 m
  - Far: 3 - 6 m



Acquired LiDAR Data of Water Bottle from 4 meters away

Design Requirement	Satisfaction
DR 1.1, 1.3	Yes

Data Processing (FR3)

DR 3.3: The on-board computer shall have sufficient processing power to compute predictions at least 1 min into the future.

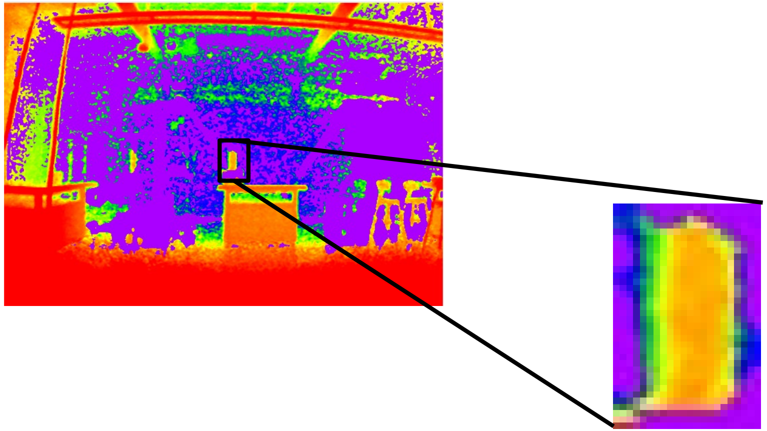
- Minimum Required Computation Power: 10-Core i7 32GB RAM
  - Initialization of algorithm took about 30 seconds
  - Improvement of algorithm efficiency and greater computation power
  - On-board Processor: Desktop
    - 12-Core i7 12th gen CPU
    - 32GB RAM
- Minimum Required Data Transfer Rate: 38.1 MBps
  - USB 3.2 Gen 2X2: 2.5GBps transfer rate
- Minimum Required Storage: 15 minutes → 34.29 Gb
  - Desktop Storage: 500GB SSD

Design Requirement	Satisfaction
DR 3.3	Yes

State Determination (FR2)

DR 2.1: The software algorithm shall identify the known client from the background.

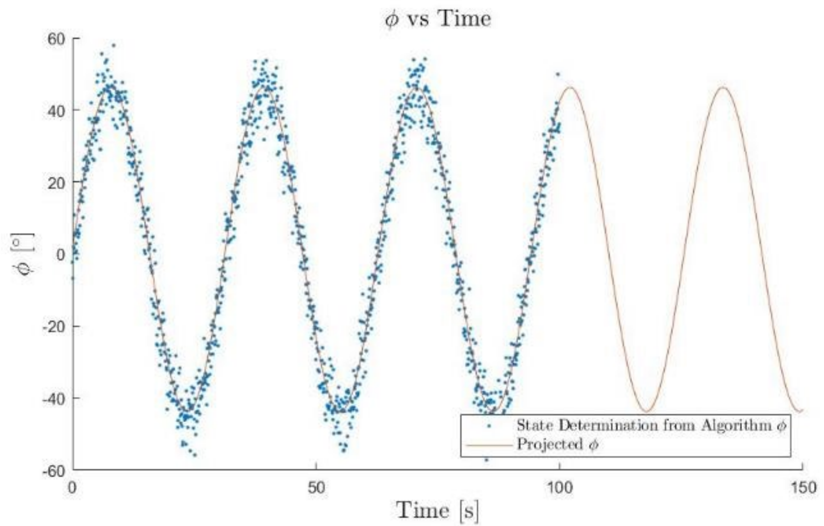
- Geometrical Noise Reduction
- The state determination module uses a bounding box to exclude the background
    - Bounding box adjusted to distance and velocity in area of client object
    - Iterate through point cloud and eliminate points that reside outside the bounding box



Design Requirement	Satisfaction
DR 2.1	Yes

State Prediction (FR2)

DR 2.2: The software algorithm shall make predictions of the client's future attitude states.
DR 2.2.1: The software algorithm shall have no more than 10% relative error to measured data, at a predicted time 1min in the



- Propagation module predicts Euler angles by matching equation to the data and then solving for the Euler angle
- Statistical approach negates the need for analytical solution, more accurate and brings down computation time

Design Requirement	Satisfaction
DR 2.2, DR 2.2.1	Yes

Project Risks

Risk Table

Risk Number	Description	Effect	Likelihood of Occurrence	Severity of Consequence	Risk Priority Number (RPN)
R1	Excessive software runtime	Predictions become useless	**4**	**5**	**20**
R2	Feature detection can't distinguish unique elements about radial symmetry of client	Failure to determine attitude state	**4**	**5**	**20**
R3	LIDAR data is too noisy to provide necessary detail at far range (3m+)	Unusable point cloud data	**3**	**5**	**15**
R4	Motors don't provide sufficient torque to rotate body about their respective axes at low speeds	Failure of client rotation about one or more axes	**3**	**4**	**12**
R5	Magnetic effects from spinning motors skews truth data measurements	Failure to provide accurate truth data	**3**	**3**	**9**
R6	Interfacing failure between client measurement sensors	Failure to provide truth data	**2**	**4**	**8**
R7	Budget exceeds $5000	Failure to continue production	**1**	**5**	**5**

Initial Risk Matrix

Acceptable	Tolerable	Unacceptable

R1: Software runtime
R2: Radial symmetry
R3: Detail at range
R4: Motor Torque
R5: Magnetic effects
R6: Truth sensor interfacing
R7: Budget

		Severity of Consequence				
		1	2	3	4	5
Likelihood of Occurrence	5					
	4					R1 R2
	3			R5	R4	R3
	2				R6	
	1					R7

Mitigated Risk Table

Acceptable	Tolerable	Unacceptable

CROACS

R1: Software runtime
R2: Radial symmetry
R3: Detail at range
R4: Motor Torque
R5: Magnetic effects
R6: Truth sensor interfacing
R7: Budget

Mitigation Methods

R1: Parallel computing, algorithm optimization

R2: Determine other parameters with missing euler angle, use reflectivity instead of features

R3: Attitude regardless of noise, reflectivity of rotation stand, increase power to lasers

R4: Gear ratios, worm gears

R5: Determine bias from Vicon testing, provide truth data from multiple sources

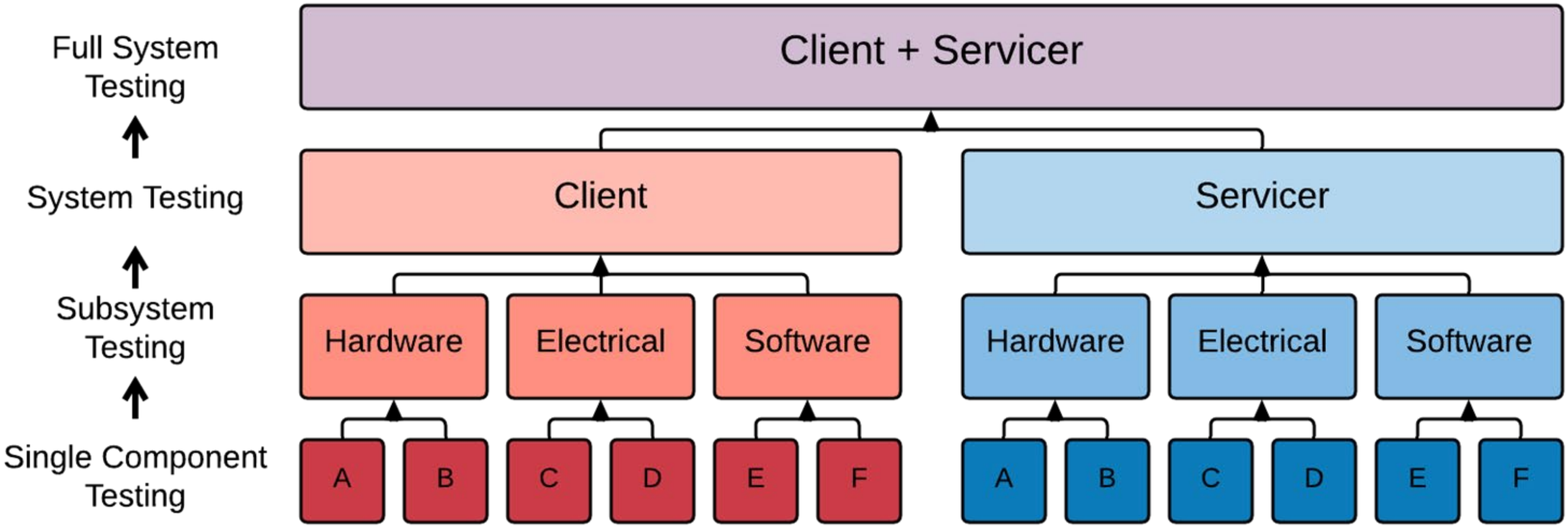
R6: Alternate interfacing methods

R7: Finding cheaper components

		Severity of Consequence				
		1	2	3	4	5
Likelihood of Occurrence	5					
	4					R1 R2
	3	R5	R4	R5	R4	R3
	2			R3 R6	R6	R2 R1
	1					R7

Verification and Validation

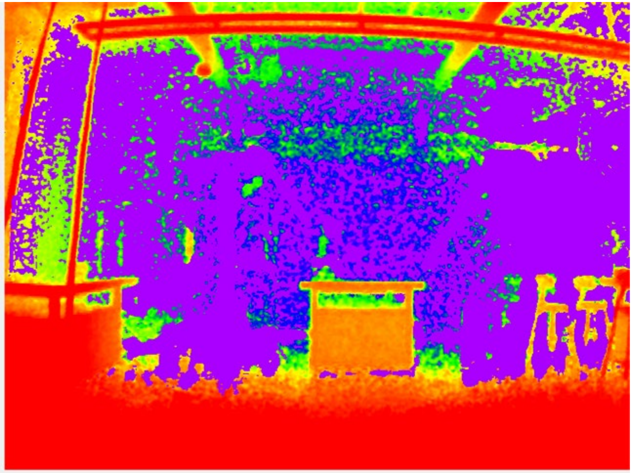
Testing Structure



Component Verification
Servicer LiDAR Sensor

DR 1.4: The sensor suite shall have a range accuracy of at least 1 cm (at 1 standard deviation).
DR 1.5: The sensor suite shall gather data under the harsh lighting conditions representative of satellites in a LEO orbit.

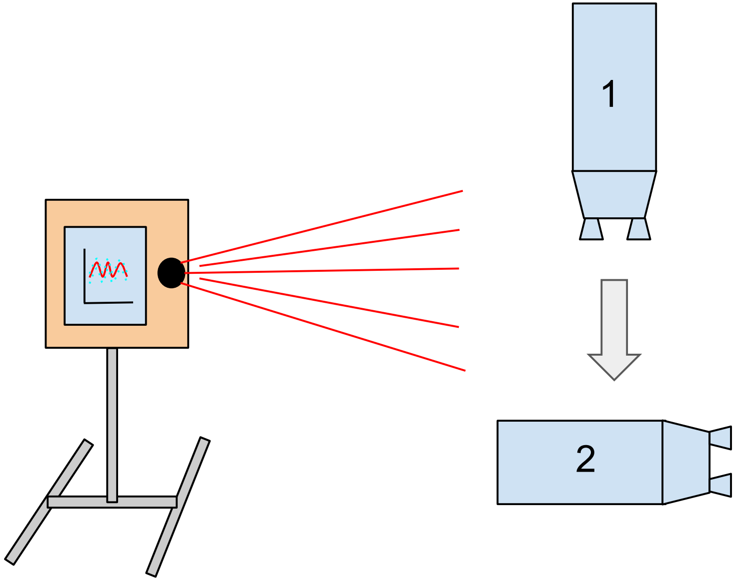
- Objective:
  - Confirm LiDAR sensor is within the accuracy tolerance
  - Prove LiDAR sensor can sense client in harsh lighting
- Testing Setup:
  - Location: Aero N200 / Fiske Planetarium
  - Equipment: AD-906TOF1-EBZ, Stage Lighting Fixtures, Dragonboard 410c, Measuring Tape
- Testing Plan:
  - Take multiple point cloud with maximum lighting
  - Compare point cloud to real world measurements
  - Take multiple point cloud with variable lighting
  - Compare accuracy between each lighting scenario
- Success Metrics / Testing Results:
  - LiDAR measure range within accuracy tolerance
  - Accuracy does not diminish between each lighting scenario



Subsystem Verification
Servicer Software

DR 2.1: The software algorithm shall identify the known client from the background.
DR 2.2: The software algorithm shall make predictions of the client's future attitude states.

- Objective:
  - Verify the servicer software meets baseline requirements
- Testing Setup:
  - Location: N200
  - Equipment: Servicer computing hardware, client model
- Testing Plan:
  - Standstill testing of servicer with LiDAR
  - Physically change orientation of client
- Success Metrics / Testing Results:
  - Differentiate client from its background
  - Less than 10% error relative to measured data at 1 min into future



Subsystem Validation
Servicer Electronics

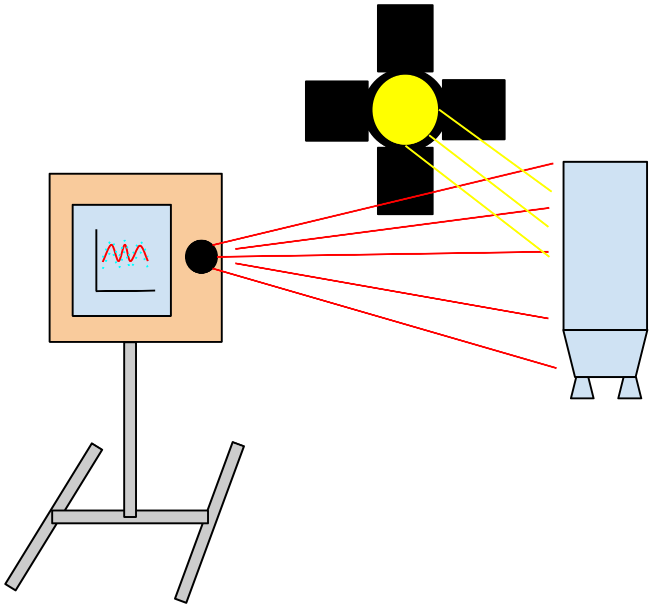
DR 3.1: The on-board computer shall handle data transfer rates of selected sensor(s)
DR 3.3: The on-board computer shall have sufficient processing power to be able to compute predictions at least 1 min into the

- Objective:
  - Validate the on-board processor is able to run the software and interface with the sensors
- Testing Setup:
  - Location: Aero N200 / TBD
  - Equipment: On-board Processor, Dragonboard 410c, AD-96TOF1-EBZ, Arduino Nano, KY-040 Rotary Encoder, Power System
- Testing Plan:
  - Connect the on-board processor with the lidar and encoder
  - Extract the lidar and encoder data
- Success Metrics / Testing Results:
  - Have the processing power to compute 1 minute in the future
  - All electronics components interface correctly
  - Electronics is able to support 15 minutes of run time

Comprehensive System Verification
Servicer System

DR 4.1: The enclosure shall be built to secure the physical electronics in place.
DR 4.2: The enclosure shall supply the correct power to all hardware and integrate electrical components it is housing.

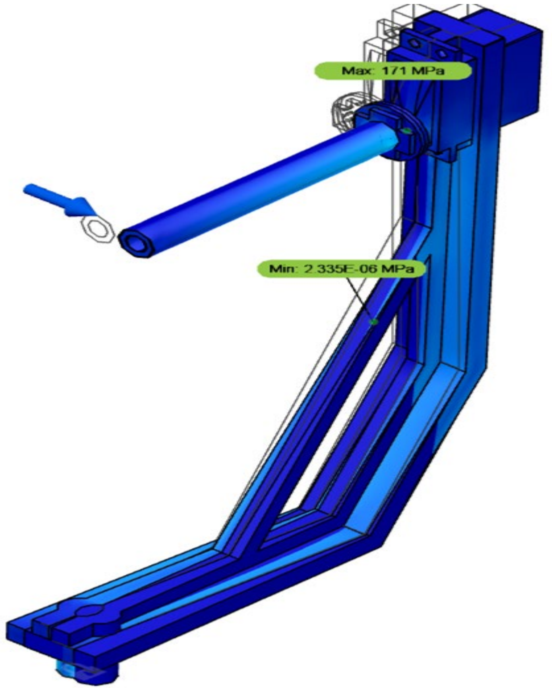
- Objective:
  - Verify successful integration of Servicer's subsystems
  - Prove integration does not hinder performance
- Testing Setup:
  - Location: Aero N200 / TBD (Ideally Planetarium)
  - Equipment: Servicer structure, Servicer electronics system, Stage Lighting Fixtures
- Testing Plan:
  - Perform monitoring for 15 minutes
  - Compare point cloud to real world measurements
  - Collect point cloud measurements at different locations and lighting
- Success Metrics / Testing Results:
  - All components connect/fit together properly
  - LiDAR sensor meets accuracy tolerance
  - Capable running for 15 minutes without data or processing issues



Subsystem Validation
Client Hardware Structures

DR 5.2: The client shall be able to spin about three different axes at a rate of at least 10 deg/sec.

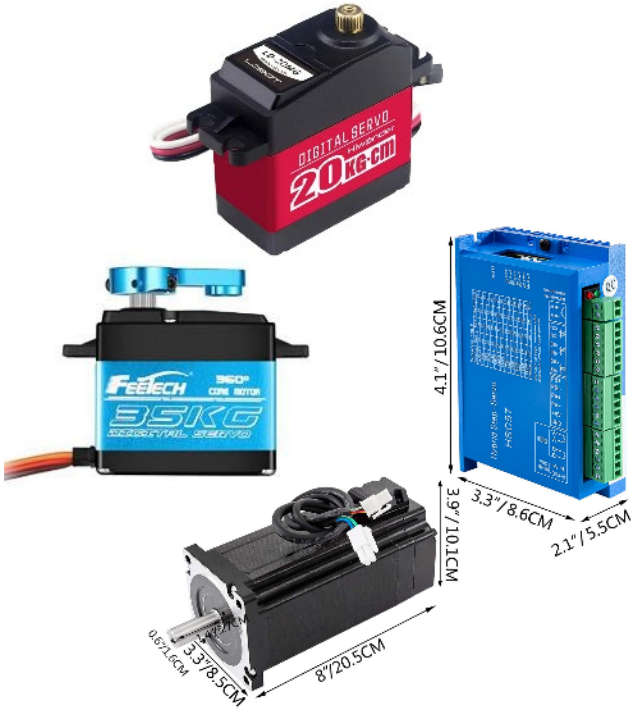
- Objective:
  - Client will be able to spin at 10 deg/sec around all 3 axis about the center of gravity
- Testing Setup:
  - Location: Aero N200 / Machine Shop
  - Equipment: Manufactured and assembled gimbal stand with client model.
- Testing Plan:
  - Displacement/stress analysis in Fusion 360
  - Load each motor axle independently
  - Load motor axles simultaneously
- Success Metrics / Testing Results:
  - Strain is kept below the yield strength of material
  - Displacement of the stand components kept below 3 mm



Subsystem Validation
Client Electronics

DR 5.1: The client shall record measurement data about its position, orientation, and angular velocity.
DR 5.2: The client shall be able to spin about three different axes at a rate of at least 10 deg/sec.

