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

Preliminary Design Review

October 18th, 2021

ASEN 4018-011 Team #6

Company Sponsor:
Astroscale

Faculty Advisor:
Dr. Yu Takahashi

Presenters:
Brandon DiLorenzo, Tyler Gaston, Jason Le,
Max Morgan, Walter Sabin, Shawn Stone

CROACS

The Team

Jake Pirnack - Brandon diLorenzo - Zackary Hubbard - Max Morgan - Nick Herrington
Tyler Gaston - Jason Le - Jash Bhalavat - Shawn Stone - Jianai Zhao - Walter Sabin

Presentation Outline

1. Project Overview - *Tyler Gaston*
2. Feasibility: Software - *Brandon diLorenzo*
3. Feasibility: Electronics - *Jason Le, Shawn Stone*
4. Feasibility: CROACS Hardware - *Max Morgan*
5. Feasibility: Client Hardware - *Walter Sabin*
6. Feasibility: Financial - *Shawn Stone*
7. Feasibility Summary - *Shawn Stone*
8. Future Work - *Tyler Gaston*

Project Overview

Project Overview

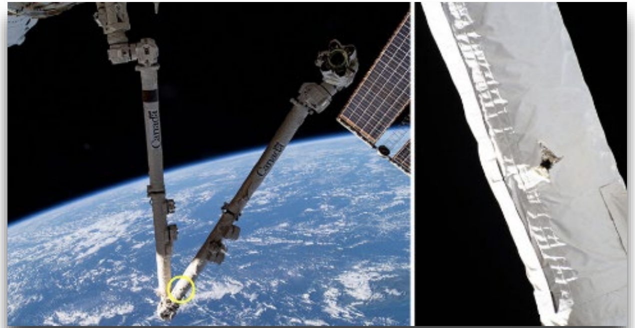
Background:

- 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 **attitude and position 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

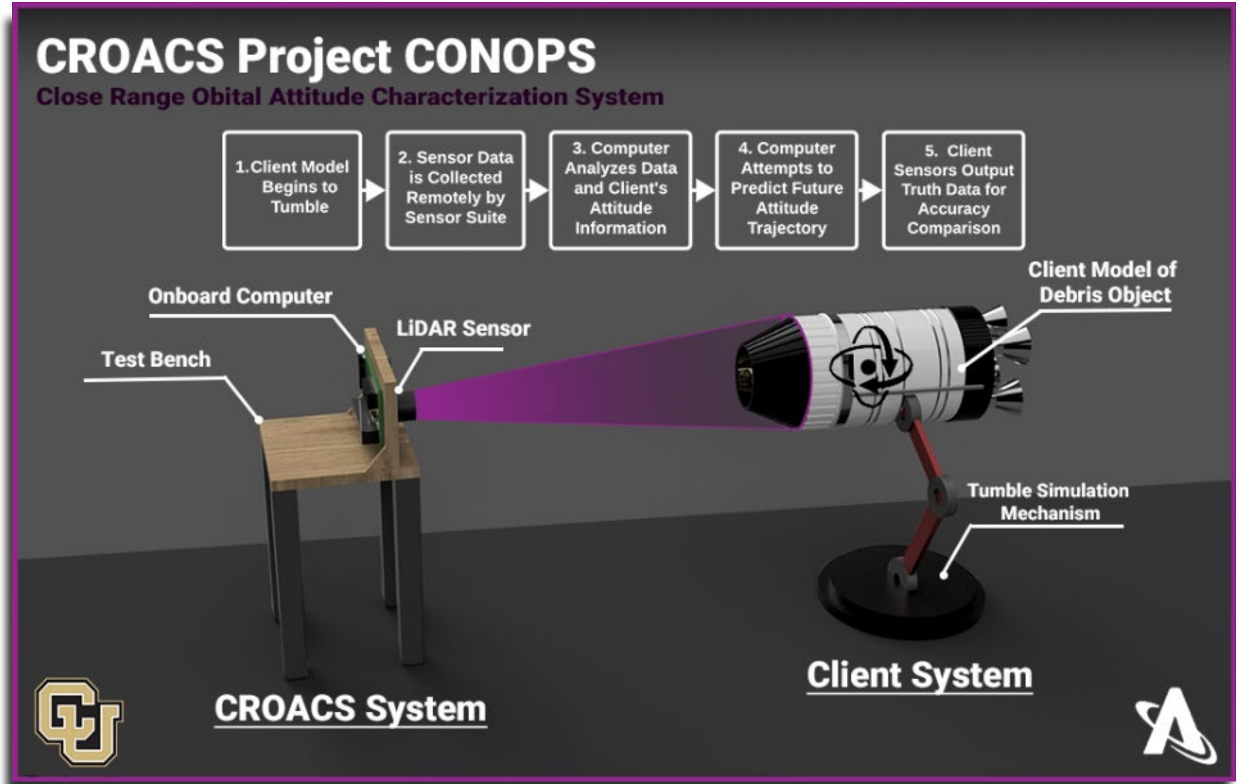


ISS Space Debris Damage https://spacenews.com/wp-content/uploads/2021/06/canadarm-debris-2021.png

Mission Statement

*"Close Range Orbital Attitude Characterization System **(CROACS)** will remotely **sense and analyze** data of a client satellite **to determine and predict relative position, relative velocity, attitude, and angular velocity.**"*

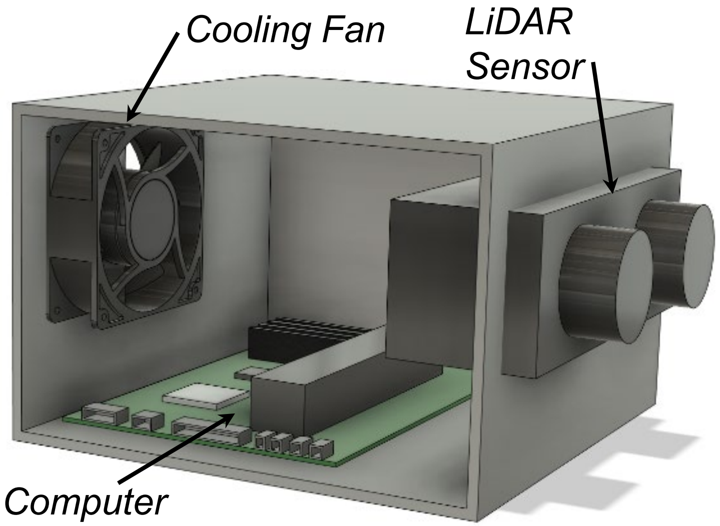
Concept of Operations



Baseline Design

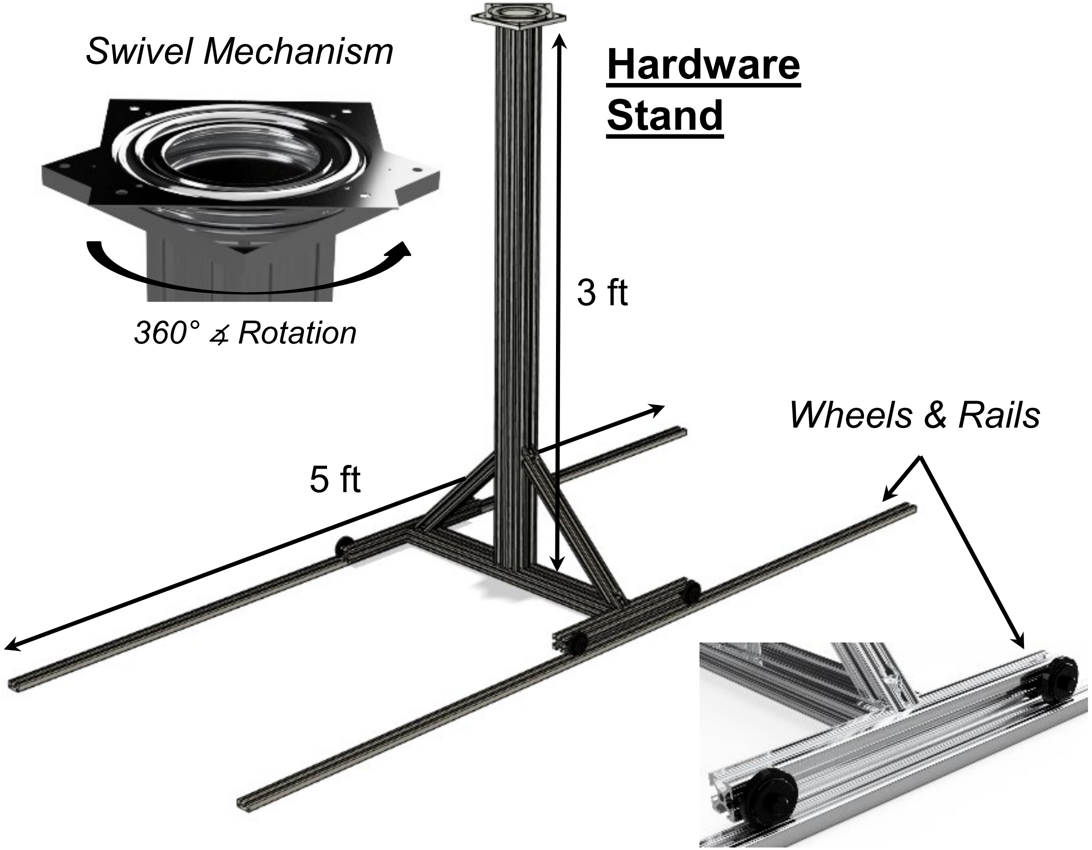
CROACS System

Electronics Enclosure



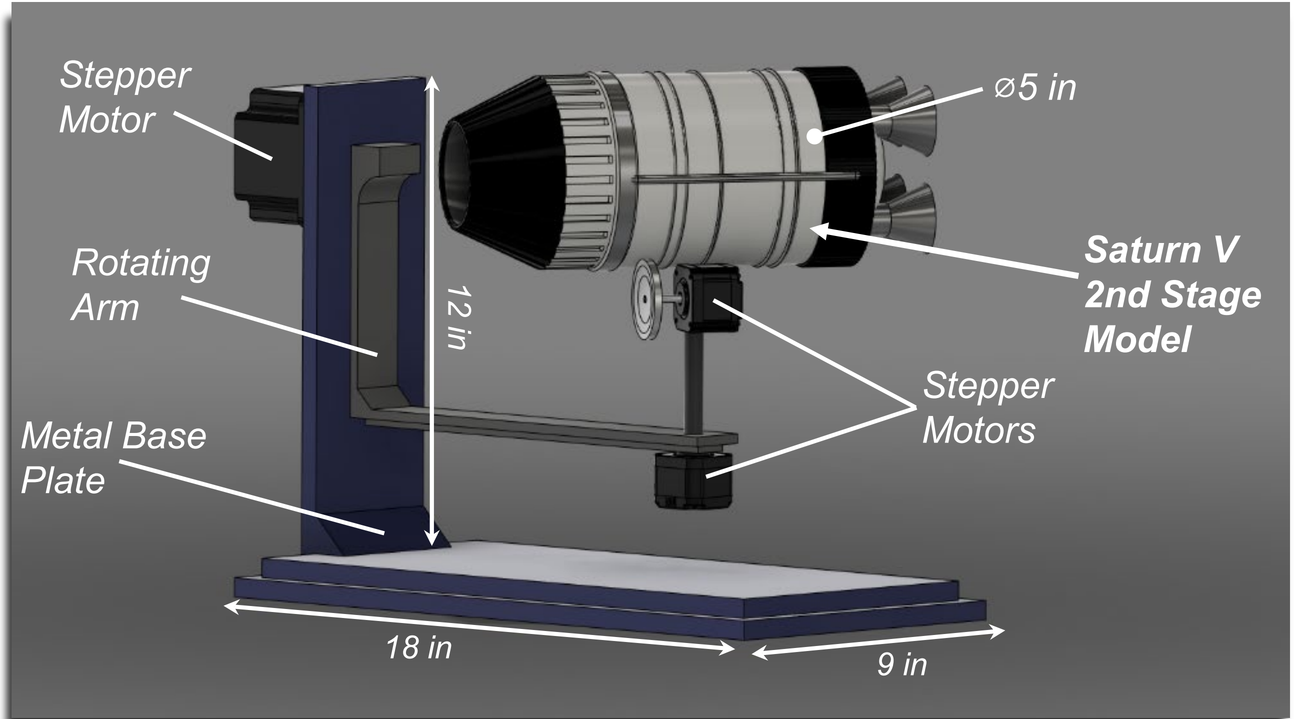
**Enclosure dimensions subject to change*

