Design and Development of an Unrestricted Satellite Motion Simulator

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Naval Academy Small Satellite Program (NASSP)

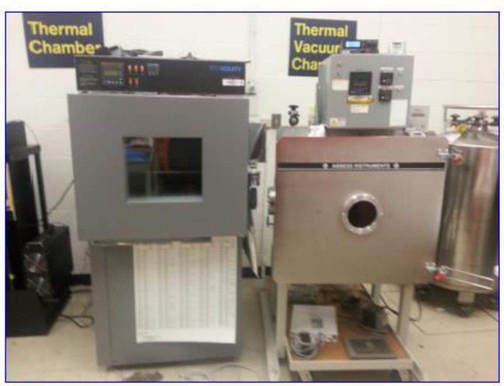
The foundation of our space systems curriculum for the Astro Track students

- Provides midshipmen full-range of hands-on space system development experiences
  - Satellite design
  - Bus and payload development, integration, and testing
  - Mission operations
- Guides students through regulatory and validation procedures
- Educates future Naval officers
- Research for future space technologies

Missions:

- Sapphire
- PCSat
- PCSat-2 (ISS)
- PCSat-3 (ISS)
- ANDE
- MidSTAR
- RAFT/MARScom
- PSAT
- DRAGONsat
- USS Langley
- BRICSat
- QIKCOM-1 (hosted)
- QIKCOM-2 (hosted)
- BRICSat-2
- PSAT-2
- RSat

Shaker



Thermal and Thermal Vacuum Chambers

Solar Simulator

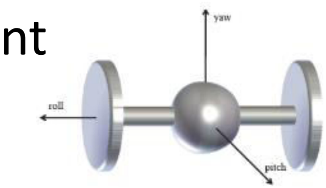
Agenda

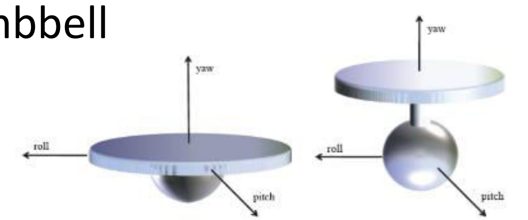
- Background
- Key Project Requirements
- System Design
- Prototype Details
- Future Work
- Conclusion

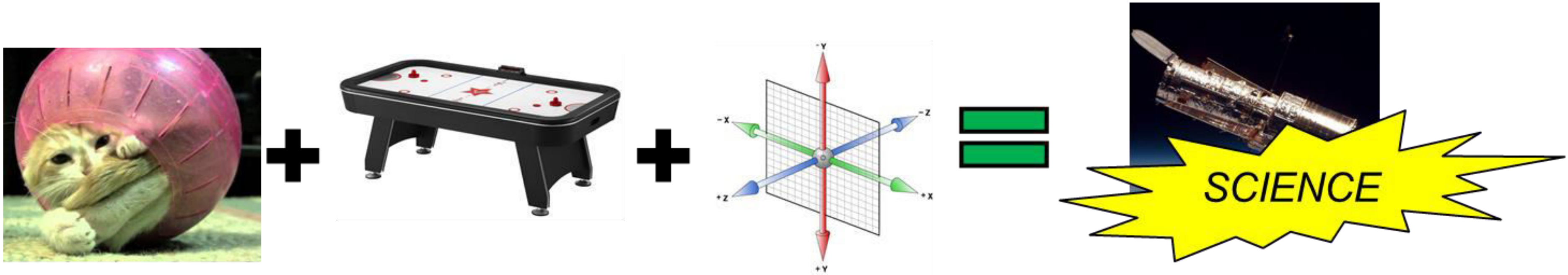
Background

- New attitude control methods and algorithms need to be tested on specific spacecraft configurations
- Current testbeds are often spacecraft specific
- Algorithms need rigorous testing prior to flight
- Without full range of motion, complex maneuvers difficult to test

- Ideally, to fully model an attitude control method, a simulator should exhibit full 360˚ rotation for all axes
- Current testbeds are restricted in their movement
  - Tabletop
  - Umbrella
  - Dumbbell







Key Project Requirements

Mission Statement: Design, build, and test a reconfigurable mass modeler to realistically simulate different satellite's Moment of Inertia and Reaction Wheel ADCS with various control algorithms.

- Spherical Housing Rotor for full 360˚ rotation about any axis
- Utilize a spherical rotor that is compatible with the specified air bearing
- Universally applicable to any spacecraft system or configuration (RW)
  - Reconfigurable internal mass system for changing Inertia
  - Reconfigurable reaction wheel assembly
- Rotate up to 4 deg/s about any axis without restriction
- Provide an accurate representation of on-orbit performance for any satellite being simulated
- Communicate wirelessly with external controllers for reaction wheel commanding and performance data retrieval
- Cost effective enough for University and CubeSat project use

System Design

- Assume Rigid body with no external torques:

$$h_{sc} = I_{sc}\omega$$

To Be Measured

Control mechanism

$$I_{sc}\omega = -I_{rw}Z\Omega$$

To Be Modeled

How to Model Multiple Spacecraft

- Normalize Principal Inertia Tensor into Inertia Ratios

$$\frac{I_{sc}}{I_{max\,sc}} = \begin{bmatrix} D & 0 & 0 \\ 0 & F & 0 \\ 0 & 0 & G \end{bmatrix} = \frac{I_{sim}}{I_{max\,sim}}$$

$$h = I\omega$$

$$\frac{h_{sc}}{I_{max\,sc}} = \frac{I_{sc}}{I_{max\,sc}}\omega = \begin{bmatrix} D & 0 & 0 \\ 0 & F & 0 \\ 0 & 0 & G \end{bmatrix}\omega = \frac{I_{sim}}{I_{max\,sim}}\omega = \frac{h_{sim}}{I_{max\,sim}}$$

$$I_{sc}\omega = -I_{rw}Z\Omega \quad \rightarrow \quad \begin{bmatrix} D & 0 & 0 \\ 0 & F & 0 \\ 0 & 0 & G \end{bmatrix}\omega = -\frac{I_{rw_{sim}}}{I_{max_{sim}}} Z\,\Omega$$

Spacecraft versus Simulator

Reaction Wheel Relationships.