- Objective:
  - Rotate model about three different axes and collect truth data
- Testing Setup:
  - Location: AERO N200
  - Equipment: Client structure and Client electronics system
- Testing Plan:
  - Ensure Client structure can rotate about three axes during construction
  - Calibrate encoders as well as IMU and integrate the data
  - Verify system testing length
- Success Metrics / Testing Results:
  - Collect verified encoder and IMU data
  - Able to rotate model about all three axes at 10 deg/sec



Comprehensive System Verification
Client System

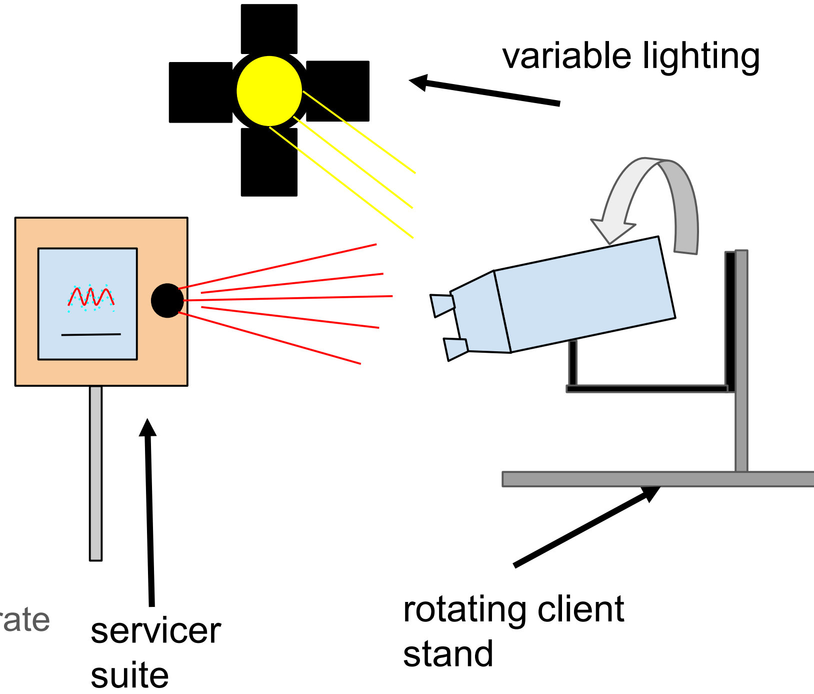
Driving Requirements: All design requirements for client

- Objective:
  - Day in the life - 3 motors, 3 encoders and 1 IMU to measure accuracy
- Testing Setup:
  - Location: CU Boulder - ASPEN Lab
  - Equipment: Vicon Sensors
- Testing Plan:
  - Mount IR balls onto physical model
  - Simulate testing conditions
  - Integrate and compare data from multiple sources
- Success Metrics / Testing Results:
  - Able to model accuracy of IMU and Encoders

Comprehensive System Testing
Servicer + Client System

Driving Requirements: All design requirements

- Objective:
  - Get the servicer to observe the rotation of the client system and generate predictions
  - “Day in the life” testing
- Testing Setup:
  - Location: Aero N200 / TBD (ideally planetarium)
  - Equipment: Complete Servicer and Client systems
  - Client model is set from 3-6 meters from servicer
- Testing Plan:
  - Rotate model with known angular velocities
  - Take LiDAR data using servicer
  - Compare truth data with algorithm results
- Success Metrics / Testing Results:
  - Algorithm data matches truth data and produces accurate prediction of rotation.



Project Planning

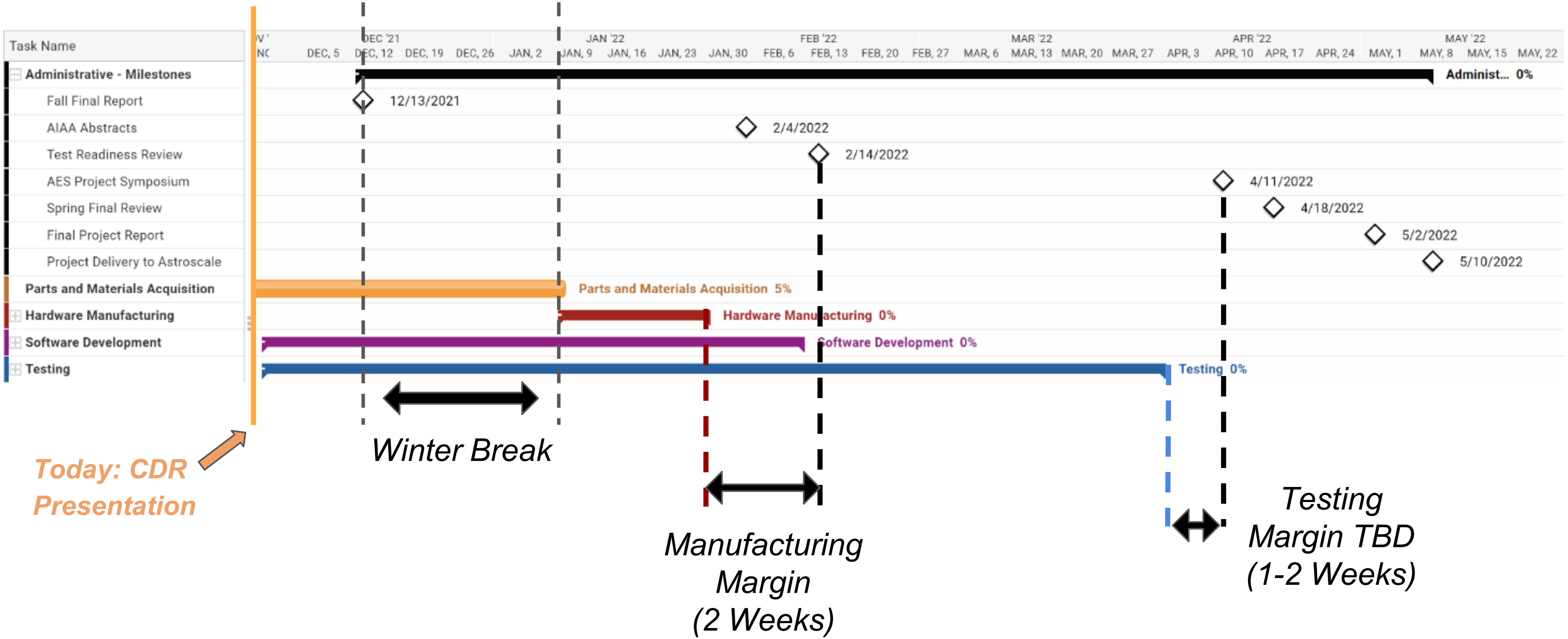
Team Structure

Project Manager
Tyler G.

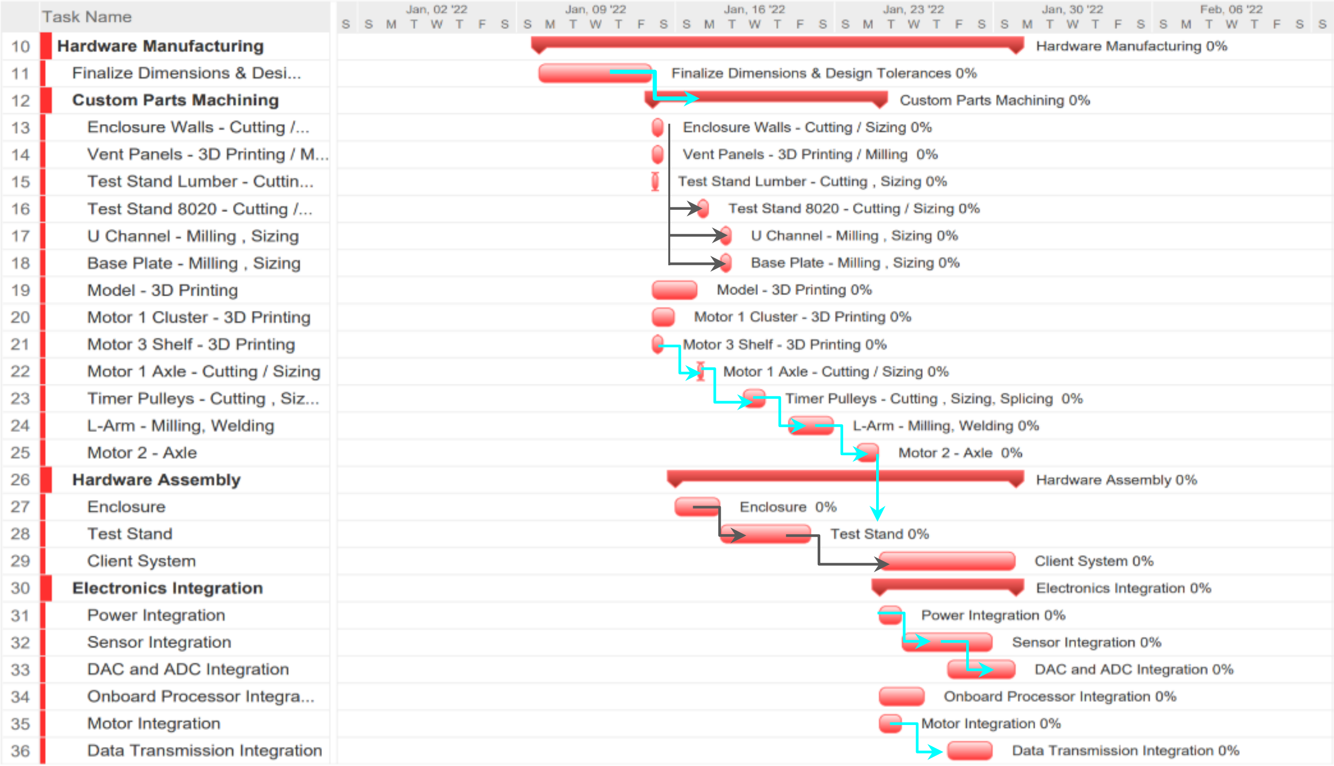
Systems Lead
Shawn S.

- **Software** — Nick H. - Brandon D.
  - Jash
  - Jason
  - Jake
  - Jianai
  - Shawn
- **Electrical** — Jason L. - Jash B.
  - Max
  - Walter
  - Nick
  - Shawn
  - Brandon
- **Servicer Hardware** — Jake P.
  - Zack
  - Max
  - Tyler
- **Client Hardware** — Walter S.
  - Brandon
  - Max
  - Zack
  - Jake
  - Jianai
  - Tyler
- **Financial** — Jianai Z.
  - Tyler
- **Safety** — Max M.
  - Zack
- **Manufacturing** — Zack H.
  - Walter
  - Tyler
  - Jianai
  - Jake
  - Shawn

Project Timeline - Looking Forward

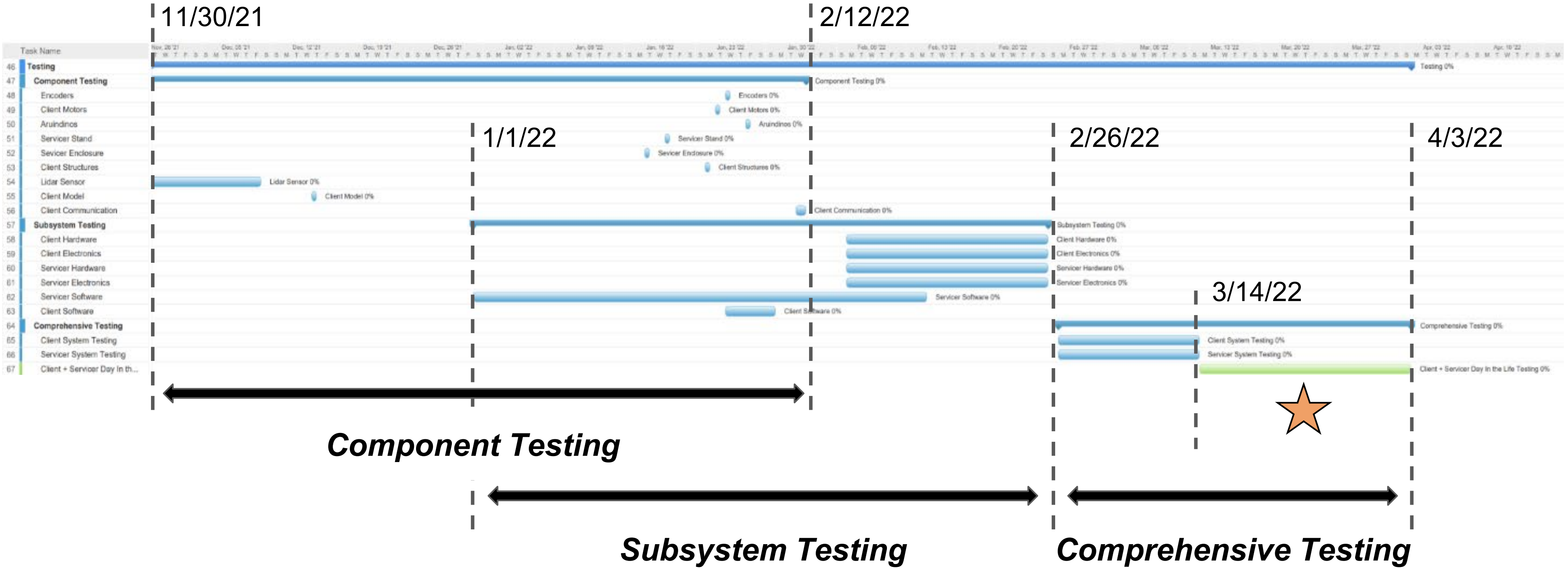


Manufacturing Timeline



- Critical Process Path

Testing Timeline



★ - *Final 3 weeks for **full system day in the life testing**.*

Testing Logistics

Test Name		Starting Date *	Ending Date *	Location	Location Feasibility	Safety Concerns
Component Testing		11/30/2021	2/2/2022			
	Encoders	1/26/2022	1/26/2022	Aero N200	✓	- Electrical Fires
	Client Motors	1/25/2022	1/25/2022	Aero N200	✓	- High Voltage / Current Steppers and Moving Parts
	Arduinos	1/28/2022	1/28/2022	Aero N200	✓	- Electrical Fires
	Servicer Stand	1/20/2022	1/20/2022	Aero N200	✓	Manufactuing Tools
	Sevicer Enclosure	1/18/2022	1/18/2022	Aero N200	✓	Manufactuing Tools
	Client Structures	1/24/2022	1/24/2022	Aero N200	✓	Manufactuing Tools
	Lidar Sensor	11/30/2021	12/10/2021	Aero N200	✓	
	Client Model	12/16/2021	12/16/2021	Aero N200	✓	Manufactuing Tools
	Client Communication	2/2/2022	2/2/2022	Aero N200	✓	
Subsystem Testing		1/1/2022	2/26/2022			
	Client Hardware	2/7/2022	2/26/2022	Aero N200 / Machine Shop	✓	Moving Parts / Weight Testing
	Client Electronics	2/7/2022	2/26/2022	Aero N200 / Aspen Lab	✓	High Wattage Components, ESD, Fire
	Servicer Hardware	2/7/2022	2/26/2022	Aero N200	✓	Large Moving Structure
	Servicer Electronics	2/7/2022	2/26/2022	Aero N200	✓	Wall Powered Parts , ESD, Fire
	Servicer Software	1/1/2022	2/14/2022	Aero N200	✓	Too much screen time. Eyeballs need breaks :)
	Client Software	1/26/2022	1/30/2022	Aero N200 / Other	✓	Too much screen time. Eyeballs need breaks :)
Comprehensive Testing		2/28/2022	4/3/2022			
	Client System Testing	2/28/2022	3/13/2022	Aero N200 / Planetarium	✓	All of the above
	Servicer System Testing	2/28/2022	3/13/2022	Aero N200	✓	All of the above
	Full Day In the Life Testing	3/14/2022	4/3/2022	Aero N200 / Planetarium / Other	✓	All of the above

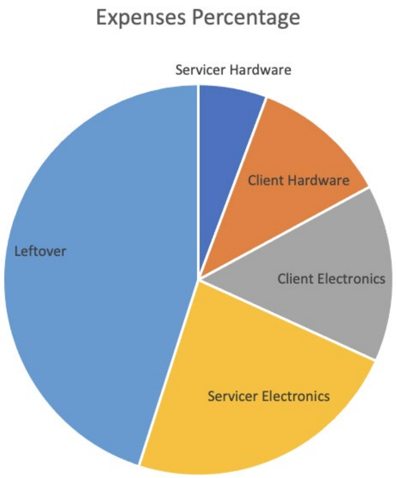
** Predicted Dates - Subject to Change*

Cost Plan

Hardware	Est. Cost
Servicer Hardware - Cost Breakdown of Servicer Hardware	$274.18
Client Hardware - Cost Breakdown of Client Hardware	$546.91
Total	**$821.69**

Subsystem	Est. Cost
Hardware	$821.69
Electrical	$1815.74
Total	**$2637.43**
Leftover*	+ $2162.57

Electrical	Est. Cost
Client Electronics - Steppers/Motors - Hardware Controller - Misc.	$705
Servicer Electronics - LIDAR Sensor - Onboard Computer - Power System - Misc. Electrical	$1110.74
Total	**$ 1815.74**



*** Heavily discounted LiDAR: significantly decreased our overall cost. ***

Acknowledgements

Astroscale:

Sandor Nemethy, Sam Laurila, and Rebeca Griego

Senior Design Coordinators:

Dr. Kathryn Wingate and Dr. Jelliffe Jackson

Our Project Advisor:

Dr. Yu Takahashi

And the rest of the PAB

Questions?

