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.
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

CROACS
Project CONOPS

1. Client Model Begins Rotating: Simulating Debris
2. Servicer Translates on Rails: Simulating Relative Motion
3. Servicer LiDAR Sensor Collects and Transmits Data to Onboard Computer
4. Computer Attempts to Calculate Current and Future Attitude States
5. Client Sensor's Relay Truth Data for Accuracy Comparison

Client System
Client Model of Debris Object
Tumble Simulation Mechanism

Servicer System
Electronics Enclosure
Test Stand
Rails

Close Range Orbital Attitude Characterization System
Design Solution
Design Progress: **PDR → CDR**

**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, Truth data collection redesign, Wheel encoder for servicer position
- **Client:** Motor selection, Materials and final part designs, BLE components for wireless comms
- **Servicer:** Simplified test stand design
- **Client:** Motor integration design, Electronics integration design
- **Servicer:** Material and part design
- **Client:** Higher fidelity booster model

**Software**
- **Servicer:** Decreased template matching time
- **Client:** Motion characterization
- **Servicer:** Prediction modules
- **Client:** Established servicer environment
Servicer Hardware

Overview
Design Solution
CPEs
Reqs. Satisfaction
Project Risks
V&V
Project Planning
Backup

Dimensions: 15" x 10.5" x 11"

Back View
Top View
Front View
Side View

LiDAR Sensor
ATX Motherboard
Cooling Fans
I/O Panel
Power Supply
Cooling Vent
Test Stand Integration

- Enclosure
- Swivel
- Encoder
- ~4ft tall
- 5ft rails

Overview, Design Solution, CPEs, Reqs. Satisfaction, Project Risks, V&V, Project Planning, Backup
Servicer Electrical Design

CROACS Electronics System

Overview Design Solution CPEs Reqs. Satisfaction Project Risks V&V Project Planning Backup

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)

Motor 1 System
- IMU
- Encoder
- Nicla Sense ME
- UNO
- Servo 1

Motor 2 System
- UNO
- Servo 2
- Encoder

Motor 3 System
- Driver
- UNO
- Stepper
- Encoder

Components:
- Arduino UNO WiFi Rev 2
- Nicla Sense ME
- Portenta H7
- JX Servo (1)
- Mophorn NEMA 34 Stepper and driver (3)
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

<table>
<thead>
<tr>
<th>CPE</th>
<th>Description</th>
<th>FR</th>
</tr>
</thead>
</table>
| **[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
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
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

<table>
<thead>
<tr>
<th>Motor</th>
<th>Torque Requirements For 10 deg/sec</th>
<th>Selected Motor Torque Rating</th>
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<tbody>
<tr>
<td>1 (Servo)</td>
<td>≈ 1 [N cm]</td>
<td>20 [kg cm] or 1.96[N m]</td>
</tr>
<tr>
<td>2 (Servo)</td>
<td>≈ 1 [N cm]</td>
<td>35 [kg cm] or 2.94[N m]</td>
</tr>
<tr>
<td>3 (Stepper Motor)</td>
<td>8 [N m]</td>
<td>9 [N m]</td>
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<table>
<thead>
<tr>
<th>Design Requirement</th>
<th>Satisfaction</th>
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<tbody>
<tr>
<td>DR 5.1, 5.2</td>
<td>Yes</td>
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</table>
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

<table>
<thead>
<tr>
<th>Design Requirement</th>
<th>Satisfaction</th>
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<tbody>
<tr>
<td>DR 1.1, 1.3</td>
<td>Yes</td>
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</table>
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

<table>
<thead>
<tr>
<th>Design Requirement</th>
<th>Satisfaction</th>
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<tr>
<td>DR 3.3</td>
<td>Yes</td>
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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**

<table>
<thead>
<tr>
<th>Design Requirement</th>
<th>Satisfaction</th>
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<tbody>
<tr>
<td>DR 2.1</td>
<td>Yes</td>
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</table>
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 1 min 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

