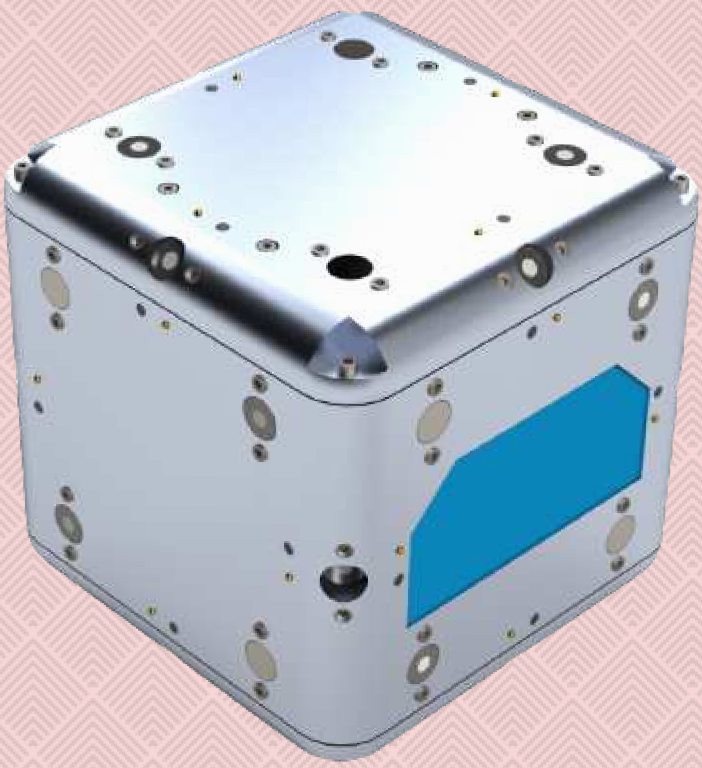
Team 3 | JPL | Design Center Colorado

Reconfigurable CubeSat Swarm

CubeSat units with reconfiguration capabilities to enable the creation of a modular spacecraft assembly.



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Introduction

Background

As humankind continues to push the limits of what is possible in space, our need to construct large structures in orbit will only increase. These structures are expensive to assemble on the ground, and require large rockets to take them to orbit. The obvious solution to this problem is to assemble the structures in space. Using the CubeSat design platform, as well as inspiration from existing projects, this project set out to create a magnetically actuated unit design meant to interface with other units to solve this problem.

Project Motivation

To design a reconfigurable CubeSat unit, used in a swarm of accompanying units, in order to create large, in-orbit super structures with the goal of reducing payload size, expenses, and allowing for dynamic reconstruction of units for unique situational requirements.

Design Inspiration

There were three existing projects that inspired our design. They were TESSERAE, Planar Catom, and M-Blocks. From these projects the biggest inspiration drawn was the idea of using electropermanent magnets in our flight-ready design, while also guiding some of our initial approach to the idea.

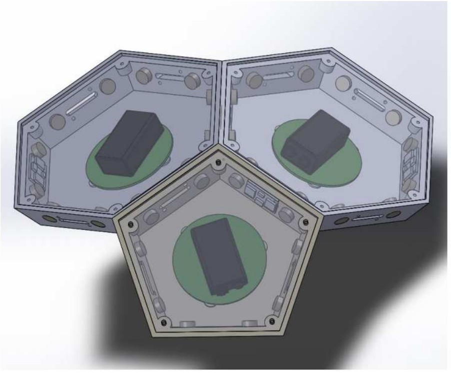


Figure: TESSERAE[1]

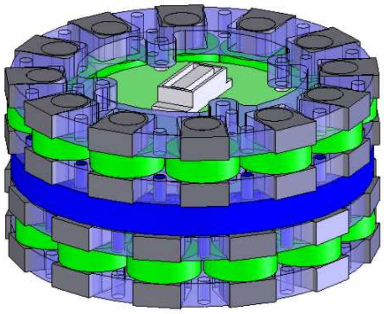


Figure: Planar Catom[2]

Figure: M-Blocks[3]

1.Ariel Ekblaw, Elisheva Shuter, and John Paradiso. "Self-Assembling Space Architecture: tessellated shell structures for space habitats." MIT, https://arc.aiaa.org/doi/abs/10.2514/6.2019-0481

2.Brian T. Kirby, Burak Aksak, Jason D. Campbell, James F. Hoburg, Todd C. Mowry, Padmanabhan Pillai, Seth Copen Goldstein. "A Modular Robotic System Using Magnetic Force Effectors Summary." Carnegie Mellon, https://www.researchgate.net/publication/221067363_A_modular_robotic_system_using_magnetic_force_effectors

3.MIT's Computer Science and Artificial Intelligence Laboratory (CSAIL). "Self-transforming robot blocks jump, spin, flip, and identify each other." CSAIL, https://news.mit.edu/2019/self-transforming-robot-blocks-jump-spin-flip-identify-each-other-1030

CubeSat and Magnet 101

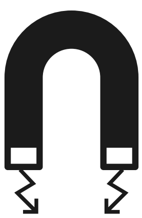
What is a CubeSat?

A CubeSat is a miniaturized satellite that is built with standardized dimensions. They are typically auxiliary payloads on research flights and are used for a wide variety of applications!

Magnet 101

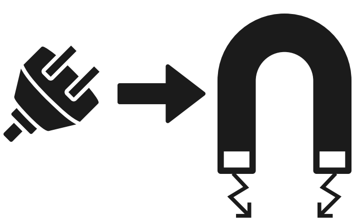
To ensure the CubeSats do not have permanently fixed links, magnets that can turn the magnetic properties on and off will be used to perform both the rotation and keep the cubes together during the passive state. Electromagnets (EMs) and Electropermanent magnets (EPMs) are able to change the magnetic properties based on electrical current and will be implemented in both the prototype and flight-ready design.

