Boulder Unmanned Sensor for Transport Events and Repositioner

Preliminary Design Review

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Project Overview
Project Motivation

- Dr. Wang’s research at LASP suggests that charged particles could be lifted by their Coulomb force
  - Dust transport events: micron-sized dust particles are charged by various sources in space and ejected from the surface of low-mass bodies
  - This has been tested in a lab setting but never in a low-gravity environment
- A dust instrument to collect data on these particles currently exists but is too large for a space application

Data on charged dust could be collected with a smaller instrument in a CubeSat form factor, for a potential mission to an asteroid
Project Statement

- Dust BUSTER will miniaturize, manufacture, and test a Technology Readiness Level (TRL) 4 dust instrument to characterize dust transport events similar to those that occur on asteroids.
- To aid the instrument, the team will also design and test an Autonomous Repositioning System (ARS) to tilt a 6U CubeSat to a specified angle for dust collection.
Overall Mission ConOps

1. CubeSat launched from mother spacecraft.
2. CubeSat lands on a specified side on a small body.
3. CubeSat determines where the Sun is.
4. CubeSat tilts based on sun location; the instrument should not face the sun.
5. Instrument aperture
6. Instrument collects dust particles. The software filters data and only stores dust particle data.
7. CubeSat sends raw particle data to the ground (Earth).
8. Data is analyzed: Charge, velocity, and mass of the particles are extracted from the data.
# Functional Requirements

<table>
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<th>FR 1</th>
<th>The CubeSat model shall contain the ARS and 2U instrument within 6U volume and mass limits.</th>
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<td>FR 2</td>
<td>The instrument shall detect dust particles that enter the instrument.</td>
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<td>FR 3</td>
<td>The ARS and mechanisms shall open the instrument door that is pointing away from the sun.</td>
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<td>FR 4</td>
<td>The ARS and mechanisms shall tilt the instrument boresight up to a maximum of 45° off the surface.</td>
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<td>FR 5</td>
<td>The electronics subsystem shall collect signals and issue commands to and from the instrument and repositioning systems.</td>
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<td>FR 6</td>
<td>The software shall be capable of data processing, detecting dust events, and running ARS algorithms.</td>
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ARS Functional Block Diagram
Baseline Design
ARS Baseline Design

Determine Sun location and tilt angle
Mechanically tilt and open dust cover doors
Sun Sensor Baseline Design

Why do we need the Sun position?
- Need to know which side of the CubeSat to actuate
  - Solar wind from the Sun can create erroneous data
- Solar keep-out and 45° actuation not always possible
  - Actuate to within 1° of highest possible angle

How? - Photodiodes
- Edges and side faces will have a sensor
  - Edges mounted 45° off sides, faces flat
Tilt Sensor Baseline Design

Why do we need tilt knowledge?

- Need to know how far we have tilted independent of ARS commanded position

How? Accelerometer: ADXL345 SparkFun

- Specifically built to measure static acceleration of gravity in tilt-sensing applications
- 13-bit resolution for 2 Gs
- High resolution: 4 mG
- Angular accuracy of 0.1°
ARS Microcontroller Baseline
Design

Why do we need an ARS Microcontroller?

- Process photodiode and accelerometer data
- Determine location of Sun and CubeSat tilt angle
- Determine how much to actuate CubeSat
- Command motors to actuate CubeSat
- Process command to open door

How? Teensy 3.6

- Arduino-compatible
- 25 analog inputs (photodiodes)
- 22 PWM outputs (stepper motor and servo)
- SPI and I2C capability (accelerometer)
Tilting Mechanism Baseline Design

Why do we need to tilt?
- The CubeSat needs to tilt up to 45° for the instrument to maximize dust collection capability
- Needs to tilt in 1° increments to reach the maximum angle that does not cause sunlight exposure

How? Scissor Lift
- 2 scissor lifts
- 2 cm from edge to leave room for doors
Dust Cover Baseline Design

Why do we need a dust cover?

▪ Protects the instrument from the solar wind
▪ Need to open the door which is not in sunlight based on ARS sensor knowledge

How? Rack & Pinion

▪ Motor turns pinion
▪ Pinion moves rack
▪ Door slides back
Instrument Baseline Design
Collecting and processing dust data
Dust Instrument Design

Why do we need an instrument?
- To collect dust data!

How do we collect dust data?
- Two Dust Trajectory Sensors (DTS) containing wire electrode arrays
- Two Deflection Field Electrodes (DFE) on each side of the Deflection Field Region (DFR) to deflect the charged dust particles
- A magnetic array in front of each chamber entrance
- Confined to a 2U volume (20x10x11.3cm)
Why do we need tension in the wires?
▪ Maintain instrument accuracy

How? Plastic Blots
▪ Electrically insulating plastic bolts screw into wall of DTS
▪ Hole in bolt for the wire electrode to pass through
Charge Sensitive Amplifier (CSA) Design

Why do we need an amplifier?
- Induced charge on wire electrodes is very small (~100 fC)
- Transform induced charge into voltage signals

How? Customer defined CSA
- The first op-amp is a charge sensitive preamplifier that translates induced charge at the input to a voltage at its output
- The second stage is a standard op-amp voltage amplifier
- Low noise design
- Linear sensitivity
Instrument Processor and Event Trigger Baseline Design

Why do we need a processor and event trigger?
▪ Real-time sampling is required to determine when a dust event occurs, so only that data is saved

How?
▪ Microcontroller meets real-time requirements for 1 kHz sampling
▪ Integrated ADCs have 24 channels for 24 wire electrodes
▪ Trigger software compares expected signal to real signals to determine when an event takes place
Post Processing Baseline Design

Why do we need post processing?
- Use raw voltage signals to extract the charge (Q), mass (m), and velocity (v) of an incident dust particle

How? MATLAB Code
- Relative voltage outputs can be used to fully reconstruct trajectory in both space and time
- Using trajectory and known instrument parameters - Q, v, and m can be determined
Feasibility Studies
Critical Project Elements