<table>
<thead>
<tr>
<th>Design Requirement</th>
<th>Satisfaction</th>
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<tbody>
<tr>
<td>DR 2.2, DR 2.2.1</td>
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\[
\phi \text{ vs Time}
\]

\[
\text{Time [s]}
\]
Project Risks
<table>
<thead>
<tr>
<th>Risk Number</th>
<th>Description</th>
<th>Effect</th>
<th>Likelihood of Occurrence</th>
<th>Severity of Consequence</th>
<th>Risk Priority Number (RPN)</th>
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<tbody>
<tr>
<td>R1</td>
<td>Excessive software runtime</td>
<td>Predictions become useless</td>
<td>4</td>
<td>5</td>
<td>20</td>
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<tr>
<td>R2</td>
<td>Feature detection can't distinguish unique elements about radial symmetry of client</td>
<td>Failure to determine attitude state</td>
<td>4</td>
<td>5</td>
<td>20</td>
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<tr>
<td>R3</td>
<td>LIDAR data is too noisy to provide necessary detail at far range (3m+)</td>
<td>Unusable point cloud data</td>
<td>3</td>
<td>5</td>
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<td>R4</td>
<td>Motors don't provide sufficient torque to rotate body about their respective axes at low speeds</td>
<td>Failure of client rotation about one or more axes</td>
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<td>4</td>
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<td>R5</td>
<td>Magnetic effects from spinning motors skews truth data measurements</td>
<td>Failure to provide accurate truth data</td>
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<td>3</td>
<td>9</td>
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<tr>
<td>R6</td>
<td>Interfacing failure between client measurement sensors</td>
<td>Failure to provide truth data</td>
<td>2</td>
<td>4</td>
<td>8</td>
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<td>R7</td>
<td>Budget exceeds $5000</td>
<td>Failure to continue production</td>
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</table>
### Initial Risk Matrix

| 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

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<td>1</td>
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#### Likelihood of Occurrence

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<th>4</th>
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## Mitigated Risk Table

<table>
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<tr>
<th>Severity of Consequence</th>
<th>Acceptable</th>
<th>Tolerable</th>
<th>Unacceptable</th>
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<tbody>
<tr>
<td></td>
<td>1</td>
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<td>3</td>
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</tbody>
</table>

### 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

<table>
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<th>Likelihood of Occurrence</th>
<th>5</th>
<th>4</th>
<th>3</th>
<th>2</th>
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<tr>
<td><strong>R1:</strong> Software runtime</td>
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<td><strong>R2:</strong> Radial symmetry</td>
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<td><strong>R3:</strong> Detail at range</td>
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<tr>
<td><strong>R4:</strong> Motor Torque</td>
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<tr>
<td><strong>R5:</strong> Magnetic effects</td>
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<tr>
<td><strong>R6:</strong> Truth sensor interfacing</td>
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<tr>
<td><strong>R7:</strong> Budget</td>
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**Overview** | **Design Solution** | **CPEs** | **Reqs. Satisfaction** | **Project Risks** | **V&V** | **Project Planning** | **Backup**
---|---|---|---|---|---|---|---
29
Verification and Validation
Testing Structure

- Full System Testing
  - System Testing
    - Subsystem Testing
      - Single Component Testing

Client + Servicer

Client
- Hardware
  - A
  - B
  - C
  - D
  - E
  - F

Servicer
- Hardware
  - A
  - B
  - C
  - D
  - E
  - F

- Electrical
- Software
Component Verification
Servicer LiDAR Sensor

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

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.
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

**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

---

**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 future.
Comprehensive System Verification
Servicer System

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

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.
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

- **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

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.
Comprehensive System Verification
Client System

● 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

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
Project Timeline - Looking Forward

Today: CDR Presentation

Winter Break

Manufacturing Margin (2 Weeks)