Permanent Magnets (PMs)



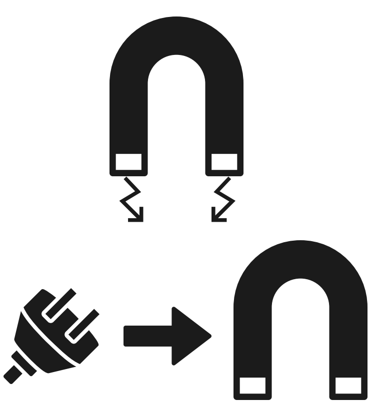
Retains magnetic properties with or without an induced field or current.

Electromagnets (EMs)



Magnetic properties are turned on when a current is passed through wires wrapped around a metallic core. When there is no current, the magnetic field will disappear. Force and polarity can be adjusted by varying the amount and direction of current inputted.

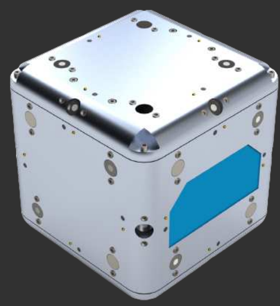
Electropermanent Magnets (EPMs)



Magnetic properties are turned off when a current is passed through a permanent magnet core with an electromagnet coil and an outer ferrous casing. When there is no current, the magnets will be constantly on and magnetized with full holding force. Typical EPMs can not switch their polarity but the level of force can be varied. They cannot attract each other on the faces so steel plates will need to be incorporated.

Project Goals

Flight-Ready Design Goals



- Select semiconductor components that would withstand vibration, thermal elements, and radiation that exists in Low Earth Orbit.
- Minimize power requirements.
- Approximate measurements of 12cmx12cmx12cm.
- Rotate without any fixed links.
- Implement a method of communication for short range inter-CubeSat communication.
- Implement a confirmation sensor to confirm rotation.
- Develop method of charging between CubeSats.
- Integrate a microcontroller that would work well with selected sensors and communication components.
- Design thermal regulation system based on analysis.
- Actuation with electropermanent magnets and electromagnets.

Prototype Design Goals

- Create a functional prototype unit on Earth.
- Approximate measurements of 10cmx10cmx10cm (1U).
- Controlled on a 2D, flat surface.
- Maximum 5mm misalignment between units.
- Rotate without any fixed links.
- Electromagnet actuation.
- Integrate position tracking features.

Design Differences

Flight Ready	Prototype
Materials selected are space grade.	Body is 3D printed out of onyx and components are off the shelf.
Powered via battery and recharged via pogo pins, backup charging via solar cells.	Powered via a power supply wired to unit.
Designed for use in a no friction, low gravity enviroment.	Designed for use on Earth, where both gravity and friction are present.
Electropermanent magnets used on the faces.	Electromagnets used on the faces.
Electromagnets used on the corners.	Permanent magnets used on the corners.
Internal sensors are used to gather feedback on the reconfiguration.	External camera system with AR tags used to track motion during reconfiguration.

Prototype System Overview

The prototype was designed around our custom electromagnets, and in order to validate the concept on a 2-dimensional test stand on Earth only 4 faces were populated with those electromagnets. For initial testing, permanent magnets were used to act as a removable hinge for a rotation between cubes to pivot on (metallic disks supported by white plastic cylinders shown below). Although as an extension of the project, electromagnets on the corner were implemented so more than one rotation would be possible. The electromagnets on each unit were controlled by a Raspberry Pi single-board computer, which communicate over WiFi to a host computer. The QR-code-like label on top was used to accurately track the motion via cameras.

A single final prototype unit is shown above (left), as well as an internal view with all components included (right). An exploded view of all major components is shown below.

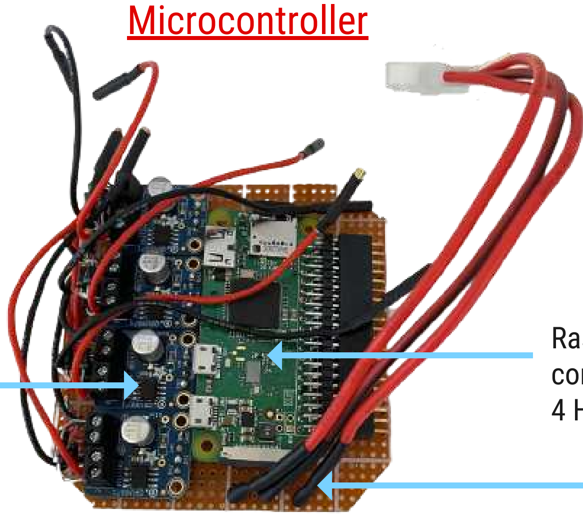
Electromagnets

Used to actuate the rotation. Custom made to operate at 40 Volts and 1 Amp, which produces 20 Newtons of force.

Onyx 3D Printed Enclosure

Houses all components. Onyx was chosen for its high heat deflection temperature.