ARS: Mechanism
- Door
- Tilting mechanism

Structure
- 6U CubeSat
- Instrument/CubeSat interface

Instrument
- Design to survive impact
- Electron deflection
- Reduction to 2U size

ARS: Sensing
- Sun determination
- Position determination

Electronics
- ARS processor
- Instrument processor
- Analog components

Software
- Event detection
- Post processing

CPEs are in red
## Critical Project Elements

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<th>Critical Project Element</th>
<th>Description</th>
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<td>Instrument is contained within a 2U volume</td>
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<td>Surviving Impact</td>
<td>Tension mechanisms maintain tension after impact</td>
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<td>Sun determination</td>
<td>Determine Sun position with 1° accuracy</td>
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<td>Tilting mechanism</td>
<td>Tilt in 1° increments up to 45°</td>
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<tr>
<td>Instrument processor and event trigger</td>
<td>Sample 24 channels at 1 kHz and run event trigger</td>
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Dust Instrument Miniaturization

The instrument must be designed to fit within a 2U volume
2.1: The detector portion of the instrument shall fit within a 2U volume (10 x 20 x 11.35 cm), not including the microcontroller.
1.1.1: The instrument shall have a maximum mass of 2.66 kg

- Customer has provided a schematic of the optimal design for 2U
- Design choices still needed:
  - Wire tension mechanism
  - Maximize wire electrode length to maximize instrument field of view
Instrument Size and Mass

- By model inspection the Dust Trajectory Sensor (DTS) can fit within the instrument 2U volume
- Thickness of DTS wall can be reduced to accommodate design
- Current mass is 735.5 g (not including magnetic arrays, bolts, and copper mesh)

Instrument Mass = 0.74 kg < 2.66 kg  
Feasible  
Instrument contained in 2U
Surviving Impact

The wire electrodes must maintain tension after impact
2.5 The wire electrodes shall remain taut - no more than 0.2mm deflection - after a 10 m/s collision on a regolith surface (1 cm to sub-micron sized particles).

- Plastic bolts maintain wire tension
- Preliminary bolt material choice is PEEK (Polyether ether ketone)
  - Shear Strength ($\tau$) = 55.2 MPa = 55.2 N/mm$^2$
  - M4 Bolt Size - 4mm diameter

Max Shear Force = Shear Strength x Bolt Cross-sectional area

$$F_{shear} = \tau \times \pi \frac{d^2}{4} = 55.2 \times \pi \frac{4^2}{4}$$

Max Shear Force = 694 N
Impact Design

- **Assumptions:**
  - 10 m/s impact velocity
  - Perfectly inelastic collision (0 m/s final velocity)
  - CubeSat mass = 12 kg
  - Force distributed on CubeSat surface is different from force distributed on the dust instrument
- Preliminary impact time range defined as 0.05s to 1.5s
- **Steps:**
  - Calculate the impulse
  - Determine range of impact forces
  - Calculate the force per unit area
  - Translate the calculated pressure to a force on the dust instrument
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  - Calculate the impulse
  - Determine range of impact forces
  - Calculate the force per unit area
  - Translate the calculated pressure to a force on the dust instrument

Feasibility Pending
Sun Knowledge

Determine Sun position with 1° accuracy
Full sky coverage is needed to determine sun position and optimal tilting angle.

- Minimum of 2 sensors must see each part of the sky
  - Two dimensional accuracy requirement means only two sensors needed
  - Two sensors will generate two Sun positions - only a difference in azimuth, not elevation

FR 3: The ARS and mechanisms shall open the instrument door that is pointing away from the sun.

3.2.2: The ARS shall determine Sun position to within +/- 5° up to 45° above the surface and to within +/- 1° from 45° to 90° above the surface.
Sun Knowledge - Full Sky Coverage

Plot below shows the number of sensors that can see each part of the sky for all azimuth and elevation angles.

Baseline design of 12 sensors mounted 45° off sides and on flat faces with 10° to 60° FOV will allow the full sky to be covered.

Minimum of 2 sensors over full sky

Feasible
What is the voltage change for 1° of sun position change?
- Calculate input power from solar spectrum
- Calculate current from photodiode gain curve
- Use transimpedance amplifier to create a measureable voltage

$$\Delta V_{\text{Voltage}} \text{ for } 10° \text{ to } 11° = 160 \text{ mV} > 0.6 \text{ mV}$$

Sunlight on photodiode is less for 11° (orange) than 10° (yellow)

Teensy minimum voltage resolution is 0.6 mV
Feasible
Mechanisms

Tilt in 1° increments up to 45°
Lift works by pinning one end and pushing the other toward it.

Possible solution: Servo motor with gear and rack.

Horizontal Actuation: The distance the free bar needs to move to extend the lift to the desired position.
4.1.2. The actuators shall tilt the CubeSat up to a maximum 45° one time from the plane of the ground.

- Tilt angle is dependent on horizontal actuation
- Maximum turning angle of servo limits horizontal actuation
- Can use different sized gears to increase the amount of actuation
Tilting

4.1.2. The actuators shall tilt the CubeSat up to a maximum 45° one time from the plane of the ground.

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Tilting Increment

4.1.2.1. The actuators shall be able to tilt the CubeSat in 1° increments.

- Motor angle required for 1° of tilt is based off of arclength equation
- Servo motors usually have a resolution of $\leq 0.3°$
- Cannot meet this requirement if the motor turning angle for 1° of tilt is not a multiple of the resolution
Tilting Increment

4.1.2.1. The actuators shall be able to tilt the CubeSat in $1^\circ$ increments.

- Motor angle required for $1^\circ$ of tilt is based off of arclength equation
- Servo motors usually have a resolution of $\leq 0.3^\circ$
- Cannot meet this requirement if the motor turning angle for $1^\circ$ of tilt is not a multiple of the resolution

![Possible Motor Turning Angles](Image)

- Multiple bar lengths and gear sizes for $1^\circ$ increments
4.1.2.2. The actuators shall be able to tilt a mass equal to 100g, with a 20g resolution, under earth's gravity field.