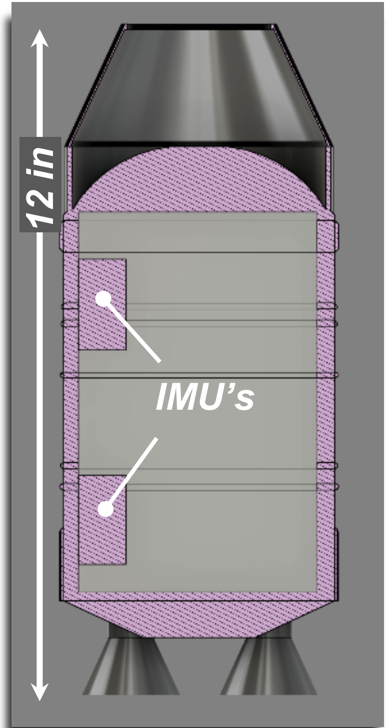
Hardware Stand



CROACS

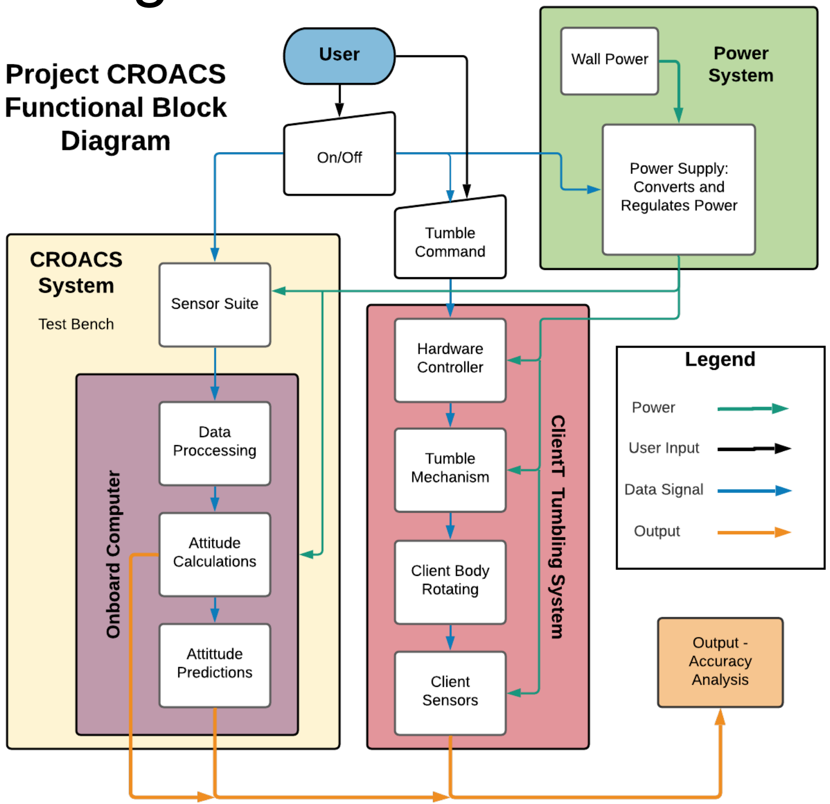
Baseline Design
Client System (Testing)





CROACS

Functional Block Diagram



Critical Project Elements

CPE	Description
[E1] Sensors and Imaging	-Imaging sensor **collects and transmits** data to **on-board computer** software verifies data is usable.
[E2] CROACS Hardware	-Physical enclosure **housing all CROACS electronics and sensors**. -Capable of **translation** during testing.
[E3] Space Debris Model	-**Physical model** of space debris with **three axes of motorized rotation simultaneously**. -Onboard **Sensors must report truth data**.
[E4] Data Processing	-Software **differentiates debris from background** and models tumble.
[E5] Prediction and Accuracy	-Software calculations must **match truth data to a <10% margin of error**. -At a 10°/sec angular rotation rate for each axis, the software is capable of making future predictions up to 5 minutes forward with <25% deviation after the first minute.

CROACS

Design Feasibility

Design Feasibility - CROACS Software

The software must be capable of processing LIDAR data and calculating a known client satellite's relative position, velocity, attitude, and angular velocity.

Software Feasibility: Data Processing

- Object detection and isolation is an important step for our software.
- Range masking is a common technique.
    - Eliminating range outside of specified bounds
- Our ability to work with LiDAR data will be facilitated by the LiDAR toolbox in MatLab
    - Has the built in ability to process raw point cloud LiDAR data

Example of Range Masking in a LiDAR Capture

Software Feasibility: Data Processing

LiDAR Data

- Object
  - Soda Can
- Captured using iPhone 12 Pro LiDAR capabilities
  - App: Poly Cam
  - Number of Points: 16440
  - Data: 409 kB
- Processing
  - Intel(R) Core(TM) i5-8350 CPU @ 1.7 GHZ, 1.9 GHz
  - RAM: 16 GB

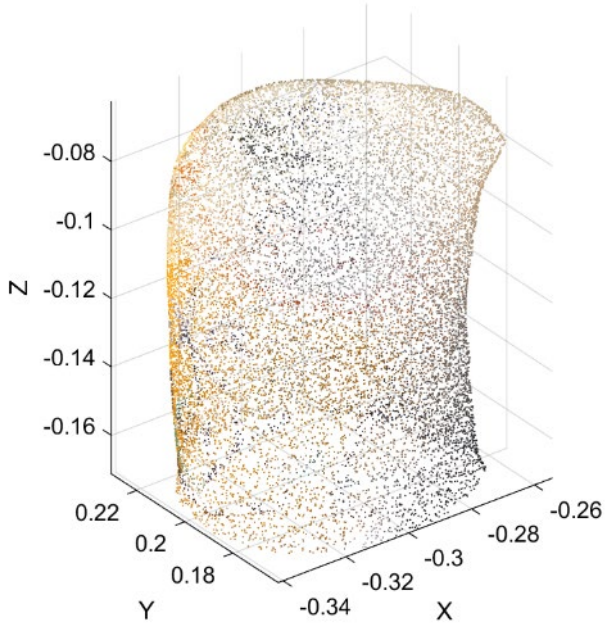
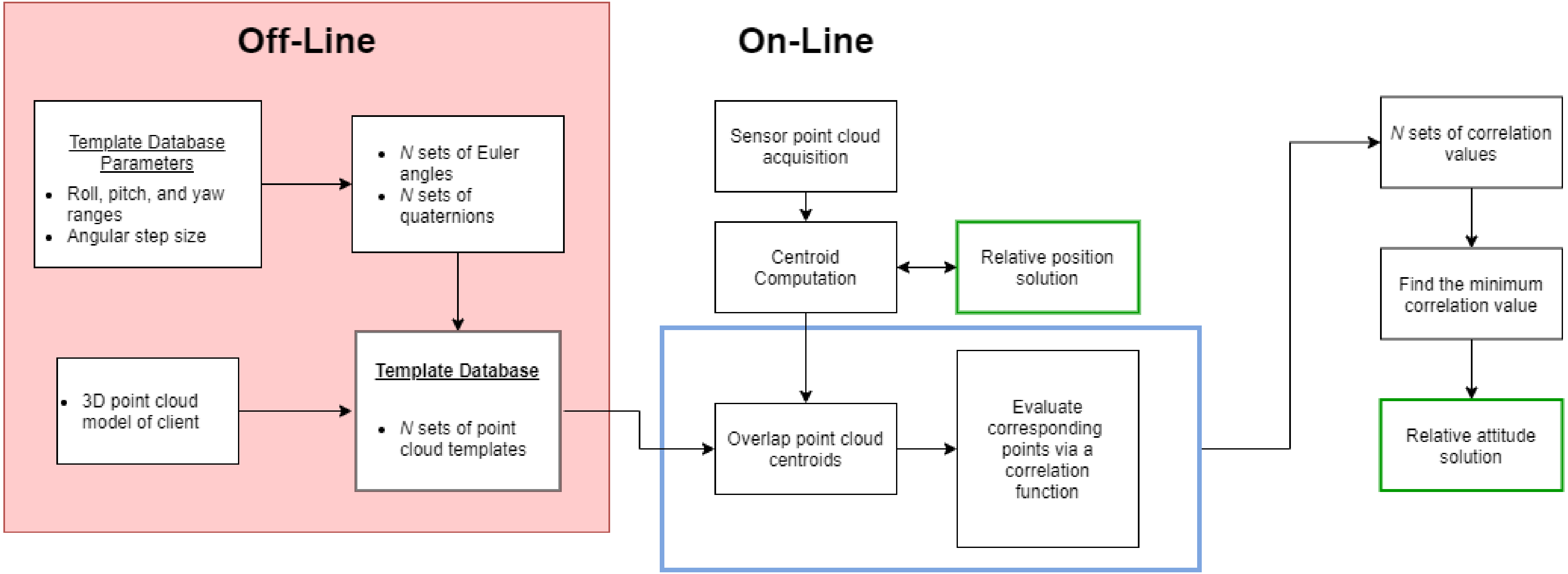


Figure: Processed LiDAR Point Cloud

Software Feasibility: Attitude Calculations

Algorithm Flowchart



Software Feasibility: Attitude Calculations

Offline: Template Database

$$\Omega = [\phi, \theta, \psi]$$

↓

$$\mathbf{q} = \begin{bmatrix} \cos(\frac{\phi}{2})\cos(\frac{\theta}{2})\cos(\frac{\psi}{2}) + \sin(\frac{\phi}{2})\sin(\frac{\theta}{2})\sin(\frac{\psi}{2}) \\ \sin(\frac{\phi}{2})\cos(\frac{\theta}{2})\cos(\frac{\psi}{2}) - \cos(\frac{\phi}{2})\sin(\frac{\theta}{2})\sin(\frac{\psi}{2}) \\ \cos(\frac{\phi}{2})\sin(\frac{\theta}{2})\cos(\frac{\psi}{2}) + \sin(\frac{\phi}{2})\cos(\frac{\theta}{2})\sin(\frac{\psi}{2}) \\ \cos(\frac{\phi}{2})\cos(\frac{\theta}{2})\sin(\frac{\psi}{2}) - \sin(\frac{\phi}{2})\sin(\frac{\theta}{2})\cos(\frac{\psi}{2}) \end{bmatrix}$$

↓

$$\mathbf{R} = \begin{bmatrix} q_1^2 + q_2^2 - q_3^2 - q_4^2 & 2(q_2q_3 - q_1q_4) & 2(q_1q_3 + q_2q_4) \\ 2(q_2q_3 + q_1q_4) & q_1^2 - q_2^2 + q_3^2 - q_4^2 & 2(q_3q_4 - q_1q_2) \\ 2(q_2q_4 - q_1q_3) & 2(q_1q_2 + q_3q_4) & q_1^2 - q_2^2 - q_3^2 + q_4^2 \end{bmatrix}$$