Supporting Slides

References

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http://graphics.stanford.edu/~smr/ICP/comparison/horn-hilden-orientation-josa88.pdf

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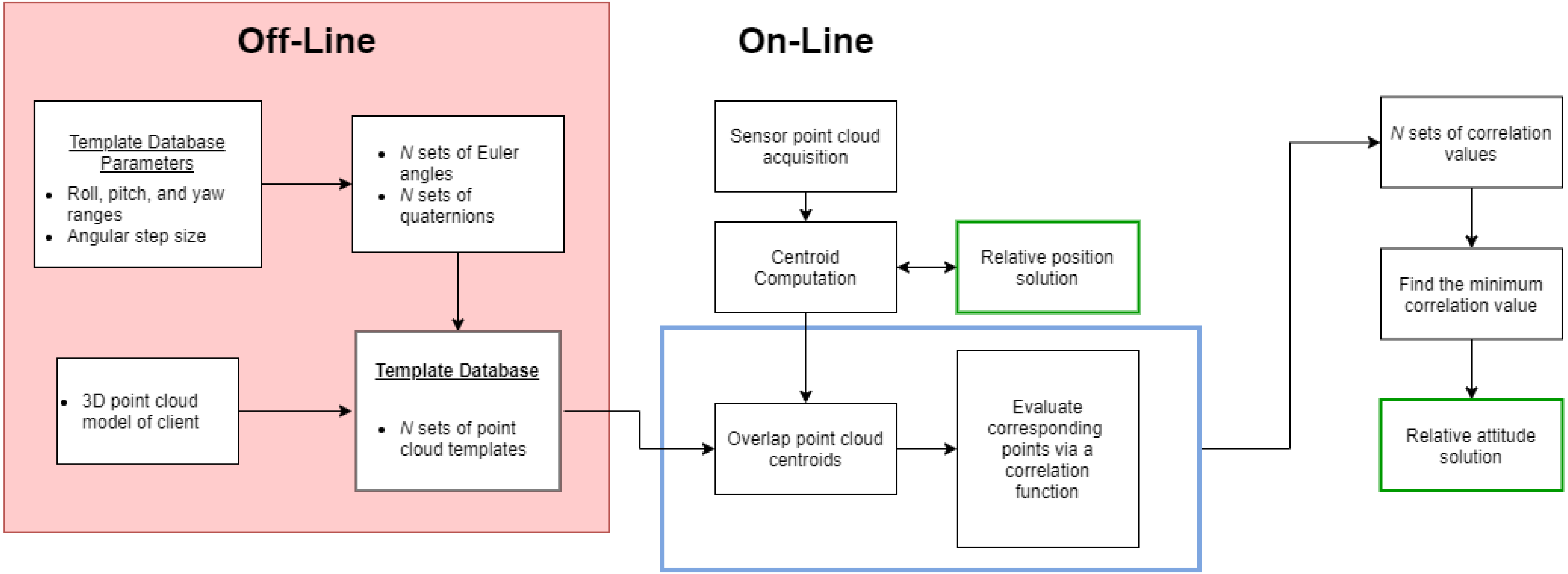
https://people.csail.mit.edu/bkph/papers/Absolute_Orientation.pdf

Servicer Software - Backup

Servicer Software - Template Matching

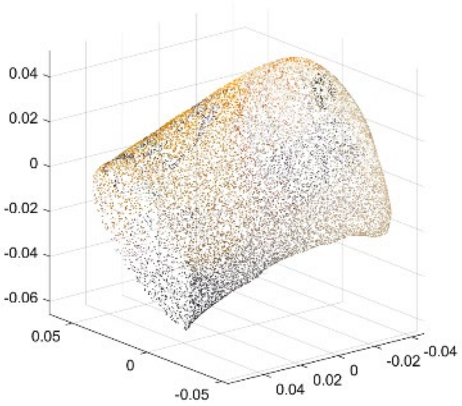


Servicer Software - Template Matching

Improved Computation Time

TEST CASE

Ω = [-132°, 56°, 8°]



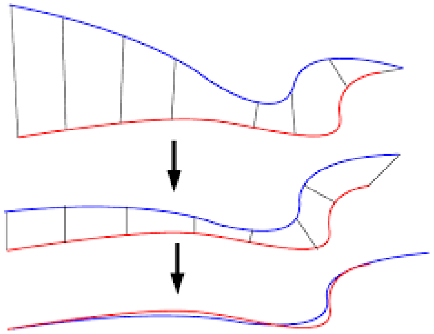
Angular Step	Comp Time @ PDR	Comp Time @ CDR
30°	~20 s	~1 s
20°	~75 s	~4 s
10°	~680 s	~28 s

With improved computation times achieving the same accuracy, we believe that 5° and 1° step sizes are feasible with enough computing storage

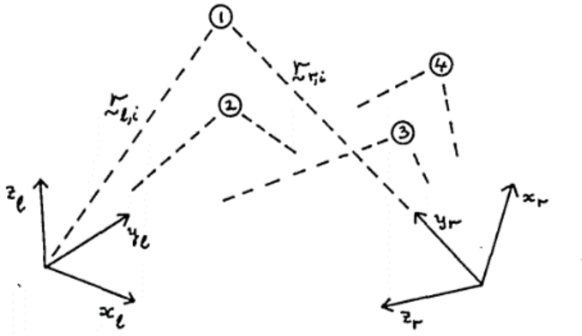
Servicer Software - Velocity Solutions

Both methods involve finding the transformation and translation between two point clouds.
Timestamps of the two clouds will allow for solving angular and translational velocities.

- Iterative Closest Point (ICP)
  - Requires threshold to be met
  - Iterative in nature



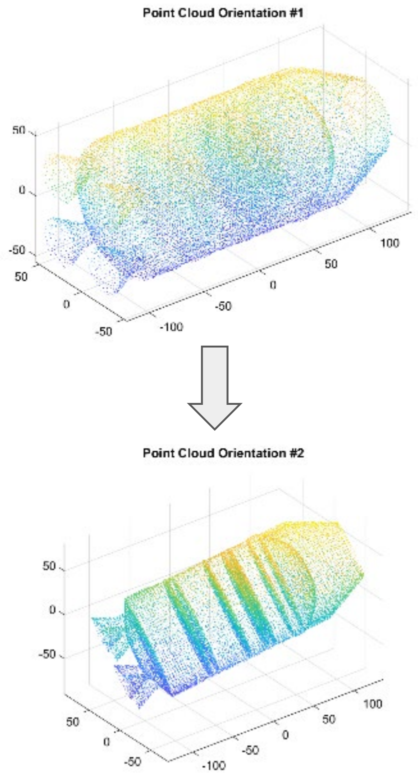
- Absolute Orientation
  - No threshold
  - Closed-form solution



Servicer Software - ICP / Absolute Orientation

Testing Plan

- Take two points clouds at different orientations
- Angular difference represents the angular velocity of the client
  - Mimics two sets of data taken one after the other
  - For testing purposes, time between frames is assumed to be 1 sec



Servicer Software - ICP / Absolute Orientation

Results - Test #1

- Initial Orientation
  - [0, 0, 0]
- Final Orientation
  - [1, 1, 1]
  - [10, 10, 10]
  - [9.16, -2.34, 3.75]

Angular Velocity (Truth)	**ICP**	**Absolute Orientation**
[1, 1, 1]	[0.983, 1.017, 0.983]	[1, 1, 1]
[10, 10, 10]	[9.537, 10.166, 0.948]	[10, 10, 10]
[9.16, -2.34, 3.75]	[8.856, -2.103, 1.107]	[9.16, -2.34, 3.75]

Servicer Software - ICP / Absolute Orientation

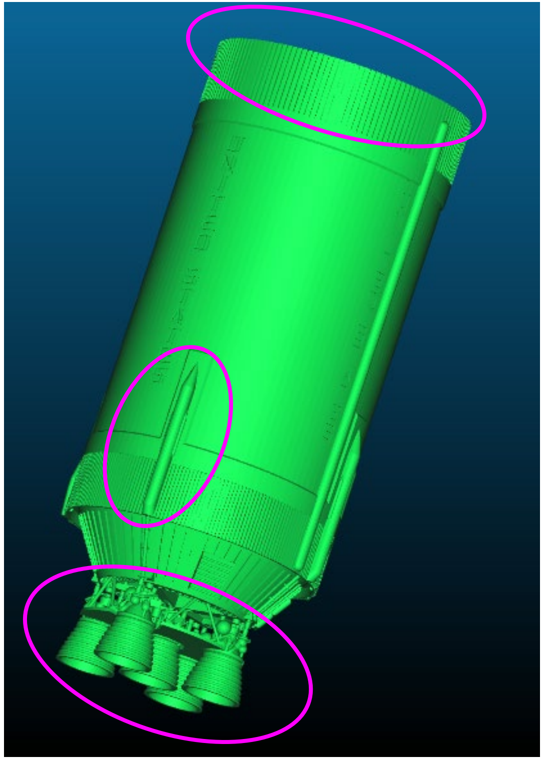
CROACS

Results - Test #2

- Initial Orientation
  - [20, 30, 40]
- Final Orientation
  - [21, 31, 41]
  - [20, 40, 50]
  - [23.75, -28.66, 49.16]

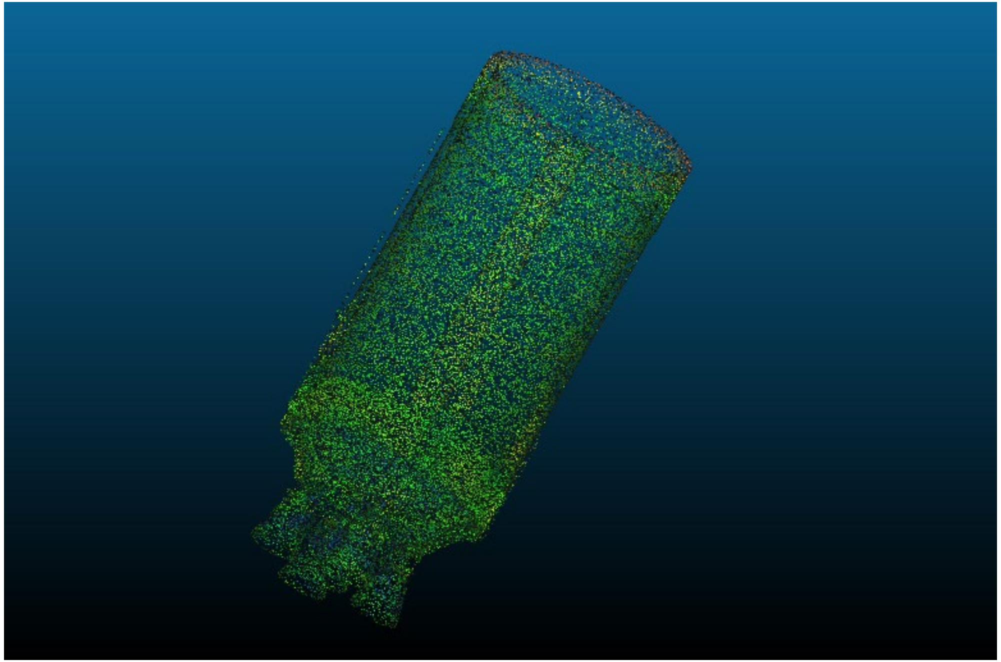
Angular Velocity (Truth)	**ICP**	**Absolute Orientation**
[1, 1, 1]	[0.983, 1.017, 0.983]	[1, 1, 1]
[10, 10, 10]	[11.066, 9.382, -4.748]	[10, 10, 10]
[9.16, -2.34, 3.75]	[9.297, -1.708, 4.076]	[9.16, -2.34, 3.75]

Servicer Software - Feature Recognition



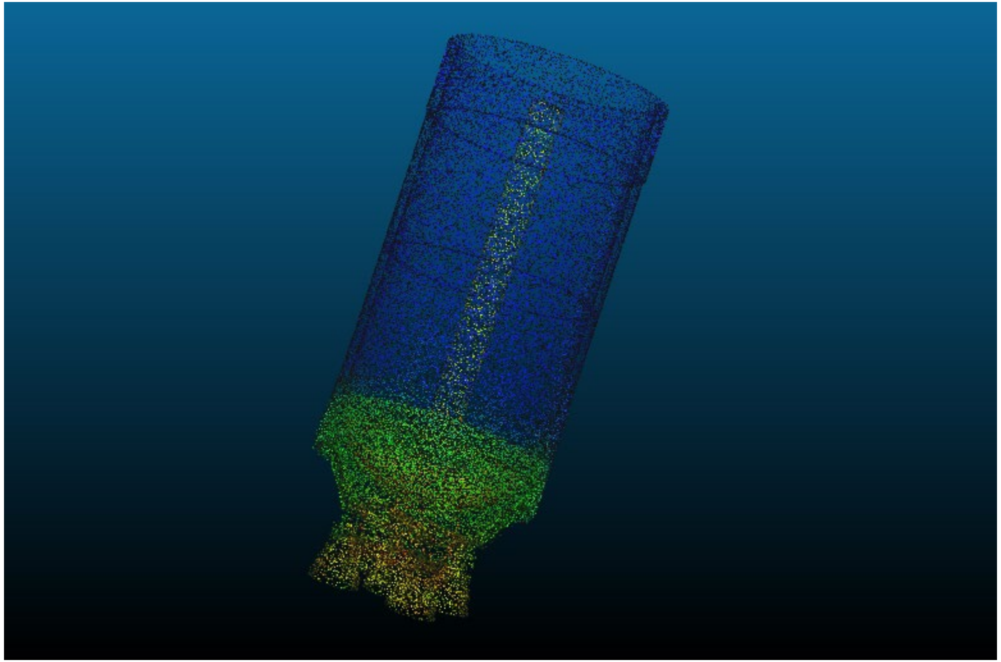
- Recognizing features plays a significant role in finding the attitude and angular velocity of the client
- Desired Features:
  - Boosters
  - Top Edge
  - Side Features

Servicer Software - Feature Recognition



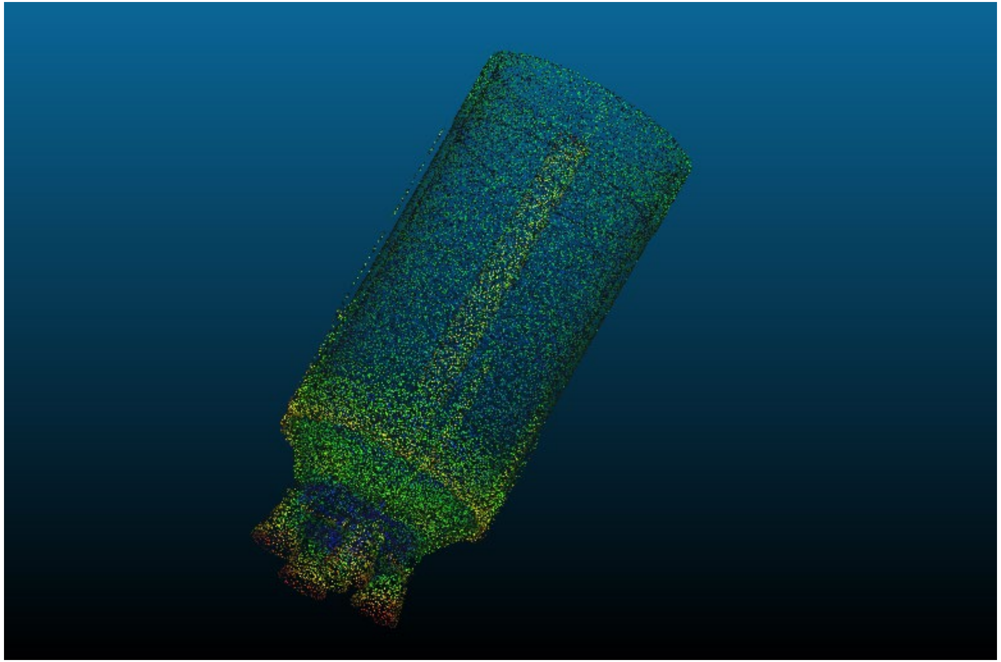
- Primary Component Analysis (PCA)
    - Good for establishing top edge of booster

Servicer Software - Feature Recognition



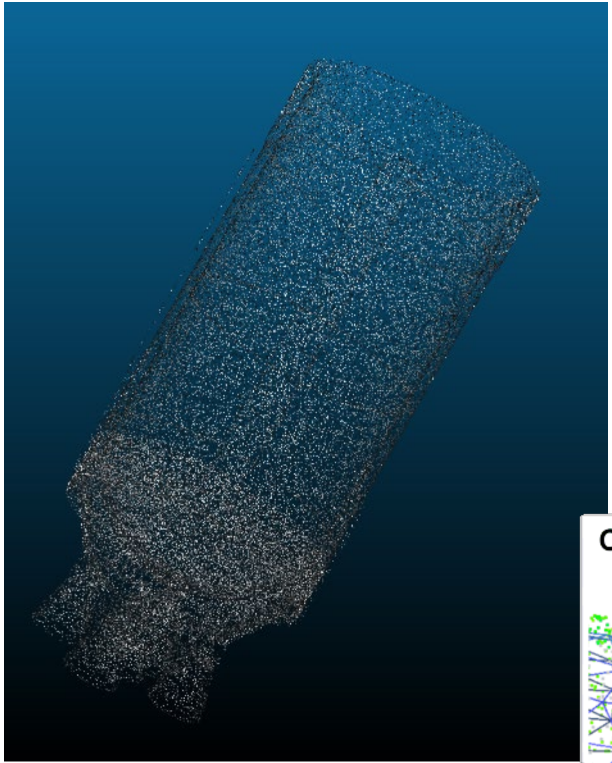
- Surface Variation
  - Good for establishing the boosters and bottom edge of booster