- Center of gravity can vary by +/- 4 cm from the geometric center. Max force required when center of gravity is farthest from the pivot point
- Assume all force from motor is applied straight down

Maximum Force required: 0.71 N

Convert to Torque: 0.16 N m

Motor Torque: 1.5 N m

1.5 N m > 0.16 N m

Feasible
Event Detection

Sample 24 channels @ 1 kHz and run event trigger in real time
Dust Data Example

Instrument data will appear similar to this existing dust data - providing the basis for preliminary testing of event trigger

- Each line is the signal from one wire electrode
- Peaks in voltage are due to passing dust inducing charge on the wire
  - Larger voltage means the dust particle is closer to the wire
- Horizontal axis represents samples (taken at an unknown frequency)
  - Shifted peaks show delay as dust passes through wire planes
Trigger Method - Filter Creation

6.3.1 The software shall be able to filter environmental noise to determine when an event has occurred

- Large signal data resembles a triangle
  - Height of triangle derived from signal to noise ratio (SNR) 6.25 of previously built charge sensitive amplifier (CSA) circuits
  - Width from estimated velocity of dust particle (1-2 m/s) and processor sampling rate (1 kHz)

- Filter provides a **signal to compare to data** to detect dust events
  - Cross correlation continuously compares filter to incoming dust data

\[
\text{Height} = \text{SNR} \times \text{Noise} \\
\text{Width} = (\text{distance/velocity}) \times \text{sampling rate}
\]
Large Signal Trigger Demonstration

Event is triggered when cross correlation passes the threshold.
Small Signal Trigger
Demonstration

Successfully triggered with large and small sample signals

Feasible
5.2.1. The hardware shall convert analog signals from each of 24 instrument amplifiers to digital at 1 kHz (total 24 KSPS).

5.2.2. The instrument processor shall be capable of temporarily storing 10 KB of data for a full event to be output if the event trigger software determines an event has occurred.

**Representative microcontroller choice:**
STMicroelectronics STM32F Series (STM32F427ZI6)
- ARM® Cortex®-M4 core processor (32-bit)
- 180 MHz clock speed
- 256 KB of SRAM
- 24 channels for three 12-bit ADCs (up to 7.2 MSPS)

7.2 MSPS > 24 KSPS
256 KB RAM > 10 KB RAM

Feasible
5.2. The instrument shall have a processor and ADC array capable of sampling all 24 amplifiers and running the event detection software.

With STM32F427ZI6:
- Worst case ADC conversion: \(12 \mu s\) for 24 channels
- Estimate event trigger software duration based on algorithm and ARM® Cortex®-M4 instruction set:
  - \(< 23 \mu s\)
- Processor free 98% of the time, ADC free 99% of the time
Status Summary and Strategy
## Critical Project Elements

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Testing Facilities

- **Dust Sensing** - IMPACT Lab
- **Impact Testing** - Idea Forge Lansmont 15D Shock Test Machine
- **ARS Mechanisms** - Flat and sandy surface with specific grain size
- **ARS Sensors** - Sommers-Bausch Observatory
  - Provides a known attitude relative to the sun
  - Need to contact SBO to discuss availability
Budget

Feasible

<table>
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<td>Total Cost</td>
<td>$2743</td>
<td>$775</td>
<td>$1482</td>
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<td>$400</td>
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Gantt Chart

- Research
  - Materials
  - Algorithms
  - Microcontrollers

- Development
  - CAD Models
  - Impact Test
  - Software

- Preliminary Verification
  - Tension Mechanism
  - Software

- Critical Path

- CDR Draft
- CDR Revision
- CDR Due
Moving Forward

- **Mechanisms**: design gear rack systems with choice for motor and locking mechanism
- **Sun Sensing**: Correlate photodiode output to solar position, create closed loop control system for tilt actuation.
- **Software**: translate algorithm to embedded software to find cross correlation in real time, output dust events over serial once detected
- **Electronics**: finalize real-time architecture and MCU choice
- **Impact modeling**: SOLIDWORKS Drop Test simulation, explore wire failure modes, refine impact time
Acknowledgements

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▪ Tim Kiley
References

References


Thank you!
Feedback?
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Sun Knowledge - Accuracy

- One Photodiode can cover a ‘doughnut’ shaped piece of sky
- Cover restricts incoming sunlight, but prevents sensing near the photodiode boresight
  - Maximum angle off center: 60°
  - Minimum angle off center: 10°
Sun Knowledge - Accuracy

- Photodiode sensitivity must be high enough that the ARS system can determine where the sun is in the sky.
- Photodiodes are not sensitive enough on their own:
  - From 0° to 30° reduction is less than 99% of output.
- Add a cover to restrict incoming sunlight:
  - Maximum angle off center: 60°
  - Minimum angle off center: 10°
- Coverage map includes these considerations.
Sun Knowledge - Accuracy

Need to know the current output of the photodiodes

- Solar irradiance spectrum is well known and provides power at every wavelength
- Photodiode relative spectral sensitivity gives relative power absorbed at every wavelength
Multiply solar irradiance spectrum and photodiode relative spectral sensitivity at each wavelength. Result is photodiode power per area across the full spectrum.

Integrate the photodiode absorption spectrum to get the total power the photodiode will receive.

\[
Ir = 457.5 \text{ W/m}^2 \text{ nm}^2
\]

\[
P = IA = 3.4 \text{ mW}
\]
Sun Knowledge - Accuracy

Expected Irradiance on photodiodes:
Ee = 0.4575 mW/cm^2
From gain curve on datasheet
I = 30 µA

Microcontrollers measure voltage, not current
Voltage measured across a resistor to ground
would be too small for Teensy microcontroller,
so voltage needs to be amplified
Implement a transimpedance amplifier to boost the signal and convert current to voltage.

\[ V_o = I_d \times R_f \]

Maximum current of 30 \( \mu \text{A} \)

\( R_f \) of 200 k\( \Omega \)

\( V_o \) max = 4.8 V

Output voltage is **within microcontroller range**
Sun Knowledge - Accuracy

What is the voltage change for 1° of sun position change?