- Reaction Wheel speeds are related by maximum inertia values:

$$\Omega_{sc} = \frac{I_{max_{sc}}}{I_{max_{sim}}} \frac{I_{rw_{sim}}}{I_{rw_{sc}}} \Omega_{sim}$$

- These relationships ensure that overall angular rotation rate (and acceleration) are the same for the spacecraft and the simulator

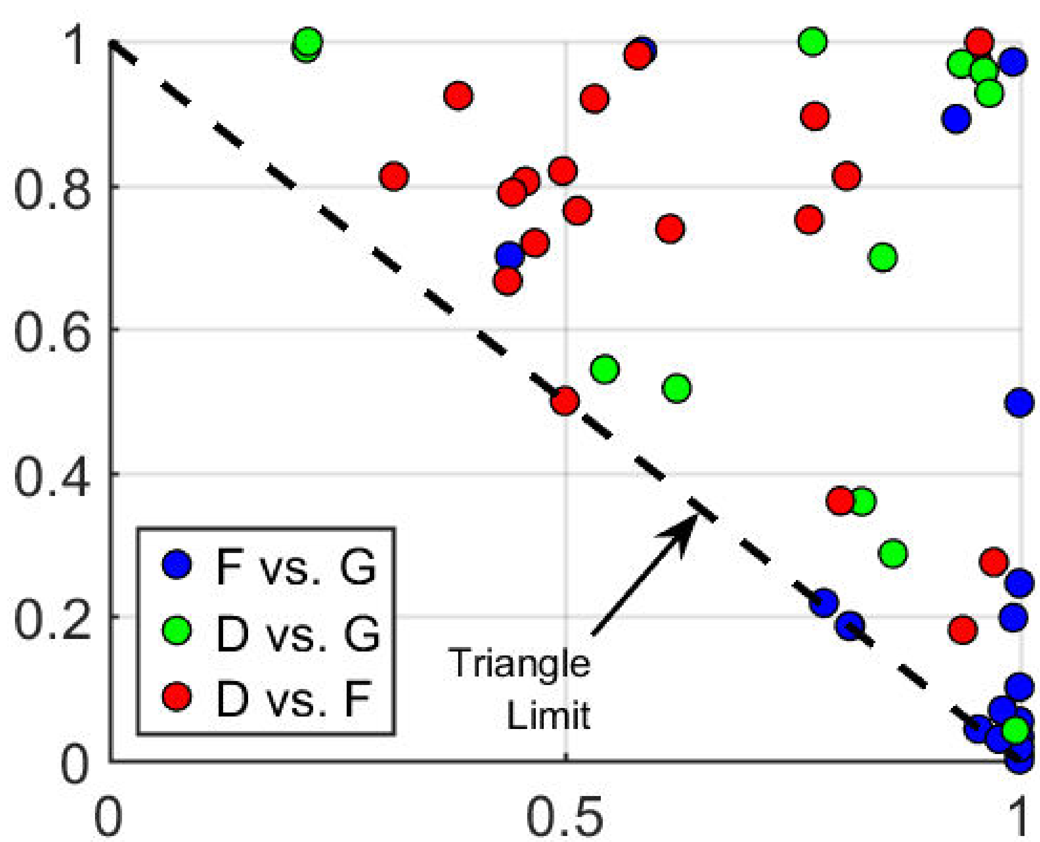
$$\omega_{sc} = \omega_{sim} = \omega$$

- The common angular rate allows an accurate and realistic demonstration of the results of any control algorithms

Establishing the Design Envelope

- Inertia Tensors collected from more than 60 different spacecraft using over 100 publically available sources.
- Multiple mission types and control methods used to baseline the design envelope
  - Not limited to Reaction Wheel spacecraft
  - Includes Commercial, Government, and Educational satellites
- Age of spacecraft ranged from
  - 1965, with Transit Research and Attitude Control (TRAAC)
  - to the yet-to-be-launched James Webb Space Telescope (JSWT).
- Absolute inertia values ranged from 0.002 to 93,000 kg m2
- Size ranged from a 1U CubeSat to the Hubble Space Telescope

Ultimate Design Envelope



$$\begin{bmatrix} D & 0 & 0 \\ 0 & F & 0 \\ 0 & 0 & G \end{bmatrix}$$

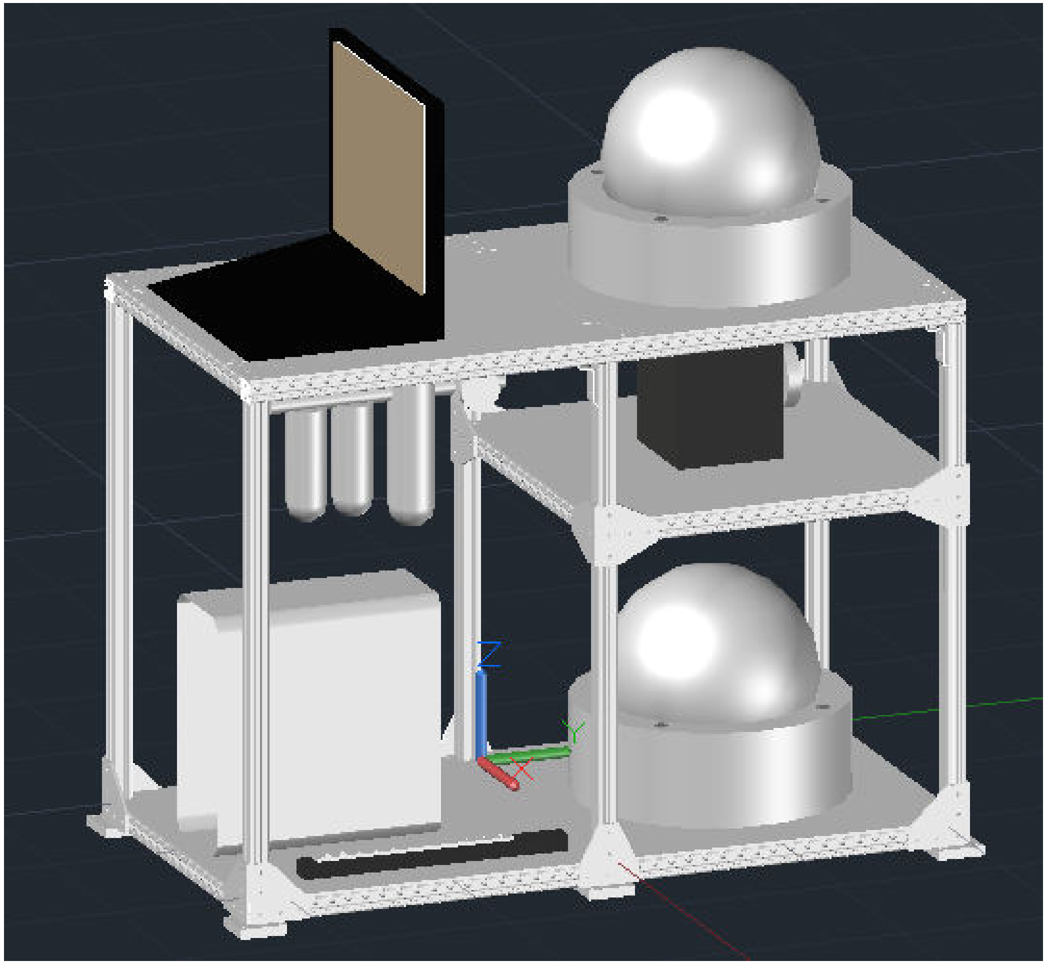
- Third ratio is = 1.0
- Inertia Ratios from the Survey Data with Triangle Limits Shown