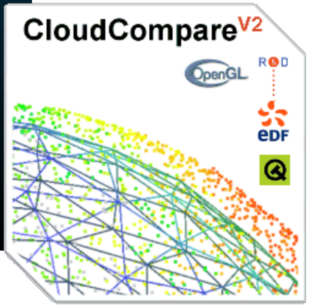
Servicer Software - Feature Recognition



- Roughness
  - Good for establishing the boosters and bottom edge of booster

Servicer Software - CloudCompare

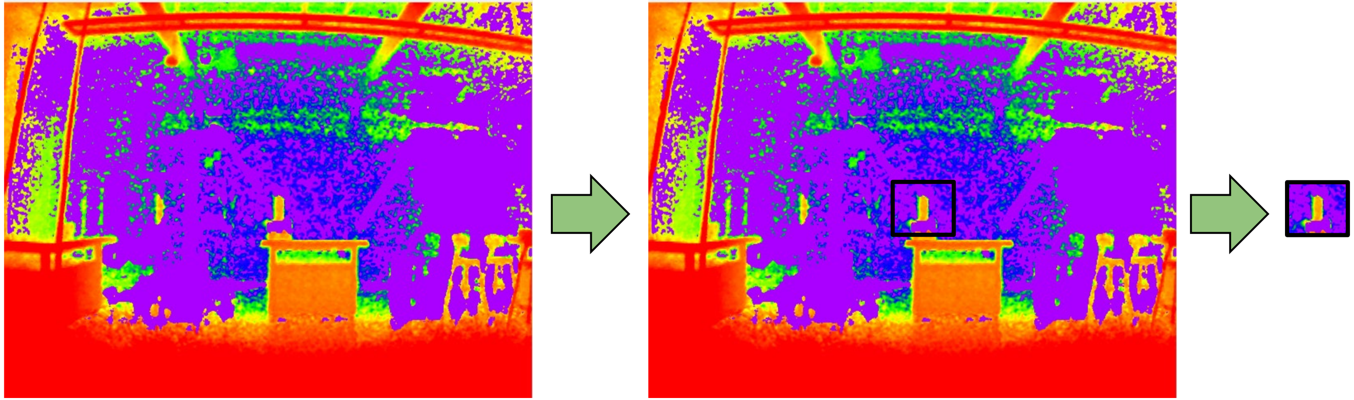




- Software designed specifically to process 3D point cloud data
- Potential Uses:
    - Feature Recognition
    - Noise Reduction
    - Iterative Closest Point (ICP)

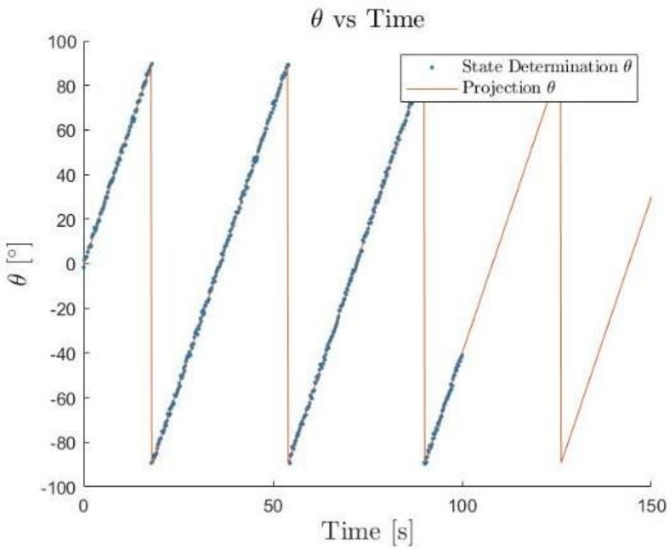
Servicer Software - Background Differentiation

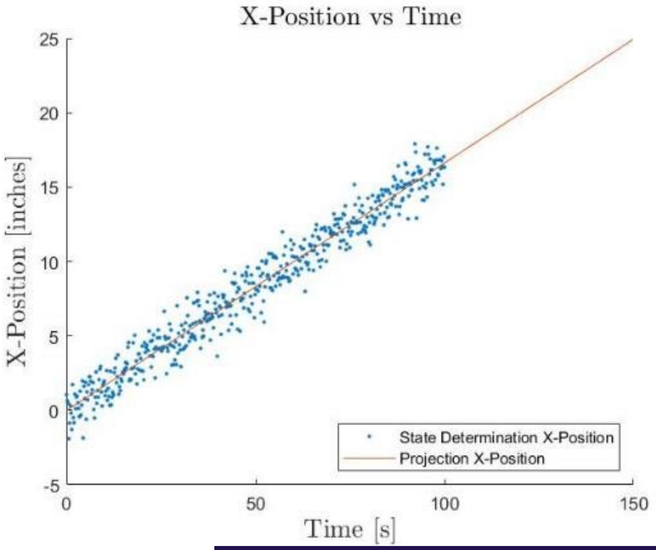
- Set bounds from known distance
- Adjust bounds with template velocity
- Bounding box excludes background



Servicer Software - Euler Angle Characterization

- Euler angles change either linearly or sinusoidally with time
- Find correlation coefficient of data to linear form, and to sinusoid form
- Whichever correlation coefficient is higher, choose that form

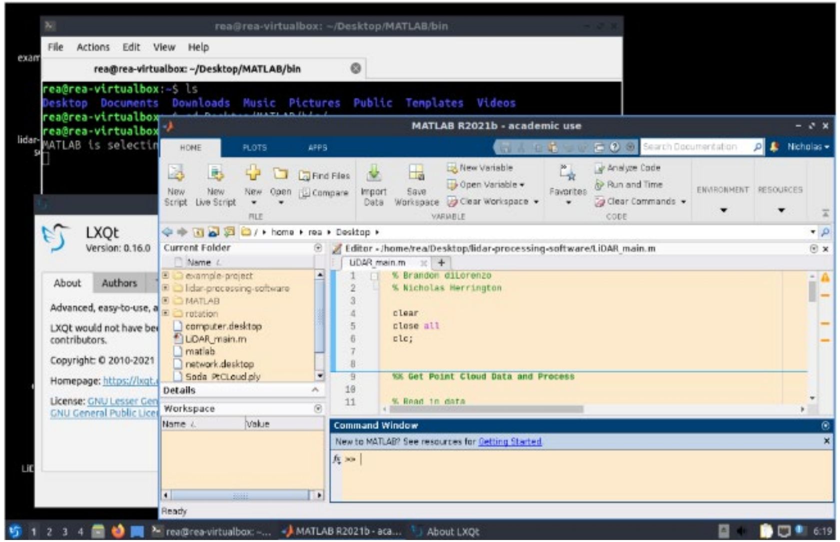




Servicer Software - Rotation Simulation

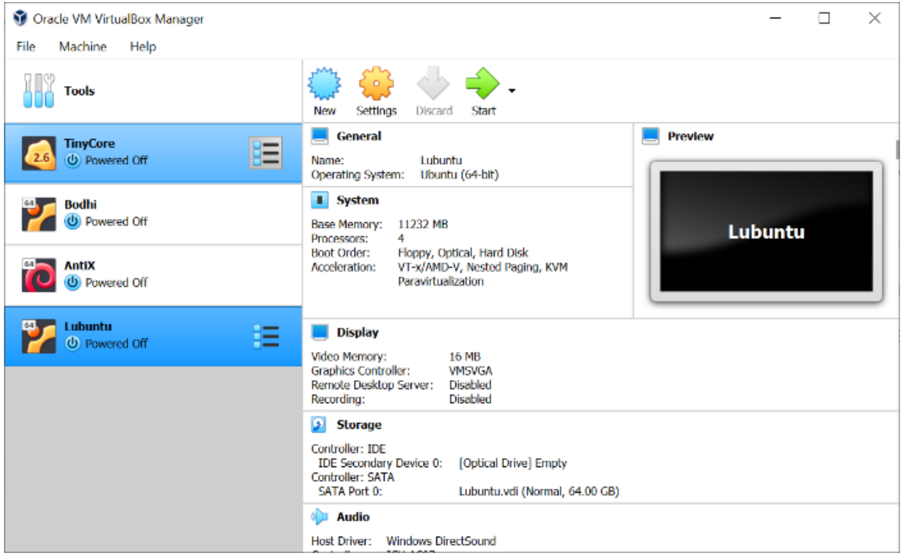
1. Use the form given from the Characterization module
2. Perform regression fit to determine equation of motion that fits the data for each individual Euler angle
3. For given range of time, input timesteps into the EOM for each Euler angle
4. Output future Euler angles
5. Send Euler angles to visualization module to create visual simulation

Servicer Software - Operating System



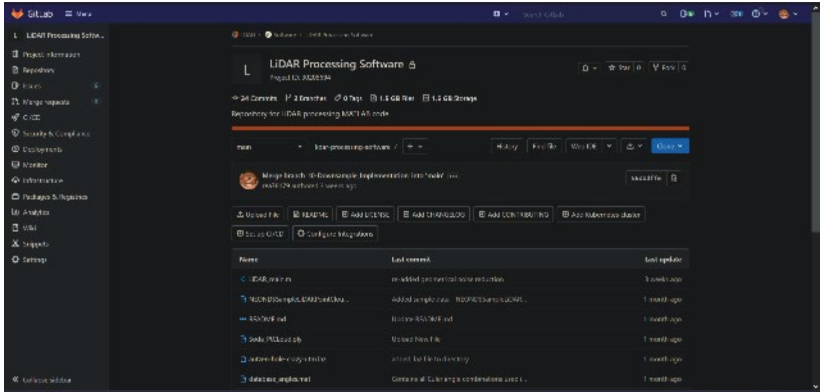
- lubuntu LxQT v0.16.0
- Lightweight OS means more computing power available to run our software suite
- Linux environment is suitable for modular application structure and for version control with git

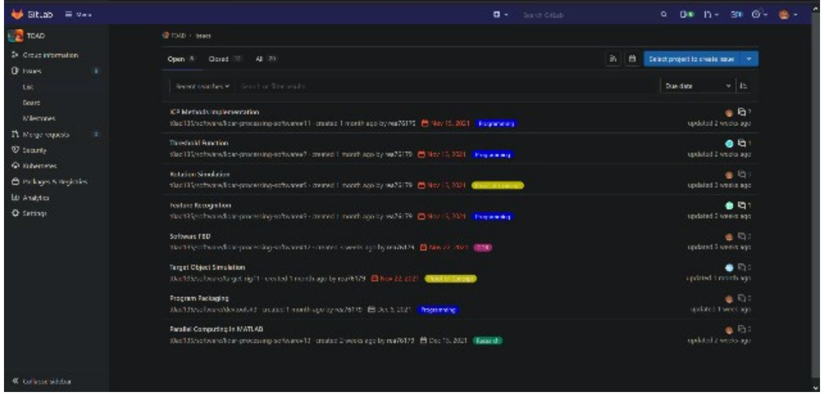
Servicer Software - Development Environment



- VirtualBox v6.1.26
- Virtual Machine used by each software team member to ensure same dev environment
- Allows virtual hardware configuration of machines

Servicer Software - Version Control





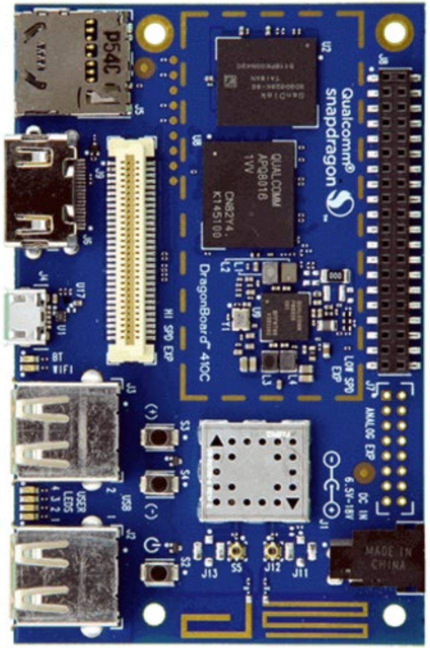
- Git v2.30.2
- Industry standard
- Software team always have latest changes
- Allows concurrent development of same modules
- Tracked changes with comments, ability to merge request and to rollback changes if needed
- Tasking on GitLab

Servicer Electronics

LiDAR System

AD-906TOF1-EBZ

DragonBoard 410c



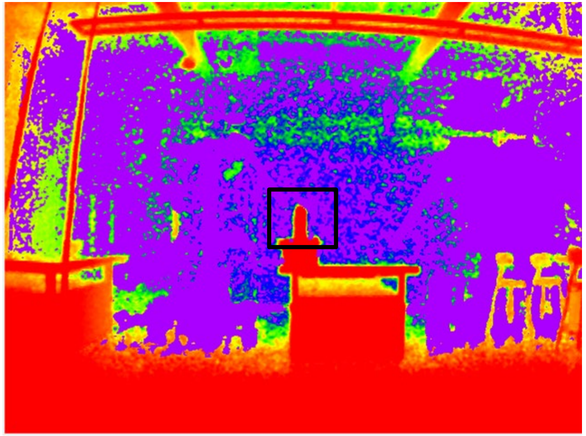
LiDAR Specs

- Range
  - Near: 25cm to 80cm
  - Medium: 30cm to 4.5m (Rev.B: 80cm to 3m)
  - Far: 3m to 6m
  - Accuracy: < 2% for all ranges
- Frame Rate: up to 30 fps dependent on processor board, OS and interface to host computer
- Resolution: 640 x 480 pixels
- Operating Temperature: -20ºC to 85ºC
- 940nm VCSEL with 110º x 85º batwing profile diffuser
- Receive lens: FoV 90º x 69.2º including 940nm BPF
- 96Board mezzanine high speed and low speed expansion connector compatibility
- Raspberry Pi camera connector to connect to any compatible processor board
- Connectivity support for USB or Network(WiFi, Ethernet)
- 5V DC Input
- 20W max power consumption

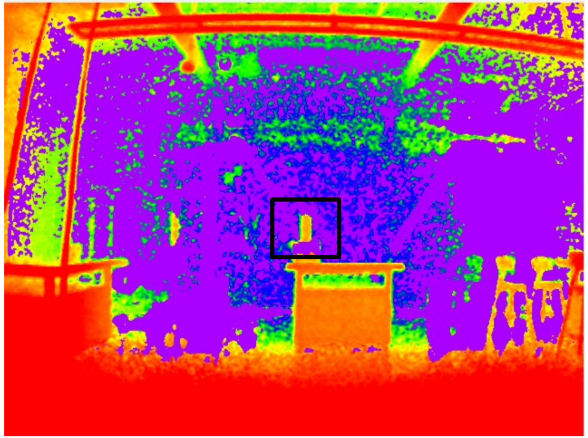
DragonBoard Specs

- **SoC** - Qualcomm APQ8016E
- **CPU** - ARM Cortex-A53 Quad-core up to 1.2 GHz per core
- **GPU** - Qualcomm Adreno 306 @ 400 MHz for PC-class graphics with support for Advanced APIs, including OpenGL ES 3.0, OpenCL, DirectX, and content security
- **RAM** - 1GB LPDDR3 SDRAM @ 533MHz
- **Storage** - 8GB eMMC 4.51 on board storage and MicroSD card slot
- **Ethernet Port** - USB 2.0 expansion
- **Wireless** - WLAN 802.11 b/g/n 2.4 GHz, Bluetooth 4.1, GPS. On board GPS, BT and WLAN antennas
- **Display** - 1 x HDMI 1.4 (Type A - full) 1 x MIPI-DSI HDMI output up to FHD 1080P
- **Camera** - Integrated ISP with support for image sensors up to 13MP
- **Expansion Interface** - 40 pin low speed expansion connector: +1.8V, +5V, SYS_DCIN, GND, UART, I2C, SPI, PCM, PWM,GPIO x12 60 pin high speed expansion connector: 4L-MIPI DSI, USB, I2C x2, 2L+4L-MIPI CSI
- **Power Source -** 8V~18V@3A, Plug specification is inner diameter 1.7mm and outer diameter 4.8mm
- **OS Support** - Android / Linux / Windows IoT Core
- **Size** - 85mm x 54mm

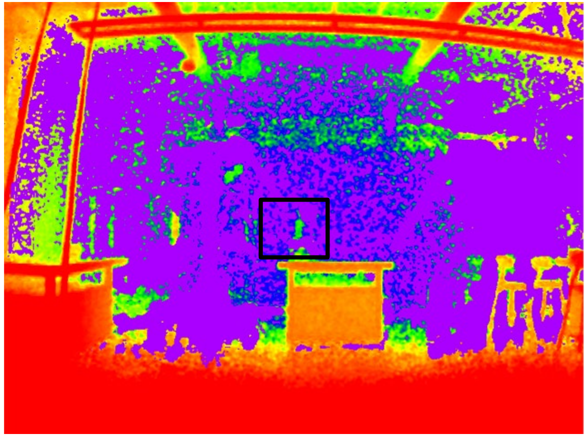
Preliminary LiDAR Testing



Camera Mode: **FAR**
Distance: **3 m**

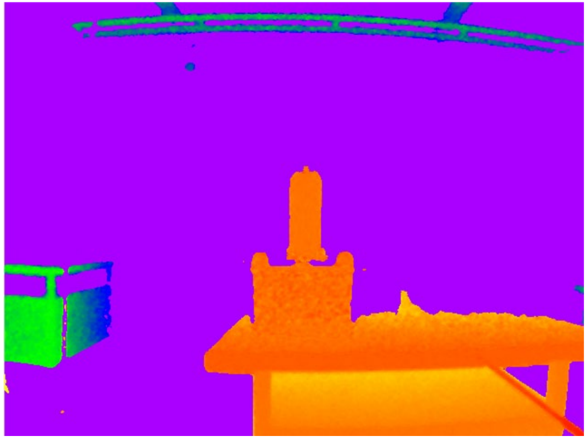


Camera Mode: **FAR**
Distance: **4 m**

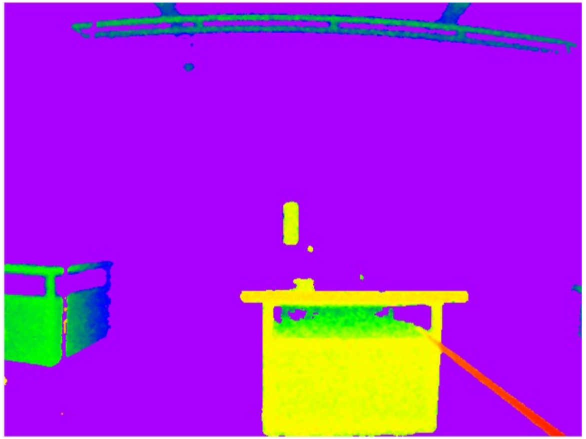


Camera Mode: **FAR**
Distance: **5 m**

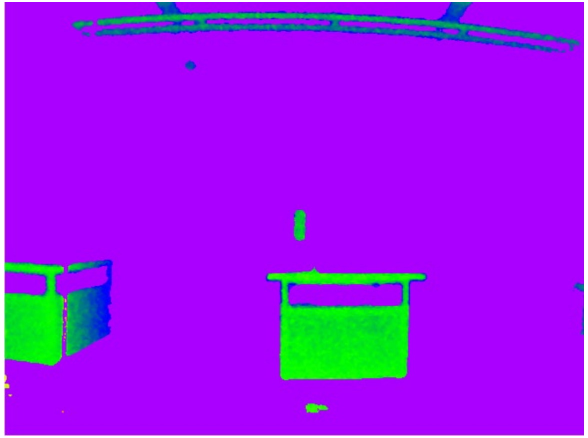
Preliminary LiDAR Testing



Camera Mode: **MEDIUM**
Distance: **1 m**



Camera Mode: **MEDIUM**
Distance: **2 m**



Camera Mode: **MEDIUM**
Distance: **3 m**

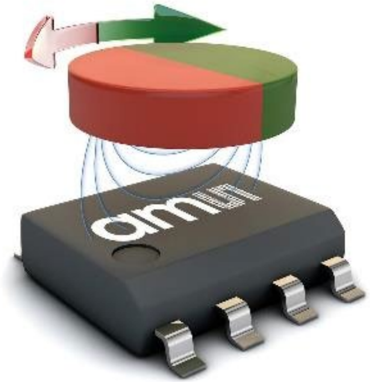
Onboard Processor Components

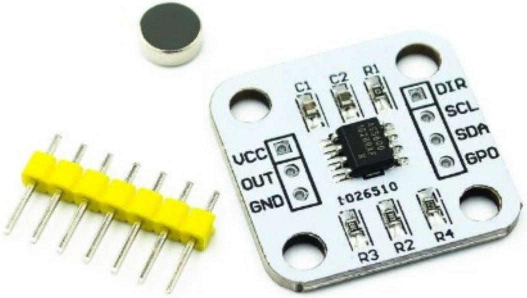
Component	Selection	Base	Promo	Shipping	Tax	Price	Where
CPU	Intel Core i7-12700KF 3.6 GHz 12-Core Processor	$429.99	—	Prime	—	$429.99	amazon.com
CPU Cooler	ARCTIC Freezer 34 eSports DUO CPU Cooler	$49.94	—	Prime	—	$49.94	amazon.com
Motherboard	MSI PRO Z690-A DDR4 ATX LGA1700 Motherboard	$219.99	-$10.00 [1]	FREE	—	$209.99	newegg
Memory	Team T-FORCE VULCAN Z 16 GB (2 x 8 GB) DDR4-3200 CL16 Memory	$50.99	—	FREE	—	$50.99	newegg
Memory	Team T-FORCE VULCAN Z 16 GB (2 x 8 GB) DDR4-3200 CL16 Memory	$50.99	—	FREE	—	$50.99	newegg
	+ Add Additional Memory						
Storage	Western Digital Blue 500 GB M.2-2280 Solid State Drive	$54.99	—	Prime	—	$54.99	amazon.com
	+ Add Additional Storage						
Video Card	+ Choose A Video Card						
Case	+ Choose A Case						
Power Supply	Corsair RM (2019) 650 W 80+ Gold Certified Fully Modular ATX Power Supply	$78.84	—	Prime	—	$78.84	amazon.com