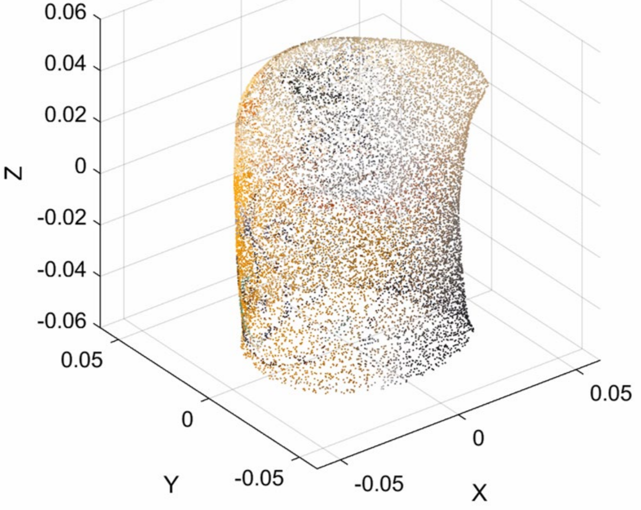
Database Parameters

Δ = 30°, 20°, **10°**

Φ , **Ψ** = (-180°, 180°)

Θ = (-90°, 90°)

Figure: Point Cloud Templates with Z-Axis Rotation [Δ = 10°]



Terminology

Φ : X-Axis Rotation , Θ : Y-Axis Rotation , Ψ : Z-Axis Rotation

Software Feasibility: Attitude Calculations
Centroid Computation

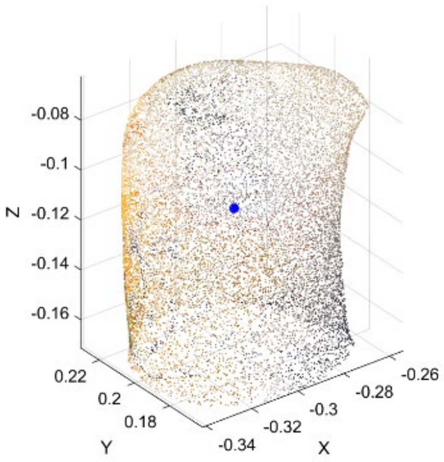


Figure: Centroid-Centered Point Cloud

$$\mu = \frac{1}{N_P}\sum_{j=1}^{N_P} \mathbf{P}_{(j)}$$

μ = Centroid

N_P = Number of Points

$P_{(j)}$ = j-th Point

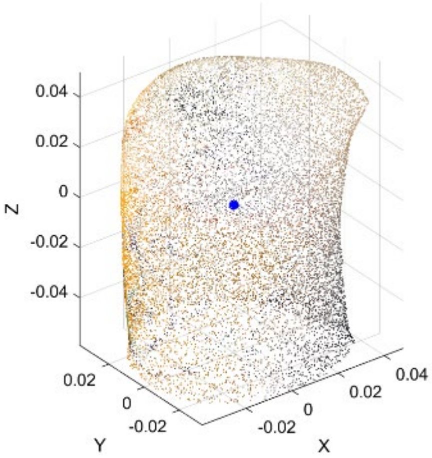


Figure: Origin-Centered Point Cloud

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Software Feasibility: Attitude Calculations

Online: Template Matching

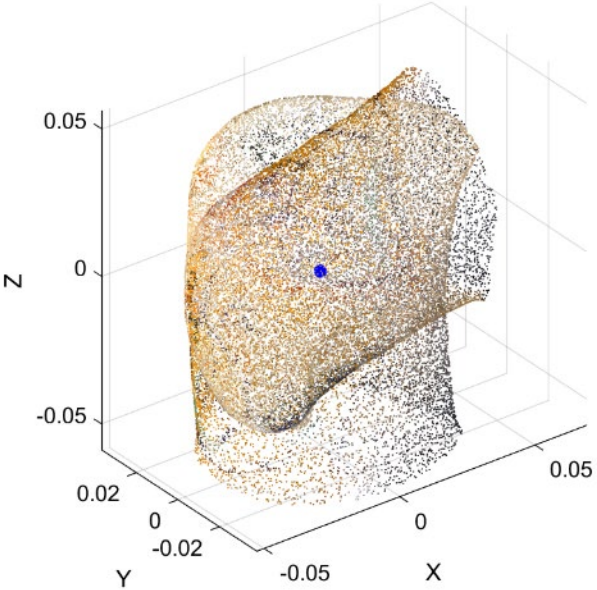

Figure: Point Clouds with Overlapping Centroids

Correlation Function

$$C(\Omega) = \frac{1}{N_P} \sum_{j=1}^{N_P} \left| \mathbf{P}^{(j)}_{SENSOR} - \mathbf{P}^{(j)}_{TEMPLATE}(\Omega) \right|^2$$

Software Feasibility: Attitude Calculations

Online: Template Matching

TEST CASE

Ω = [-132°, 56°, 8°]

Angular Step	Attitude Estimate [3-2-1]	Total Attitude Error
30°	[-120°, 60°, 30°]	5.91%
20°	[-140°, 50°, 0°]	4.58%
10°	[-130°, 60°, 10°]	2.36%

Initial attitude characterization is feasible within accuracy requirements, future work required for velocity and determining object from background.

$$\sigma_\phi = \frac{|\phi - \phi_{est}|}{360^\circ} \qquad \sigma_\theta = \frac{|\theta - \theta_{est}|}{180^\circ} \qquad \sigma_\psi = \frac{|\psi - \psi_{est}|}{360^\circ}$$

$$\sigma_{total} = 100\% * \sqrt{(\sigma_\phi)^2 + (\sigma_\theta)^2 + (\sigma_\psi)^2}$$

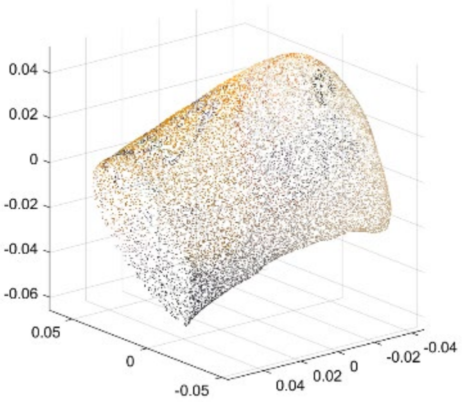

Figure: Point Cloud at Test Case Orientation

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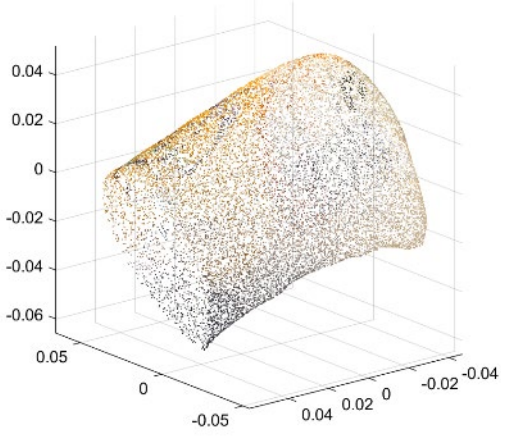
Design Feasibility - Electronics

Sensors and other electronic hardware must have specifications capable of meeting accuracy requirements.

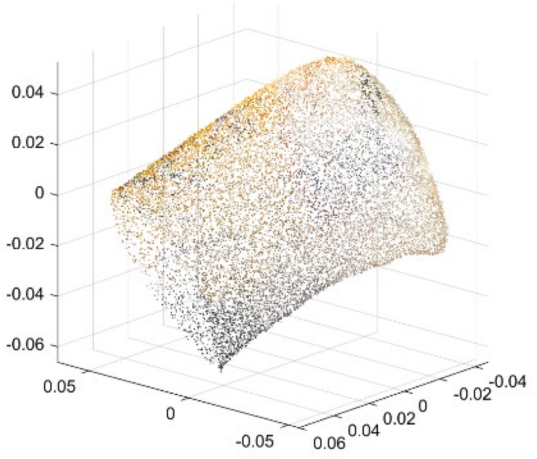
Electronics Feasibility: CROACS Electronics

LIDAR Sensor Error

TEST CASE
Ω = [-132°, 56°, 8°]



Point Cloud at Test Case Orientation



Point Cloud at Test Case Orientation with 1% range error

Maximum expected LIDAR error is ±0.06m at 20m (0.3%)

Angular Step	Attitude Estimate	Total Attitude Error	Total Attitude Error with 1% LIDAR range error (FOS > 3)
30°	[-120°, 60°, 30°]	5.91%	5.91%
20°	[-140°, 50°, 0°]	4.58%	4.58%
10°	[-130°, 60°, 10°]	2.36%	2.36% ✓

Electronics Feasibility: CROACS Electronics

Onboard Processing - File Size

- LAS - typical LiDAR point cloud data format
- LIDAR sensor points per second (pps) varies: roughly 100,000 to 2M
  - Does not account for elimination of background information

Table 2: Comparison of the space (MB) and average time (in milliseconds) for queries *getRegion* and *FilterAttRegion*.

Dataset	# points	Space (MB)			GetRegion (ms)		FilterAttRegion (ms)	
		LAS	*LAZ*	k^3*-lidar*	*LAZ*	k^3*-lidar*	*LAZ*	k^3*-lidar*
PNOA-small	13,265,144	254	**43**	119	1,524	**249**	1,517	**145**
PNOA-medium	25,108,130	479	**80**	225	2,521	**424**	2,655	**374**
PNOA-large	52,627,503	1004	**173**	471	6,859	**1,189**	6,283	**1,264**
TUB1	32,597,694	622	**196**	304	6,145	**383**	–	–
FireBrigade	10,406,389	199	**77**	100	1,717	**74**	–	–

Ladra, 2019 [1]

CROACS

Electronics Feasibility: CROACS Electronics

Onboard Processing - Transfer Speeds

	# of Points	MB for LAS file type	Points per MB (ppMB)
	13,265,144.00	254.00	52,224.98
	25,108,130.00	479.00	52,417.81
	52,627,503.00	1,004.00	52,417.83
	32,597,694.00	622.00	52,407.87
	10,406,389.00	199.00	52,293.41
TOTAL	**134,004,860.00**	**2,558.00**	**52,386.58**

Expected data transfer rates are feasible, but required storage might affect processor choice or data acquisition time.

