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Active Permanent Magnet Attitude Control for CubeSats Using Mu-Metal Shielding

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Active Permanent Magnet Attitude Control for CubeSats Using Mu-Metal Shielding

An Undergraduate Honors College Thesis
in the
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2 Abstract

Cube-Satellites (CubeSats) are nanosatellites composed of cube shaped units, each nominally 10cm to a side and around 1kg in mass. Due to their inherent size and weight limitations, it is often impractical to use conventional attitude, or rotational, control methods such as thrusters on these small satellites [1]. Several methods, including magnetorquer rods and small reaction wheels, are often used instead of traditional methods to work around the size and weight limitations [1]. As a new alternative to these methods, a permanent magnet mounted on a rotatable shaft could be used to achieve attitude control. In much the same way that a compass aligns itself with the Earth’s magnetic field, a permanent magnet mounted on a rotatable shaft could be rotated out of alignment with the magnetic field. The torque generated as the magnet attempts to realign itself could be used to provide rotational control to a CubeSat. Such a system would be significantly lighter than most alternatives and require very little power to operate. In addition, through the use of a 16-bit magnetic encoder, maneuvers with the system would be very precise when target overshoot is compensated for. In the unlikely event of a failure, possibly in the motor providing the rotation, the magnet could be locked in one orientation relative to the satellite. This would result in a constant orientation for the satellite when the stationary magnet aligns itself with Earth’s magnetic field. This problem could be greatly mitigated through the use of a magnetic shield pushed or pulled into place by muscle wire. Once the shield is deployed, backup attitude control systems could be used. The author and another undergraduate honors student have already proven the concept of using a permanent magnet for spacecraft attitude control in 2015. The goal of this research is to advance this concept to a more practical state. These advancements will include the development of a failsafe using a Mu-Metal shield as well as reworking and documenting the testing methods for future researchers.

3 Introduction

Cubesatellites are nanosatellites on the order of 1kg in mass. These satellites serve a variety of purposes from instrument testing to data collection and are part of a program intended to open up spaceflight capabilities to universities and small organizations. There are limitations, however, to the capabilities of satellites at this scale, and these limitations are primarily due to size and weight restrictions. Most satellites need some method of controlling their rotation, or attitude. Traditionally, this is done with thrusters or large reaction wheels. On CubeSats however, it is impractical to store propellant for thrusters, and reaction wheels need to be much smaller [1]. Magnetorquers are another option, but are slower to rotate than the other two [1]. The upside to magnetorquers is, due to their design as electromagnets, when they are not powered on, they induce no torque. This acts as a failsafe in case of hardware malfunction, so that the satellite is not locked into one orientation, and backup control methods can be used. This research aims to provide an alternative to magnetorquers that exceeds their induced rotation rate with just as much failsafe potential.

3.1 Permanent Magnets as Attitude Control

The proposed attitude control mechanism involves the simple principal of a compass. When a magnet is rotated out of alignment with the Earth's magnetic field, if allowed to freely rotate, it will tend to realign itself with the field. By attaching something to the magnet, like a satellite, the torque induced by the magnet as it attempts to realign itself will be transferred to the satellite, causing it to rotate. This is the principal magnetorquers are based on, as they are just electromagnets. The same effect could also be achieved with a permanent magnet. Permanent magnets, as opposed to magnetorquers, require no power to generate a magnetic field, and depending on the power available, often exceed electromagnets in terms of field strength.

Mounting a permanent magnet on the end of a motor shaft would provide full rotational control to a spacecraft on one axis. For example, if the magnet were to start out aligned with the field, then rotated out of alignment by a certain angle θ, when the magnet realigns itself, the spacecraft would have rotated an angle -θ about the magnet's axis.

3.2 Previous Research

In 2015, the author and another freshman researcher began work on the project where another team had left off. The previous team had demonstrated the feasibility of using a motor and permanent magnet to achieve attitude control, doing a number of rotational, or slew, tests to gather data [2]. In 2015, the rotational tracking codes were reworked and more tests were ran, further proving the concept. However, despite the reworked codes, the testing environment and methods were not well documented. The test setup from 2015 can be seen in Figure 1 below. A BeagleBone Black computer controller with a Wi-Fi dongle was used to provide wireless control of the motor through a Secure Shell connection [3]. Geometric asymmetrical markers were used in conjunction with LabView machine vision to determine the orientation of the disk and permanent magnet [3]. The permanent magnet and motor are hidden underneath the close pair of geometric markers near the top of the figure. The magnet and motor are mounted vertically in reference to the Styrofoam disk that the assembly is affixed to. The entire assembly was placed in a shallow pool of water with a camera overhead to monitor the markers [3]. This provided a low friction environment for the magnet to be rotated out of alignment with the Earth's magnetic field and the torque generated as the magnet realigned to produce rotation in the disk. An average rotation rate of 1.54°/sec was recorded over several slew tests [3].