Microcontroller



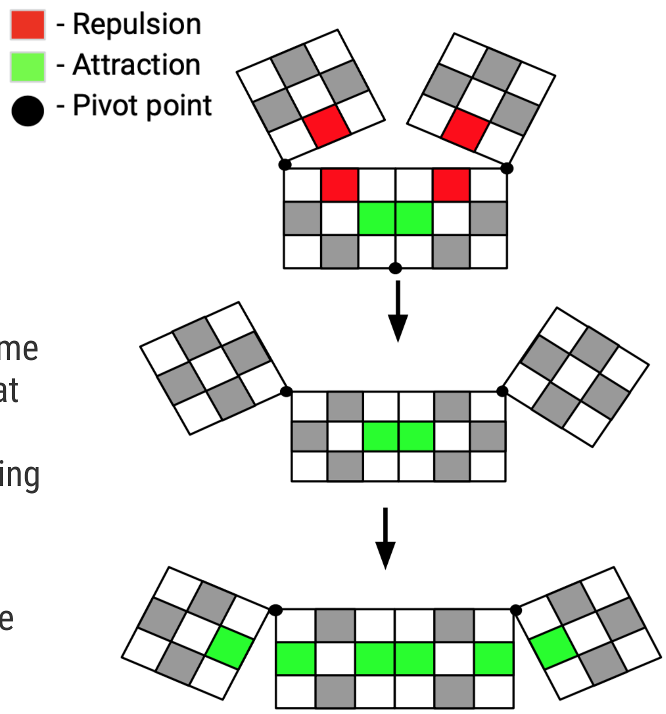
H-bridges are used to precisely control all 4 EMs

Raspberry Pi Zero is used to communicate and control all 4 H-bridges.

In from 40 Volt and 5 Volt power supplies.

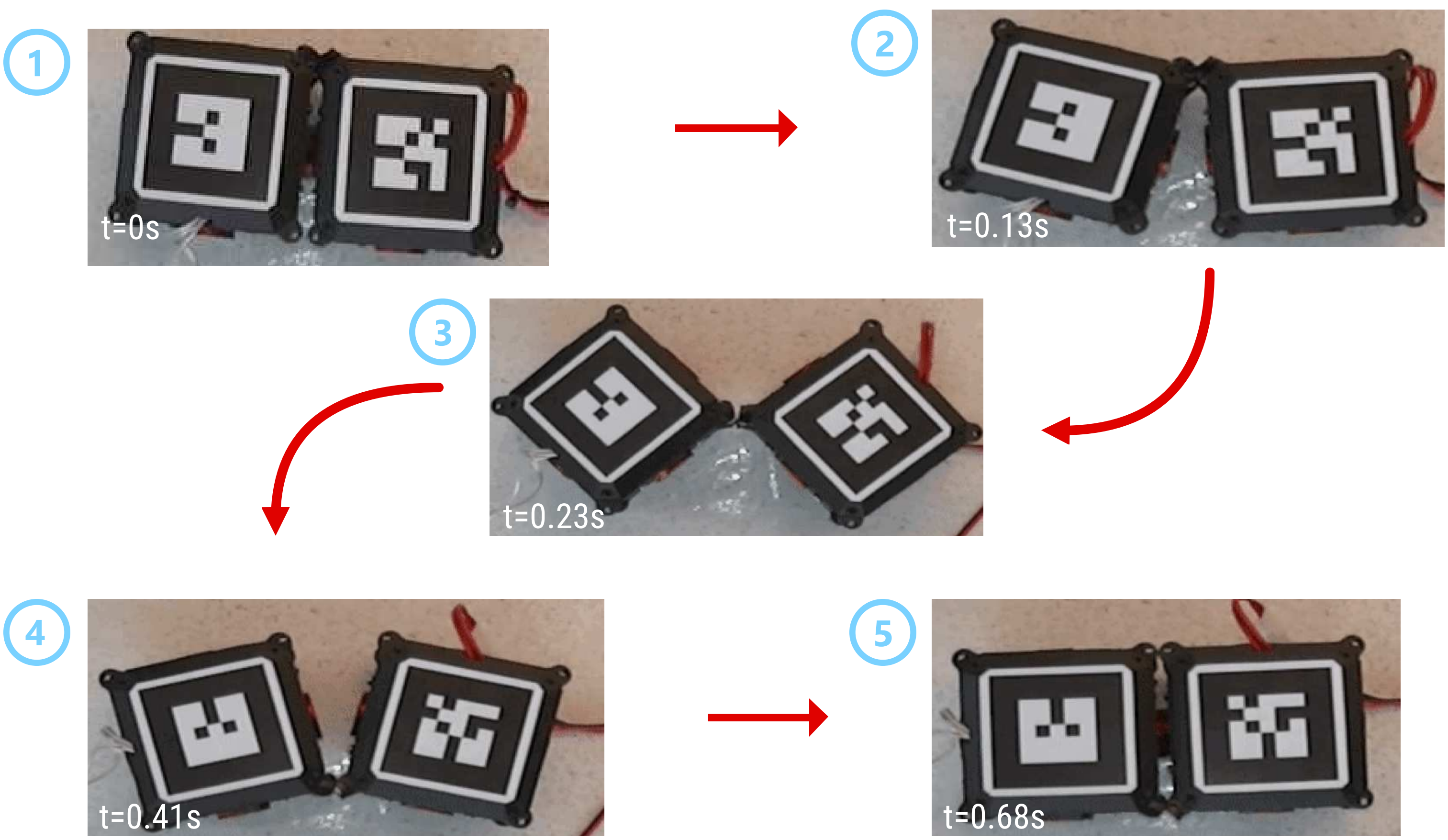
Prototype Operation

The prototype units act as a proof of concept for self-assembly of CubeSat swarms. The figure to the right illustrates how a set of four of these units could be reconfigured from a 2x2 cube to a 4x1 boom-like structure. The red and green squares represent the face electromagnets on each unit, where the color distinction indicates the repelling or attracting configuration used.