- 2M pps for worst case → 38.1 MBps maximum data transfer rate
  - Typical read/write speeds on the order of GB/s
- Sensor running continuously for 15 minutes → 34.29 Gb of total storage

Electronics Feasibility: Client Electronics

Truth Data Sensor System

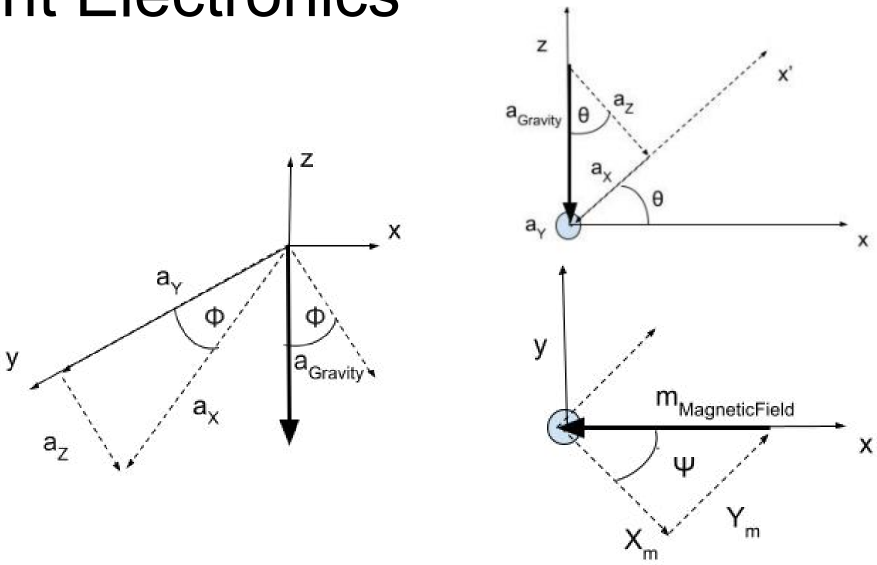
Fundamental equations:

$$\theta = -\arctan\left(\frac{a_x}{a_y}\right) \qquad \phi = -\arctan\left(\frac{a_y}{a_z}\right)$$

$$\psi = \arctan\left(\frac{Y_m}{X_m}\right)$$

$$X_m = m_x \cos(\theta) - m_y \sin(\phi)\sin(\theta) + m_z \cos(\phi)\sin(\phi)$$

$$Y_m = m_y \cos(\phi) + m_z \sin(\phi)$$



From IMU Specifications:

- Accelerometer error (a_x, a_y, a_z): **±4%**
  - Reduces to **±2.83% for 2 IMU's**
- Magnetometer error (m_x, m_y, m_z): **±8%**
  - Reduces to **±5.66% for 2 IMU's**

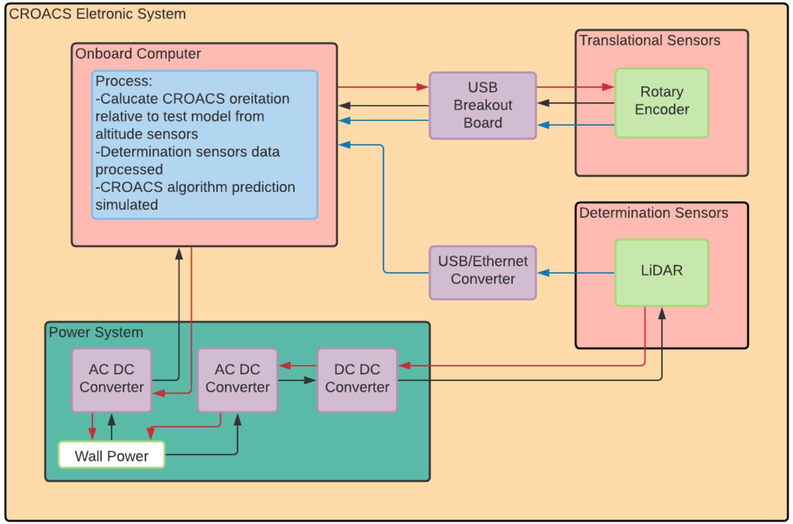
Using General Rule Error Propagation:

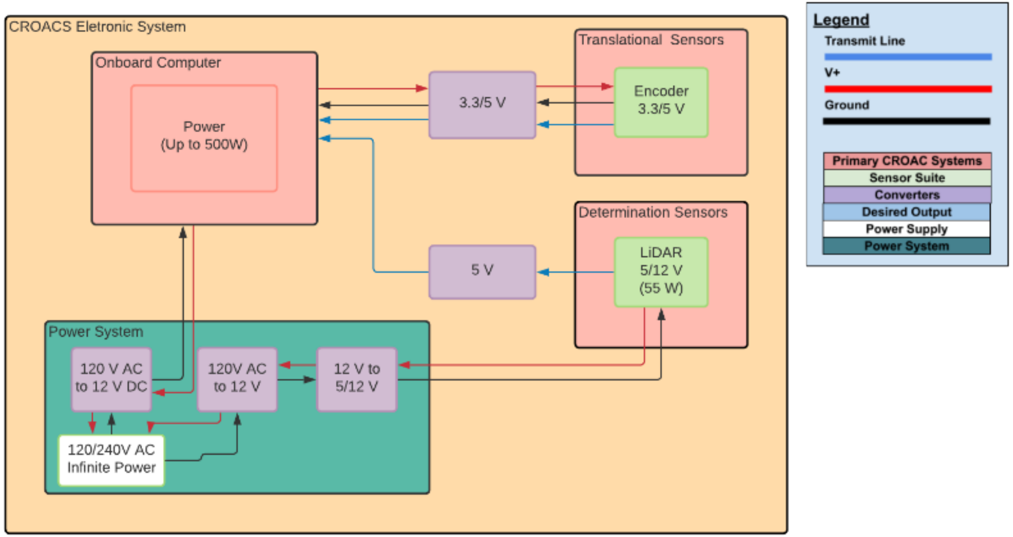
- $\delta_\theta = 0.013$
- $\delta_\Phi = 0.022$
- $\delta_\Psi = 0.029$

Truth Data Sensor System is feasible based on Euler angle error less than 3%

Electronics Feasibility: CROACS Electronics

CROACS Power Diagram

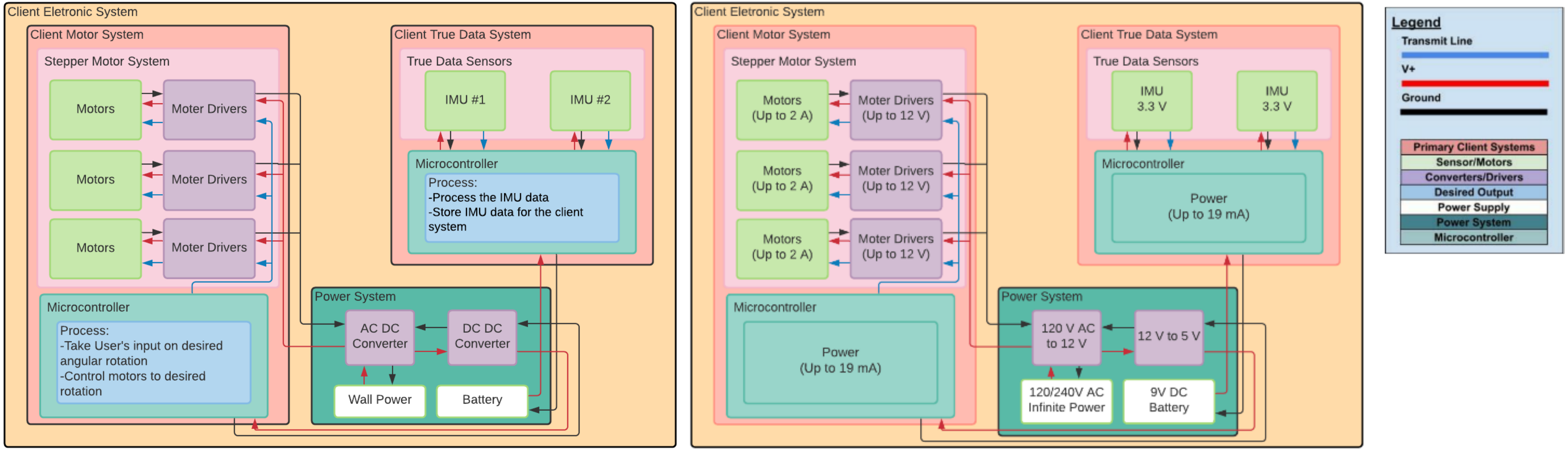




CROACS electronics are <u>power feasible</u> as the project is not power limited and wall power is accessible.

Electronics Feasibility: Client Electronics

Client Power Diagram



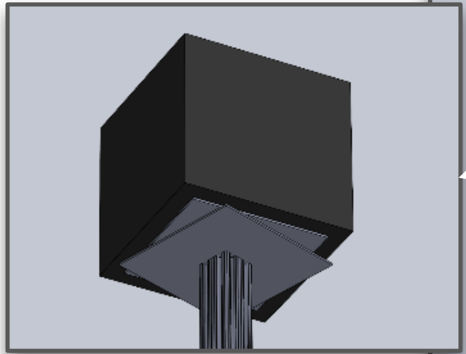
Client electronics are <u>power feasible</u> as the project is not power limited and wall power is accessible.

Design Feasibility - CROACS Hardware

The test bench shall have sufficient dimensions capable of enclosing the onboard computer and LIDAR sensor. The enclosure must be able to rotate and translate to perform testing.

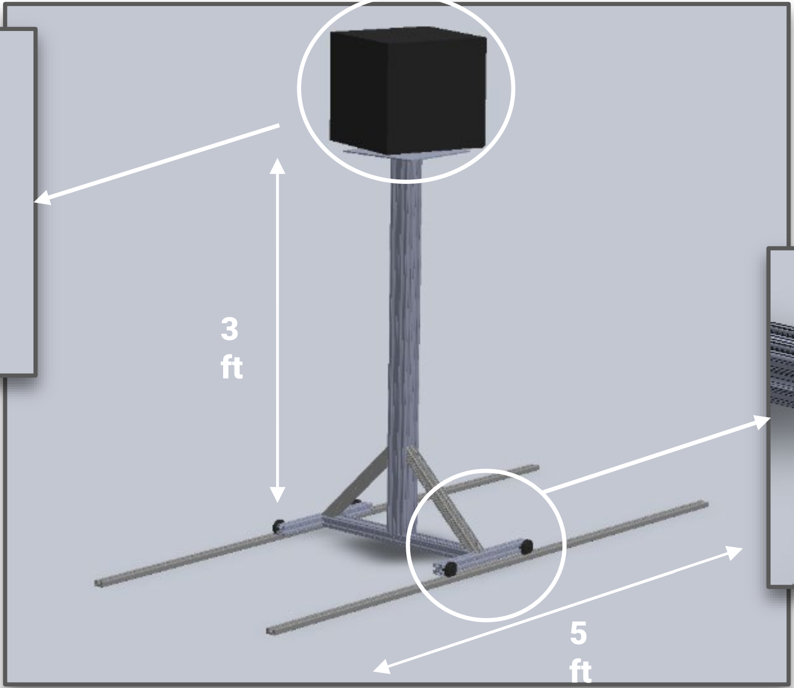
Hardware Feasibility: CROACS Hardware

Test Bench & Sensor Suite Housing



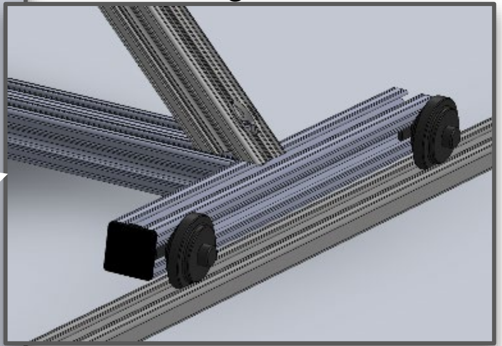
Swivelling Sensor Suite Housing

- Test Bench: 80/20 T-slot components
- Housing: ABS plastic & foam sheets



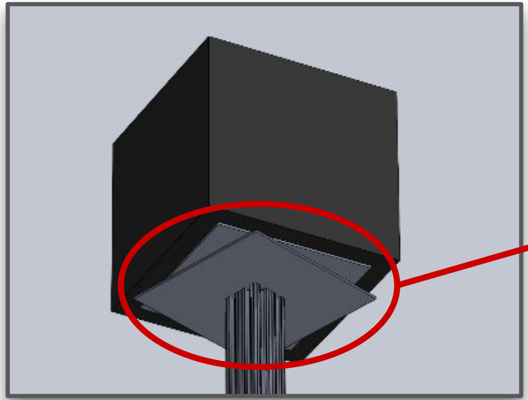
CROACS hardware <u>can feasibly</u> meet requirements to swivel and translate.