Testing Margin TBD (1-2 Weeks)
Manufacturing Timeline

- Critical Process Path
Testing Timeline

- Final 3 weeks for full system day in the life testing.
# Testing Logistics

<table>
<thead>
<tr>
<th>Test Name</th>
<th>Starting Date *</th>
<th>Ending Date *</th>
<th>Location</th>
<th>Location Feasibility</th>
<th>Safety Concerns</th>
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<tbody>
<tr>
<td>Component Testing</td>
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</tr>
<tr>
<td>Encoders</td>
<td>1/26/2022</td>
<td>1/26/2022</td>
<td>Aero N200</td>
<td>✓</td>
<td>- Electrical Fires</td>
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<tr>
<td>Client Motors</td>
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<td>1/25/2022</td>
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<td>- High Voltage / Current Steppers and Moving Parts</td>
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<tr>
<td>Arduinos</td>
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<td>1/28/2022</td>
<td>Aero N200</td>
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<td>Servicer Stand</td>
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<td>1/20/2022</td>
<td>Aero N200</td>
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<td>Manufacturing Tools</td>
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<tr>
<td>Subsystem Testing</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Client Hardware</td>
<td>2/7/2022</td>
<td>2/26/2022</td>
<td>Aero N200 / Machine Shop</td>
<td>✓</td>
<td>Moving Parts / Weight Testing</td>
</tr>
<tr>
<td>Client Electronics</td>
<td>2/7/2022</td>
<td>2/26/2022</td>
<td>Aero N200 / Aspen Lab</td>
<td>✓</td>
<td>High Wattage Components, ESD, Fire</td>
</tr>
<tr>
<td>Servicer Hardware</td>
<td>2/7/2022</td>
<td>2/26/2022</td>
<td>Aero N200</td>
<td>✓</td>
<td>Large Moving Structure</td>
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<tr>
<td>Servicer Electronics</td>
<td>2/7/2022</td>
<td>2/26/2022</td>
<td>Aero N200</td>
<td>✓</td>
<td>Wall Powered Parts, ESD, Fire</td>
</tr>
<tr>
<td>Servicer Software</td>
<td>1/1/2022</td>
<td>2/14/2022</td>
<td>Aero N200</td>
<td>✓</td>
<td>Too much screen time, Eyeballs need breaks :)</td>
</tr>
<tr>
<td>Client Software</td>
<td>1/26/2022</td>
<td>1/30/2022</td>
<td>Aero N200 / Other</td>
<td>✓</td>
<td>Too much screen time, Eyeballs need breaks :)</td>
</tr>
<tr>
<td>Comprehensive Testing</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Client System Testing</td>
<td>2/28/2022</td>
<td>3/13/2022</td>
<td>Aero N200 / Planetarium</td>
<td>✓</td>
<td>All of the above</td>
</tr>
<tr>
<td>Servicer System Testing</td>
<td>2/28/2022</td>
<td>3/13/2022</td>
<td>Aero N200</td>
<td>✓</td>
<td>All of the above</td>
</tr>
<tr>
<td>Full Day In the Life Testing</td>
<td>3/14/2022</td>
<td>4/3/2022</td>
<td>Aero N200 / Planetarium / Other</td>
<td>✓</td>
<td>All of the above</td>
</tr>
</tbody>
</table>

*Predicted Dates - Subject to Change*
**Heavily discounted LiDAR: significantly decreased our overall cost.**

### Cost Plan

#### Hardware

<table>
<thead>
<tr>
<th>Service Hardware</th>
<th>Est. Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>$274.18</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Client Hardware</th>
<th>Cost Breakdown of Client Hardware</th>
</tr>
</thead>
<tbody>
<tr>
<td>$546.91</td>
<td></td>
</tr>
</tbody>
</table>

**Total** $821.69

#### Subsystem

<table>
<thead>
<tr>
<th></th>
<th>Est. Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hardware</td>
<td>$821.69</td>
</tr>
<tr>
<td>Electrical</td>
<td>$1815.74</td>
</tr>
</tbody>
</table>