$$\frac{|D-G|}{F} < 1$$

$$\frac{|F-D|}{G} < 1$$

$$\frac{|F-G|}{D} < 1$$

USMS Prototype Design



Control and Data Laptop

Air Filtration

Air Compressor

External Power Supply

Testing Sphere

Resting Stand/ Testing Boundary

Mechanical Jack Lift

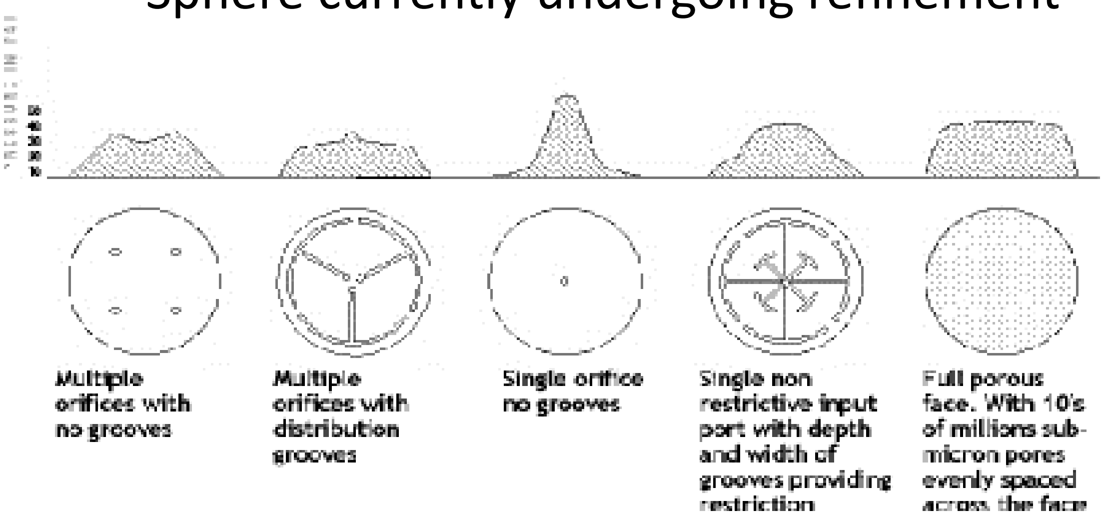
Spare Sphere and Holder

8020 Aluminum Frame

Air Bearing and Sphere

- Air bearing size (thus rotor diameter) was specified as a project requirement for compatibility with a previous USAFA research effort with EyaSat, LLC.
- New Way Air Bearing uses porous carbon material to provide a more uniform air pressure.
- Sphere currently undergoing refinement

www.newwayairbearings.com



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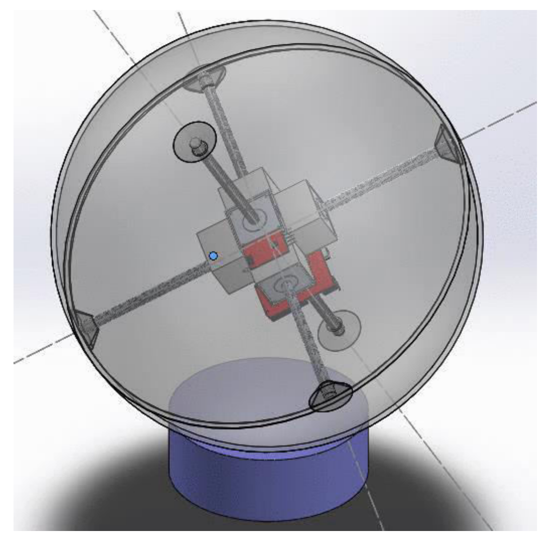
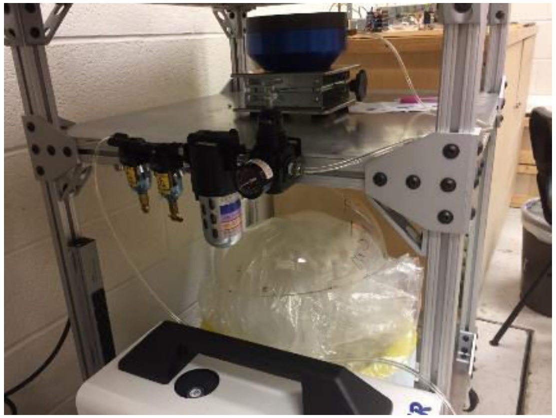


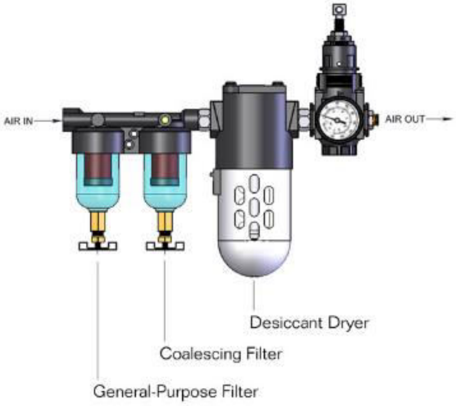
Air Pump and Filtration

SIL-AIR Compressor

- Extremely Quiet, classroom capable
- Max 114 PSI
- 15 minute operating limit
- *Limits simulation run time, but made it portable*

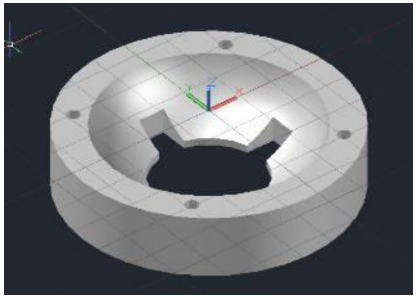
- Porous Stator (Air bearing) require very clean air & care
- Must be properly cleaned and dried
- Not affected by large particles or dust
- Contaminants: Water, Oil, rust, etc.