Translating Test Bench



Hardware Feasibility: CROACS Hardware

Swivel Structural Analysis



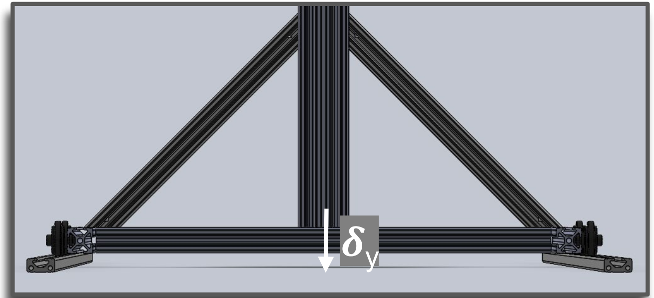
12-way seat swivel

- <u>Structural Feasibility:</u>
  - Intended support load ≈ 250 lb
  - Estimated weight of enclosure with electronics < *20 lb,* including:
    - Housing structure
    - Harnessing
    - Sensor suite
    - On-board processor
  - Required load 20 lb << max load 250 lb

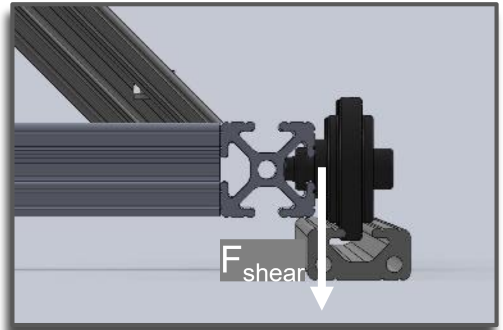
Hardware Feasibility: CROACS Hardware

Test Bench Structural Analysis

Vertical Deflection at Center of Cross Beam



Shear Strength of Wheel Axials



	80/20 T-Slot Profile	**Wheels**
Material:	Aluminum	Nylon PA Glass Fiber Reinforced
Grade:	6105-T5	K222-D
Yield Strength:	35 ksi / 241.32 MPa	7.98 ksi / 55 MPa
Young's Modulus:	10,200 ksi / 7.033 GPa	174 ksi / 1.20 GPa

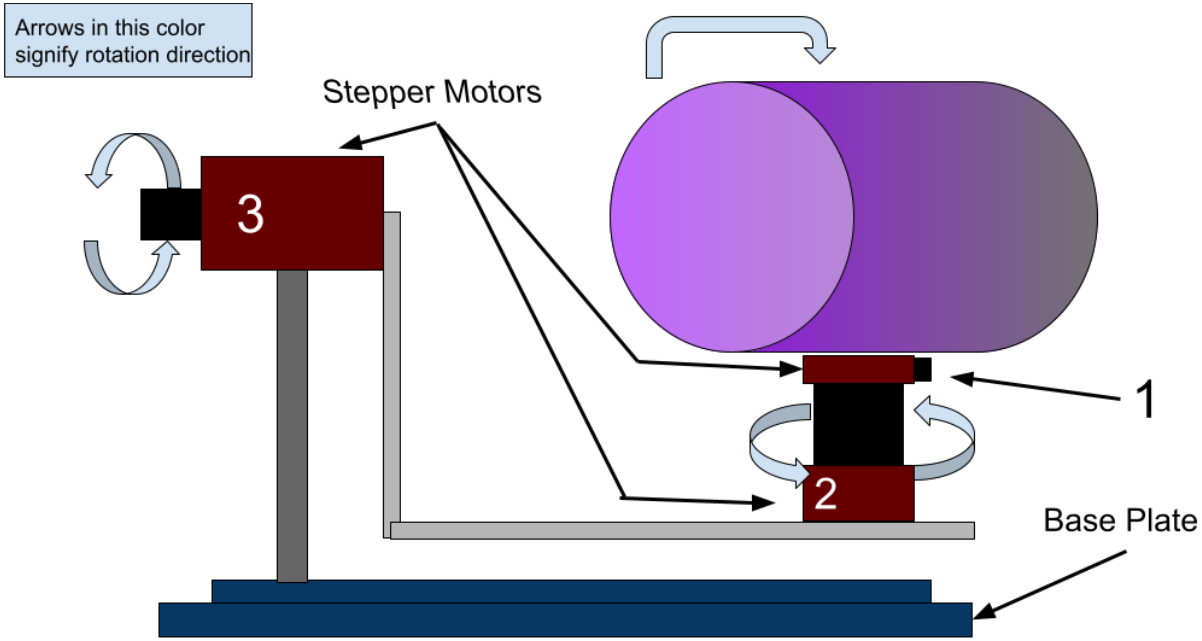
- Deflection Feasibility:
  - Estimated applied load *21.14 lb* w/ FOS
  - ***FOS = 1.5***
  - *Assumptions:* center point load, 2-fixed ends
  - δ_y = **0.0008 inches ≈ 0**
- Shear Strength Feasibility:
  - Tensile Strength = 7980 psi
  - Estimated Shear Strength = 4788 psi
  - Estimated applied load (w/ FOS)
    - *24.65 lb* total
    - *6.16 lb* per wheel
  - Cross-sectional Area of Axial = 0.0192 in^2
  - **Required Shear Strength = 320.9 psi << 4788 psi**

Design Feasibility - Client Hardware

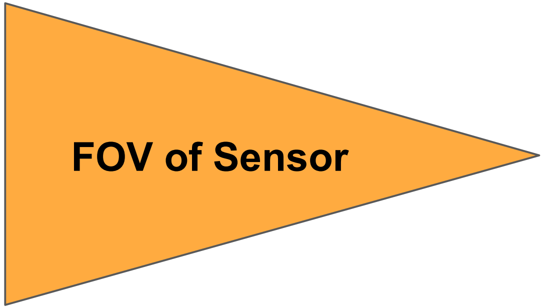
The client satellite model must be able rotate around 3 axes simultaneously without interfering with the CROACS sensing.

Hardware Feasibility: Client Hardware

Rotational Stand Lidar Interference Diagram



Sensor suite should have a clear, unobstructed view of client model during rotation.



Client stand is <u>LiDAR FOV feasible</u> based on current design and LiDAR masking techniques.

Hardware Feasibility: Client Hardware

Stepper Motor Torque Analysis

- Estimate torque experienced by Motor 3 to see if solution is feasible

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

$T = mgr = (2.35)(9.81)(0.1778)$
$T = 4.01 Nm$
$\mathbf{T = 4.0 Nm}$

Hardware Feasibility: Client Hardware

Stepper Motor Torque Analysis

- Expected torque, **T = 4.0Nm** becomes **T_s= 8.0Nm** (Factor of Safety = 2)
    - Numerous motors exist that have sufficient torque ratings
    - Many fall within desired price window (< $150)

Example:
Nema 34 CNC Stepper Motor
- 9 Nm torque rating
- Cost = $118
    - Via DHL

https://www.omc-stepperonline.com/s-series-nema-34-closed-loop-stepper-motor-9-nm-1274-76oz-in-encoder-1000cpr.html?search=Nema%2034%20closed%20loop

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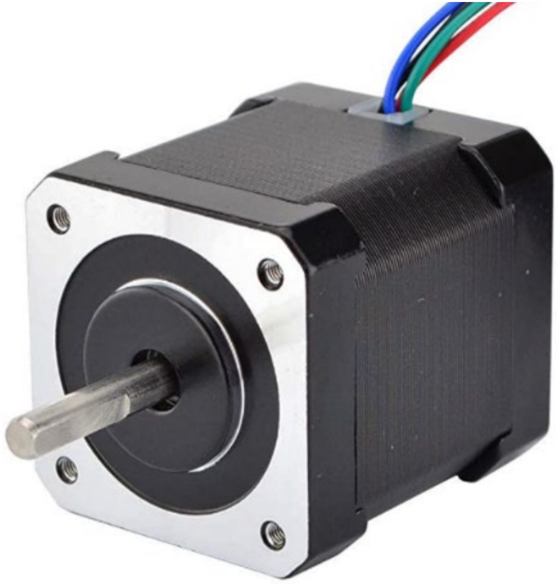
Hardware Feasibility: Client Hardware

Stepper Motor Torque Analysis - Motors 1 & 2

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



https://www.amazon.com/STEPPERONLINE-Stepper-Bipolar-Connector-compatible/dp/B00PNEQKC0/ref

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]**

Nema 17 Stepper Motor

- 59 [N cm]
  - Well over FOS = 2
- $13.99
  - Ships from U.S

Client hardware motors <u>are feasible</u> based on current client designs and motor options

Design Feasibility - Financial

Cost of all purchase should under $4800 after deducting $200 for tool kit damage deposit.

Finances

Hardware	Est. Cost
CROACS Hardware - Cost Breakdown of CROACS Hardware	$300 ± 50
Client Hardware - Cost Breakdown of Client Hardware	$300 ± 50
Total	**$600 ± 100**

Electrical	Est. Cost
Client Electronics - IMU x2 - Stepper Motors - Hardware Controller - Misc./Power	$500 ± 150
CROACS Electronics - LIDAR Sensor - Onboard Computer - Power System - Misc. Electrical	$2000 ± 600
Total	**$2500 ± 750**

Subsystem	Est. Cost
Hardware	$600 ± 100
Electrical	$2500 ± 750
Manufacturing Budget	$500
Total	**$3600** ± 850 (<$4800)
Leftover*	+ $350

CROACS project is financially feasible based on current designs and current market prices.

Est. Cost = Mean(Price Points) ± Est. Margin = (avg) ± σ

Total Est. Margin = $\sqrt{(\sigma_1)^2+(\sigma_2)^2+(\sigma_3)^2+\ldots}$

*Leftover: Buffer in budget accounting for max Est. Cost

Used for miscellaneous parts, damaged parts, expedited shipping fees...etc.

Feasibility Conclusions

CROACS

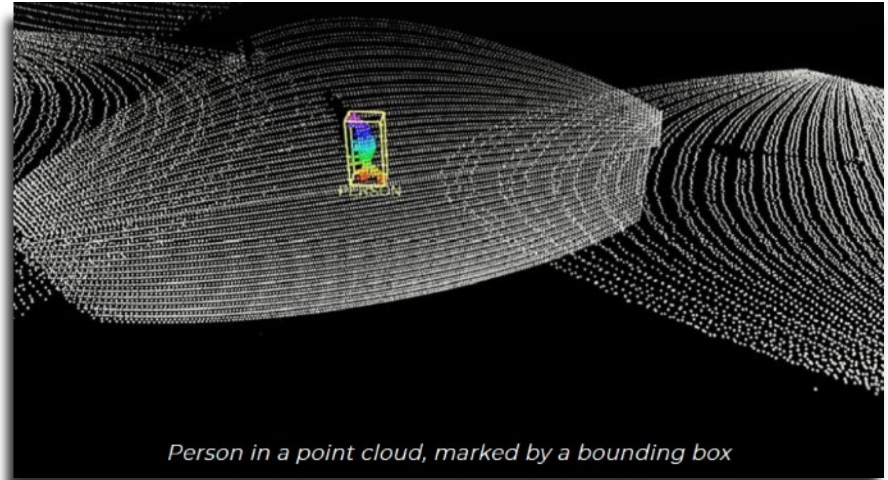
Feasibility Conclusions

System	CPE	Feasible	Reasoning
Software	**E4, E5**	**Yes***	Attitude can be found within accuracy requirements, need to implement method of determining object from background. Computational time is also a concern.
CROACS Electronics	**E1, E2**	**Yes***	LiDAR range accuracy is acceptable for attitude characterization. Onboard processor can handle data transfer rates but storage might affect processor choice or data acquisition time.
Client Electronics	**E3, E5**	**Yes**	Truth data sensors give measurements within acceptable limits.
CROACS Hardware	**E2**	**Yes**	CROACS hardware meets functional requirements (swivel and translation), also meets structural needs.
Client Hardware	**E3**	**Yes**	Custom rotational stand doesn't interfere with sensor line of sight, motors can feasibly torque weight of model.
Cost	**N/A**	**Yes**	Total cost of parts, accounting for alternate selections, manufacturing costs, and tool kit deposit, is below $4800.