**Total** $2637.43

**Leftover** + $2162.57

#### Electrical

<table>
<thead>
<tr>
<th>Client Electronics</th>
<th>Cost Breakdown of Client Electronics</th>
</tr>
</thead>
<tbody>
<tr>
<td>$705</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Servicer Electronics</th>
<th>Cost Breakdown of Servicer Electronics</th>
</tr>
</thead>
<tbody>
<tr>
<td>$1110.74</td>
<td></td>
</tr>
</tbody>
</table>

**Total** $1815.74

**Expenses Percentage**

- Servicer Hardware
- Client Hardware
- Client Electronics
- Servicer Electronics
- Leftover

---

*Ann and H.J. Smead Aerospace Engineering Sciences*

**CROACS**
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


Servicer Software - Backup
Servicer Software - Template Matching

**Off-Line**
- **Template Database**
  - Parameters
    - Roll, pitch, and yaw ranges
    - Angular step size
  - 3D point cloud model of client
- **Template Database**
  - $N$ sets of point cloud templates

**On-Line**
- Sensor point cloud acquisition
- Centroid Computation
- Relative position solution
- Evaluate corresponding points via a correlation function
  - Overlap point cloud centroids
- $N$ sets of correlation values
  - Find the minimum correlation value
  - Relative attitude solution
Improved Computation Time

**TEST CASE**  
\( \Omega = [-132^\circ, 56^\circ, 8^\circ] \)

<table>
<thead>
<tr>
<th>Angular Step</th>
<th>Comp Time @ PDR</th>
<th>Comp Time @ CDR</th>
</tr>
</thead>
<tbody>
<tr>
<td>30°</td>
<td>~20 s</td>
<td>~1 s</td>
</tr>
<tr>
<td>20°</td>
<td>~75 s</td>
<td>~4 s</td>
</tr>
<tr>
<td>10°</td>
<td>~680 s</td>
<td>~28 s</td>
</tr>
</tbody>
</table>

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

<table>
<thead>
<tr>
<th>Angular Velocity (Truth)</th>
<th>ICP</th>
<th>Absolute Orientation</th>
</tr>
</thead>
<tbody>
<tr>
<td>[1, 1, 1]</td>
<td>[0.983, 1.017, 0.983]</td>
<td>[1, 1, 1]</td>
</tr>
<tr>
<td>[10, 10, 10]</td>
<td>[9.537, 10.166, 0.948]</td>
<td>[10, 10, 10]</td>
</tr>
<tr>
<td>[9.16, -2.34, 3.75]</td>
<td>[8.856, -2.103, 1.107]</td>
<td>[9.16, -2.34, 3.75]</td>
</tr>
</tbody>
</table>
Servicer Software - ICP / Absolute Orientation

Results - Test #2

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

<table>
<thead>
<tr>
<th>Angular Velocity (Truth)</th>
<th>ICP</th>
<th>Absolute Orientation</th>
</tr>
</thead>
<tbody>
<tr>
<td>[1, 1, 1]</td>
<td>[0.983, 1.017, 0.983]</td>
<td>[1, 1, 1]</td>
</tr>
<tr>
<td>[10, 10, 10]</td>
<td>[11.066, 9.382, -4.748]</td>
<td>[10, 10, 10]</td>
</tr>
<tr>
<td>[9.16, -2.34, 3.75]</td>
<td>[9.297, -1.708, 4.076]</td>
<td>[9.16, -2.34, 3.75]</td>
</tr>
</tbody>
</table>
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**: -20°C to 85°C
- **940nm VCSEL with 110° x 85° batwing profile diffuser**
- **Receive lens**: FoV 90° x 69.2° 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

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

**Magnetic Encoders**

- **AS5600**
  - 12-bits
  - Analog/PWM/I^2^C 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

- Battery Power
- Arduino Nano
- Encoder

Wired to motherboard for data collection
Servicer Hardware -

Motherboard Mount Adapter
Client Electronics - Backup
Client Electronics - Power Budget