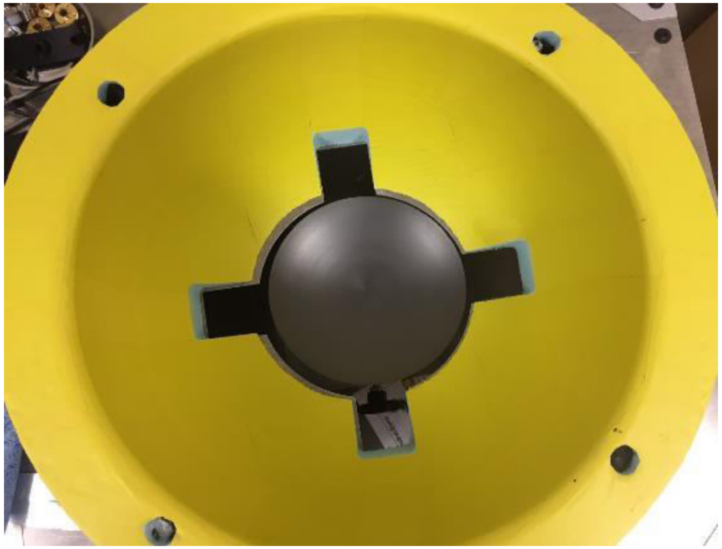




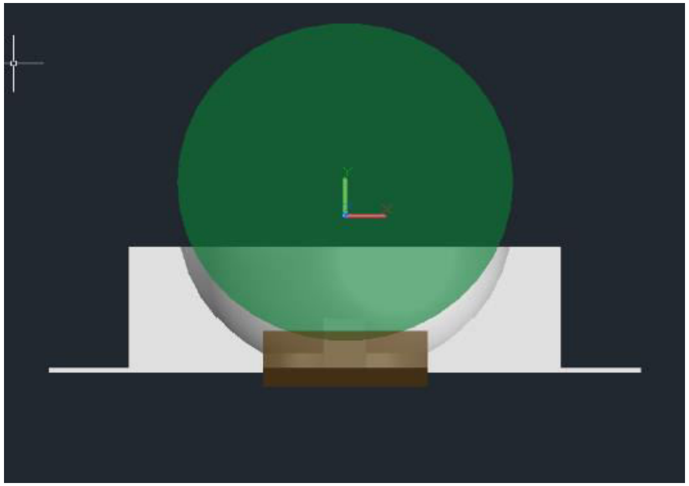
Housing and Lifting Mechanism

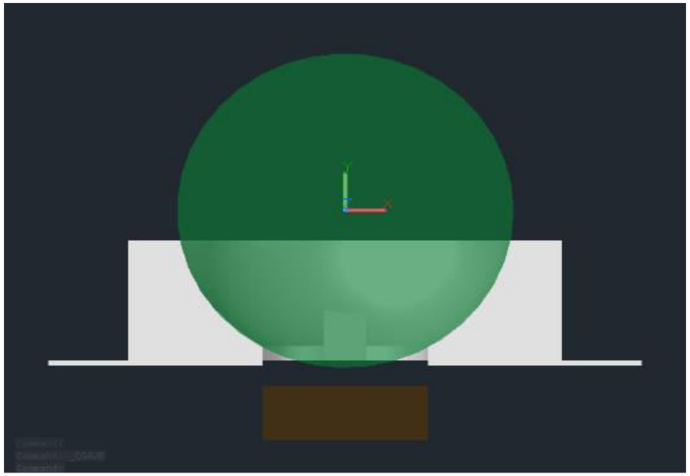
- Fixed Housing automatically centers the sphere and prevent sphere from departing the bearing area while in use





Top View of Resting Stand with NEWWAY Air Bearing Below



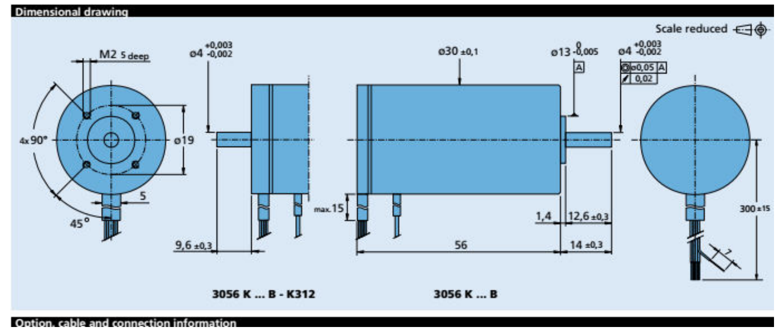


- Sphere is secured when **not** in use
- Additional stand for underneath storage

Reaction Wheels & Power

Motor

- Angular momentum required by performance specs: 0.035 Nms
  - Simulator capable of up to 4°/s
- Faulhaber Series 3056 012 B
  - Rated for 33 mNm torque
  - max ω ~ 9000 rpm at 10 mNm