Future Work

Future Work
Software

- **Object Detection** (Edge tracking, range masking, etc)
- Research and testing for **Iterative Closest Point** (ICP) method for angular velocity
- Research and testing for integration of position data to get **translational & angular velocity**
- Further research into template matching **Algorithm Optimization**



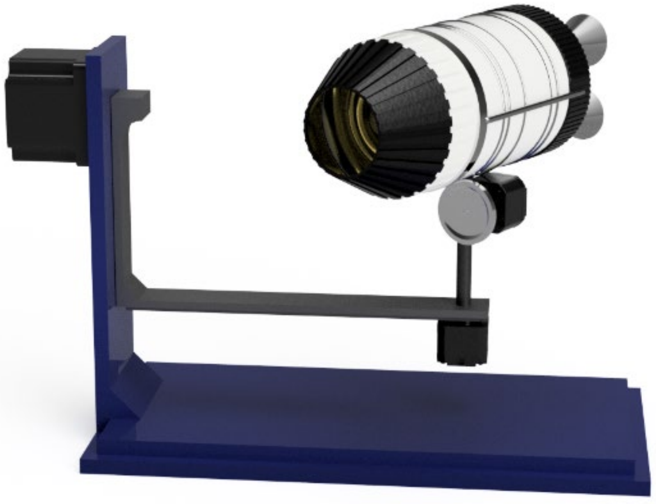
Object detection in LiDAR data [7]

Future Work
Electronics

- Down selecting **specific LiDAR sensor**
- Determining **specific onboard processor**
    - Further investigate **minimum hardware specifications** for reliable software execution.
- Interfacing between selected LiDAR sensor and on board processor
- **IMU selection**
- Selecting specific **power converters**

Future Work
Hardware

- CROACS Hardware
  - Determine electronics **enclosure dimensions**
  - Ensure **electronics compatibility**
  - Analyze **electronic thermal output** to determine required cooling
- Client Hardware
  - Ensure no **rotation stand LiDAR interference**
  - Integrate **electronic pathing** into design
  - Designing **motor interfacing**
    - Specifically **motor 1 with client model**



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Our Project Advisor:

Dr. Yu Takahashi

The Projects Advisory Board Members

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Questions?

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Backup Slides

Administrative/Financial

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The Team - *Team Organization*

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
- **CROACS Hardware** — Jake P.
  - Zack
  - Max
  - Tyler
- **Target Hardware** — Walter S.
  - Brandon
  - Max
  - Zack
  - Jake
  - Jianai
  - Tyler
- **Financial** — Jianai Z.
- **Safety** — Max M.
  - Zack
- **Manufacturing** — Zack H.
  - Walter
  - Tyler
  - Jainai

Critical Feasibility Statements

Category	Statement	CPE	Functional Requirement
Electronics	Sensors and other electronic hardware must have specifications capable of meeting accuracy requirements.	**E1,E3**	**FR1,FR3**
CROACS Hardware	The test bench shall have sufficient dimensions capable of enclosing the onboard computer and LIDAR sensor. The enclosure must be able to rotate and translate to perform testing.	**E2**	**FR4**
Client Hardware	The client satellite model must be able rotate around 3 axes simultaneously without interfering with the CROACS sensing.	**E3**	**FR5**
Software	The software must be capable of processing LIDAR data and calculating a known client satellite's relative position, velocity, attitude, and angular velocity.	**E4,E5**	**FR2**
Financial	Cost of all purchase should under $4800 after deducting $200 for tool kit damage deposit.	**E1,E2,E3**	**N/A**

Cost Breakdown of CROACS Hardware

Supplier	Description	Part Number	Cost		Quantity	Totals		Shipping
80/20	10 series one-sided beam	1050	$0.20	per inch	120	$24.00	$205.44	Website: https://8020.net/shipping-information. 40 days for shipping. $33.83 for current order
	10 series 45 degree 12" beam	2570	$18.24	per	2	$36.48		
	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	36	$24.84		
	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		
McMASTER-CARR	corner-reinforcing bracket	15705A34	$2	per bracket	6	$15	$29	
	corner bracket	15705A45	$0.77	per bracket	2	$1.54		
	10-24 screws	91772A374	$5.64	per 100 pack	1	$5.64		
	surface mount hinge	1488A11	$7.10	per hinge	1	$7.10		Normal shipping cost
Other (Amazon)	ABS Plasic Sheets	https://www.ama	$4.37	per 12"x12" sheet	3	$13.11	$64.72	
	Foam Sheets	https://www.ama	$14.92	per 10 pack of 9"x12" sheets	1	$14.92		
	swivel plate	Amazon.com: S	$36.69	per part	1	$36.69		Normal shipping cost
Miscellaneous	plywood, 3D printer components, clips, other mounting hardware, etc.	N/A	N/A	N/A	N/A	N/A	$25	
Estimated Total	$324.38							

Cost Breakdown of Client Hardware

	Description	Part Number	Cost		Quantity	Totals	
8020	0.25" Aluminum sheet	2455	$36.60	per sq.ft.	1.5	$54.90	$85.42
	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	
McMASTER-CARR	corner bracket	15705A45	$0.77	per bracket	2	$1.54	$7.18
	10-24 screws	91772A374	$5.64	per 100 pack	1	$5.64	
Other (Amazon)	ABS Plasic Sheets	https://www.ama	$4.37	per 12"x12" sheet	3	$13.11	$35.60
	Overature PLA		$14.99	per kg	1.5	$22.49	
Motors	0.59Nm Stepper Motor		$13.99	per unit	1	$13.99	
	1Nm Stepper Motor		$25.99	per unit	1	$25.99	
	7.07Nm Stepper Motor		$71.42	per unit	1	$71.42	$111.40
Estimated Total	$239.60						

Cost Breakdown of Onboard Processor

Processors:	Cost:	AC DC Converters:	Cost:	DC DC Converters:	Cost:	LiDAR:	Cost:	Encoders:	Cost:	Miscellaneous:	Cost:
Intel NUC 5	$519	Wagan EL9903 - 5 amp AC to DC Power Adapter, 5A Power Converter, Converts 110V AC to 12V DC	$29.99	Buck Converter 24v to 5v,	$10.49	Neuvition Titan S1	$1,399.00	SparkFun Qwiic Twist	$22.95	Wires	$10
MSI Cubi	$549.99	12V 5A Power Supply, Waysse Power Supply Adapter, AC DC Converter	$9.99	12V to 5V DC USB Buck Converter, DROK Dual USB Port Fast Charger	$12.99	Analog Devices AD-96TOF1-EBZ	$812.50	Cylewet 5Pcs KY-040 Rotary Encoder Module with 15×16.5 mm with Knob Cap for Arduino	$9.29		
HP EliteDesk	$396.74	ALITOVE DC 12V 5A Power Supply Adapter Converter Transformer AC 100-240V	$11.99	12v to 5v Converter - iGreely DC 12V 24V to 5V 10A Step Down Converter Adapter DC	$10.99	Cygbot 3D Dual Solid State ToF LiDAR	$170.00	Cylewet 5Pcs 360 Degree Rotary Encoder Code Switch Digital Potentiometer	$8.89		
Jetson TX2	$520	Chanzon UL Listed 12V 5A 60W AC DC Power Supply Adapter 2.1x5.5 2.5x5.5 Plug (Input 110V-220V,	$15.99	12v to 5v Volt Converter, DROK DC Voltage Regulator Board Power Supply Module	$12.59	Yujin YRL Series 3d LiDAR	$1,200.00	Signswise Incremental Optical Rotary Encoder for Arduino	$15.99		
HP TG01 i5	749.99$	2V 5A Power Supply, LeTaoXing AC 100-240V 50/60Hz to DC 12V 5A	$12.98	UCTRONICS DC 6V 9V 12V 24V to DC 5V 5A Buck Converter Module	$14.99	Terabee TeraRanger Evo 64px	$127.51	Taiss/Incremental Rotary Encoder DC 5-24v Wide Voltage Power Supply 6mm Shaft Optical	$20.99		
OptiPlex 3080 Micro	$689										
Statistics:											
Processor Mean	$571	AC DC Converter Mean	$16.19	DC DC Converter Mean	$12.41	LiDAR Mean	$741.80	Encoder Mean	$15.62	Miscellaneous Mean	$10
Processor Standard Deviation	128.1203456	AC DC Converter Standard Deviation	8.013489876	DC DC Converter Standard Deviation	1.783816134	LiDAR Standard Deviation	581.198119	Encoder Standard Deviation	6.481984264	Miscellaneous Standard Deviation	#DIV/0!

CROACS

Cost Breakdown of LiDAR Sensor

Neuvition Titan S1	https://www.neuvitio	See folder in drive	LIDAR-video fusion? Possibly proprietery software	$1,399.00	Waiting for email response		Yes	
Analog Devices AD-96TOF1-EBZ	https://www.analog.c	Found on main link	Open software (cross platform library), max range of 6m	$812.50	https://www.mouse	up to 13 weeks	Yes	
Leddar Pixell	https://leddartech.co	Found on main link	Used for autonomous driving applications, has strange interfacing & specs	Need to look at specific distributors	https://leddartech.	Can come from Canada, China, South Korea, Japan, or the UK	Maybe	
Velodyne HDL-32E	https://velodynelidar.	Found on main link	Used for drones, has 360deg FOV	Need to email	Need to email	Need to email	Need to email	
Velodyne Puck (VLP 16)	https://velodynelidar.	Found on main link	Used for drones, has 360deg FOV	Need to email	Need to email	Need to email	Need to email	
Velodyne Puck Hi-Res	https://velodynelidar.	Found on main link	Used for drones, has 360deg FOV	Need to email	Need to email	Need to email	Need to email	
Livox Horizon	https://www.livoxtech	Found on main link	Autonomous driving, 81.7°H ×25.1°V, **HAS POINT CLOUD DATA AVAILABLE**	$800.00	Need to email	Need to email	Need to email	Scanning Lidar, not scannerless
Livox Mid-70	https://www.livoxtech	Found on main link	70deg circular FOV, used for close range applications	$799.00	Need to email	Need to email	Need to email	Scanning Lidar, not scannerless
Cygbot 3D Dual Solid State ToF LiDAR	https://www.cygbot.c	https://fd6aa090-08e	Budget LiDAR, 120h 65v FOV	$170.00	https://www.sparkf	1-5 Business Days	Yes	
Yujin YRL Series 3d LiDAR	https://yujinrobot.cor	Found on main link	Used for robots, 270h 90v FOV	$1,200.00	https://www.robots		Yes	
Quanergy M8-Series Lidar	https://quanergy.com	See folder in drive	ToF lidar with 360H +- 20V FOV	Waiting for email response				https://on-demand.gputechconf.com/gtc/2016/presentation/s6726-louay-eldada-quanergy-systems.pdf
Headwall Photonics Sensors	https://www.headwa	Found on main link	I dont think they are applicable, pretty sure they are all scanning LIDAR. However they seem really unique (they can scan across a wide range of wavelengths?)					
Intel® RealSense™ LiDAR Camera L515	https://www.intelreal	Found on main link	Works like a camera, but does LIDAR? Separate LIDAR + camera system? Not sure how to classify this one, has 70H 55V FOV.	$589.00	https://store.intelre		Yes	Says its going to be discontinued in Feb 2022, and links a bunch of other options here: https://www.intelrealsense.com/message-to-customers/
Advanced Scientific Concepts LLC: GSFL-4K 3D Full Motion Video LIDAR	https://asc3d.com/gs	Found on main link	Solid State Flash/Pulsed LIDAR with 15 to 45deg scalable FOV	Waiting for email response				
Cepton Vista-P60	https://www.cepton.c	Waiting for email response	60H by 22V FOV with 10Hz frame rate	$4,000.00	Need to email	3-4 weeks	Yes	
Robosense RS-LiDAR-M1	https://www.roscomp	https://www.roscomp	Solid State LIDAR with 120H by 25V FOV	$5,434.28	https://www.roscor	Need to email	Yes	
Terabee TeraRanger Evo 64px	https://www.roscomp	https://www.roscomp	Only 64 pixels, 15deg (square?) FOV	$127.51	https://www.roscor	15 business days	Yes	
Opsys SP- Series LIDAR	https://www.opsys-te	Waiting for email res	Solid State LIDAR with 45-120H (custom) by 13V FOV	Waiting for email response				Scanning Lidar, not scannerless
Pandar LIDAR Sensors	https://www.hesaitec	See folder in drive	Found through matlab documentation, **HAS POINT CLOUD DATA AND OPEN SOURCE CODE**	Waiting for email response				Scanning Lidar, not scannerless
Ouster OS1	https://ouster.com/pr	See folder in drive						Scanning Lidar, not scannerless
Ouster ES2 Solid State	https://ouster.com/pr	See folder in drive						