<table>
<thead>
<tr>
<th>Subsystem</th>
<th>Components</th>
<th>Required Input Current</th>
<th>Notes</th>
<th>Data Sheet</th>
<th>Total Current</th>
<th>Battery</th>
<th>Operational Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>IMU System</td>
<td>Nicola Microcontroller</td>
<td>250mA</td>
<td>Likey much higher estimate than will actually be drawn during operation</td>
<td>ABX00050-data</td>
<td>250mA</td>
<td>Li-poly - 500mAh</td>
<td>~2hrs</td>
</tr>
<tr>
<td></td>
<td>IMU</td>
<td>N/A</td>
<td>On Nicola MC</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Motor 1 System</td>
<td>Arduino Uno MC</td>
<td>160mA</td>
<td>40mA per I/O pins used. 2 for servo, 2 for encoder.</td>
<td>UNO_wifi (mous)</td>
<td>166.5mA + 221.61mA</td>
<td>9V - 600mAh</td>
<td>~1.55hrs (min)</td>
</tr>
<tr>
<td></td>
<td>Magnetic Encoder</td>
<td>6.5mA</td>
<td>Under normal operating conditions. Also has low power mode options</td>
<td>AS5600 (mous)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Servo 1</td>
<td>221.6mA</td>
<td>Estimated max based on stall torque and rpm rating at 6V</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Motor 2 System</td>
<td>Arduino Uno MC</td>
<td>280mA</td>
<td>40mA per I/O pins used. 2 for servo, 6 for encoder.</td>
<td>UNO_wifi (mous)</td>
<td>368mA + 390mA</td>
<td>9V - 600mAh</td>
<td>~0.79hrs (min)</td>
</tr>
<tr>
<td></td>
<td>ATM Encoder</td>
<td>86mA</td>
<td>16mA for operation. 15mA per single channel (x3). 25mA per differential channel (x1)</td>
<td>AMT13-V Kit Da</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Servo 2</td>
<td>180mA</td>
<td>stall current (maximum value)</td>
<td><a href="https://www.feet6.com">https://www.feet6.com</a></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>390mA</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
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 Nicola 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 Nicola 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^2^C 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
L Arm Stress Analysis

Max Reaction Force = 142.2 N

Maximum Displacement = 0.86 mm
Max Stress = 32 MPa

Maximum Displacement = 0.86mm

L Arm Stress Analysis
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)
Estimate torque experienced by Motor 3

**Mass Estimation:** Items rotated by Motor 3

<table>
<thead>
<tr>
<th>Object</th>
<th>Expected Mass [kg]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1/82 Scale Saturn V Second Stage</td>
<td>1.74</td>
</tr>
<tr>
<td>Motor 1</td>
<td>0.13</td>
</tr>
<tr>
<td>Motor 2</td>
<td>0.23</td>
</tr>
<tr>
<td>Extra PLA (supports and connections)</td>
<td>0.25</td>
</tr>
<tr>
<td><strong>Total Mass</strong></td>
<td><strong>2.35</strong></td>
</tr>
</tbody>
</table>

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

**Torque Calculation:**

\[ T = mg \cdot r \]

\[ T = (2.35)(9.81)(0.1778) \]

\[ T = 4.01 \text{Nm} \]

\[ T = 4.0 \text{Nm} \]

FOS of 2 was used: \[ T = 8.0 \text{Nm} \]
Motors 1 and 2 Torque Estimates

\[ \alpha = 0.1745 \text{ [rad/sec}^2] \]

<table>
<thead>
<tr>
<th>Expected Moment:</th>
<th>( I_Y = 0.0306 \text{ [kg m}^2] )</th>
<th>( I_z = 0.034 \text{ [kg m}^2] )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Required Torque:</td>
<td>( T_2 = 0.5 \text{ [N cm]} )</td>
<td>( T_1 = 0.6 \text{ [N cm]} )</td>
</tr>
</tbody>
</table>