10° power = 3.43 mW
11° power = 3.41 mW

10° current = 30 µA
11° current = 29 µA

10° Voltage = 4.80 V
11° Voltage = 4.64 V

Sunlight on photodiode is less for 11° (orange) than 10° (yellow)

Teensy minimum voltage resolution is 0.0006 V
Instrument

Q, v, m calculation; DFR bias; and election deflection
Methods for Q, v, & m extraction

DTS Unit (sub-section)

 Definitions:

\( p \sim \) plane number
\( n \sim \) wire number in given plane
\( i \sim \) wire w/ highest voltage
\( j \sim \) wire w/ 2\textsuperscript{nd} highest voltage
\( t_p \sim \) time particle crosses plane \( p \)
\( d \sim \) wire spacing
\( \Delta x \sim \) plane spacing
\( h_n \sim \) z-coordinate of wire \( n \)
\( q_n \sim \) charge induced on wire \( n \)
\( V_n \sim \) voltage signal from wire \( n \)
Methods for Q, v, & m extraction

DTS Unit (sub-section)

- Charge Sensitive Amplifier (CSA) creates voltage from induced charge:
  - Sensitivity: $\rho = 18$ mV/fC
Key assumption: when particle crosses a wire plane the induced charge is only on the wires in that plane

Steps:

1. Q calculation (@ t = t₁)

\[
Q = \rho \sum_{n=1}^{6} V_n \quad \text{n} \sim \text{wire number (in plane)}
\]
Methods for Q, v, & m extraction

Steps (Cont.):

2. Distance from closest wire

\[ d_i = \frac{d}{1 + \frac{V_i}{V_j}} \]

2. Absolute z-coordinate

\[
\begin{align*}
\text{If } i > j & \Rightarrow z_p = h_i - d_i \\
\text{If } i < j & \Rightarrow z_p = h_i + d_i
\end{align*}
\]

2. Repeat steps 2 & 3 for every plane

\((p = 1 \rightarrow 4)\)
Methods for $Q$, $v$, & $m$ extraction

Steps (Cont.):

5. Velocity calculation

\[ v = \frac{\sqrt{(\Delta x)^2 + (z_1 - z_2)^2}}{t_2 - t_1} \]
Methods for Q, v, & m extraction

Steps (Cont.):

6. Calculate turning angle $\delta$

$$\tan(\delta) = \frac{\Delta x (z_1 - z_2 - z_3 - z_4)}{(\Delta x)^2 + (z_4 - z_3)(z_2 - z_1)}$$
Methods for Q, v, & m extraction

Steps (Cont.):

7. Calculate mass (where \( l = 0.07 \) m is the length of the deflection region)

\[
m = \frac{QEl}{v^2 \tan(\delta)}
\]
Electron Deflection

Cylindrical magnets:
- $D = 1.59 \pm 0.10$ mm
- $t = 1.59 \pm 0.10$ mm
- Magnetic Remanence:
  - $B_r = 1.48$ T

- Need to prove gyroradius of 100 eV electron to be sufficiently as to not penetrate the instrument more than 1 cm (first wire plane)
- Gyroradius:
  
  $$r_q = \frac{mv}{qB}$$
Electron Deflection

Using six magnet bars: $d = 14$ mm

From $10 \rightarrow 1$ mm: $B_{\text{mean}} \approx 6.6$ mT

$r_q \approx 5.1$ mm (e$^-$ gyroradius)
ARS Test ConOps

1. Place CubeSat model on testbed. Smooth, level surface or flat surface covered in grains of a particular radius. Light source is put in a known position.

2. Sensors determine sun position and calculate a sun vector. Vector verified by team on control computer using known positions.

3. ARS begins to tilt CubeSat in the specified direction. Closed loop control monitors sun vector and tilt angle.

4. ARS reaches either the 45° position, or optimal angle based on sun position.

5. ARS verifies it is in a good attitude for science collection and notifies control computer.

6. Instrument door is opened by command. ARS tasks complete and system stops calculations.

7. Team resets test for new position of light source. Test is repeated until team is satisfied with performance.
Instrument Test ConOps

1. Bring instrument to IMPACT for testing. Dust samples, a pickup tube, and vacuum chamber, are provided.

2. Place instrument in vacuum chamber with test stand including a dust source and a pickup tube.

3. Connect Instrument to external computer and then pump down to vacuum.

4. Drop individual dust particles to test the instrument's ability to detect charged particles.

5. Remove instrument and modify as necessary.

The Pickup Tube measures the charge on the dust particle.

Feed through for voltage data and power wires.

The instrument is translated inside the chamber to test different particle trajectories. The data is streamed directly to the computer and charge, velocity, and mass are extracted.
Structures Backup Slides
Impact Test ConOps

1. Build a representative model of the instrument structure with mounted wire electrodes included.

2. Mount an accelerometer to the side of the instrument model.


4. Enter the desired drop height on the machine controller.

5. Command the machine to release the platform.

6. Check that the model received the desired acceleration/force.

7. Verify wire electrodes are still attached and verify that the wires remain taut.
6U CubeSat Model

1: The CubeSat model shall contain the ARS and 2U instrument within 6U volume and mass limits.
Top View of CubeSat Model

- System
  - Dust Instrument
  - Door Mechanism
  - Scissor Lift Mechanism
  - Avionics (Out of Scope)

Dimensions:
- 36.6 cm
- 23.9 cm
6U CubeSat Model

1.1: The CubeSat model -- containing all project subsystems -- and instrument combined shall have a maximum total mass of 12 kg.