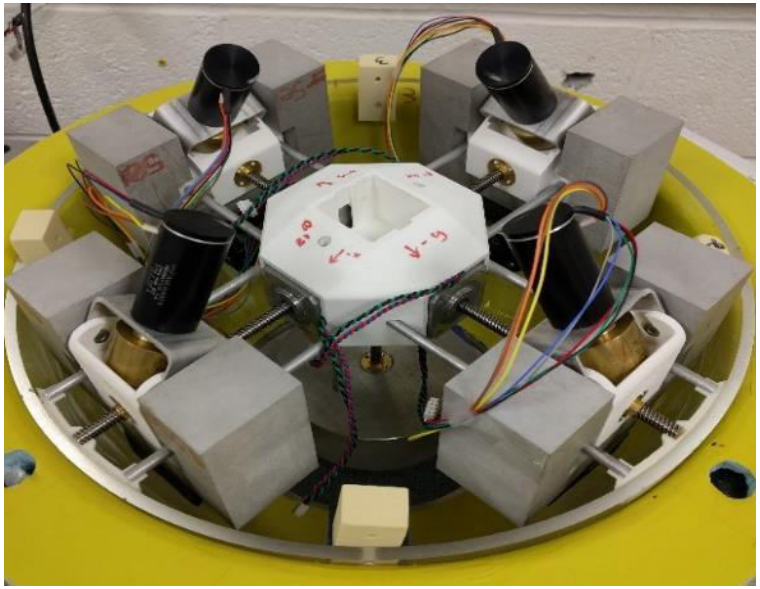


Power

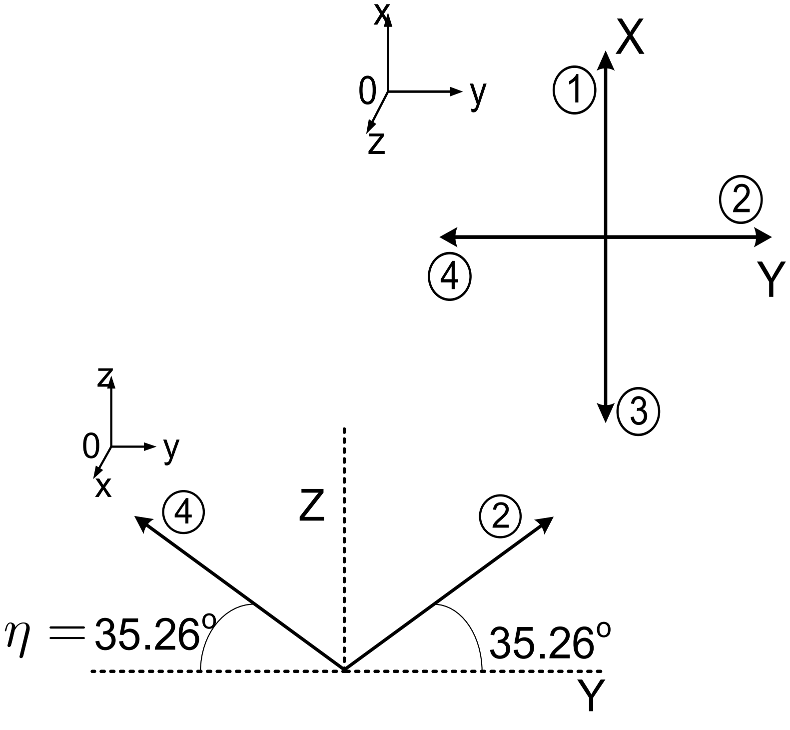
- 12 V Battery packs
- Able to run ~1.3 hrs
  - Only 15 min run time required

Reaction Wheels Assembly Design

$$\mathbf{Z} = \begin{bmatrix} \cos(\eta) & 0 & -\cos(\eta) & 0 \\ 0 & \cos(\eta) & 0 & -\cos(\eta) \\ \sin(\eta) & \sin(\eta) & \sin(\eta) & \sin(\eta) \end{bmatrix}$$



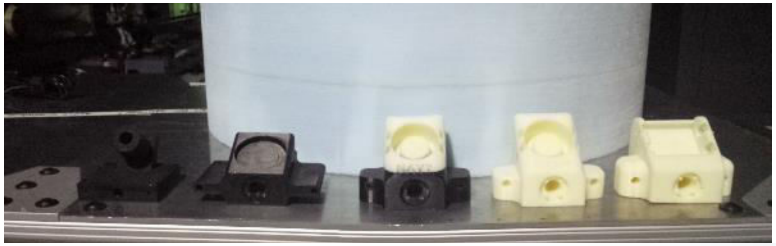
Internal Components of the Simulator

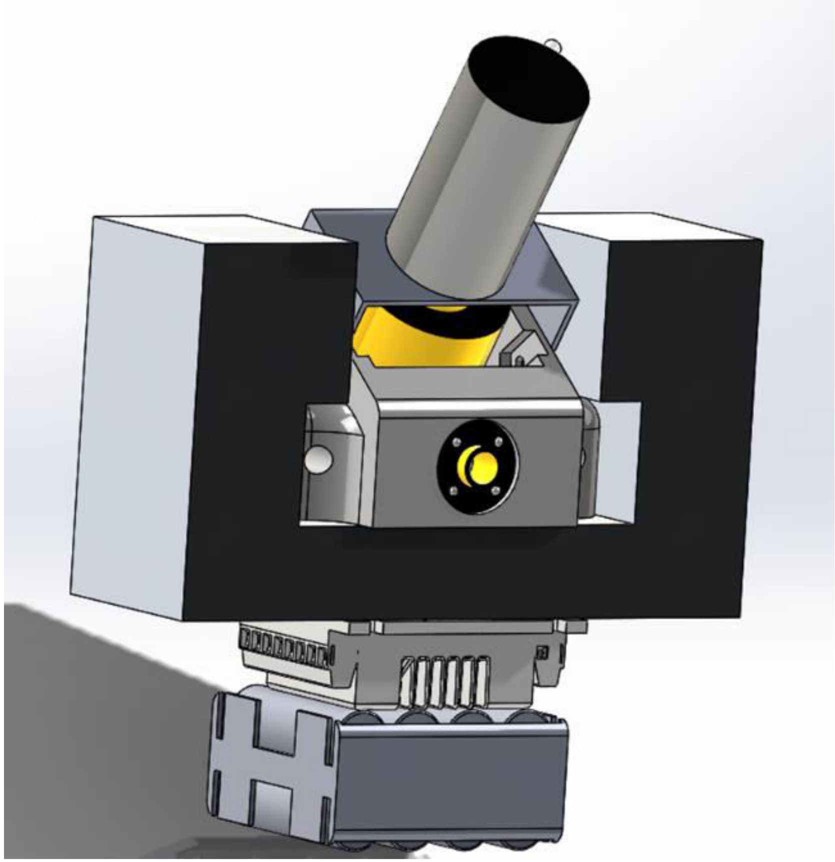


Four Reaction Wheel Configuration

X - Y Traveler Design

- Components
  - Reaction Wheels
  - Aluminum motor mount
  - Traveler Frame
    - 3D printed ABS
    - Threaded Rod Nuts
  - Aluminum counterweight
  - Speed controller
  - Battery Pack
- Dimensions
  - Total Mass = 2 kg
  - 7.5 inches tall
  - 6 inches wide
- Current Iteration of Traveler supports the initial 4 wheel 35.26° configuration.