In order to test our prototype units on Earth, we had to overcome the force of friction between our CubeSats and the surface that we set them on. We selected a teflon surface with plenty of teflon-silicone lubricant to minimize the effects of friction during these tests. Additionally, each unit rolls on stainless steel casters.

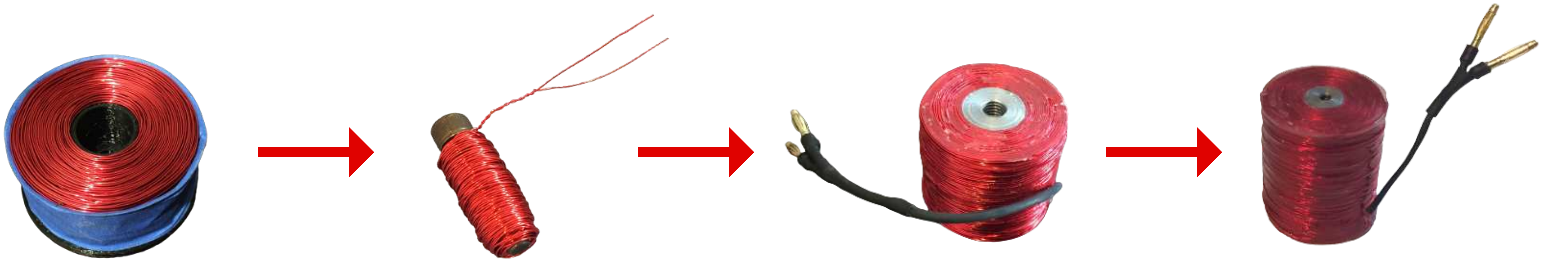
Below are consecutive frames in a single test showing how the rotation between two cubes is performed. Initially, each of the magnets on each unit that are touching are turned on in a repelling configuration. After the cubes have rotated 90 degrees with respect to each other, the opposite magnets are turned on in an attracting configuration, thus completing the rotation. One rotation takes less than a second.



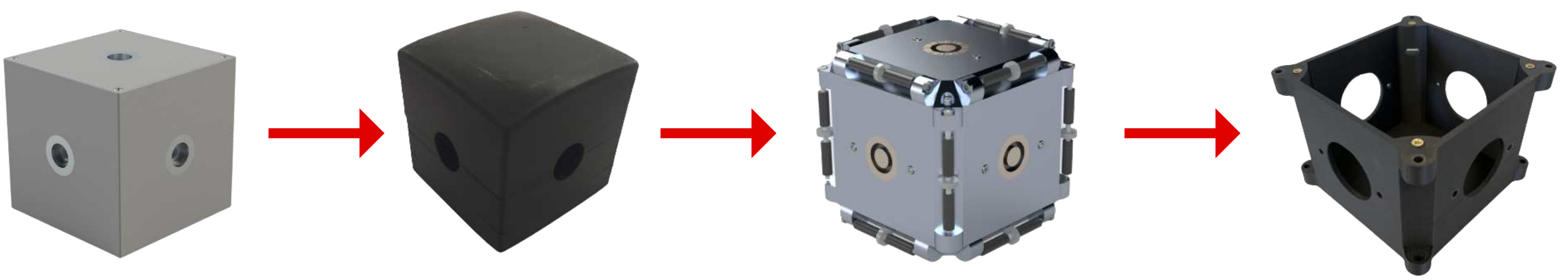
Prototype Journey

Final Results

Our set goal for the prototype was to demonstrate the feasibility of reconfiguring CubeSat units into different configurations, while using only the forces exerted by internal electromagnets. Through our thorough investigation of magnetic interactions, analysis of the reconfiguration dynamics and design optimization, our hand-wound electromagnets and test setup performed just as expected during our first few tests. The tests that we performed, and the data that was collected, has proven that CubeSat swarms actuated solely by electromagnets have the potential to assemble in space.



We went through many iterations of our electromagnet design. From left to right: first hand-wound air-core electromagnet, first ferrous-core electromagnet wound around a bolt, first FEA optimized design, and final electromagnet design.



The enclosure design developed throughout the design process. From left to right: conceptualized CubeSat with one electromagnet per face, test print out of PLA, further developed one electromagnet-per-face design, and final print out of Onyx.