<table>
<thead>
<tr>
<th>System</th>
<th>Mass</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dust Instrument</td>
<td>0.7355 kg</td>
</tr>
<tr>
<td>Door Mechanism</td>
<td>0.3580 kg</td>
</tr>
<tr>
<td>Scissor Lift Mechanism</td>
<td>0.6600 kg</td>
</tr>
<tr>
<td>Avionics (Out of Scope)</td>
<td>1.5000 kg</td>
</tr>
<tr>
<td>Microcontrollers (not pictured)</td>
<td>0.1000 kg</td>
</tr>
<tr>
<td>CubeSat Model Shell</td>
<td>2.5000 kg</td>
</tr>
<tr>
<td><strong>Total Mass</strong></td>
<td><strong>5.8535 kg</strong></td>
</tr>
</tbody>
</table>

Total Mass < Mass Requirement 5.8535 kg < 12.0000 kg

Feasible
Tension Mechanism Trade Study

Metrics

Manufacturability: ability to manufacture the design
Tension Control: precision and control over tension in wires
Volume: there is a limited amount of volume available to fit in the 2U volume
Impact Risk: what type of failure could occur from impact and the risk associated with it
Tension Mechanism Trade Study

Options

Bolt  
Winch  
Plate  
Post
## Trade Study Table

<table>
<thead>
<tr>
<th></th>
<th>Weight</th>
<th>Bolt</th>
<th>Winch</th>
<th>Plate</th>
<th>Post</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Manufacturability</strong></td>
<td>0.3</td>
<td>5</td>
<td>4</td>
<td>5</td>
<td>4</td>
</tr>
<tr>
<td><strong>Tension Control</strong></td>
<td>0.35</td>
<td>5</td>
<td>5</td>
<td>5</td>
<td>4</td>
</tr>
<tr>
<td><strong>Volume Needed</strong></td>
<td>0.10</td>
<td>3</td>
<td>2</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td><strong>Impact Risk</strong></td>
<td>0.25</td>
<td>4</td>
<td>3</td>
<td>4</td>
<td>2</td>
</tr>
<tr>
<td><strong>Weighted Score</strong></td>
<td>4.55</td>
<td>3.9</td>
<td>4.45</td>
<td>3.4</td>
<td></td>
</tr>
</tbody>
</table>
Impact Collision Calculations

Assumptions:
- Perfectly inelastic collision \((v_f = 0 \text{ m/s})\)
- Point mass model for CubeSat

Knowns:
- CubeSat mass \((m_{CS}) = 12 \text{ kg} \text{ (max)}\)
- Impact velocity \((v_i) = 10 \text{ m/s}\)

\[
J_{CS} = m_{CS}(v_f - v_i)_{CS} = 12(10 - 0) = 120 Ns
\]

\[
J_{CS} = F_{impact}\Delta t \Rightarrow F_{impact} = J_{CS}\Delta t
\]
Impact Collision Calculations

Point mass force will likely be distributed

\[ P_{\text{impact}} = \frac{F_{\text{impact}}}{S\,A_{\text{base}}} \Rightarrow \frac{F_{\text{impact,DI}}}{S\,A_{\text{base,DI}}} = \frac{F_{\text{impact,CS}}}{S\,A_{\text{base,CS}}} \]

\[ \Rightarrow F_{\text{impact,DI}} = F_{\text{impact,CS}} \times \frac{S\,A_{\text{base,DI}}}{S\,A_{\text{base,CS}}} = 0.2286 F_{\text{impact,CS}} \]
Impact Collision Calculations

Impact Collision Time:

Impact Time [s] vs Impact Crater Depth [cm]

Impact Collision Force:

Impact Time [s] vs Impact Force [N]
Impact Modeling Test

- In order to determine a number for the force of impact, the time of impact must be known.
- Impact time is difficult to measure without high speed filming capabilities.
- A simple analysis can stem from crater depth (distance needed to stop).
- Assuming constant acceleration:

\[
t_{impact} = \frac{2d}{v_f + v_i} \rightarrow t_{impact} = \frac{d}{5}
\]
Wire Electrode Impact Analysis

Modeling worse case scenario.
Wire Electrode Impact Analysis

Given:
- Yield Strength ($\tau$): 199.9 N/mm$^2$
- Wire Length ($L_0$): 7.0 mm
- Modulus of Elasticity ($E$): 117.0 N/mm$^2$

Assumptions: Rigid Body Analysis

Find: elongation ($\delta$), deflection distance ($d$), deflection angle ($\alpha$), and impact force that would break the wire ($F_{\text{impact}}$)

\[
\delta = L_0 \times \frac{\tau}{E} = 0.042 mm
\]

\[
\alpha = \sin^{-1} \left( \frac{d}{\frac{L_0 + \delta}{2}} \right) = 1.982^\circ
\]

\[
d = \sqrt{\left(\frac{L_0 + \delta}{2}\right)^2 + \left(\frac{L_0}{2}\right)^2} = 1.211 mm
\]

\[
F_{\text{impact}} = F_T \sin(\alpha) = 0.4752 N
\]
Software Backup Slides
ARS Software Flow Diagram

Read analog inputs from photodiodes, processed through ADC

- Store data
- Repeat until desired amount of data is collected
- Determine incidence angle as function of voltage

- Sun is outside keep out zone
  - Sun is on +x side
    - Actuate +x door to 45°
  - Sun is on -x side
    - Actuate -x door to 45°

- Sun is inside keep out zone
  - Sun is on +x side
    - Determine maximum dust collection angle to still keep instrument shaded
    - Actuate +x side to optimal angle
  - Sun is on -x side
    - Actuate -x side to optimal angle
Event Trigger Software Cycle Count

Assume a filter, $f[n]$ that is 20 samples in width. The signal is $g[n]$. So, the cross correlation at time $n$ is:

$$c[n] = \sum_{m=1}^{20} g[m] f[m + n]$$

<table>
<thead>
<tr>
<th>Explanation</th>
<th>Number of instructions</th>
<th>Cycles per instruction</th>
<th>Total Clock Cycles</th>
</tr>
</thead>
<tbody>
<tr>
<td>Load signal and filter for each channel</td>
<td>24 x 40 = 960</td>
<td>2</td>
<td>1920</td>
</tr>
<tr>
<td>$f[m] g[m+n]$ multiplication</td>
<td>24 x 20 = 480</td>
<td>1</td>
<td>480</td>
</tr>
<tr>
<td>Sum from $m = 1$ to 20</td>
<td>24 x 20 = 480</td>
<td>1</td>
<td>480</td>
</tr>
<tr>
<td>Program control overhead</td>
<td>&lt; 1000</td>
<td>1</td>
<td>&lt; 1000</td>
</tr>
<tr>
<td>Worst case</td>
<td></td>
<td></td>
<td>&lt; 4000</td>
</tr>
</tbody>
</table>
Event Trigger Software Runtime