Servicer Encoders

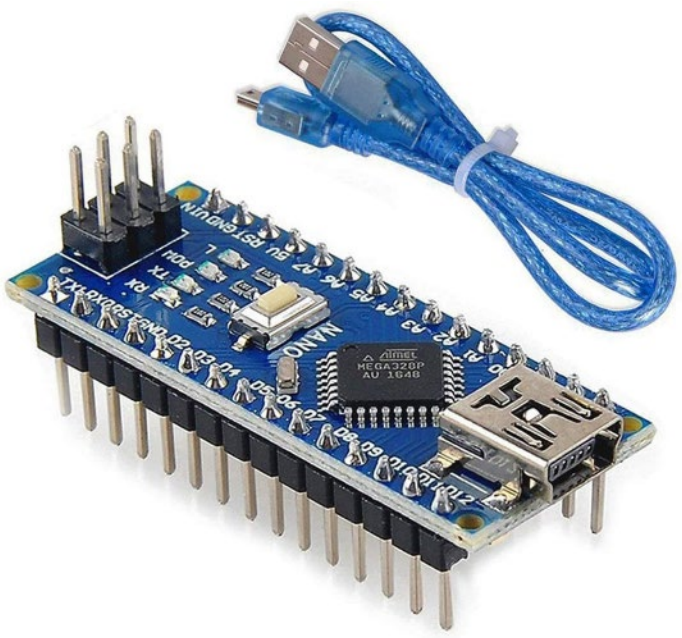
Magnetic Encoders

- AS5600
  - 12-bits
  - Analog/PWM/I^2C interface
  - 3-3.6 V OR 4.5-5.5 V Input





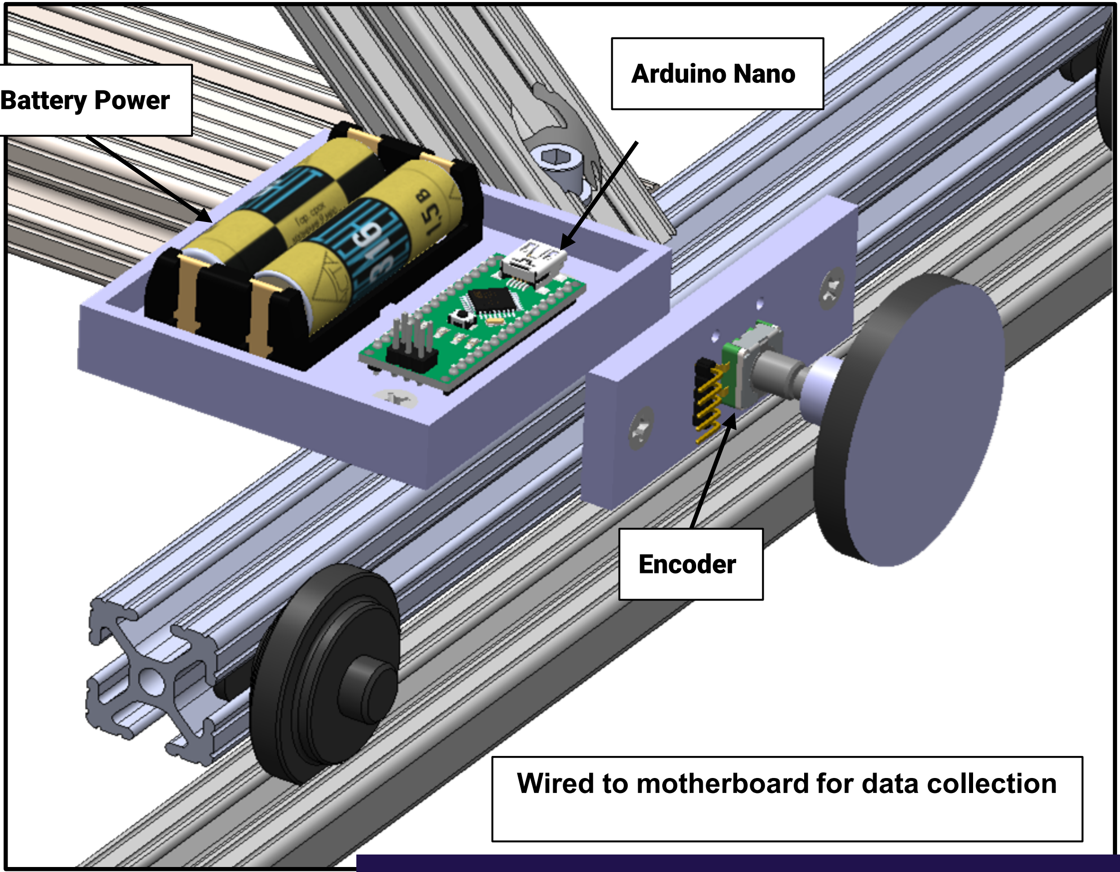
Servicer - Arduino Nano



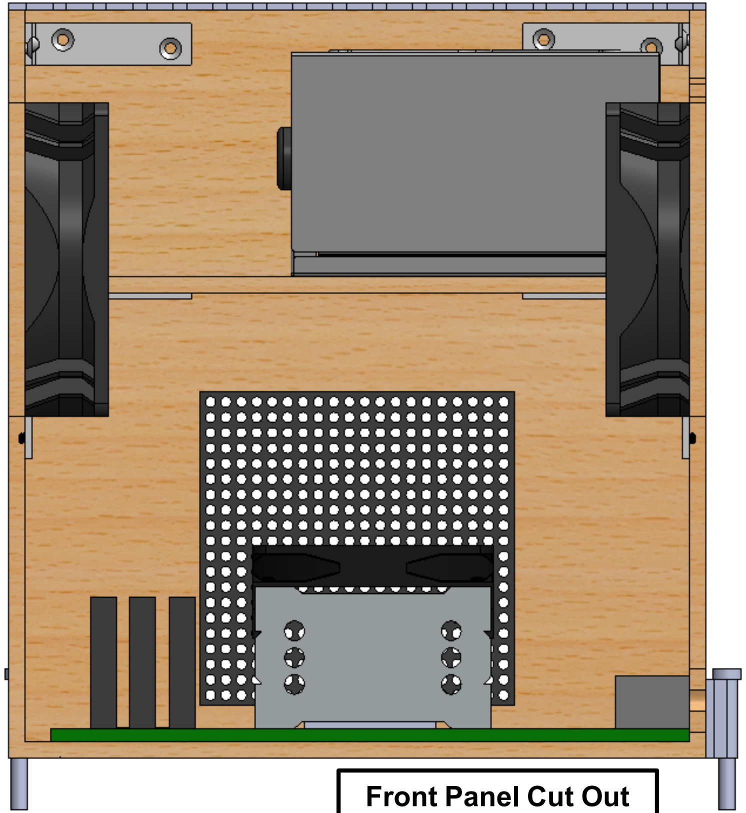
- **Microcontroller:** ATmega328P
- **Operating Voltage:** (logic level) 5 V
- **Input Voltage:** (recommended) 7V-12V
- **Digital I/O Pins:** 14 (of which 6 provide PWM output)
- **Flash Memory:** 32 KB (ATmega328) of which 2 KB used by bootloader

Servicer Hardware - Backup

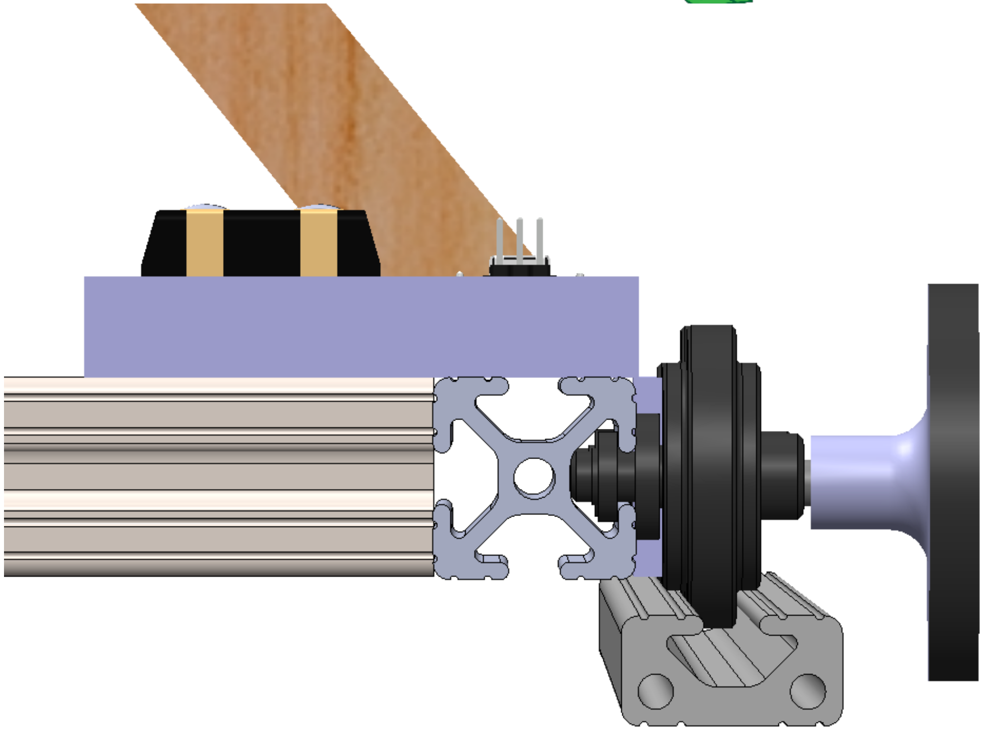
Servicer Hardware - Translation



Servicer Hardware -

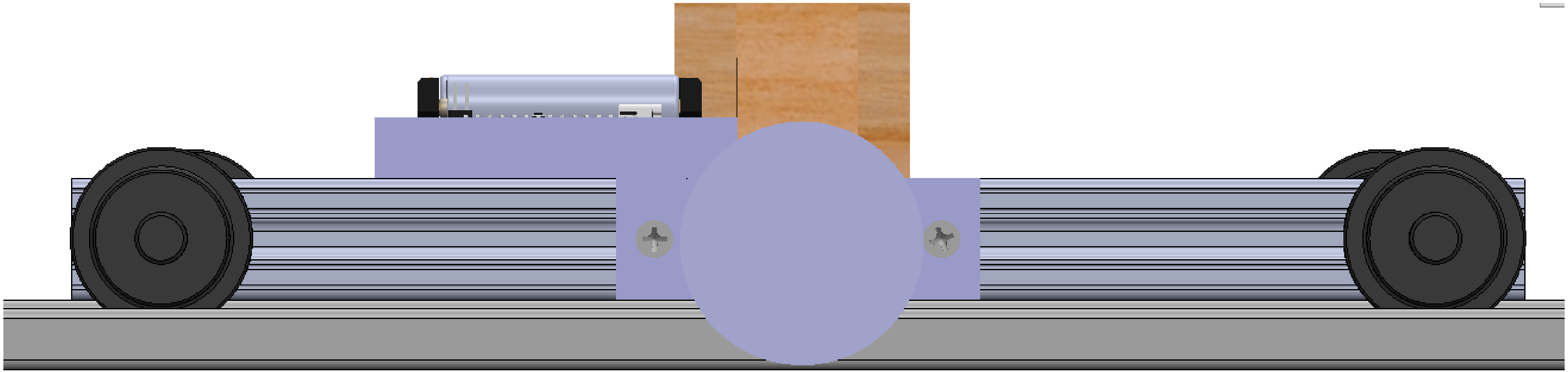


Front Panel Cut Out



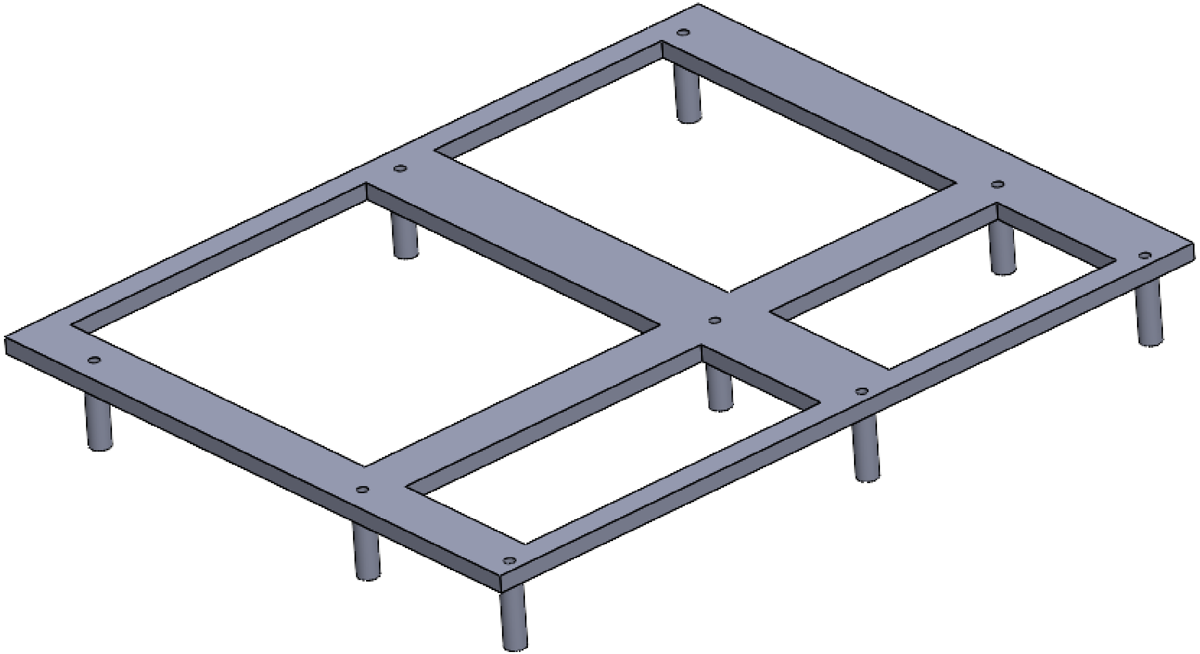
Encoder Front View

Servicer Hardware -



Encoder Side View

Servicer Hardware -



Motherboard Mount Adapter

Client Electronics - Backup

Client Electronics - Power Budget

Subsystem	Components	Required Input Current	Notes	Data Sheet	Total Current	Battery	Operational Time
IMU System	Nicola Microcontroller	250mA	Likey much higher estimate than will actually be drawn during operation.	ABX00050-datas	250mA	Li-poly - 500mAh	**~2hrs**
	IMU	N/A	On Nicola MC	N/A			
Motor 1 System	Arduino Uno MC	160mA	40mA per I/O pins used. 2 for servo, 2 for encoder.	UNO_wifi (mous	166.5mA + 221.61mA	9V - 600mAh	**~1.55hrs *(min)***
	Magnetic Encoder	6.5mA	Under normal operating conditions. Also has low power mode options.	AS5600 (mouse			
	Servo 1	221.6mA	Estimated max based on stall torque and rpm rating at 6V				
Motor 2 System	Arduino Uno MC	280mA	40mA per I/O pins used. 2 for servo, 6 for encoder.	UNO_wifi (mous	366mA + 390mA	9V - 600mAh	**~0.79hrs *(min)***
	ATM Encoder	86mA	16mA for operation. 15mA per single channel (x3). 25mA per differential channel (x1)	AMT13-V Kit Da			
	Servo 2	180mA	no load	https://www.feete			
		390mA	stall current (maximum value)				

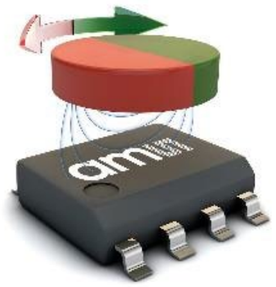
Client Electronics - IMU Drift/Magnetometer

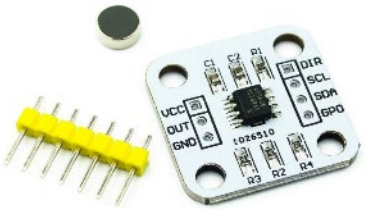
- Gyro drift results in a change in what would be expected during the collection of data
- It is measurable, and if measured prior to testing, can be corrected for by applying a small, constantly increasing offset to balance out any drift
- Additionally, the Nicola Sense ME includes Bosch sensor fusion algorithm BSX, which has the ability to account for sensor drift
  - The level of BSX integration into the Nicla Sense ME is not well documented, so testing will have to be done after sensor acquisition to determine if this fully accounts for gyro drift that may occur, or if external processing will be required to account for drift
- The gyro and accelerometer sensors are able to be used without the magnetometer on the Nicla Sense ME; their use will be avoided due to the potential for magnetic interference from the motors.