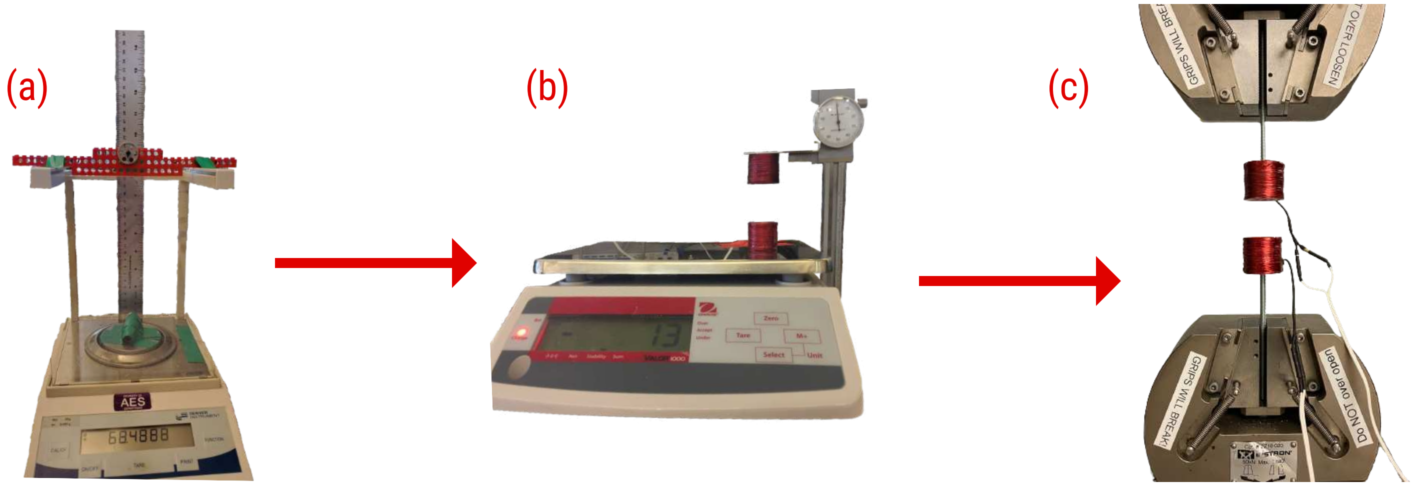
Learning Experiences

This project presented many technical challenges from designing a manufacturable and readily assembled enclosure to selecting an optimal electromagnet design and controlling the rotation through suitable electronics and software. Designing the enclosure took many design, test and redesign cycles and fitting many components into such a small volume (10cm cube) was especially challenging. The electromagnet design selection consisted of many magnet design, test and redesign cycles with increasing fidelity in modeling, fabrication and testing. Our first test consisted of hand wound coils held together with tape held over an inaccurate scale to measure the force exerted. Our final tests consisted of a magnet design optimized via hundreds of FEMM simulations, magnets wound around iron cores and sealed in epoxy tested on a very accurate tensile testing machine.
The final prototype units consist of many specialized components, all of which went through iterative development and thorough testing. Through these processes we were able to apply knowledge from all aspects of our coursework, and learn many new skills such as FEA and advanced electromagnetic theory.

Prototype Verification ☑

Testing and Results

Friction was the biggest hurdle that needed to be overcome for the prototype unit. Therefore, one of the first tests we did was to determine the surface that would have the lowest coefficient of friction. We settled on stainless steel rollers on the bottom of the cube, and a Teflon sheet surface with silicone lubricant. This provided a coefficient of friction of 0.09 and was used to calculate the frictional force in order to make an informed decision on the strength of our custom magnets.



We also needed to test our electromagnets to confirm their force output. Originally, we did preliminary strength testing using scales and rulers (a and b), but then we moved on to using a universal testing machine (UTM) to get more accurate data (c). The curves that were generated from the UTM were compared with the theoretical results we got from the FEMM software and we used these force curves to approximate the amount of time it would take for the cubes to rotate. We found that time to be approximately one second. We also noticed during testing that the magnets became very hot, so we decided to test the temperature of the magnets when left on. To do this we created a voltage divider, and we used a thermistor and a resistor so we could measure the change in resistance. This change in resistance could then be used to calculate the change in temperature. We found that the magnets heated up from room temperature to about 60 degrees Celsius after being on for five minutes.

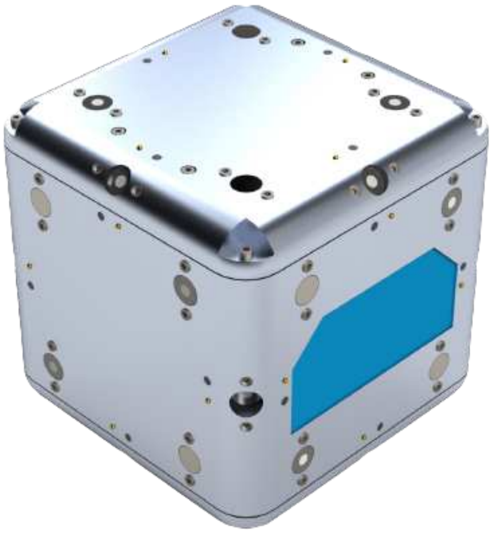
Future Work

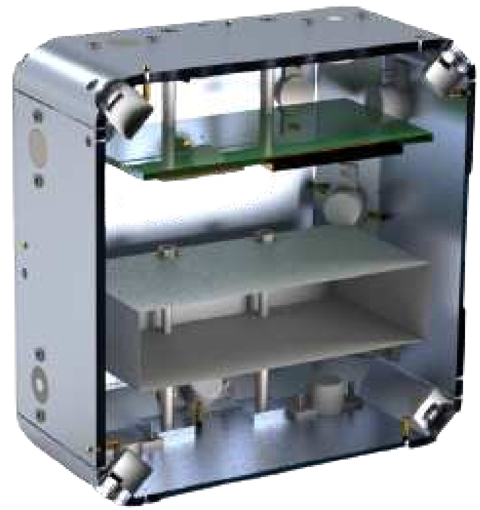
In order to further improve the prototype design, the permanent magnets at the corners would need to be more permanently attached to the enclosure. This could potentially be accomplished via epoxy, fasteners, etc. Instead of finding a method of attachment for the corner magnets, another consideration for these magnets is to replace them with EMs in order to improve the rotation of our prototype CubeSats and better simulate the EMs that would be present in the flight-ready design.

In addition to these improvements to our prototype and flight-ready designs, the team is also in the process of securing a spot on a ZERO-G flight offered by MIT. This flight would be used to test our prototypes in a microgravity environment, and would further prove the feasibility of reconfiguring CubeSats in space. The test results would be used to increase the fidelity of our prototypes, as well as inform and improve the flight-ready design. A collaboration between this project and MIT is currently taking place due to a shared interest in reconfiguration in space. MIT has extended the offer to assist with progressing this project by contractually sharing the information they currently have for an electromagnet design.