The event trigger software requires <4000 clock cycles, so, at a 180 MHz clock speed:

\[ t_{\text{trigger}} = \frac{4000 \text{ cycles}}{180 \times 10^6 \text{ cycles/s}} = 22.2 \mu\text{s} \]

For the ADC:

\[ t_{\text{conversion}} = 15 \times t_{\text{ADC\_clock}} = 15 \times 0.5 \mu\text{s} \]

\[ \therefore t_{\text{conversion,24}} = 12 \mu\text{s} \]
Trigger Method - Cross Correlation

- Cross correlation (sliding dot product) measures overlap between two signals
- Trigger software takes cross correlation to compare filter and data stream
- Dust event triggered when cross correlation value exceeds threshold
  ▫ Threshold will be determined from calibration with multiple data sets

\[(f \star g)(t) = \int_{-\infty}^{\infty} \bar{f}(T)g(t + T)dT\]
# Trade Study: Door Mechanism

<table>
<thead>
<tr>
<th>Criteria</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mass</td>
<td>≥ 650 g</td>
<td>&lt; 650 g</td>
<td>&lt; 600 g</td>
<td>&lt; 550 g</td>
<td>&lt; 500 g</td>
</tr>
<tr>
<td>Cost</td>
<td>≥$175</td>
<td>&lt;$175</td>
<td>&lt;$150</td>
<td>&lt;$125</td>
<td>&lt;$100</td>
</tr>
<tr>
<td>Size</td>
<td>≥ 250 cm³</td>
<td>&lt; 250 cm³</td>
<td>&lt; 225 cm³</td>
<td>&lt; 200 cm³</td>
<td>&lt; 175 cm³</td>
</tr>
<tr>
<td>Mechanical Complexity</td>
<td>-interferes w/ instrument</td>
<td>-≥ 4 actuators</td>
<td>-3 actuators</td>
<td>-2 actuators</td>
<td>-1 actuator</td>
</tr>
<tr>
<td></td>
<td></td>
<td>-no interference w/ instrument</td>
<td>-no interference w/ instrument</td>
<td>-no interference w/ instrument</td>
<td>-no interference w/ instrument</td>
</tr>
</tbody>
</table>

## Weighted Total

<table>
<thead>
<tr>
<th>Criteria</th>
<th>Weight (%)</th>
<th>Options</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Hinged</td>
</tr>
<tr>
<td>Mass</td>
<td>10</td>
<td>4</td>
</tr>
<tr>
<td>Cost</td>
<td>20</td>
<td>2</td>
</tr>
<tr>
<td>Size</td>
<td>30</td>
<td>3</td>
</tr>
<tr>
<td>Mechanical Complexity</td>
<td>40</td>
<td>2</td>
</tr>
<tr>
<td><strong>Weighted Total</strong></td>
<td>100</td>
<td>2.5</td>
</tr>
</tbody>
</table>
# Trade Study: Tilting Mechanism

<table>
<thead>
<tr>
<th>Criteria</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of Actuators</td>
<td>8 actuators</td>
<td>4 actuators, also requires gears</td>
<td>4 actuators</td>
<td>2 actuators, legs are jointed</td>
<td>2 actuators</td>
</tr>
<tr>
<td>Difficulty to design and implement</td>
<td>100% custom design, interferes with door</td>
<td>100% custom design, no door interference</td>
<td>COTS &amp; custom design, interferes with door</td>
<td>COTS &amp; custom design, no door interference</td>
<td>COTS, no door interference</td>
</tr>
<tr>
<td>Volume Required</td>
<td>&gt;1000 cm³</td>
<td>750-1000 cm³</td>
<td>500-750 cm³</td>
<td>250-500 cm³</td>
<td>&lt;250 cm³</td>
</tr>
<tr>
<td>Mass</td>
<td>&gt;3 kg</td>
<td>2.3-3 kg</td>
<td>1.6-2.3 kg</td>
<td>1-1.6 kg</td>
<td>&lt;1 kg</td>
</tr>
<tr>
<td>Cost</td>
<td>&gt;$900</td>
<td>$650-$900</td>
<td>$400-$650</td>
<td>$150-$400</td>
<td>&lt;$150</td>
</tr>
</tbody>
</table>

## Criteria Weighting

<table>
<thead>
<tr>
<th>Criteria</th>
<th>Weight (%)</th>
<th>Telescoping Legs</th>
<th>Lever Arm</th>
<th>Scissor Lift</th>
<th>Jointed Arm</th>
<th>Gear Rack</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of Actuators</td>
<td>25</td>
<td>2</td>
<td>5</td>
<td>4</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>Difficulty to design/impl</td>
<td>25</td>
<td>1</td>
<td>4</td>
<td>3</td>
<td>1</td>
<td>4</td>
</tr>
<tr>
<td>Volume Required</td>
<td>20</td>
<td>1</td>
<td>3</td>
<td>5</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Mass</td>
<td>10</td>
<td>1</td>
<td>4</td>
<td>5</td>
<td>2</td>
<td>4</td>
</tr>
<tr>
<td>Cost</td>
<td>20</td>
<td>3</td>
<td>4</td>
<td>5</td>
<td>4</td>
<td>1</td>
</tr>
<tr>
<td>Weighted Total</td>
<td>100</td>
<td>1.65</td>
<td>4.05</td>
<td>4.25</td>
<td>1.9</td>
<td>2.5</td>
</tr>
</tbody>
</table>
Scissor Lift Tilting Increment

First Need To Determine Length of Leg

Then Need To Determine Horizontal Actuation

Finally, determine motor turning accuracy

\[ L = 22 \times \tan(\theta) \]
\[ \theta = \text{Tilt Angle} \]

\[ X = \sqrt{B^2 - (2)^2} \]

\[ X' = \sqrt{B^2 - \left(2 + \frac{L}{2}\right)^2} \]

Motor Turning Angle
\[ \phi = \frac{360^\circ \times \Delta X}{2 \times \pi \times r} \]