Client Electronics - Encoders

Magnetic Encoders

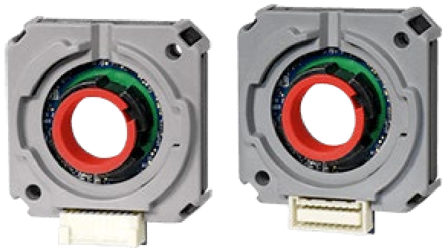
- AS5600
  - 12-bits
  - Analog/PWM/I^2C interface
  - 3-3.6 V OR 4.5-5.5 V Input





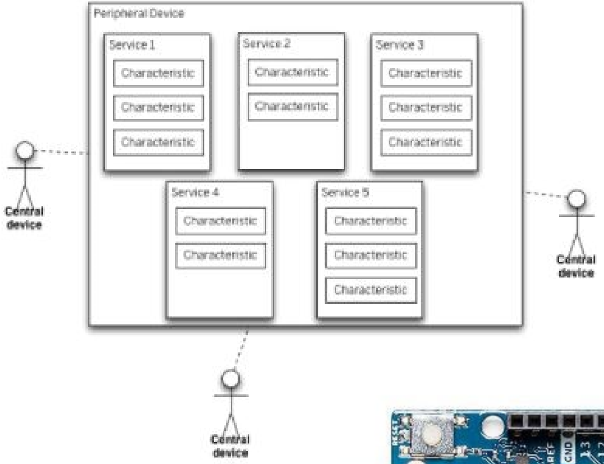
Modular Encoders

- AMT132Q
  - Up to 12-bits
  - Quadrature output
  - Incremental/Absolute encoder



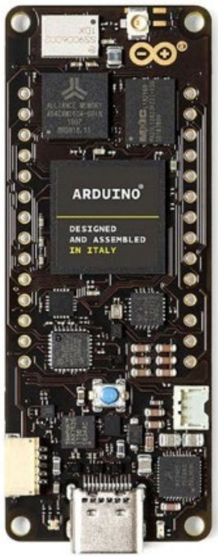
Client Electronics - Arduino BLE Library

- BLE - Bluetooth Low Energy
- Central Devices
  - View the services
  - Get the data
  - Move on
- Peripheral Devices
  - Post data for all radios to read
  - Servers in a client-server transaction



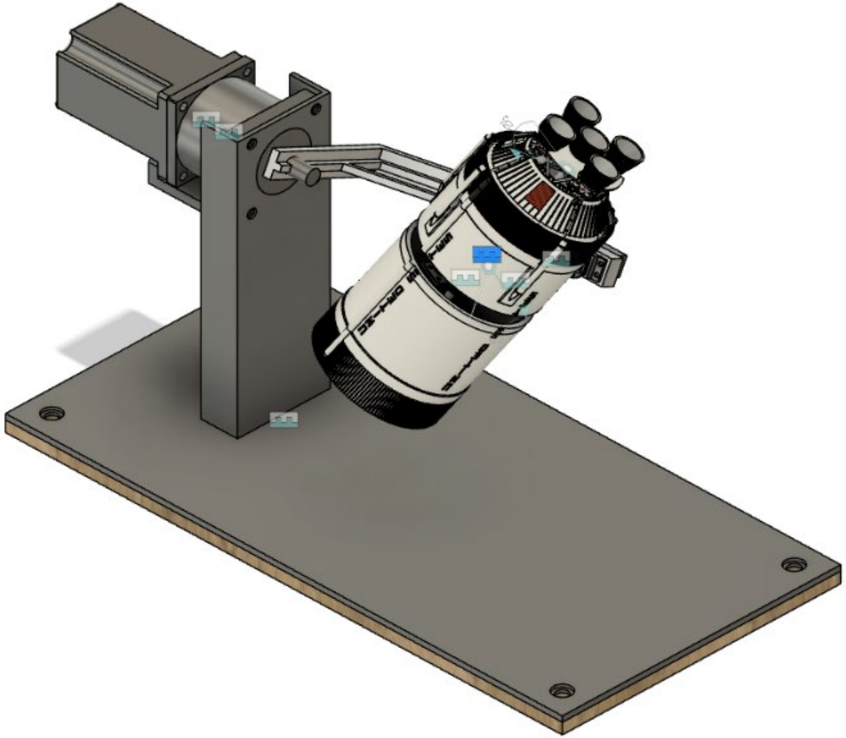
Client Electronics - Portenta H7

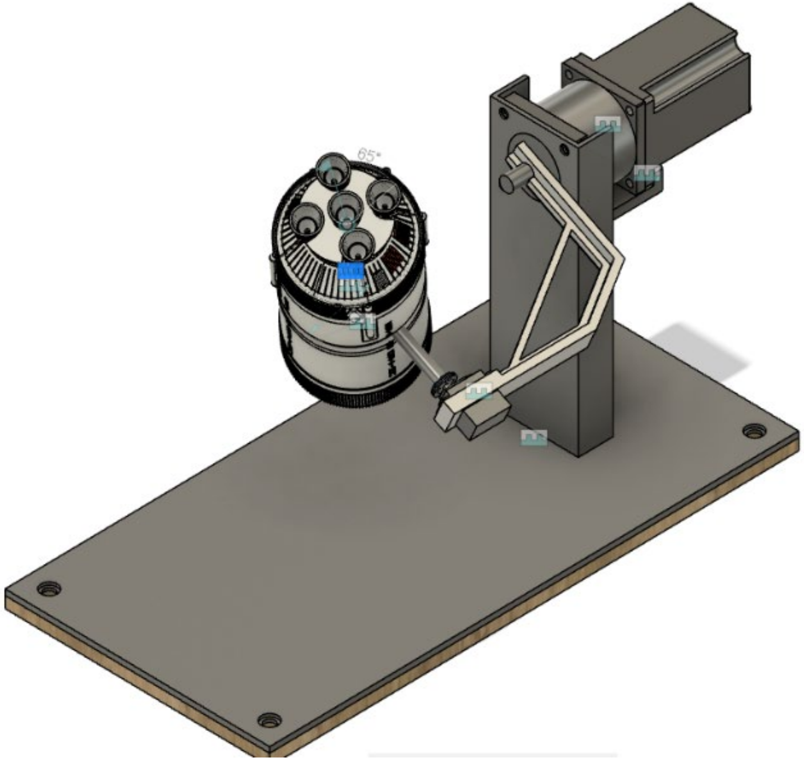
- Specs
  - Two Cores
    - Cortex® M7 - 480 Mhz
    - Cortex® M4 - 240 Mhz
  - STM32H747 processor's on-chip GPU
  - 16MB NOR Flash
  - WiFi/BT Module
  - External Antenna
- Speeds
  - Each instruction is about 8.3 ns
  - Handling of data and receiving data should be under 1000 ns with interrupts