Torque Estimation (Motors 1&2)

\[
\begin{align*}
I_Y &= \frac{m}{12} \times (3(R_2^2 + R_1^2) + h^2) \\
I_z &= \frac{m}{2} \times (R_1^2 + R_2^2)
\end{align*}
\]

\[
\begin{align*}
m &= 1.7385 \text{ [kg]}; & R_1 &= 6 \text{ [in]} = 0.1524 \text{ [m]}; & R_2 &= 5 \text{ [in]} = 0.127 \text{ [m]}; \\
h &= 12 \text{ [in]} = 0.3048 \text{ [m]} \\
W &= 2(10 \text{ [deg/sec]}) = 0.349 \text{ [rad/sec]}; & t &= 2 \text{ [sec]} \\
\alpha &= \Delta w/ t; & T &= I\alpha
\end{align*}
\]
Project Planning - Cost Analysis
## Client Electronics - Component Costs

<table>
<thead>
<tr>
<th>Component</th>
<th>Website</th>
<th>Cost (without tax)</th>
<th>Link</th>
<th>Quantity</th>
<th>Datasheet</th>
<th>Location</th>
<th>Purpose</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Servo 1</td>
<td>Amazon</td>
<td>$20.00</td>
<td>IX Serve</td>
<td>1</td>
<td>Inside Model</td>
<td>Modal - Roll</td>
<td>Measure motor rotation</td>
<td></td>
</tr>
<tr>
<td>Servo 2</td>
<td>Amazon</td>
<td>$30.00</td>
<td>FEETECH</td>
<td>1</td>
<td>Outside Model</td>
<td>Modal - Yaw</td>
<td>Measure motor rotation</td>
<td></td>
</tr>
<tr>
<td>AS5600</td>
<td>eBay</td>
<td>$5.00</td>
<td>AS5600</td>
<td>2</td>
<td>On Servo 1 and 2</td>
<td>Outside Model</td>
<td>Stepper and Driver</td>
<td></td>
</tr>
<tr>
<td>Motor 3 and Driver</td>
<td>Amazon</td>
<td>$170</td>
<td>NEMA 34_Driver</td>
<td>1</td>
<td>Outside Model</td>
<td>Stepper and Driver</td>
<td>Measure motor rotation</td>
<td></td>
</tr>
</tbody>
</table>
| AMT132G-V          | Future Electronics | $33.00         | AMT_13_Series | 2        | On Stepper motor | Measure motor rotation | Substitute to PCB - Connect components | [https://www.cyl
devices.com/pr
oduct/resource/
amt13-v.pdf](https://www.cyl
devices.com/pr
oduct/resource/
amt13-v.pdf) |
| Vector Board       | Mouser          | $23                | Vector0001    | 1        | Inside Model | Inside Model | Substrate to PCB - Connect components |                                                                          |
| Battery            | Amazon          | $34                | EBL 9V Batteries | 1        | Inside Model | Inside Model | Provide power |                                                                          |
| Quadrature clock   | Digi-Key        | $6                 | LS7884        | 3        | Inside Model | Inside Model | Convert encoder data         |                                                                          |
| Arduino UNO        | Mouser          | $45.00             | Arduino UNO WiFi Rev2 | 3        | Inside Model | Inside Model | Control motors and data from encoders |                                                                          |
| Portenta H7        | Arduino         | $104.00            | Arduino Portenta H7 | 1        | Primary Controller | Primary Controller | Control all 3 motors and encoders |                                                                          |
## Client Electronics - Component Costs