CROACS

Cost Breakdown of Client Electronics

Component	Website	Cost (without tax	Link	Quantity
Stepper Motor (NEMA 17)	Amazon	$13.99	https://www.ama	1
Stepper Motor (NEMA 23) 1 Nm	StepperOnline	$25.99	https://www.omc	1
Stepper Motor (NEMA 23) 7.07 N	StepperOnline	$71.42	https://www.omc	1
A4988 Stepper Motor Driver	Amazon	$9.29	https://www.ama	1
EASON DM556	Amazon	$28.89	https://www.ama	2
Arduino UNO	Arduino	$23	https://store-usa	2
Nano 33 BLE	Arduino	$20.20	https://store-usa	1
IMU	Adafruit	$19.95	https://www.adaf	1
Battery	Mouser	$7	https://www.mou	1
Misc (Wires, solder, etc.)		$15		1
Total		**$286.57**		

Software

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Software - Computation Time

Angular Step	Attitude Estimate [3-2-1]	Total Attitude Error	Computation Time
30°	[-120°, 60°, 30°]	5.91%	~20 s
20°	[-140°, 50°, 0°]	4.58%	~75 s
10°	[-130°, 60°, 10°]	2.36%	~680 s

- Intel(R) Core(TM) i5-8350 CPU @ 1.7 GHZ, 1.9 GHz
- RAM: 16 GB

Software - Edge Detection

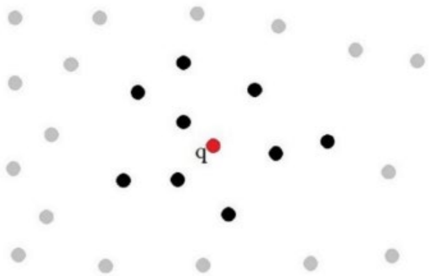


Figure: Nearest Neighbor

- Involves finding the nearest neighbors to each point
  - Euclidean Distance
- Finds the deviation of each point to its neighbors
- The points whose deviation passes a threshold are classified as “edge points”

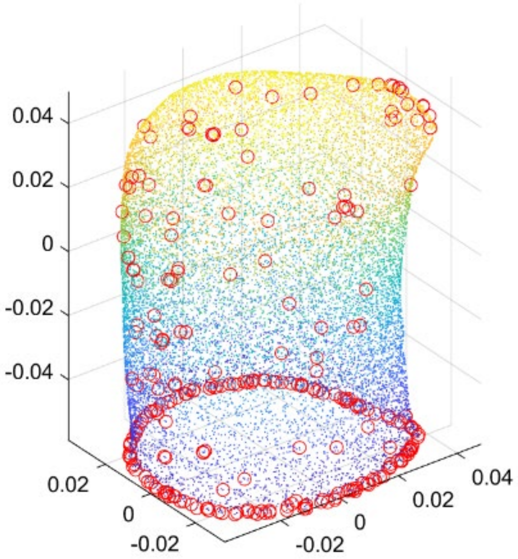


Figure: LiDAR Point Cloud with Edge Detection

Software - ICP Algorithm

1. Get an initial guess for the transformation and translation
2. Associate each point in the transformed point cloud with the nearest point in the original point cloud
3. Solve for the optimal transformation and translation
4. Repeat until convergence

Software - ICP Optimization

Step 1: Centroid Computation

$$\mu_s = \frac{1}{n}\sum_{j=1}^{n} \mathbf{P}_{\mathbf{s}}^{(\mathrm{j})} \qquad \mu_{s'} = \frac{1}{n}\sum_{j=1}^{n} \mathbf{P}_{\mathbf{s'}}^{(\mathrm{j})}$$

Step 2: Point Cloud Spread

$$\mathbf{W}_{s's} = \frac{1}{n}\sum_{j=1}^{n} (\mathbf{P}_s^{(j)} - \mu_s)(\mathbf{P}_{s'}^{(j)} - \mu_{s'})^T$$

Step 3: Singular Value Decomposition

$$\mathbf{W}_{s's} = \mathbf{USV}^T$$

$$\widehat{\mathbf{C}}_{s's} = \mathbf{U} \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & \det \mathbf{U} \det \mathbf{V} \end{bmatrix} \mathbf{V}^T$$

Step 4

$$\widehat{\mathbf{r}}_s^{s's} = \mu_s - \widehat{\mathbf{C}}_{s's}^T \mu_{s'}$$

Software - Programming Language

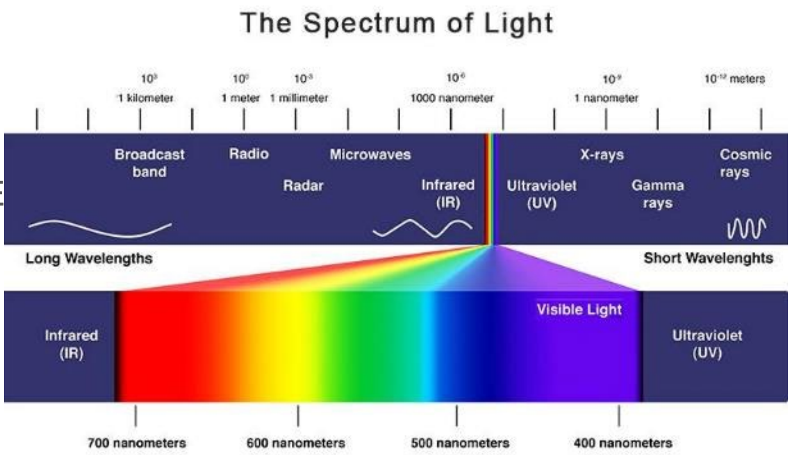
- MATLAB
  - Already known to our team
  - Robust signal processing toolbox
  - More efficient matrix algebra operations
  - Proprietary code
  - Portability Issues
  - Multi-threading
- Python
  - Object-based language
  - More versatile class and function definitions
  - Not as good documentation for python LiDAR processing libraries
  - Does not have true multi-threading capabilities, only multiprocessing
- Conclusion: MATLAB

Software - OS

- Windows
  - System instabilities due to oversimplified design
  - Higher resource usage
  - More user-friendly GUI
  - Limited Customization options
  - Widespread and well-known to team
- Linux
  - Deep-rooted emphasis on process management, system security, and uptime
  - Lighter resource usage
  - More versatile
  - Easier integration between software modules

Software - iPhone LiDAR

- Flash Illumination and No Scanning
  - Emission
    - Vertical Cavity Surface-Emitting Lasers (VCSE
  - Detector
    - Single Photon Avalanche Diode (SPAD)
  - Wavelength
    - 800-899 nm
  - Range
    - 5 m



References

1. Forbes
2. Ars Technica

Electronics

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Electronics - Sensor Suite

Background Information:

LIDAR Sensor	Points per Second (pps)	Range Accuracy
Neuvition Titan S1 [10]	230,000	± 3cm at 50m
Yujin YRL Series 3d LiDAR [11]	130,000	± 1cm at 20m
Analog Devices AD-96TOF1-EBZ [12]	300,000	± 6cm at 20m
Vista X90 [13]	1,000,000	± 2.5cm at 50m

Electronics - Onboard Processing

Background Information:

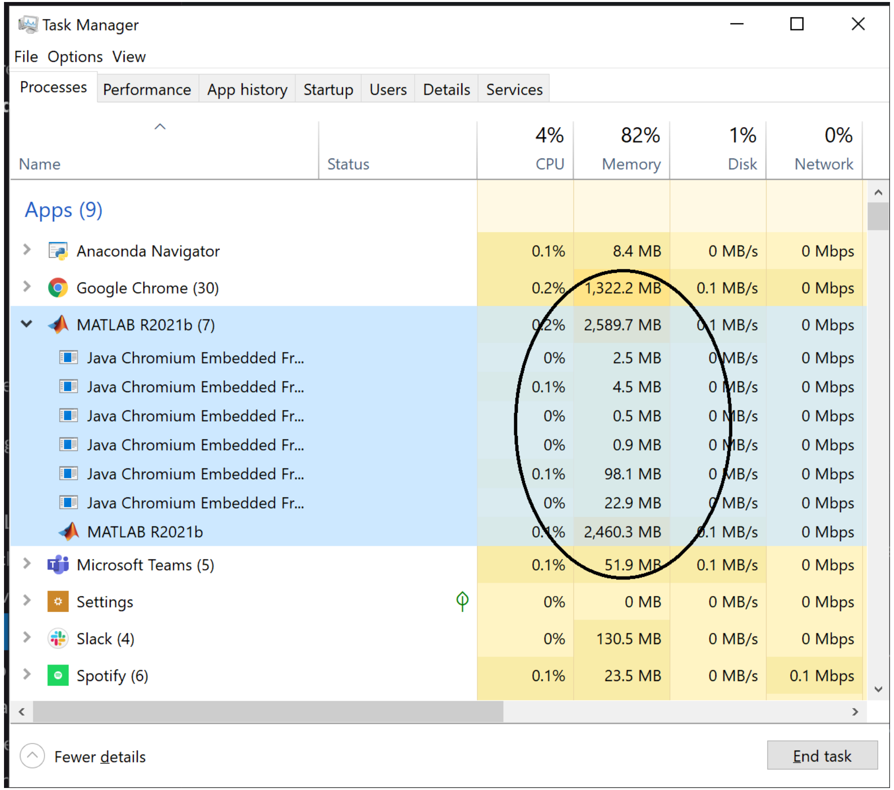
Processor	Storage (GB)	Read/Write Speed (GB/s)	RAM (GB)
MSI Cubi [17]	500	0.6	4
OptiPlex 3080 Micro [16]	128	3.5	8
Jetson TX2* [15]	32	5	8
Intel NUC [14]	64	0.6	16

*Optimized for AI and computer vision performance

Electronics Feasibility: CROACS Electronics Onboard Processing

With 16GB of RAM ⇒ Under 2 minutes processing for current algorithm

- Used 72% of total RAM



Name	Status	4% CPU	82% Memory	1% Disk	0% Network
Apps (9)					
Anaconda Navigator		0.1%	8.4 MB	0 MB/s	0 Mbps
Google Chrome (30)		0.2%	1,322.2 MB	0.1 MB/s	0 Mbps
MATLAB R2021b (7)		0.2%	2,589.7 MB	0.1 MB/s	0 Mbps
Java Chromium Embedded Fr...		0%	2.5 MB	0 MB/s	0 Mbps
Java Chromium Embedded Fr...		0.1%	4.5 MB	0 MB/s	0 Mbps
Java Chromium Embedded Fr...		0%	0.5 MB	0 MB/s	0 Mbps
Java Chromium Embedded Fr...		0%	0.9 MB	0 MB/s	0 Mbps
Java Chromium Embedded Fr...		0.1%	98.1 MB	0 MB/s	0 Mbps
Java Chromium Embedded Fr...		0%	22.9 MB	0 MB/s	0 Mbps
MATLAB R2021b		0.1%	2,460.3 MB	0.1 MB/s	0 Mbps
Microsoft Teams (5)		0.1%	51.9 MB	0.1 MB/s	0 Mbps
Settings		0%	0 MB	0 MB/s	0 Mbps
Slack (4)		0%	130.5 MB	0 MB/s	0 Mbps
Spotify (6)		0.1%	23.5 MB	0 MB/s	0.1 Mbps

Electronics - Truth Data Sensor System

GOAL - Truth data sensor system must be self-contained and fit inside the physical model.