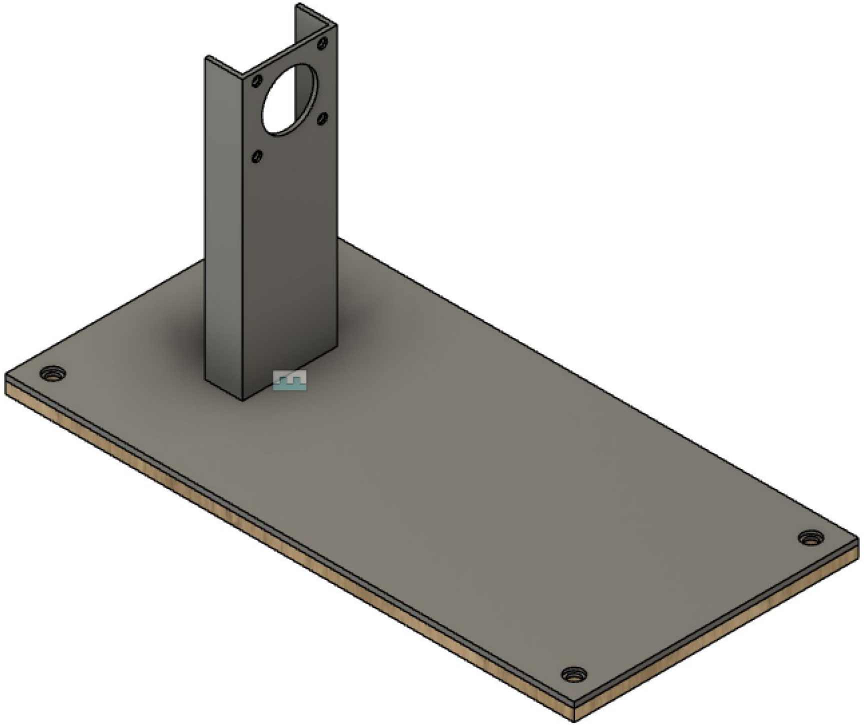
Client Hardware - Backup

Test Stand Assembly

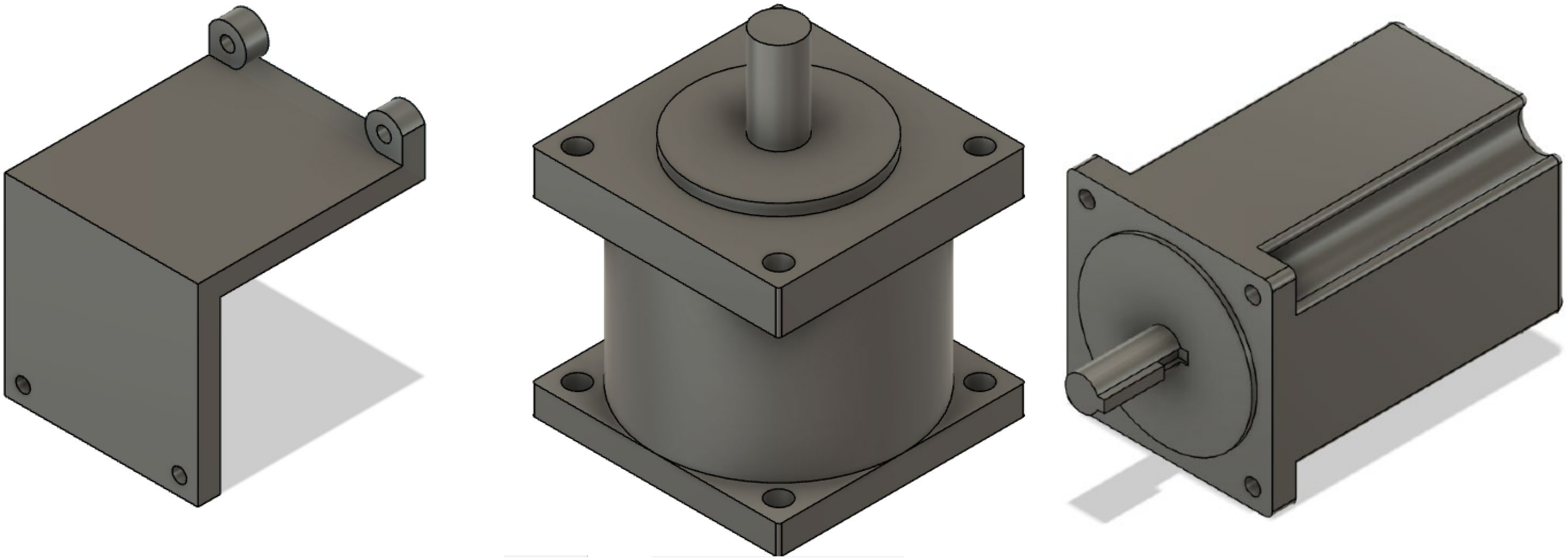




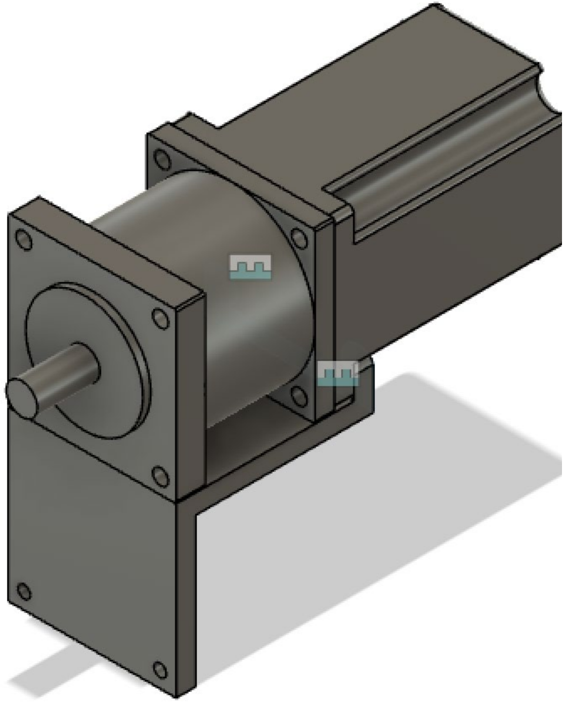
Base Plate Design

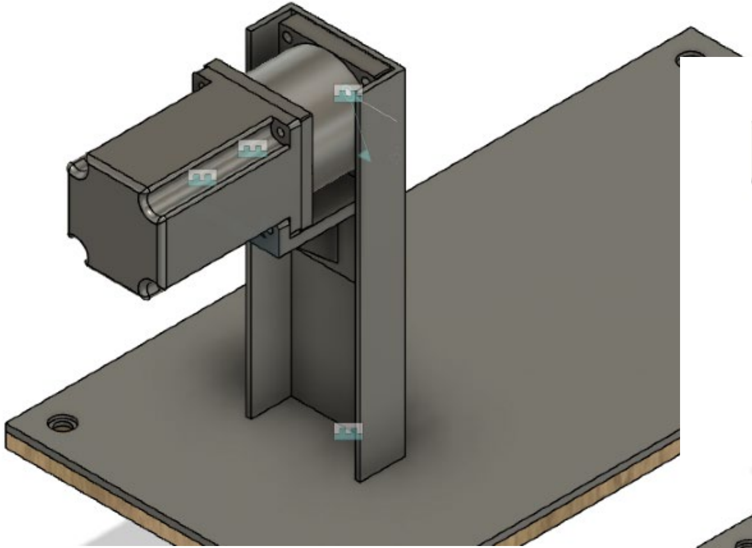


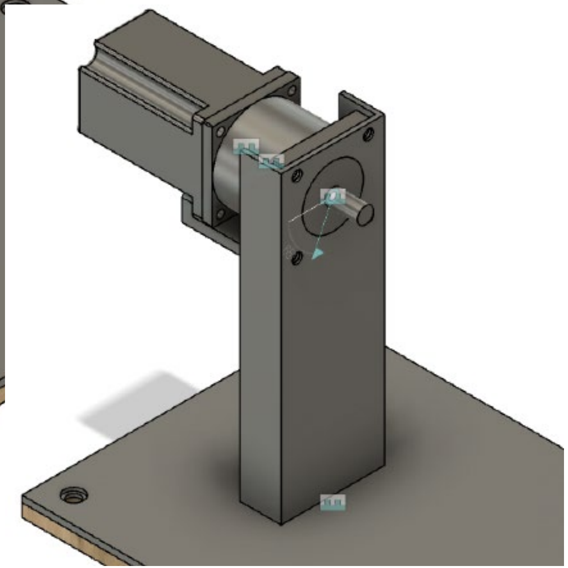
Motor 3 Integration



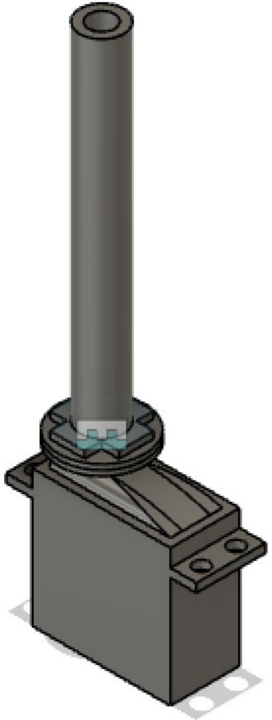
Motor 3 Integration

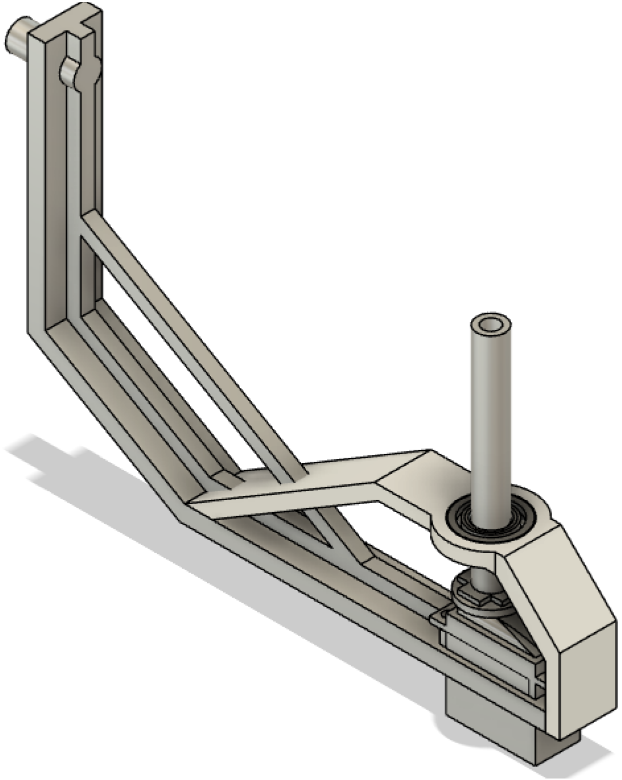


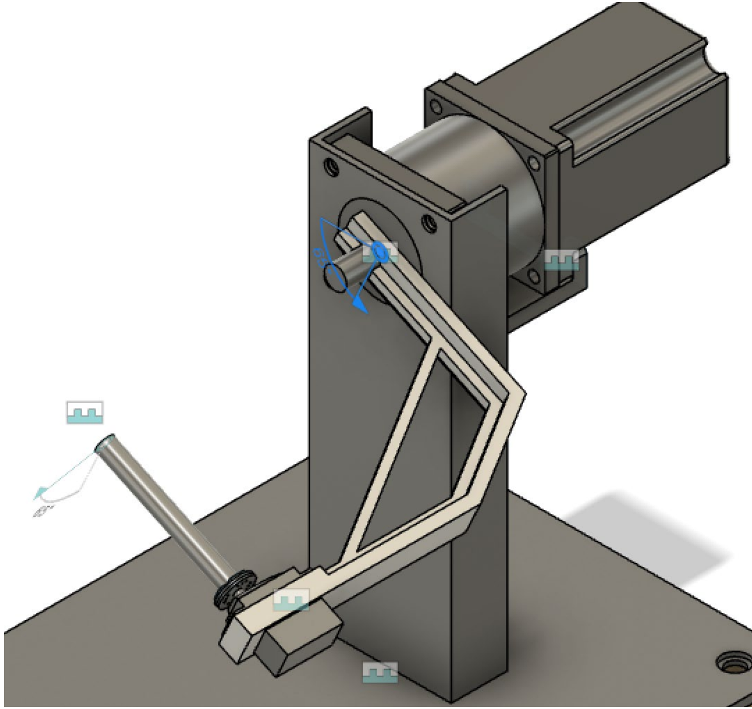




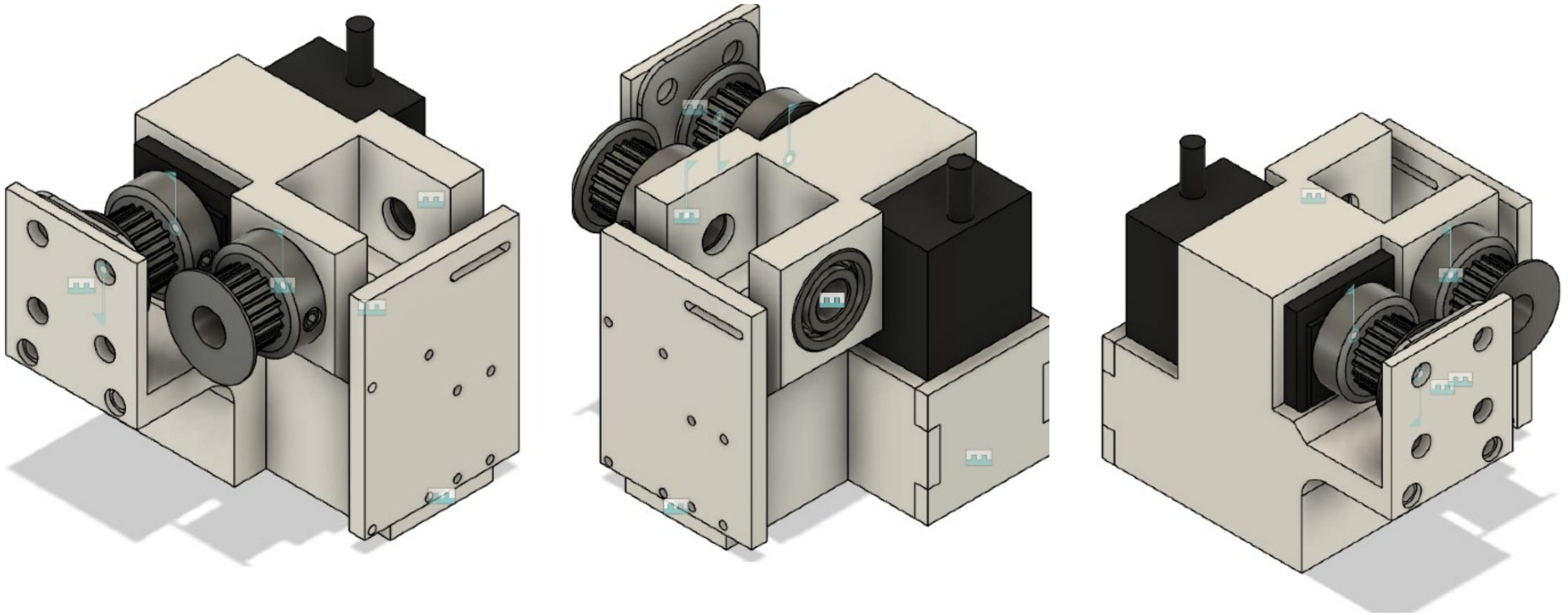
Motor 2



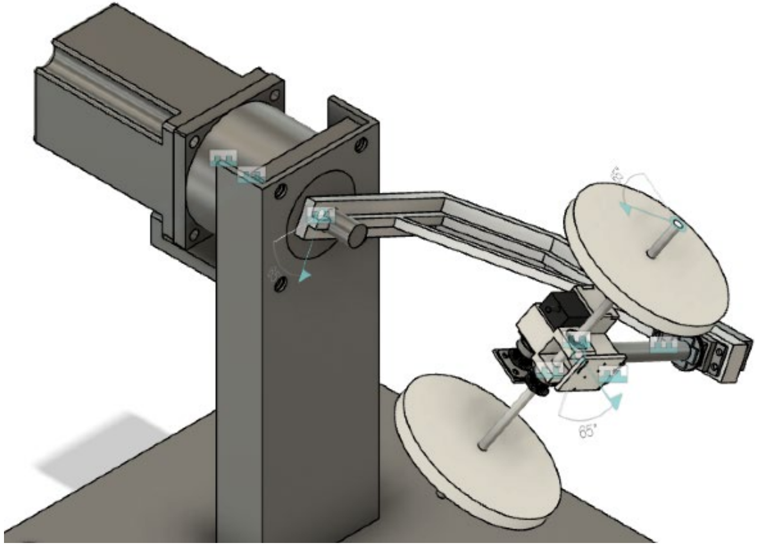


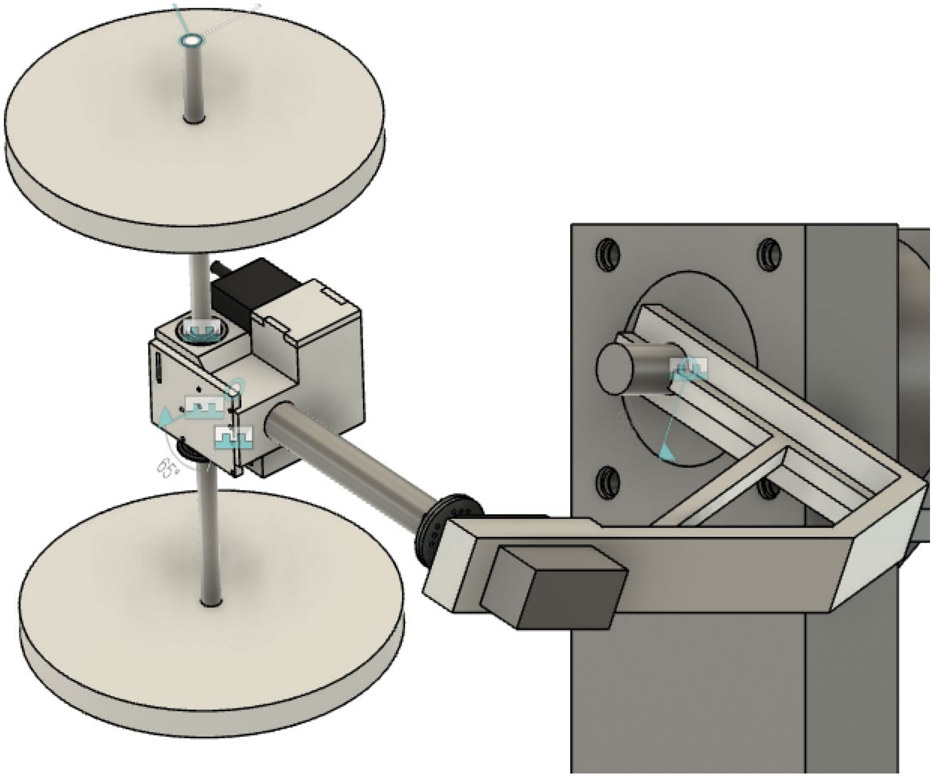


Motor 1

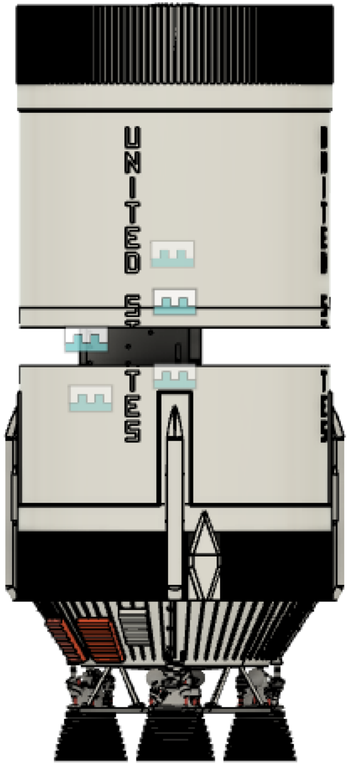


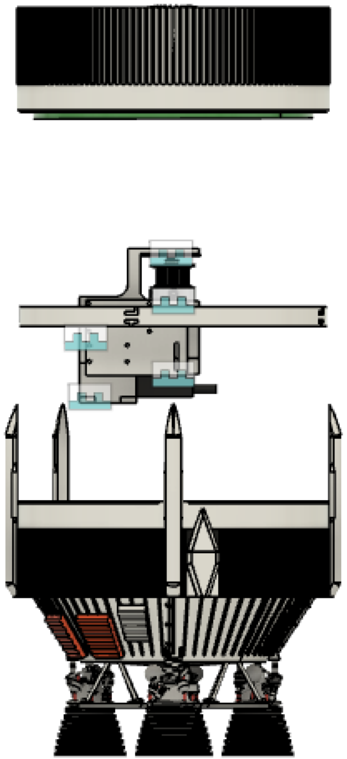
Motor 1



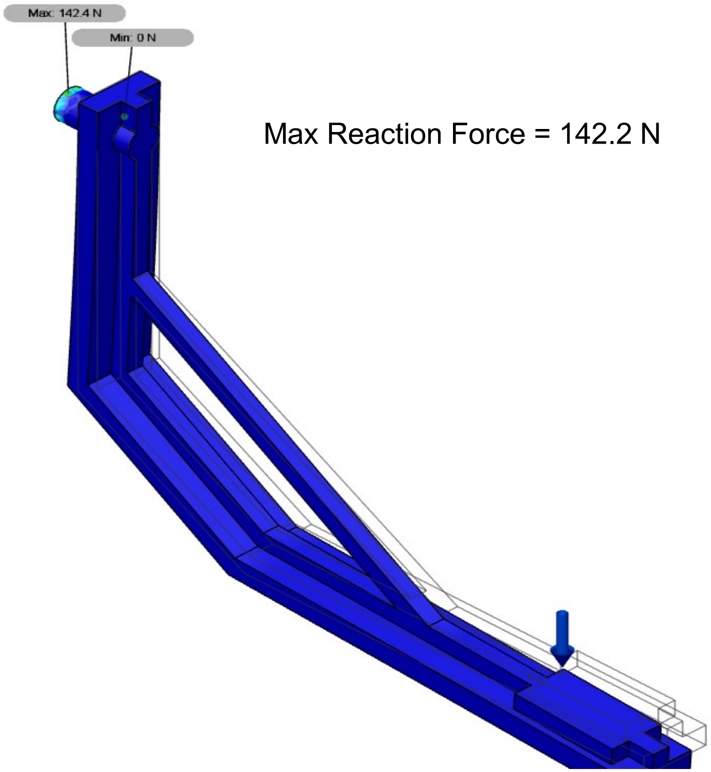


Client



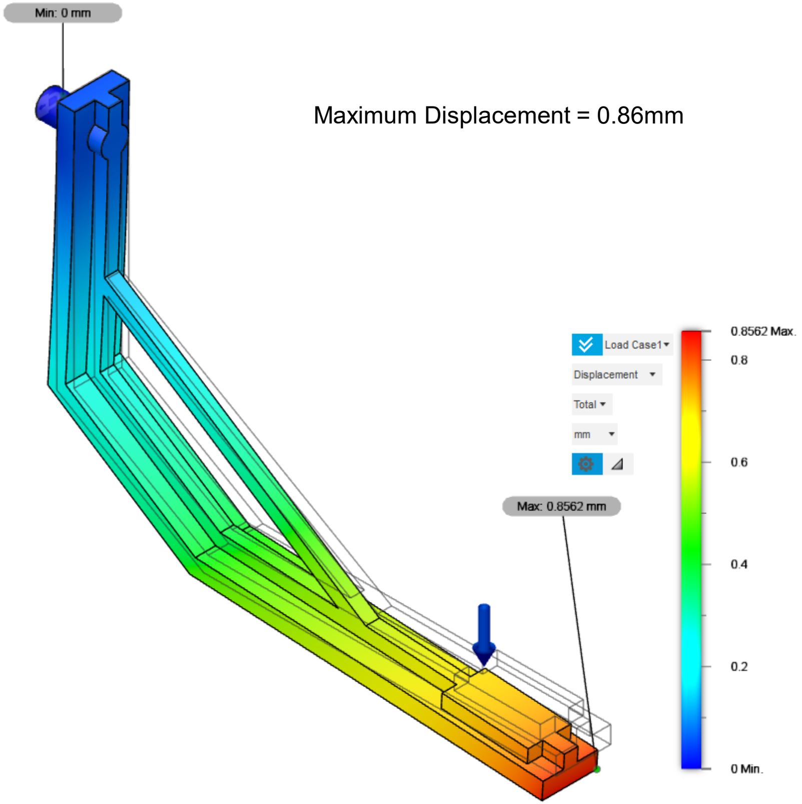


L Arm Stress Analysis



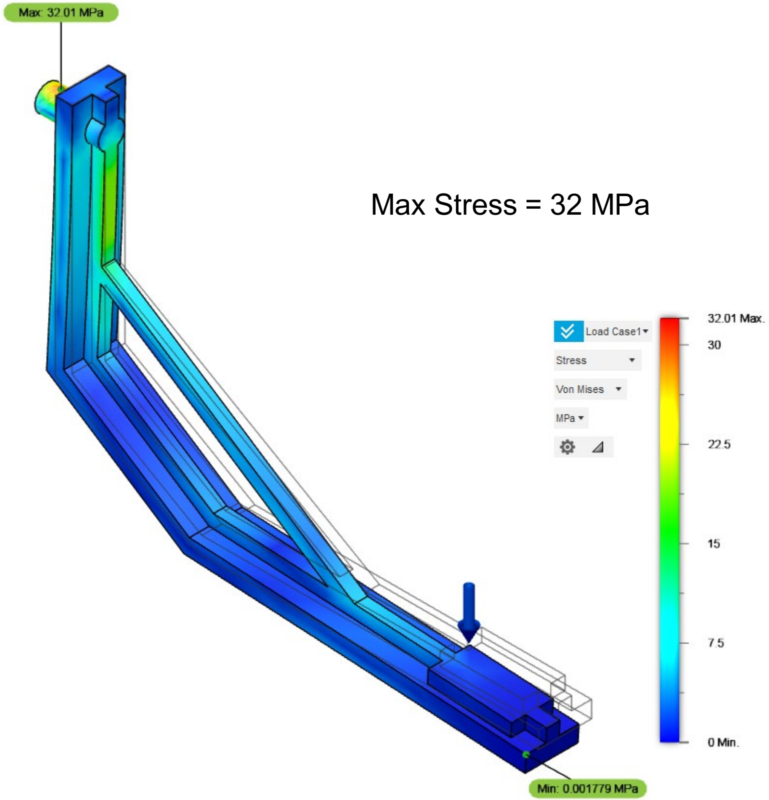
Max Reaction Force = 142.2 N

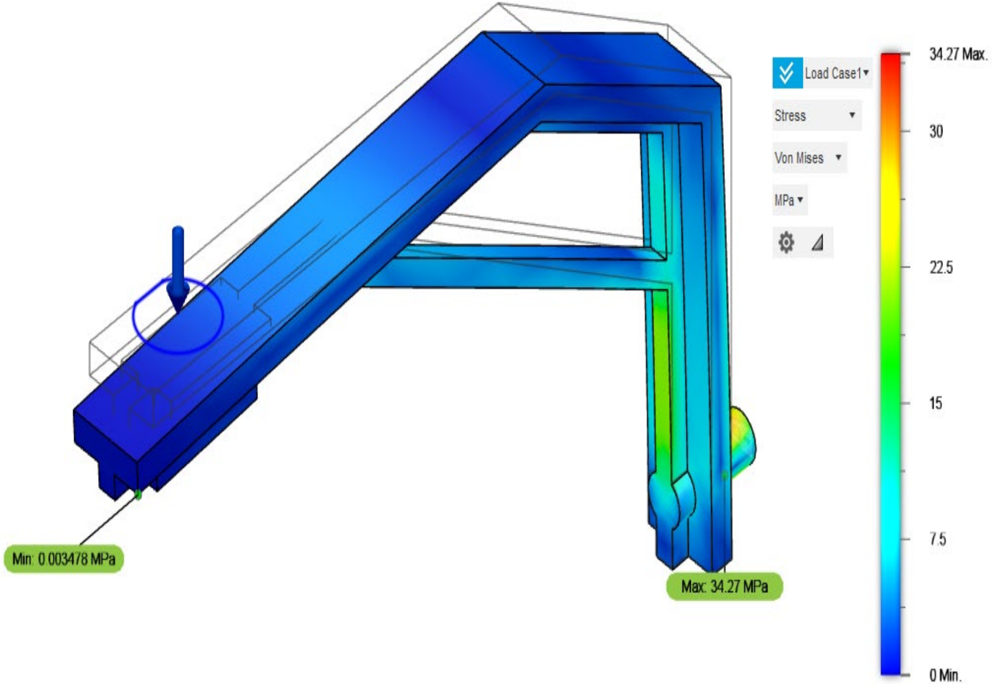
Maximum Displacement = 0.86mm



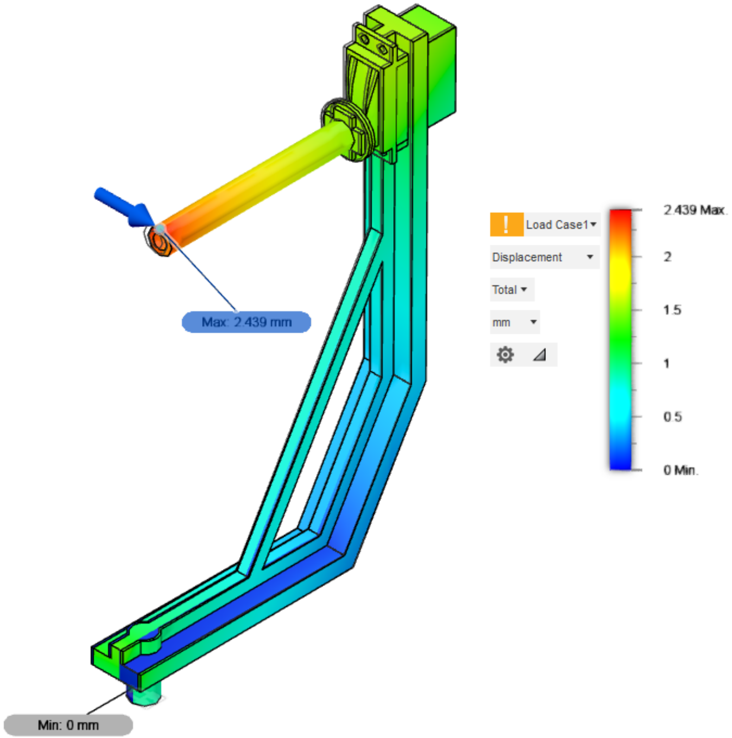
L Arm Stress Analysis

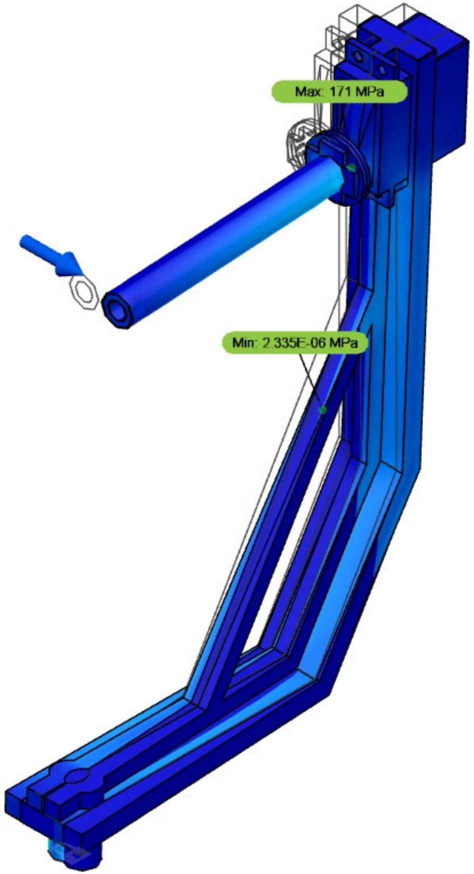
Max Stress = 32 MPa





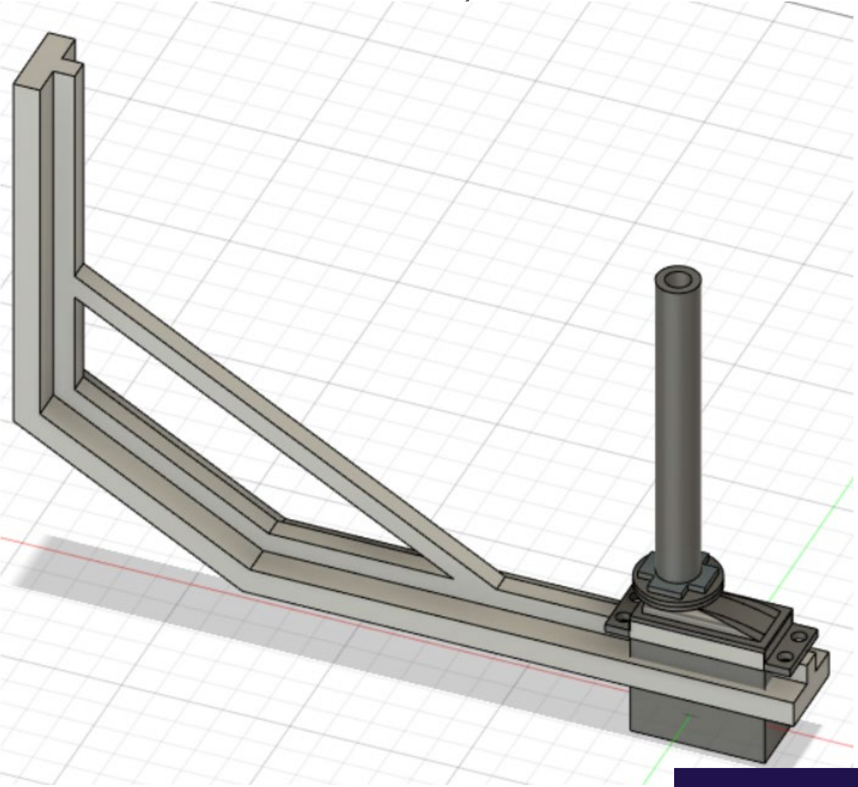
L Arm Stress Analysis

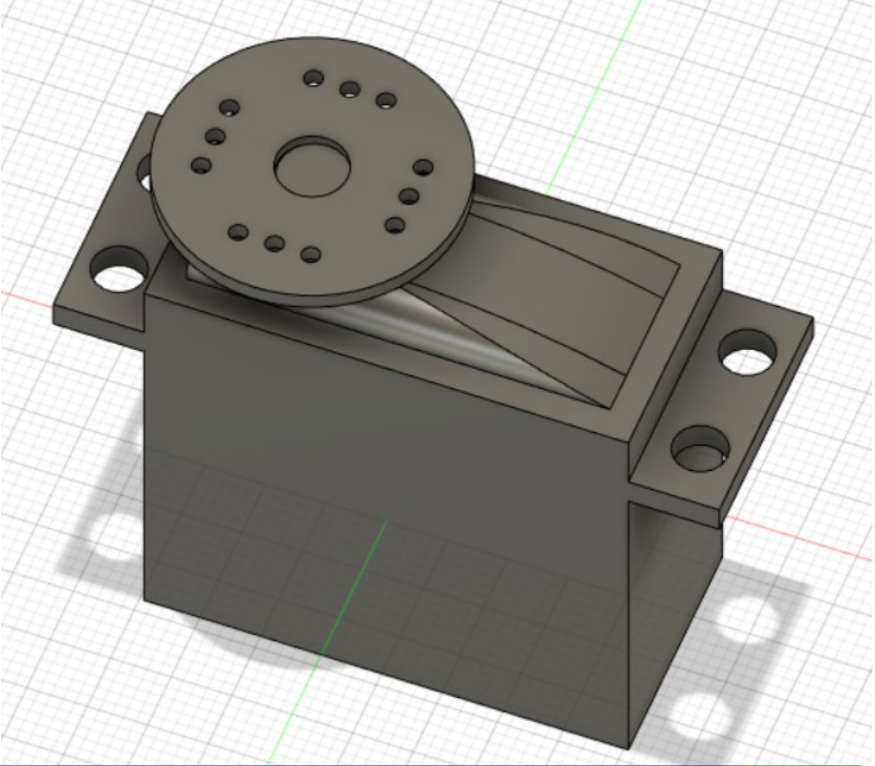




Client Hardware Interfacing: Motor 2

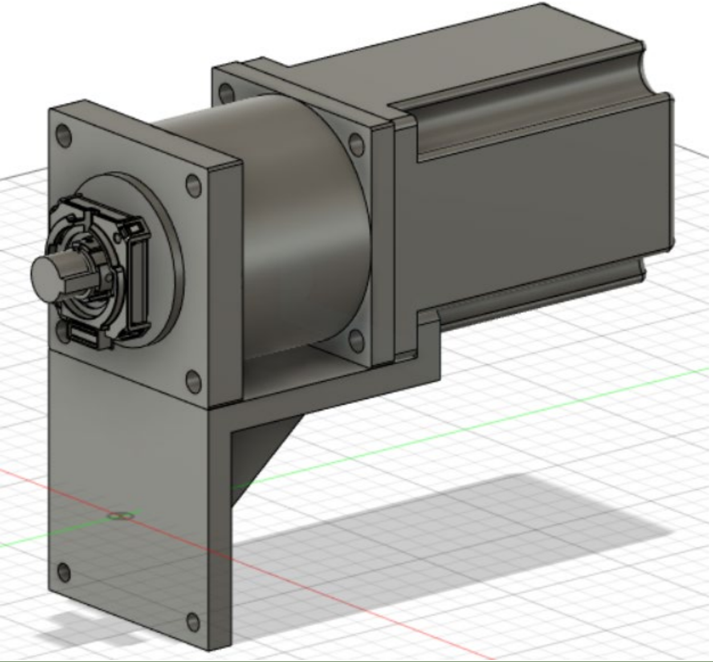
- Mounted in L-arm, drives stem that rotates motor 1 system

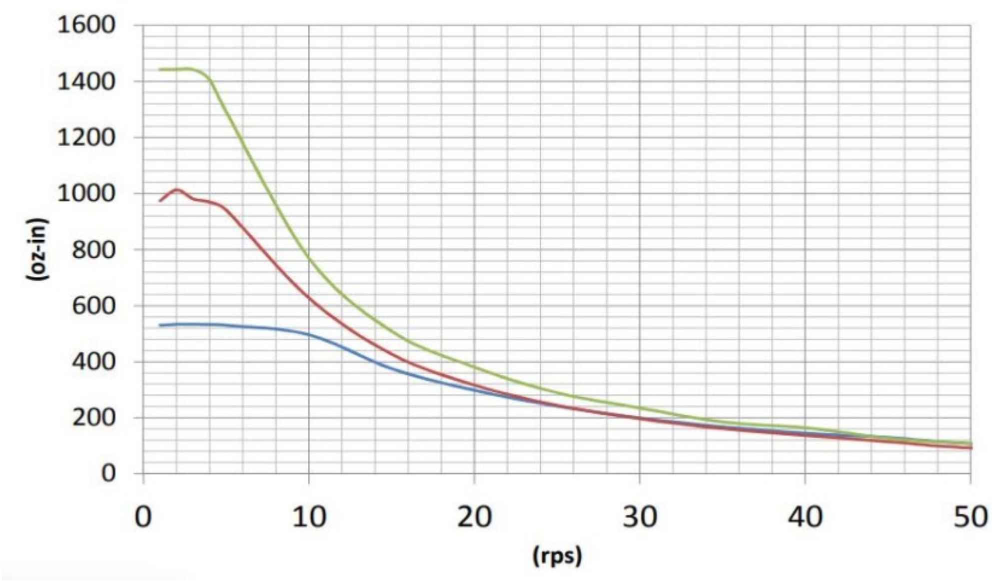




Client Hardware Interfacing: Motor 3

- Mounted to U-bar connected to base, directly drives L-arm
- Planetary gearbox steps down rotation speed so required torque can be achieved (see torque curve)





CROACS

- Estimate torque experienced by Motor 3

Mass Estimation: Items rotated by Motor 3

Object	Expected Mass [kg]
1/82 Scale Saturn V Second Stage	1.74
Motor 1	0.13
Motor 2	0.23
Extra PLA (supports and connections)	0.25
Total Mass	2.35

From initial design, the moment arm that motor 3 sees is expected to be 7in = 0.1778m

Torque Calculation:
T = torque ; m = total mass
r = expected moment arm
g = acceleration due to gravity

T = mgr = (2.35)(9.81)(0.1778)
T = 4.01Nm
T = 4.0Nm

FOS of 2 was used: T = 8.0Nm

Motors 1 and 2 Torque Estimates

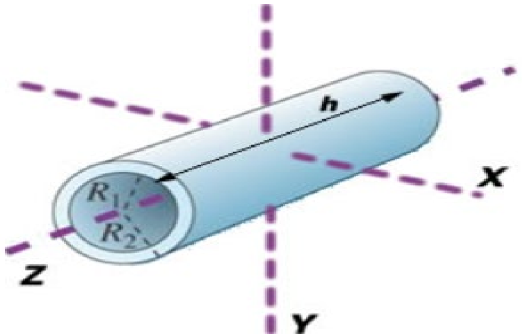
$\propto$ = 0.1745 [rad/sec^2]

Expected Moment:	I_Y = 0.0306 [kg m^2]	I_z = 0.034 [kg m^2]
Required Torque:	**T_2 = 0.5 [N cm]**	**T_1 = 0.6 [N cm]**

Torque Estimation (Motors 1&2)

Mass moment of inertia about y axis	I_y= (m/12) * (3*(R_2^2+R_1^2) + h^2)
Mass moment of inertia about z axis	I_z= (m/2) * (R_1^2+R_2^2)

Source: https://amesweb.info/inertia/hollow-cylinder-moment-of-inertia.aspx



m = 1.7385 [kg]; R_1= 6 [in] = .1524 [m]; R_2= 5 [in] = 0.127 [m];

h = 12 [in] = 0.3048 [m]

W = 2(10 [deg/sec]) = 0.349 [rad/sec]; t = 2 [sec]

$\propto = \Delta w/ t$; $T = I\propto$

Project Planning - Cost Analysis

Client Electronics - Component Costs

CROACS

Component	Website	Cost (without tax)	Link	Quantity	Datasheet	Location	Purpose	Comments
Servo 1	Amazon	$20.00	JX Servo	1		Inside Model	Model - Roll	
Servo 2	Amazon	$30.00	FEETECH	1		Outside Model	Model - Yaw	
AS5600	EBay	$5.00	AS5600	2		On Servo 1 and 2	Measure motor rotation	
Motor 3 and Driver	Amazon	$170	NEMA 34. Drive	1		Outside Model	Stepper and Driver	
AMT132Q-V	Future Electronics	$33.00	AMT 13 Series	2		On Stepper motor	Measure motor rotation	https://www.cuidevices.com/product/resource/amt13-v.pdf
Vector Board	Mouser	$23	Vector8001	1		Inside Model	Substitute to PCB - Connect components	
Battery	Amazon	$34	EBL 9V Batteries	1		Inside Model	Provide power	
Quadrature clock	Digi-Key	$6	LS7184	3		Inside Model	Convert encoder data	