Flight-Ready System Overview

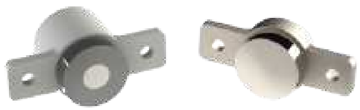
In order to make our design flight-ready, we had to account for satellite orbital conditions including vibration, thermal vacuum, and low levels of radiation that the CubeSats would be subject to in space. These units also needed to be powered wirelessly via a battery pack. In order to recharge the battery, pogo pins with mating contact pads were chosen because they are not reliant on a specific orientation relative to the Sun. Solar panels were used as a redundant recharging solution. All electronic components were selected to be as small as possible and consume minimal power.





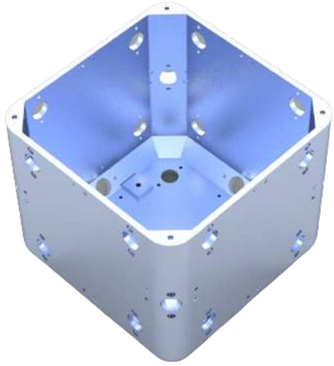
A single flight-ready unit is shown above (left), as well as an internal view with all components included (right). An exploded view of all major components is shown below.

Electromagnets, Electropermanent Magnets, and Steel Mating Plates



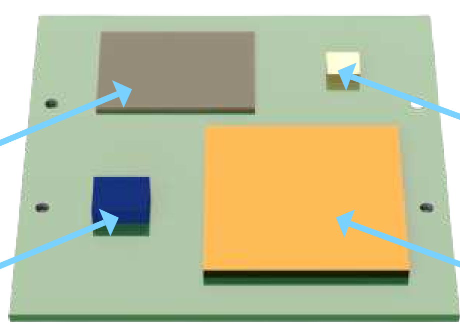
Our EMs are placed on the corners of our CubeSat to aid in rotation. Our EPMs are on the faces of our CubeSat to hold the cubes together. The EPMs and EMs appear identical (left). Our steel mating plates (right) are also on the faces of the CubeSat and mate with the EPMs.

Aluminum 6061 Enclosure



Houses all Components. Al 6061-T6 was chosen due to its spaceflight heritage, machinability, and affordability.

Custom PCB



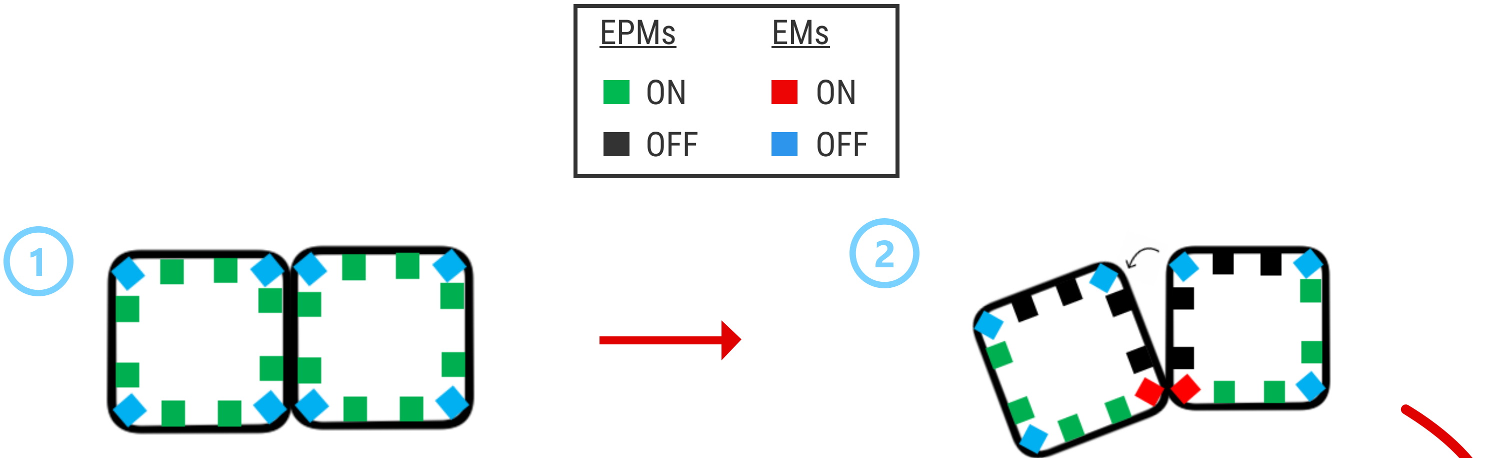
Military-grade Zigbee radio used for inter-CubeSat communication.

Inertial Measurement Unit with a 3-axis gyroscope used to confirm the full rotation of the cube.

Low-dropout regulator used to regulate the voltage coming from the battery to the PCB components.