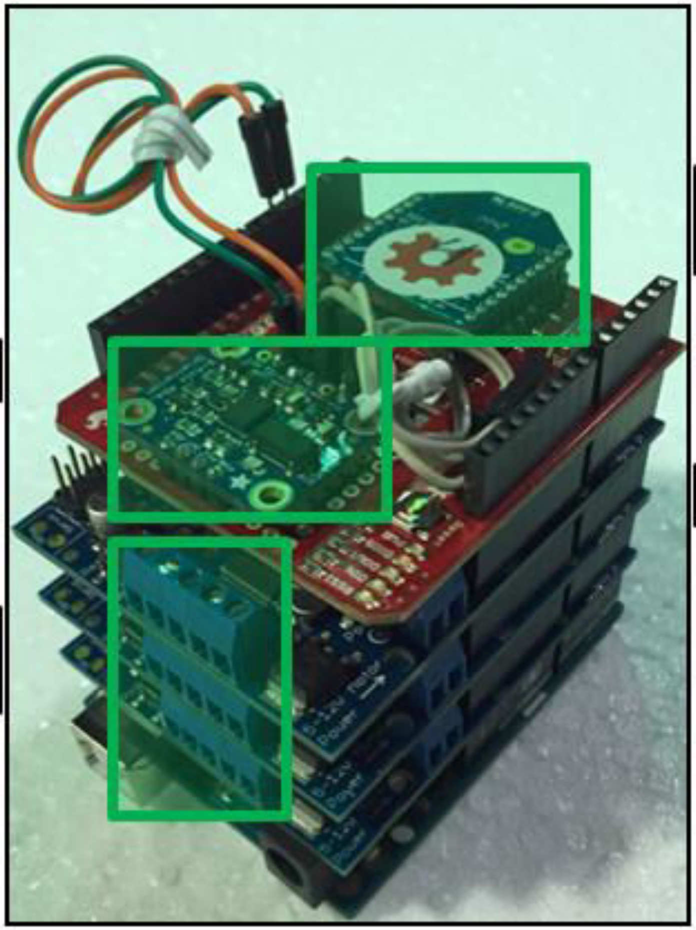


Moving the Travelers

- Stepper Motors and Threaded Shaft through the center of each traveler.
  - Motion is along Traveler Center of Mass (nominally)
- Stepper Motor moves Traveler mass in or out to achieve desired Inertia Ratios.
- Moving the masses change the Inertia Ratios
  - Desired, but also induces potential imbalances
  - Cross-coupling effects are significant
- Balancing is critical to eliminate external Torques
  - Center of Mass must be the same as the Center of Rotation
  - Inertia Ratios must remain constant during balancing which provides a challenge to the balancing algorithm

Stepper Motor with Threaded Shaft and Mounting Nut

Wireless Controls & Sensors



9DOF Fusion IMU

- Integrated into XBee shield prototyping area

Adafruit Motor Shield V2

- 3: motor shields
- 6: stepper motor control
- Each shield has unique hex address

XBee RF Module
- Series 1

- XBee module shield
- Power source
  - Arduino Uno

Unused Pins

- 4: pins used
  - Power
  - Ground
  - Analog 4
  - Analog 5
- Large potential for additional capabilities

USMS: Future Work

- Automatic Mass Balancing System
  - Currently, the USMS relies on manual estimation on where to reposition the masses and then the Inertia is recalculated to ensure constant inertia ratios
  - An automatic algorithm will be produced that will iterate until the masses are balanced and the inertia constraints are maintained
- Better Sphere design and manufacturing
  - The first generation spherical rotor was not manufactured precisely enough to ensure a symmetrical, spherical shape
  - Research into alternate materials, manufacturers, and mold methods is being conducted to solve this issue
  - Lower inertia
  - Minimal deformation
  - Strong and Transparent

Conclusions

- We believe it is possible to have a fully-functional, accurate, and flexible attitude control algorithm testbed for multiple spacecraft that does not restrict the direction of motion of the spacecraft
- We have shown how to simulate different satellites and their momentum control in a common system using Inertia Ratios
- USMS will provide the ability to demonstrate and validate new attitude control methods and algorithms on hardware that accurately represents the satellite performance at a fraction of the cost
  - Critically valuable for any program, but especially those programs whose budget or schedule do not allow for expensive testing apparatus