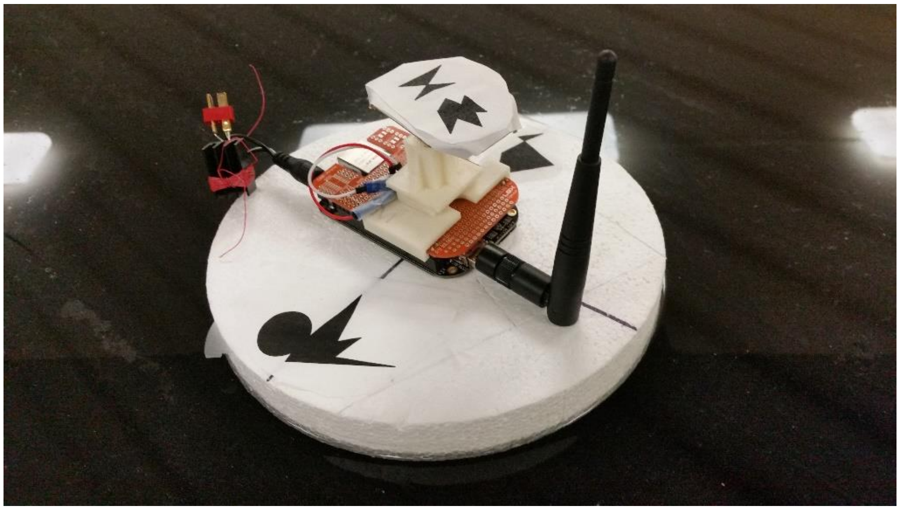

Figure 1: 2015 Test Setup [3]

4 Research Goals

4.1 Provide Failsafe Mechanism

Because permanent magnets constantly produce a magnetic field, a hardware failure, in the motor perhaps, would lock the satellite into one orientation without the ability to rotate the magnet. This could spell mission failure if no failsafe and backup control system is in place. In order to prevent a single component failure from jeopardizing an entire mission, a system to "turn off" the magnet must be developed.

4.2 Rework, Streamline, and Document Previous Research

While previous research provided proof of concept, each time the project was picked up again, the experimental methodology needed to be reworked. Whether because of program incompatibility or lack of documentation, this time was no exception. As part of the rest of the research, the testing methodology will be made as simple as possible to set up and will be well documented so as to make it repeatable for future researchers without as much upfront setup.

5 Hardware

5.1 Diametrically Magnetized Neodymium Magnets

The magnets used during this research are the same magnets that were used in the previous work done. In particular, they are diametrically magnetized Neodymium Iron Boron disk magnets [4]. Diametrically magnetized means that instead of the disk's flat surfaces being the north and south poles of the magnet, as they are commonly made to be, the north and south poles are instead lined up along the diameter of the magnet [4]. A picture of the magnet used and the manufacturers magnetization diagram can be seen in Figure 2 below.

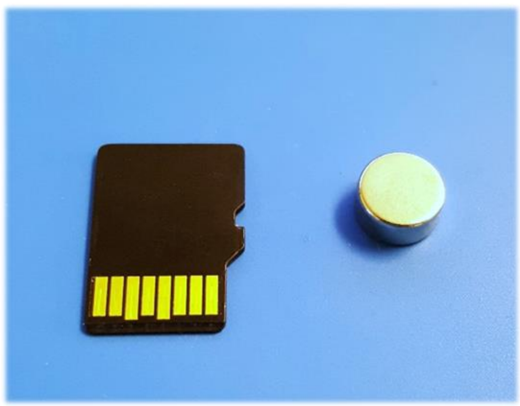

Figure 2: Actual Magnet (top, MicroSD card for scale) and Diagram (bottom) [4]

These magnets are 0.25" diameter by 0.125" thick, and have a surface field of 6898 Gauss [4].

5.2 Mu-Metal

The proposed failsafe system will need to neutralize the persistent torqueing effect of the permanent magnet. It was determined that an alloy known as Mu-Metal would be a good candidate to accomplish this goal. Mu-Metal is a proprietary alloy used in numerous magnetic shielding applications [5]. It is primarily composed of Nickel and Molybdenum but also contains trace amounts of Silicon, Manganese, Carbon, and Iron in varying quantities [6]. This particular alloy produces a material that has an extremely high electromagnetic permeability, and it is this property that gives the Mu-Metal its ability to shield magnetic fields [5]. Permeability quantifies how well a material contains an electromagnetic field within itself. Mu-Metal's high permeability means that it can redirect the strong magnetic field created by the Neodymium magnet through itself, greatly reducing the measurable field on the other side of the shield [5]. By using a canister made of Mu-Metal that can be pushed into place over the magnet and motor assembly, the magnet's interactions with the Earth's magnetic field can be greatly diminished. The Mu-Metal half cans used in this research are shown in Figure 4 below.