Horizontal Actuation = \[ \Delta X = X - X' \]
Tilting Mechanism Force Calculations

- Assume center of mass is at the center of the CubeSat

\[ \sum M_A = F(0.22) + mg(0.12) = 0 \]

\[ F = \frac{mg(0.12)}{0.22} = \frac{(0.1)(9.81)(0.12)}{0.22} = 0.545 \, N \]
Tilting Mechanism Force Calculations: Maximum

- Assume center of mass is at the maximum distance from the pivot

\[ \sum M_A = F(0.22) + mg(0.16) = 0 \]

\[ F = \frac{mg(0.16)}{0.22} \]

\[ F = \frac{(0.1)(9.81)(0.16)}{0.22} = 0.713 \, N \]

\[ \tau = F(0.22) = 0.713(0.22) = 0.157 \, N \, m \]
Motor Torque/Force

Motor Torque: 1.5 N m

1 cm radius

\[ F = \frac{\tau}{r} = \frac{1.5}{0.01} = 150N \]

1.5 cm radius

\[ F = \frac{\tau}{r} = \frac{1.5}{0.015} = 100N \]

2 cm radius

\[ F = \frac{\tau}{r} = \frac{1.5}{0.02} = 50N \]

\[ F > 0.73 \text{ N} \quad \text{Feasible} \]
Leg Volume and Mass Calculation

Leg Dimensions: 2 x 16 x 0.3175 cm ⇒ 10 cm³
Number of Bars: 4
Density of Aluminum: 2.70 g/cm³

\[ \rho = \frac{m}{V} \quad \text{Where } m \text{ is mass and } V \text{ is volume} \]

\[ m = \rho V \]

\[ m = (2.70)(10) \]

\[ m = 27g = 0.027kg \]

\[ m_l = 4m \]

\[ m_l = 4(0.027) = 0.110 kg \]

\[ m_t = 2m_l \]

\[ m_t = 2(0.110) = 0.220 kg \]
Leg Location Determination

- Need less accurate actuation the farther out the leg is from tilting edge.
  - Makes tilting easier further out leg is.
- The farther the leg is, the more room we have to work with.
Possible Locking Mechanisms

- Solenoid Brake
  - Small
  - Inexpensive
  - Works with servo motor

- Worm Gear Box
  - Larger in size and mass
  - Expensive
  - Would require stepper motor

Both methods are feasible and meet all requirements
Mass and Volume

1.1.2. The ARS shall take up less than 3U of the CubeSat model's interior.
1.2.1. The combination of the ARS, sensor processor and CubeSat model shell shall have a maximum mass of 7.84 kg.

<table>
<thead>
<tr>
<th>Component</th>
<th>Mass (kg)</th>
<th>Volume (cm³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Leg Motors</td>
<td>0.11</td>
<td>346</td>
</tr>
<tr>
<td>Legs</td>
<td>0.22</td>
<td>81</td>
</tr>
<tr>
<td>Door Motors</td>
<td>0.11</td>
<td>346</td>
</tr>
<tr>
<td>Door Mechanisms</td>
<td>0.069</td>
<td>26</td>
</tr>
<tr>
<td>ARS Microcontroller</td>
<td>0.05</td>
<td>40</td>
</tr>
<tr>
<td>Instrument Microcontroller</td>
<td>0.05</td>
<td>100</td>
</tr>
<tr>
<td>Shell</td>
<td>2.5</td>
<td>1000</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>3.109</strong></td>
<td><strong>1939</strong></td>
</tr>
</tbody>
</table>

Available Mass: 7.84 kg
Margin: 4.73 kg
Feasible

Available Volume: 3U = 5073.5 cm³
Margin: 3134.5 cm³
Feasible
CSA Circuit (Given)

- Given by the client as a low noise method to translate a charge induced on a wire electrode into an amplified voltage
- The first op-amp is a charge sensitive preamplifier with gain of $1/C_1$
- Second is an AC coupled voltage amplifier with a gain of 91

Sensitivity: $\frac{1}{C_1} \times 91 = 18\text{mV/C}$

ADC resolution will be much greater than needed
Thermal

Assumptions:

- Chamber is very large relative to microcontroller (black body)
- Chamber walls at constant 293.15 K
- Microcontroller is a black body

\[ \dot{Q}_{in} = \dot{Q}_{out} \]

\[
\sigma A_{micro} T_{chamber}^4 + P_{micro} = \sigma A_{micro} T_{micro}^4
\]

\[
(5.67e-8)(2)(.07)^2(293.15)^4 + 0.5 = (5.67e-8)(2)(.07)^2 T_{micro}^4
\]

\[
T_{micro} = 301.7 K
\]
## Instrument Hardware Cost

### (Analog)

<table>
<thead>
<tr>
<th>ITEM</th>
<th>UNIT COST ($)</th>
<th># REQUIRED</th>
<th>TOTAL COST ($)</th>
</tr>
</thead>
<tbody>
<tr>
<td>LTC6240 OpAmp</td>
<td>1.2</td>
<td>30</td>
<td>36</td>
</tr>
<tr>
<td>OP275 OpAmp</td>
<td>3</td>
<td>15</td>
<td>45</td>
</tr>
<tr>
<td>10 GΩ Resistors</td>
<td>9.5</td>
<td>90</td>
<td>855</td>
</tr>
<tr>
<td>5 pF Capacitor</td>
<td>0.1</td>
<td>60</td>
<td>6</td>
</tr>
<tr>
<td>15 pF Capacitor</td>
<td>0.5</td>
<td>30</td>
<td>15</td>
</tr>
<tr>
<td>2.2 µF Capacitor</td>
<td>0.2</td>
<td>30</td>
<td>6</td>
</tr>
<tr>
<td>1kΩ Resistor</td>
<td>0.1</td>
<td>30</td>
<td>3</td>
</tr>
<tr>
<td>10 kΩ Resistor</td>
<td>0.1</td>
<td>30</td>
<td>3</td>
</tr>
<tr>
<td>1 MΩ Resistor</td>
<td>0.1</td>
<td>30</td>
<td>3</td>
</tr>
<tr>
<td>PCB</td>
<td>66</td>
<td>1</td>
<td>66</td>
</tr>
<tr>
<td>Misc.</td>
<td></td>
<td></td>
<td>50</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td></td>
<td></td>
<td><strong>1038</strong></td>
</tr>
<tr>
<td>ITEM</td>
<td>UNIT COST ($)</td>
<td># REQUIRED</td>
<td>TOTAL COST ($)</td>
</tr>
<tr>
<td>-------------------</td>
<td>---------------</td>
<td>------------</td>
<td>----------------</td>
</tr>
<tr>
<td>Development Board</td>
<td>40</td>
<td>1</td>
<td>40</td>
</tr>
<tr>
<td>Microcontroller</td>
<td>15</td>
<td>2</td>
<td>30</td>
</tr>
<tr>
<td>PCB</td>
<td>66</td>
<td>1</td>
<td>66</td>
</tr>
<tr>
<td>Peripherals</td>
<td></td>
<td></td>
<td>30</td>
</tr>
<tr>
<td>Support Programmer</td>
<td>100</td>
<td>1</td>
<td>100</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td></td>
<td>40-226</td>
</tr>
</tbody>
</table>
# ARS Mechanisms Cost