Arduino UNO	Mouser	$45.00	Arduino UNO WiFi Rev2	3		1x Inside Model 2x Outside Model	Control motors and data from encoders	
Portenta H7	Arduino	$104.00	Arduino Portenta H7	1		Primary Controller	Control all 3 motors and encoders	

Client Electronics - Component Costs

Component	Website	Cost (without tax)	Link	Quantity	Datasheet	Location	Purpose	Comments
Nicla Sense ME	Arduino	$71.00	Nicla Sense ME	1		Inside Model	IMU	Should be 1 system!
Adafruit 1578 Lithium-Ion-Polymer	Amazon	$13.00	Adafruit Li-Po Battery	1		Inside Modle	Charge IMU	
Battery Charger	Adafruit	$7.00	Adafruit Micro-Lipo Charger	1		Outside Model		
JST wires	Sparkfun	$2.00	https://www.sparkfun.com/products/13685	2		Outside Model	connect arduino to encoder	
Encoders Connector	Digi-Key	$30.00	AMT-18C-3-036	2		Outside Model	Connect AMT encoder to Arduino	Request Samples!!!!!
Misc	N/A	$17.00				N/A	Jumper wires, header pins, etc.	

Servicer Electronics - Component Costs

Component	Cost
Computer	
CPU	$430.00
Cooler	$50.00
Motherboard	$200.00
Ram	$100.00
SSD	$60.00
PSU	$80.00
Fans	$20.00
Encoder	$25.00
Arduino Nano	$10.00
Lidar Sensor + Dragon Board	$185.00
Power Cables / margin	$40.00
	$1,200.00

Manufacturing Materials Cost - Servicer

CROACS

Element	Supplier	Description	Part Number	Cost		Quantity	Totals		Link
Test Bench	80/20	10 series one-sided beam	1050	$0.20	per inch	120	$24.00	$144.12	Website: https://8020.net/shipping-information. 40 days for shipping. $33.83 for current order
		10 series beam	1010	$0.28	per inch	24	$6.72		
		10 series wide beam	1020	$0.48	per inch	18	$8.64		
		20 series beams	2020	$0.69	per inch	0	$0.00		
		10 series wheels	2281	$17.34	per wheel	4	$69.36		
		10 series inside corner bracket + mounting HW	4119	$4.05	per bracket + mounting HW	4	$16.20		
		20 series inside corner bracket + mounting HW	20-4113	$7.16	per bracket + mounting HW	2	$14.32		
		end caps	2015	$1.22	per cap	4	$4.88		
	Home Depot	1" x 1" x 36" pine square dowel	N/A	$4.84	per piece	2	$9.68	$52.25	Woodgrain Millw
		1/4" x 4' x 8' Plywood	N/A	$29.92	per sheet	1	$29.92		Sandeply 5.2mm
		4x4 stand center beam	N/A	$12.65	per piece	1	$12.65		https://www.hom
Enclosure	Amazon	120mm fan covers	N/A	$8.39	per pack of 4	1	$8.39	$104.57	https://www.ama
		soft close hinge	N/A	$5.89	per hinge	2	$11.78		e Cabinet Hinge
		mesh wire lid	N/A	$11.77	per sheet	1	$11.77		Amazon.com: 30
		120mm fans	N/A	$13.99	per two pack	1	$13.99		Amazon.com: Ve
		Swivel	N/A	$36.68	per piece	1	36.68		https://www.ama
	Home Depot	Pins for securing enclosure	N/A	$5.49	per pin	4	$21.96		Prime-Line Whit

Manufacturing Materials Cost - Client

Client Stand	Fast Metals	Metal base plate	10408	$33.91	per sheet	1"x2"x0.25"	$33.91	$58.76	/products/1-4-hot
		U Channel	10106	$15.55	per piece	4"x12"	$15.55		e50b2c15bdf8d1
		Aluminum L arm base	10230	$4.74	per piece	24"x1"x3/8"	$4.74		tions/aluminum-e
		Aluminum L arm Channel	10605	$4.56	per piece	24"x.25"x.25"	$4.56		ons/aluminum-ex
	Online Metals	Motor 2 Aluminum Pipe	1217	$10.87	per ft	0.25" x Sched. 40 x 12"	10.87	$14.71	0-25-nom-schedu
		Motor 1 Aluminum Round Bar	1080	$3.84	per ft	0.25"x12"	3.84		ium/0-25-aluminu
	Amazon	R4 Bearing	N/A	$9.30	per 10 pack	1	$9.30	$48.07	-2RS-Sealed-Be
		Timer Pulleys	N/A	$7.99	per 5 pack	1	$7.99		/ref=sr_1_4?keyw
		Pulley Belt	N/A	$9.79	per 8 pack	1	$9.79		a-c41c-422e-990
		PLA	N/A	$20.99	per kg	1	$20.99		a+filament+for+3
	Ebay	Planetary Gearbox	N/A	$90.00	per gearbox	1	$90.00	$90.00	472252&targetid=
	Home Depot	Miscellaneous Fasteners	N/A					$30.00	
Total Cost	**$542.48**								