Component	Size	Volume
Nano 33 BLE	45 mm x 18 mm x 5 mm	4050 mm^3
BNO055	27 mm x 20 mm x 3 mm	1620 mm^3
Battery	21 mm x 19 mm x 2 mm	798mm^3
TOTAL		**6468 mm^3**

Physical Model Dimensions - 1.6988 e6 mm^3

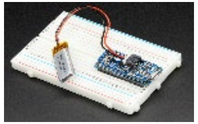
Micro Controller & IMU

Nano 33 BLE

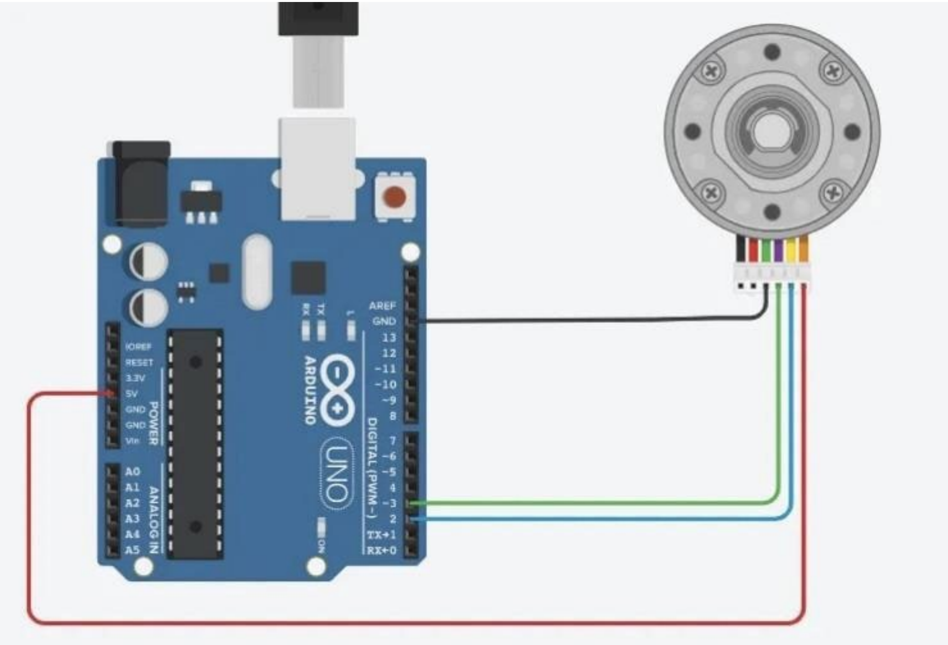
BNO055

Power

Fully Contained IMU Sensor System



Translation Truth Data

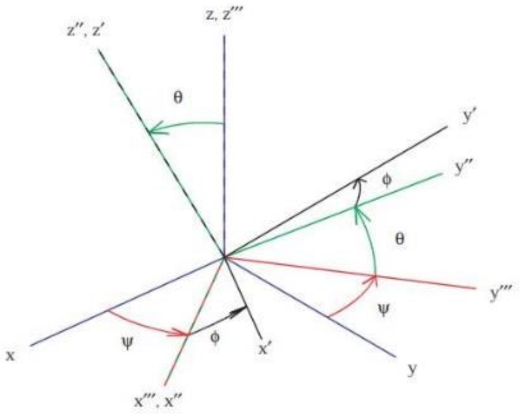


Motor encoders will be used on the axles of the wheels along with the known circumference of the wheels on the rail system to determine the true translation of the CROACS test bench

https://www.electroniclinic.com/arduino-dc-motor-speed-control-with-encoder-arduino-dc-motor-encoder/

Truth Data Transformation

To calculate X_m, Y_m and the Euler angles (ϕ, θ, Ψ) here when the IMU is not aligned with the physical model axes i.e. the body axes are not aligned with the inertial axes, the following equations can be used.



$$R_{313}(\phi,\theta,\psi) = R_3(\phi)R_1(\theta)R_3(\psi)$$
$$= \begin{pmatrix} cos(\phi)cos(\psi) - sin(\phi)cos(\theta)sin(\psi) & cos(\phi)sin(\psi) + sin(\phi)cos(\theta)cos(\psi) & sin(\phi)sin(\theta) \\ -sin(\phi)cos(\psi) - cos(\phi)cos(\theta)sin(\psi) & sin(\phi)sin(\psi) + cos(\phi)cos(\theta)cos(\psi) & cos(\phi)sin(\theta) \\ sin(\theta)sin(\psi) & -sin(\theta)cos(\psi) & cos(\theta) \end{pmatrix}$$

$$R_B = R_E^B R_E$$

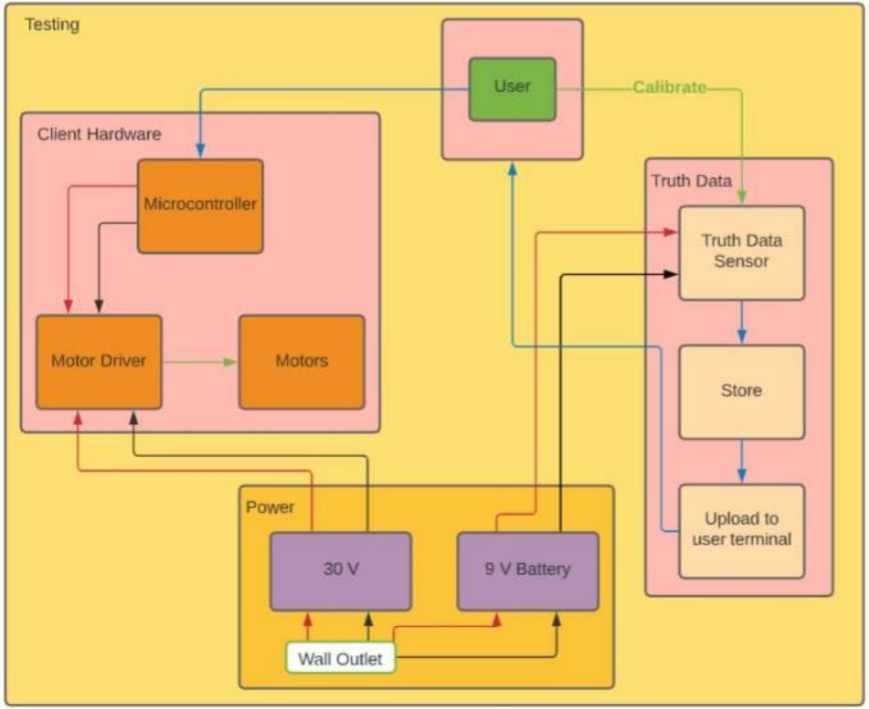
After converting the vector to the body frame, all the equations here can be applied.

Diebel, James (2006). Representing Attitude: Euler Angles, Unit Quaternions, and Rotation Vectors
https://www.astro.rug.nl/software/kapteyn-beta/_downloads/attitude.pdf

Electronics - Motor System - Power

GOAL - All the client hardware shall run off of the wall power outlets and the drivers should be able to drive the motors from commands given by the microcontroller.

Stepper Motor	Torque	Rated Current	Driver
NEMA 17	0.59 Nm	2.0 A	TB6600
NEMA 23 P Seri	1.0 Nm	5.5 A	EASON DM556
NEMA 34	4.5 Nm	5.5 A	EASON DM556
NEMA 34	7.07 Nm	2.12 - 4.24 A	EASON DM556



Electronics - Feasibility Analysis - Testing

Stepper Motor	Torque	Rated Current	Driver
NEMA 17	0.59 Nm	2.0 A	A4988
NEMA 23 P series	1 Nm	5.5 A	EASON DM556
NEMA 34	4.5 Nm	5.5 A	EASON DM556
NEMA 34	7.07 Nm	2.12 - 4.24 A	EASON DM556

Hardware

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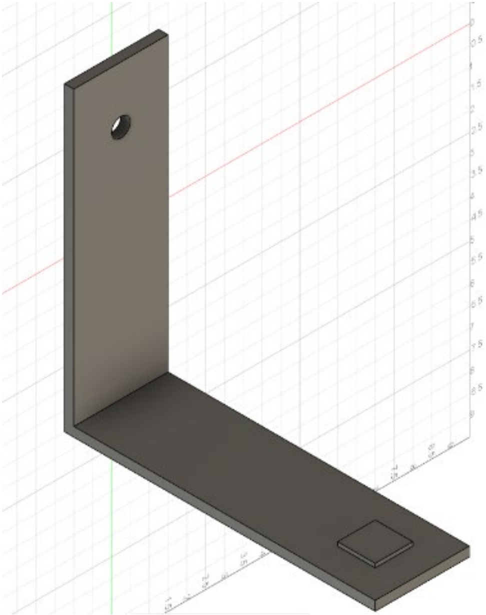
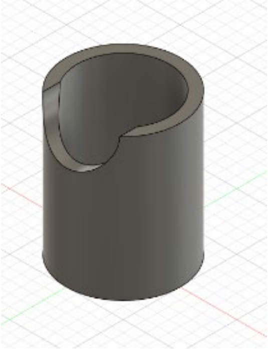
CROAACS Hardware Weight Estimates

Category	Component	Estimated Weight (lbs)		Totals w/o FOS	
8020 Hardware	1010	1.0176		Weight on Swivel:	**5.888**
	1020	1.324		Weight for Deflection Calculation:	**14.0948**
	2020	4.3128		Weight on Wheels:	**16.4364**
	4119	0.15			
	20-4113	0.15		**Totals w/ FOS**	
	2015	0.032		Weight on Swivel:	**8.832**
	2570	1.162		Weight for Deflection Calculation:	**21.1422**
Housing Structure	swivel	2.4		Weight on Wheels:	**24.6546**
	foam (660 in^2)	0.5			
	1/8" thick ABS plastic (500 in^2)	1.807			***FOS = 1.5***
	miscellaneous hardware	0.25			
Electronics	LiDAR sensor suite	1			
	on-board processor	1.8			
Other	plywood (10" x 10" x 1/4")	0.531			

Hardware Feasibility: Estimation of Support weight

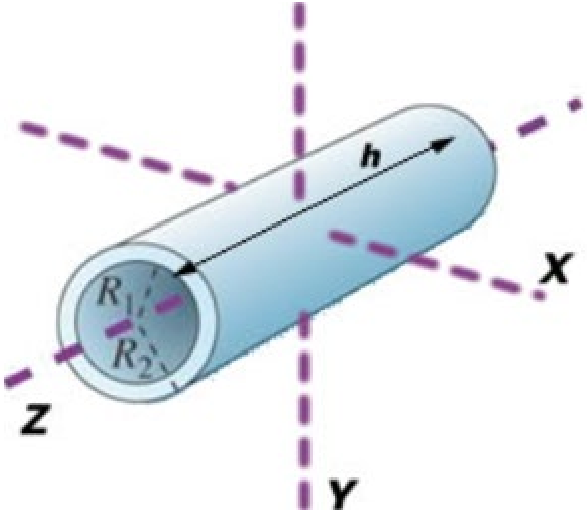
- Support components are likely to be made out of PLA
- Rough models were made using CAD
  - Mass was taken from properties list
- Expected of combined PLA support is approx. 0.25kg





Hardware Feasibility: 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	$I_z = (m/2) * (R_1^2+R_2^2)$



$m = 1.7385$ [kg]; $R_1 = 6$ [in] = .1524 [m];

$R_2 = 5$ [in] = 0.127 [m];

$h = 12$ [in] = 0.3048 [m]

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

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

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