Figure 3: Mu-Metal Half Cans

These cans have an internal diameter and depth of 0.75" and a wall thickness of 0.032".

5.3 NiTiNol

NiTiNol is a Nickel Titanium shape memory alloy [7]. As it is heated to various temperatures, it undergoes a series of unique phase changes [7]. These phase changes can be used to revert the shape of a NiTiNol wire to its original set shape after a deformation [7]. In order to reverse the deformation, the NiTiNol must be heated up. This initiates the phase changes and can be done in a variety of ways. The most common way is by joule heating the wire with an electric current [7]. As an example, consider a straight piece of NiTiNol. If a sharp bend is made in the wire and then a current applied, the wire will snap straight again. This allows motion and actuation to be used in places where motors are impractical. The NiTiNol used in this research is 250 μm in diameter and can be seen in Figure 4 below. About 1” of this wire is used in this research. 5V at 1A of current was found to be sufficient power to activate the shape memory effect at this length.

Figure 4: NiTiNol wire used

5.4 Attitude Control and Shield Assembly

A housing for the motor, magnet, and shielding system was designed. It is shown in Figure 5 below.

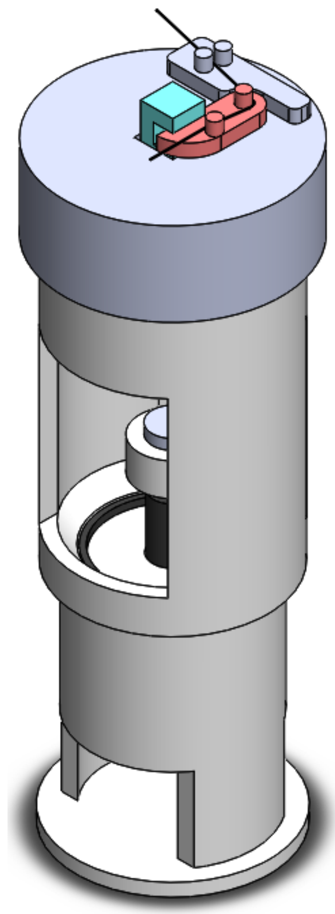

Figure 5: Control and Shield Assembly

Inside the assembly, an insert holds the motor in place in one of the Mu-Metal half cans. The magnet is in a holder which is press fit onto the motor shaft. Above this assembly is the other half can, which is press fit into a retaining cup with a hook on top. These components and their positions can be seen in the labelled Figure 6 below.