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

<table>
<thead>
<tr>
<th>Component</th>
<th>Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Computer</td>
<td></td>
</tr>
<tr>
<td>CPU</td>
<td>$430.00</td>
</tr>
<tr>
<td>Cooler</td>
<td>$50.00</td>
</tr>
<tr>
<td><strong>Motherboard</strong></td>
<td><strong>$200.00</strong></td>
</tr>
<tr>
<td>Ram</td>
<td>$100.00</td>
</tr>
<tr>
<td>SSD</td>
<td>$60.00</td>
</tr>
<tr>
<td>PSU</td>
<td>$80.00</td>
</tr>
<tr>
<td>Fans</td>
<td>$20.00</td>
</tr>
<tr>
<td>Encoder</td>
<td>$25.00</td>
</tr>
<tr>
<td>Arduino Nano</td>
<td>$10.00</td>
</tr>
<tr>
<td>Lidar Sensor + Dragon Board</td>
<td>$185.00</td>
</tr>
<tr>
<td>Power Cables / margin</td>
<td>$40.00</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>$1,200.00</strong></td>
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# Manufacturing Materials Cost - Servicer

<table>
<thead>
<tr>
<th>Element</th>
<th>Supplier</th>
<th>Description</th>
<th>Part Number</th>
<th>Cost</th>
<th>Quantity</th>
<th>Totals</th>
<th>Link</th>
</tr>
</thead>
<tbody>
<tr>
<td>Test Bench</td>
<td>80/20</td>
<td>10 series one-sided beam</td>
<td>1050</td>
<td>$0.20</td>
<td>120</td>
<td>$24.00</td>
<td>Website: <a href="https://8020.net">https://8020.net</a></td>
</tr>
<tr>
<td></td>
<td></td>
<td>10 series beam</td>
<td>1010</td>
<td>$0.28</td>
<td>24</td>
<td>$6.72</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>10 series wide beam</td>
<td>1020</td>
<td>$0.48</td>
<td>18</td>
<td>$8.64</td>
<td></td>
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<tr>
<td></td>
<td></td>
<td>20 series beams</td>
<td>2020</td>
<td>$0.69</td>
<td>0</td>
<td>$0.00</td>
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<tr>
<td></td>
<td></td>
<td>10 series wheels</td>
<td>2281</td>
<td>$17.34</td>
<td>4</td>
<td>$69.36</td>
<td></td>
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<tr>
<td></td>
<td></td>
<td>10 series inside corner bracket + mounting HW</td>
<td>4119</td>
<td>$4.05</td>
<td>4</td>
<td>$15.20</td>
<td></td>
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<tr>
<td></td>
<td></td>
<td>20 series inside corner bracket + mounting HW</td>
<td>20-4113</td>
<td>$7.16</td>
<td>2</td>
<td>$14.32</td>
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<tr>
<td></td>
<td></td>
<td>end caps</td>
<td>2015</td>
<td>$1.22</td>
<td>4</td>
<td>$4.88</td>
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</tr>
<tr>
<td></td>
<td>Home Depot</td>
<td>1&quot; x 1&quot; x 36&quot; pine square dowel</td>
<td>N/A</td>
<td>$4.84</td>
<td>2</td>
<td>$9.68</td>
<td>Website: <a href="https://www.xyzy.com">https://www.xyzy.com</a></td>
</tr>
<tr>
<td></td>
<td></td>
<td>1/4&quot; x 4&quot; x 8&quot; Plywood</td>
<td>N/A</td>
<td>$29.92</td>
<td>1</td>
<td>$29.92</td>
<td>Website: <a href="https://www.gggg.com">https://www.gggg.com</a></td>
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<tr>
<td></td>
<td></td>
<td>4x4 stand center beam</td>
<td>N/A</td>
<td>$12.65</td>
<td>1</td>
<td>$12.65</td>
<td>Website: <a href="https://www.sss.com">https://www.sss.com</a></td>
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<tr>
<td>Enclosure</td>
<td>Amazon</td>
<td>120mm fan covers</td>
<td>N/A</td>
<td>$0.39</td>
<td>1</td>
<td>$0.39</td>
<td>Website: <a href="https://www.amazon.com">https://www.amazon.com</a></td>
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<tr>
<td></td>
<td></td>
<td>soft close hinge</td>
<td>N/A</td>
<td>$6.89</td>
<td>2</td>
<td>$13.78</td>
<td>Website: <a href="https://www.amazon.com">https://www.amazon.com</a></td>
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<tr>
<td></td>
<td></td>
<td>mesh wire lid</td>
<td>N/A</td>
<td>$11.77</td>
<td>1</td>
<td>$11.77</td>
<td>Website: <a href="https://www.amazon.com">https://www.amazon.com</a></td>
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<tr>
<td></td>
<td></td>
<td>120mm fans</td>
<td>N/A</td>
<td>$13.99</td>
<td>1</td>
<td>$13.99</td>
<td>Website: <a href="https://www.amazon.com">https://www.amazon.com</a></td>
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<td></td>
<td></td>
<td>Swivel</td>
<td>N/A</td>
<td>$36.69</td>
<td>1</td>
<td>$36.69</td>
<td>Website: <a href="https://www.amazon.com">https://www.amazon.com</a></td>
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<tr>
<td></td>
<td>Home Depot</td>
<td>Pins for securing enclosure</td>
<td>N/A</td>
<td>$5.49</td>
<td>4</td>
<td>$21.96</td>
<td>Website: <a href="https://www.amazon.com">https://www.amazon.com</a></td>
</tr>
</tbody>
</table>