Acknowledgements

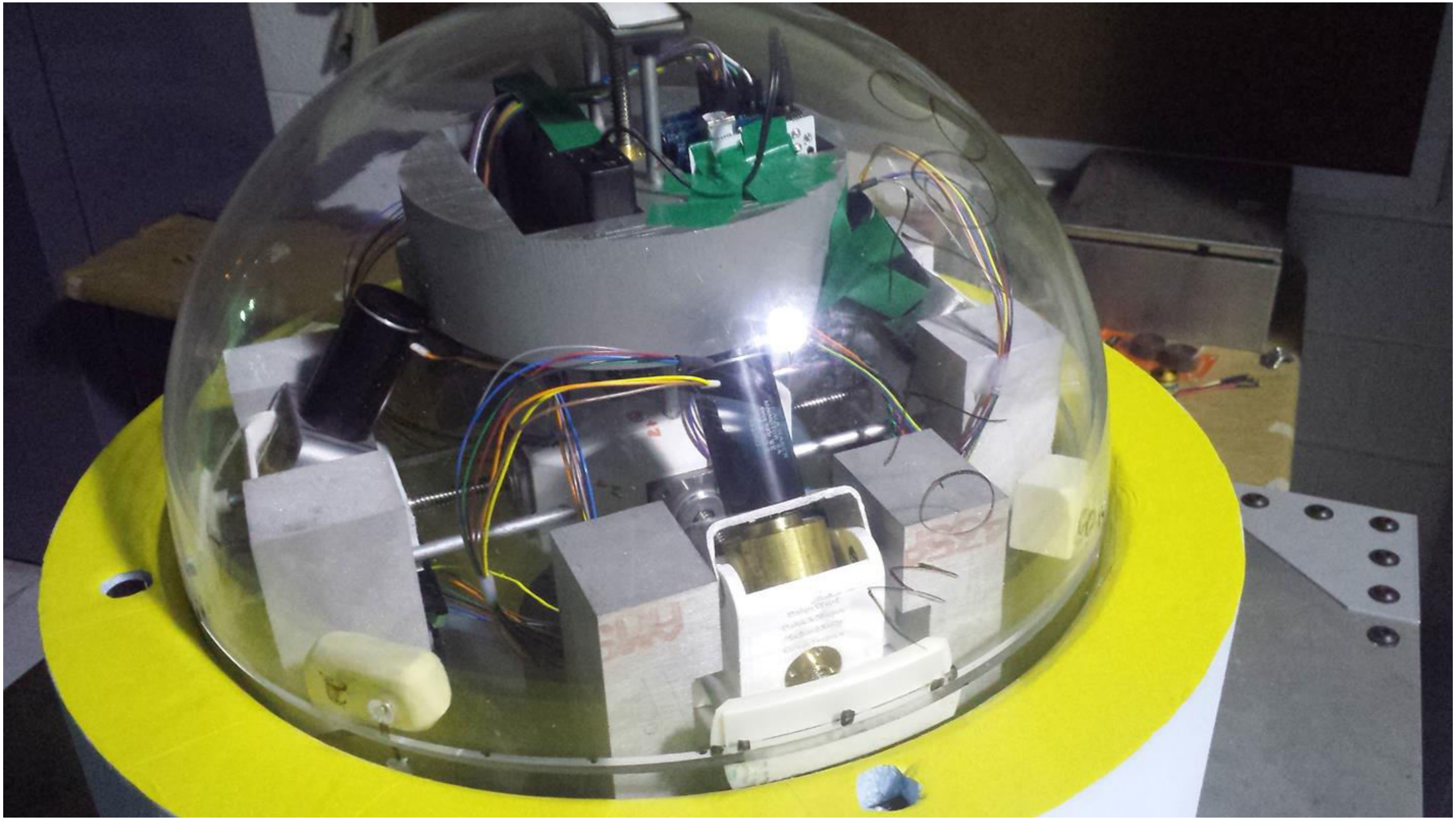
- We gratefully acknowledge the support from Dr. Mark Karpenko at the Naval Postgraduate School in funding and guidance.

- The views and conclusions contained herein are those of the authors and should not be interpreted as necessarily representing the official policies or endorsements, either expressed or implied, of the U.S. Government.

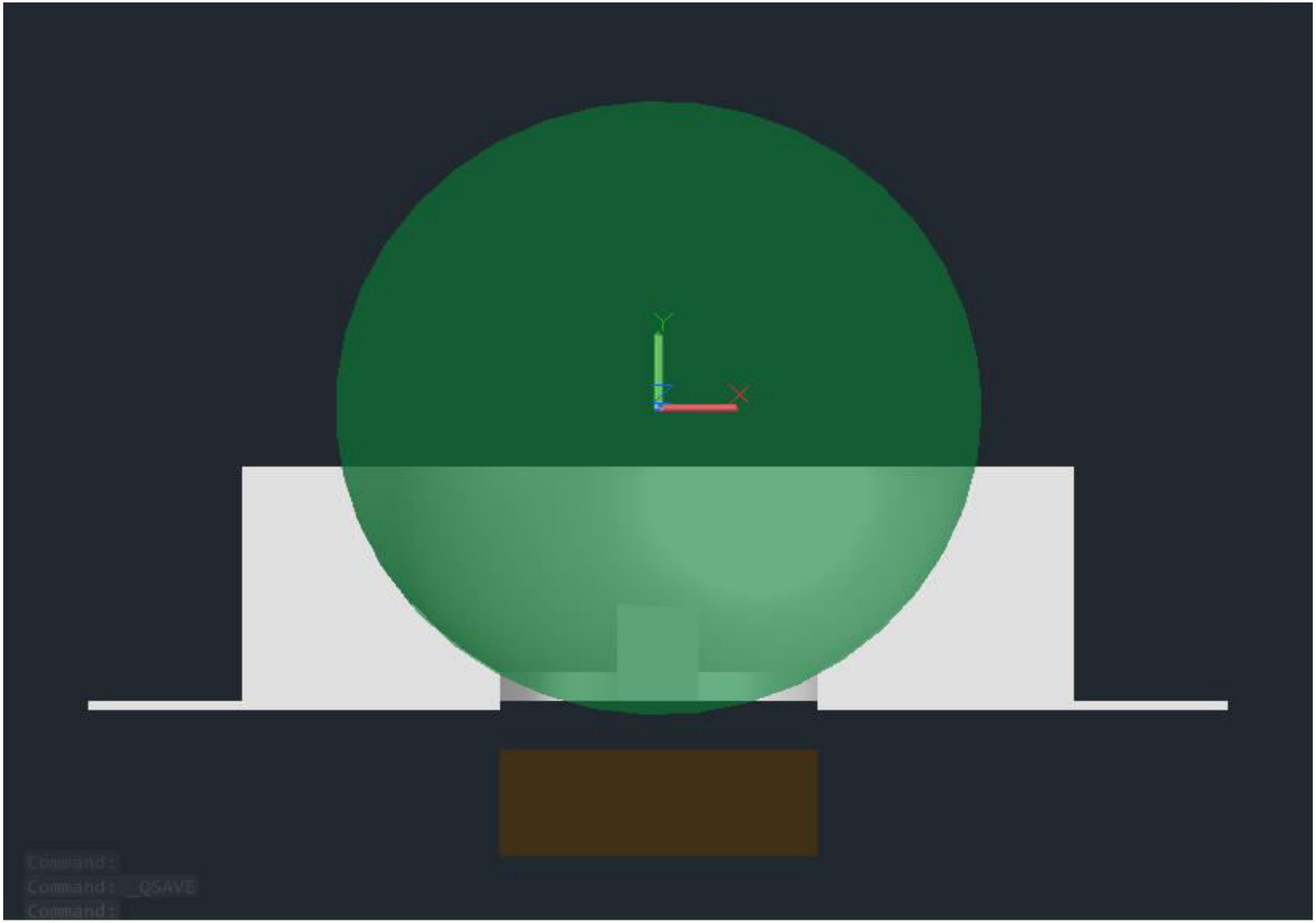
Questions?