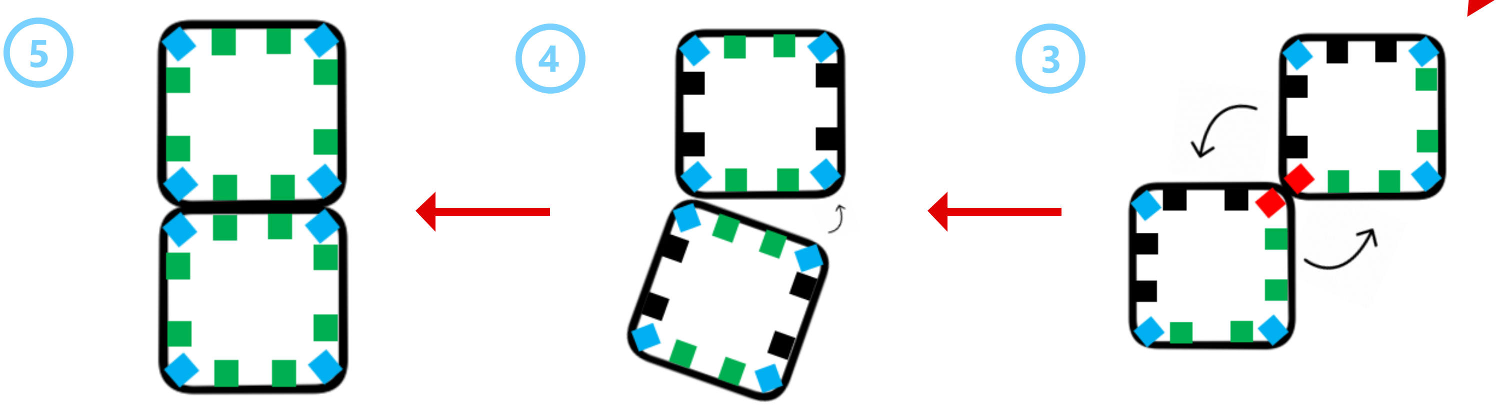
Radiation hardened FPGA, selected as the microcontroller (instead of the Raspberry Pi).

Flight-Ready Operation



All face EPMs are on and all corner EMs are off.

Radio sends commands to FPGA from host spacecraft. Adjacent face EPMs switch off and corner EMs switch on.



Now the rotation is complete. The IMU sensor confirms rotation and all EMs are turned off.

Adjacent face EPMs switch off to aid in rotation.

Coasting phase of our rotation.

The flight-ready design incorporates commercially available EMs with 3 Newtons of force in face-to-face contact, with a custom made stainless steel harness. The EMs for flight-ready design are 10 mm in diameter by 10 mm in height off-the-shelf Magma Magnets. Each corner of the cubes has 1 of these magnets, and will only be turned on to assist in a reconfiguration.

EPMs with 5 Newtons of force in face-to-face contact, also with a custom made stainless steel harness, are used in the flight-ready CubeSats. The steel plates that mate with the EPMs are custom made with a harness attached. Similar to the EMs, the EPMs for the flight-ready design are 10 mm in diameter by 10 mm in height off-the-shelf Magma Magnets. Each of the CubeSats have 2 EPMs and 2 steel plates on faces of the cubes.

EPMs are best used on the faces of the flight-ready cubes since they will be used to hold the cubes together. During reconfiguration, some of the adjacent face EPMs need to be turned off depending on the orientation of the cubes. Due to the usage of EPMs on the faces and EMs on the corners, there will be a higher power consumption during rotation and a lower power consumption outside of rotation. Since the cubes will be outside of rotation for a longer period of time to hold a shape, it is important there is lower power consumption outside of rotation.

Flight-Ready Journey

The Strategy

Funding

JPL asked us to develop a *theoretical* flight-ready design since we did not have the funding or accessibility to build this design and send it into orbit.

Initial Research

We looked at many research papers in order to study CubeSats and make theoretical decisions about our design.

Brainstorming

Since our CubeSats' desired capabilities were unique to the ones studied in past designs, we consulted with a CubeSat engineer and JPL to make further decisions.

Theoretical Testing

We explored components without spaceflight heritage and studied how they would react to vibration, thermal expansion, and radiation.

Final Design

We examined how components in the design, such as magnets, would interfere with other components in the cube before finalizing our design.

Learning Experiences

We learned about types of radio communication used in CubeSats and examined a theoretical method of inter-CubeSat communication. Traditional methods of ground-to-satellite communication, such as UHF / VHF and S Band radios, have bulky transceivers that consume lots of power. Since close range inter-CubeSat communication is a relatively new concept, we were compelled to choose a radio that has not yet been used in Low Earth Orbit. We chose a military grade Zigbee radio that has been used in unmanned systems and theorized how it would react to vibration, thermal expansion, and radiation.

The ultrasonic sensors that we originally chose for the prototype do not work in Low Earth Orbit. We looked at laser rangefinders, but these were bulky and did not work well at close range. We looked at magnetometers, but the interference from the magnetic field generated by the corner and face magnets would be problematic. We looked at accelerometers, but learned that they would not work with respect to gravity. Ultimately, we decided on an Inertial Measurement Unit sensor, which includes a 3-axis gyroscope, to derive angular acceleration and calculate angular displacement.

It was imperative to choose a microcontroller that would use as little space and power as possible. Rather than an on-board computer, we opted for an FPGA. This FPGA would communicate through the radio to a computer on a separate satellite. This FPGA is radiation hardened and has flight heritage, meaning it should not be problematic when compared to other components in the CubeSat.

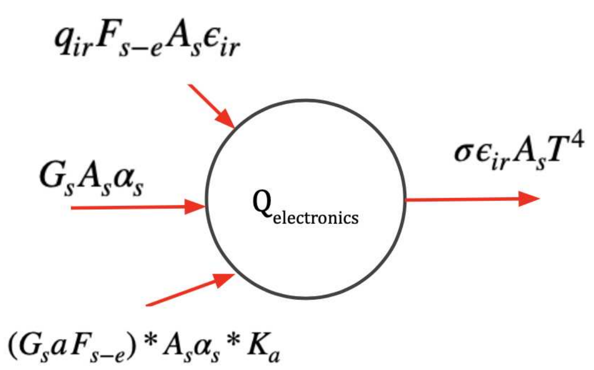
Flight-Ready Verification

Because our flight-ready design wasn't built, we performed several forms of verification in order to prove the feasibility of our design, as outlined below.