<table>
<thead>
<tr>
<th>ITEM</th>
<th>UNIT COST ($)</th>
<th># REQUIRED ($)</th>
<th>TOTAL COST ($)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Servo Motors</td>
<td>50</td>
<td>2</td>
<td>100</td>
</tr>
<tr>
<td>Stepper Motors</td>
<td>20</td>
<td>2</td>
<td>40</td>
</tr>
<tr>
<td>12&quot;x12&quot;x1/8&quot; 6061 Aluminum</td>
<td>20</td>
<td>3</td>
<td>60</td>
</tr>
<tr>
<td>3/16&quot;x12&quot; 6061 Al Rod</td>
<td>5</td>
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<td>5</td>
</tr>
<tr>
<td>Gear Rack</td>
<td>50</td>
<td>1</td>
<td>50</td>
</tr>
<tr>
<td>Gears</td>
<td>50</td>
<td>4</td>
<td>200</td>
</tr>
<tr>
<td>Rack Rail</td>
<td>10</td>
<td>1</td>
<td>10</td>
</tr>
<tr>
<td>Misc Mounting Equipment</td>
<td></td>
<td></td>
<td>100</td>
</tr>
<tr>
<td>Testing Equipment</td>
<td></td>
<td></td>
<td>100</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td></td>
<td></td>
<td><strong>665</strong></td>
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</tbody>
</table>
## ARS Sun Sensing Cost

<table>
<thead>
<tr>
<th>ITEM</th>
<th>UNIT COST ($)</th>
<th># REQUIRED</th>
<th>TOTAL COST ($)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Photodiodes</td>
<td>5</td>
<td>20</td>
<td>100</td>
</tr>
<tr>
<td>Microcontroller</td>
<td>50</td>
<td>1</td>
<td>50</td>
</tr>
<tr>
<td>(Teensy 3.6)</td>
<td>50</td>
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</tr>
<tr>
<td>PCB</td>
<td>66</td>
<td>1</td>
<td>66</td>
</tr>
<tr>
<td>Peripherals</td>
<td></td>
<td></td>
<td>50</td>
</tr>
<tr>
<td>Accelerometer</td>
<td>20</td>
<td>1</td>
<td>20</td>
</tr>
<tr>
<td>Misc (cables, etc)</td>
<td>50</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td></td>
<td>336</td>
</tr>
</tbody>
</table>
# CubeSat Structure Cost

<table>
<thead>
<tr>
<th>ITEM</th>
<th>UNIT COST ($)</th>
<th># REQUIRED</th>
<th>TOTAL COST ($)</th>
</tr>
</thead>
<tbody>
<tr>
<td>12&quot;x24&quot; 0.125&quot; Thickness 6061 T6 Al Sheet</td>
<td>35</td>
<td>1</td>
<td>35</td>
</tr>
<tr>
<td>24&quot;x24&quot; 0.125&quot; Thickness 6061 T6 Al Sheet</td>
<td>30</td>
<td>1</td>
<td>30</td>
</tr>
<tr>
<td>Misc</td>
<td></td>
<td></td>
<td>100</td>
</tr>
<tr>
<td>Total</td>
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<td></td>
<td>165</td>
</tr>
</tbody>
</table>
## Instrument Structure Cost

<table>
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<th>UNIT COST ($)</th>
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<th>TOTAL COST ($)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.3125&quot; Thick, 24&quot;x24&quot; 6061 Al</td>
<td>140</td>
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<tr>
<td>0.04&quot; Thick, 12&quot;x12&quot; 6061 Al</td>
<td>6</td>
<td>1</td>
<td>6</td>
</tr>
<tr>
<td>0.02&quot; Copper Wire 1/4lb spool</td>
<td>7</td>
<td>1</td>
<td>7</td>
</tr>
<tr>
<td>M4 Screws</td>
<td>17</td>
<td>8</td>
<td>136</td>
</tr>
<tr>
<td>0.04&quot; Thick, 12&quot;x12&quot; 6061 Al</td>
<td>6</td>
<td>1</td>
<td>6</td>
</tr>
<tr>
<td>0.04&quot; Thick, 12&quot;x12&quot; 6061 Al</td>
<td>6</td>
<td>1</td>
<td>6</td>
</tr>
<tr>
<td>3/8&quot;x3/8&quot;x12&quot; Delrin Bar (Black)</td>
<td>3</td>
<td>1</td>
<td>3</td>
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<tr>
<td>Polished 6061 0.125&quot; Thick, 12&quot;x12&quot; plate</td>
<td>45</td>
<td>1</td>
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<tr>
<td>Magnets</td>
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<td></td>
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<tr>
<td><strong>Total</strong></td>
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<td><strong>449</strong></td>
</tr>
</tbody>
</table>
Project Scope

- **TRL 4**
  - Integration of different components
  - Validation in laboratory environment
  - Do not have to design for intended environment