Backup Slides

Assembled Sphere



Subsystem Design: Centering Mechanism



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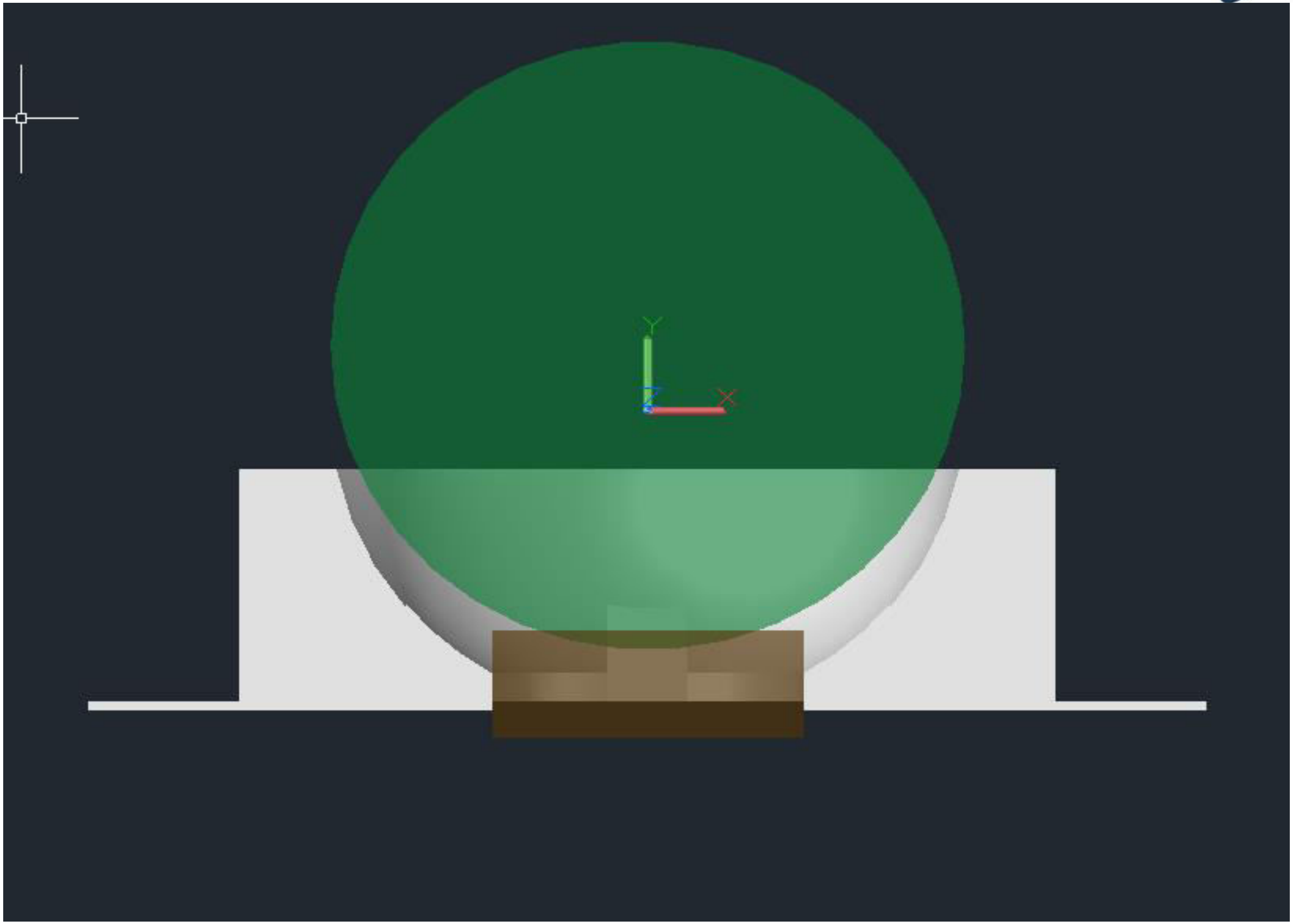
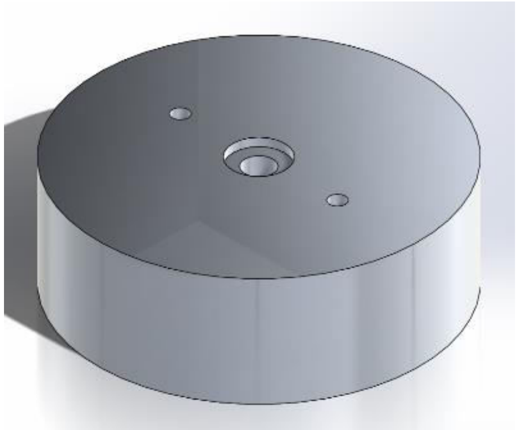
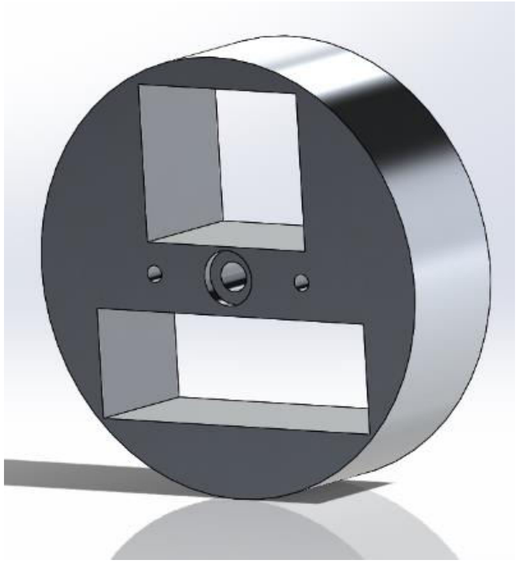


Subsystem Design: Traveler Final Design

- Aluminum body
- Purpose
  - Top
    - Mass for balancing and inertial determination
  - Bottom
    - Carry Arduino boards and batteries
- Dimensions
  - Total Mass Each = 2 kg
  - Top diameter = 5.5 inches
  - Bottom diameter = 7 inches



Top Traveler



Bottom Traveler