Dynamics Calculations

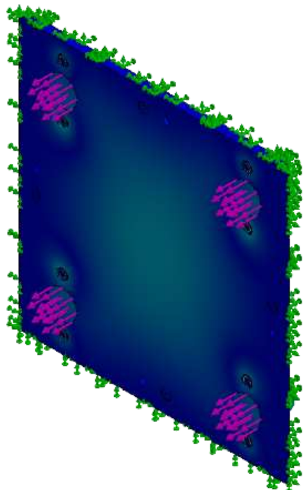
This dynamics calculations for the flight-ready design had to be done differently compared to the prototype because of the change in environment. Without gravity, there was no friction the cube needed to overcome. Also, the force that initially propels the cubes comes from the pogo pin spring decompression as opposed to the electromagnets in the prototype. These pins produce less force than the electromagnets (only 1.2 N), so the time it takes to complete a rotation increases to 85 seconds.

Thermal Analysis



A single spherical node, steady-state thermal analysis was completed in order to get a worst case temperature range for our CubeSats in an assumed ISS orbit (shown left). The resulting range was from -78.25 to 28.04 degrees Celsius, and when compared our critical electronics temperatures, this range was concluded to be too cold. This could be corrected using simple thermofoil heaters.

Structural Analysis



In order to verify the structural integrity of our flight-ready design, we performed two primary simulations in SolidWorks. The first was an analysis on wall bending based on the force of the magnets pulling on the enclosure, and the second was the stress experienced by the pogo pins upon reconfiguration. We found both these failure modes to be unlikely with factors of safety of 1.96 and 21.8, respectively.

Future Work

Further improvements to the flight-ready design would need to be implemented in order for the units to be ready to manufacture and test. Firstly, increasing the fidelity of the custom PCB would need to be accomplished prior to implementing the FPGA, IMU, Zigbee radio, and other electronics to ensure that they can operate cohesively within the same PCB. Before including all of these electronics within the PCB, some of the electronics would need to be tested, specifically the IMU and Zigbee radio, to prove that they can withstand the vibrational, thermal vacuum, and radiation environments that they would be subject to in Low Earth Orbit. Finally, the potential for the pogo pins to scratch through the anodization on the CubeSat enclosure would need to be remedied. There is a potential to use G10 blocks to surround the pogo pins and contact pads to allow for slight misalignment and ensure the pins won’t scratch the aluminum. Self-aligning magnets could also be possible to implement, however, there are currently no powered self-aligning magnet options on the market.

Meet The Team

(Left to Right)

Jeremy Balderrama | CAD Engineer
Jeremy is majoring in Mechanical Engineering with a minor in Electrical Engineering. For this project, he has largely worked on the designing, manufacturing, and testing of the prototype CubeSats. This includes designing the CubeSat enclosure in SolidWorks, soldering and testing the electrical components, and assembling, testing and collecting data on the finished units. After graduation, he hopes to work full time in the aerospace or automotive industry.

Justin Cochrane | Logistics Manager
Justin is majoring in Mechanical Engineering with a minor in Business. For this project he has worked on the research and design of the electromagnets used in reconfiguration as well as their testing. For the flight ready design he worked in the design and selection of materials as well as performed structural load analysis. As logistics manager he managed all outgoing group communication and organized meetings among other roles. After graduation he will pursue a career focused in renewable energy based out of Denver.

Kai Cui | Test Engineer
Kai is majoring in Mechanical Engineering with a Space minor. In this project, she has mainly worked on the design of the prototype CubeSat and setting up the low friction test stand. For the flight ready design, she researched and selected various magnet types, selected materials for the enclosure, and assisted in the structural analysis. After graduation, she will be working as a thermal vacuum test engineer at the Crew and Thermal Systems Division of NASA Johnson Space Center.

Rebecca Gipe | Project Manager
Rebecca is majoring in Mechanical Engineering with a minor in Music. Her main contributions to this project were organizing and distributing the team's action items, and managing the overall project schedule to ensure deliverable deadlines were met. In addition to her managerial role, she assisted with the prototype microcontroller design, and then pivoted to the flight-ready power system design and thermal analysis. She will be working as a full-time engineer within the aerospace/defense industry after graduating in May.

Reid Glaze | Financial Manager
Reid is majoring in Mechanical Engineering, and is currently enrolled in the BAM program. In addition to managing and tracking the team's finances, he assisted with the flight ready design. Through research and consulting, he chose components that would work together to meet the functional requirements of the design. He explored the elements that these components would be subject to in Low Earth Orbit and used this information to make final selections.

Greg Lund | Software Engineer
Greg is majoring in Mechanical Engineering and Computer Science with a minor in Applied math. For this project he has mostly worked on the hardware and software for the prototype design. He headed the electromagnet finite element analysis and design selection in the first semester of the project, and was heavily involved in the electronics and software design to control the CubeSats. In addition he was involved in testing and data collection for the final design. In the fall he will be pursuing his Master's in Aeronautics and Astronautics at Stanford University.

Callum Schulz | Systems Engineer
Callum is majoring in Mechanical Engineering with a minor in Space. For this project, he mainly focused on the testing and data collection of the electromagnets as well as building a theoretical dynamics model and calculating the force requirements for the prototype design. For the flight ready design, he focused on outlining the dynamic operations of the cubes. After graduation, he will be commissioned by the Navy to work with nuclear reactors.

Lazarus West | Manufacturing Engineer
Lazarus is majoring in Mechanical Engineering. In this project, he contributed with the electromagnet research and electromagnet testing for the prototype. In addition, for the flight ready design he contributed by designing the CubeSat in Solidworks. Accounting for all components and making a complete assembly of the finished flight ready design. After graduation, he will be working as a manufacturing engineer with the OE&P team at Ball Aerospace.