Total: $24.00 + $6.72 + $8.64 + $0.00 + $69.36 + $15.20 + $14.32 + $4.88 = $144.12

Total: $9.68 + $29.92 + $12.65 = $52.25

# Manufacturing Materials Cost - Client

<table>
<thead>
<tr>
<th>Client Stand</th>
<th>Material/Part Description</th>
<th>Quantity</th>
<th>Unit Cost</th>
<th>Unit</th>
<th>Total Cost</th>
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<tbody>
<tr>
<td>Fast Metals</td>
<td>Metal base plate</td>
<td>10408</td>
<td>$33.91</td>
<td>per sheet</td>
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<tr>
<td></td>
<td>U Channel</td>
<td>10105</td>
<td>$15.55</td>
<td>per piece</td>
<td>$15.55</td>
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<tr>
<td></td>
<td>Aluminum L arm base</td>
<td>10230</td>
<td>$4.74</td>
<td>per piece</td>
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<tr>
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<td>Aluminum L arm Channel</td>
<td>10605</td>
<td>$4.56</td>
<td>per piece</td>
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<td></td>
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<td><strong>$58.76</strong></td>
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<tr>
<td>Online Metals</td>
<td>Motor 2 Aluminum Pipe</td>
<td>1217</td>
<td>$10.07</td>
<td>per ft</td>
<td><strong>10.07</strong></td>
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<tr>
<td></td>
<td>Motor 1 Aluminum Round Bar</td>
<td>1080</td>
<td>$3.84</td>
<td>per ft</td>
<td>3.84</td>
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<tr>
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<td></td>
<td><strong>$14.71</strong></td>
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<td></td>
<td></td>
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<tr>
<td>Amazon</td>
<td>R4 Bearing</td>
<td>N/A</td>
<td>$9.30</td>
<td>per 10 pack</td>
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<tr>
<td></td>
<td>Timer Pulleys</td>
<td>N/A</td>
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<tr>
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<td>Pulley Belt</td>
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<td>$9.79</td>
<td>per 8 pack</td>
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<tr>
<td></td>
<td>PLA</td>
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<td>per kg</td>
<td><strong>$20.99</strong></td>
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<tr>
<td>Ebay</td>
<td>Planetary Gearbox</td>
<td>N/A</td>
<td>$90.00</td>
<td>per gearbox</td>
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<tr>
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</tr>
<tr>
<td>Home Depot</td>
<td>Miscellaneous Fasteners</td>
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<td></td>
<td><strong>$30.00</strong></td>
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**Total Cost:** $542.48