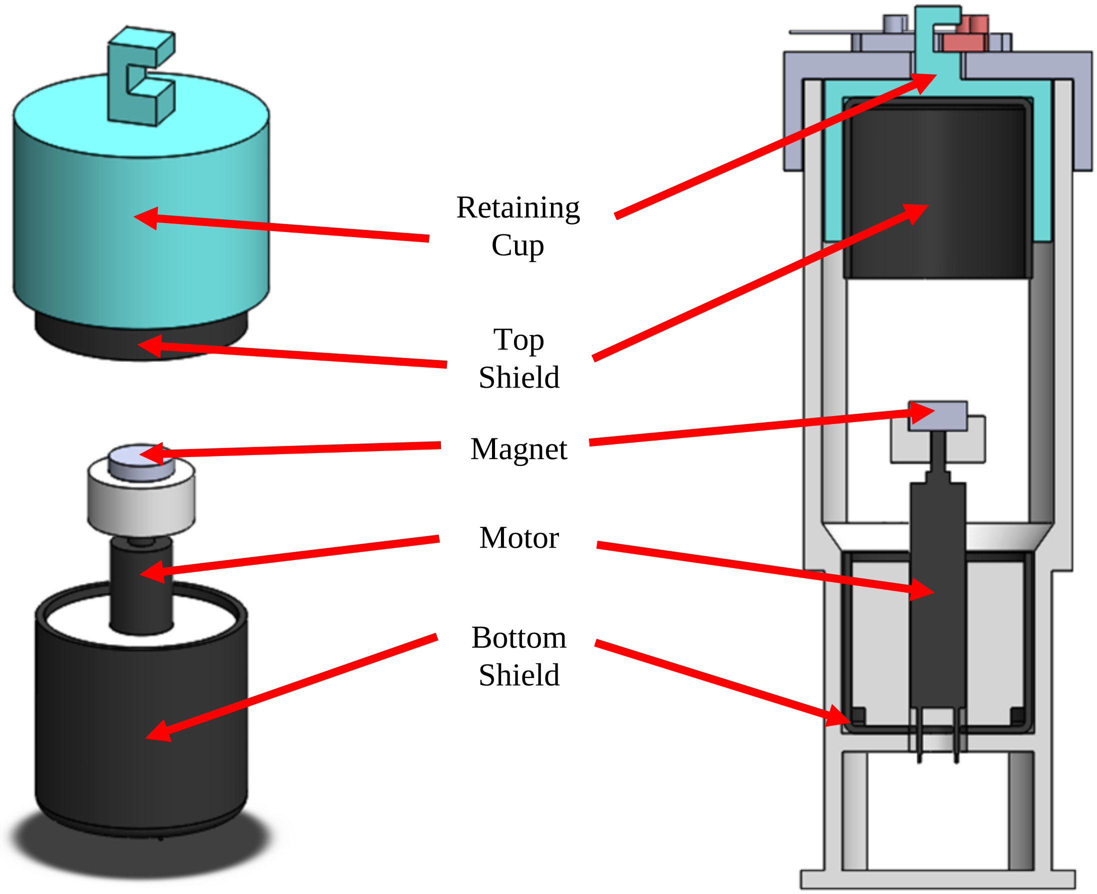

Figure 6: Motor and Magnet with Shield and Cross Section with Labels

At the top of the assembly is a latch that interfaces with the hook on the retaining cup. In Figure 7 below, the latch is in red and the retaining cup hook is in light blue. The latch and the cap it sits on, colored grey, have pegs on their surfaces. Threaded through these pegs is a piece of NiTiNol, colored black.

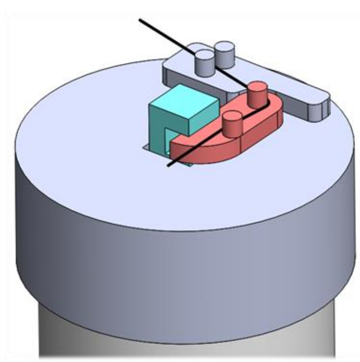

Figure 7: Shield Release Latch with NiTiNol

The NiTiNol is shape set to a straight wire. As can be seen, the NiTiNol bends around one of the pegs on the latch. The latch can pivot about this peg and when the NiTiNol is activated, it will straighten out, pushing against and rotating the latch and allowing the retaining cup to fall due to gravity. The inside of the frame is tapered inward at the bottom toward the edges of the bottom shield. This helps the upper shield to fall into place and interface more fully with the bottom shield. With the shield in the upward position, the magnet is able to interact with the Earth's magnetic field. When the shield drops, the two halves meet, sealing the magnet and motor inside and attenuating the field. All parts of this assembly except for the magnet, motor, Mu-Metal cans, and NiTiNol were 3D printed with ABS plastic. The Attitude Control and Shield Assembly is shown in Figure 8 below.

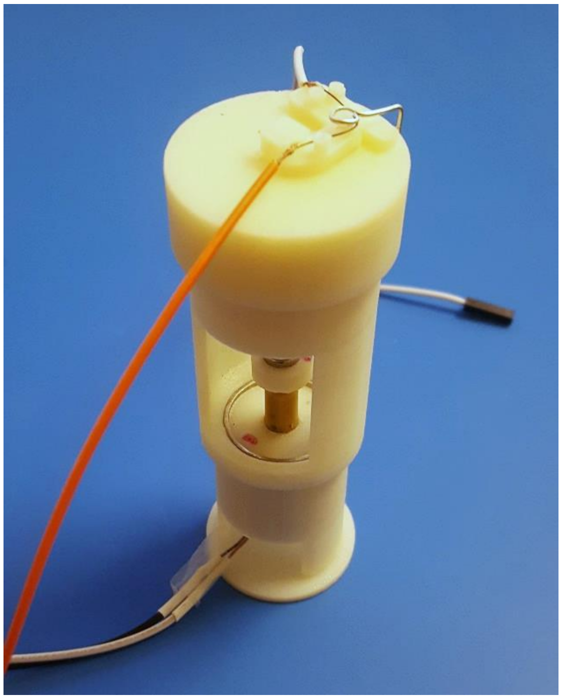

Figure 8: Attitude Control and Shield Assembly

5.5 Motor and NiTiNol Control

Control of the NiTiNol and motor is accomplished using a Raspberry Pi 3 Model B and some peripheral electronics. Control code for the Pi 3 was written in Python and used the Pi 3's general purpose input and output pins to interface with the rest of the electronics. The Pi 3's GPIO pins can only output 3.3V at a current insufficient for most applications outside of providing a signal. To work around this, two circuits were developed to provide power and control to the motor and NiTiNol. The first, shown to the left in Figure 9 below, uses an L293D Dual Full H-Bridge motor driver to accept signals from the Pi 3 and use them to drive the motor. The second, shown to the right in Figure 9, uses an electromechanical relay to switch power from a separate battery to the NiTiNol. The relay requires 5V to activate, so a 2N4401 bi-junction transistor is used to switch a 5V source on the Pi 3 using one of the 3.3V GPIO pins.

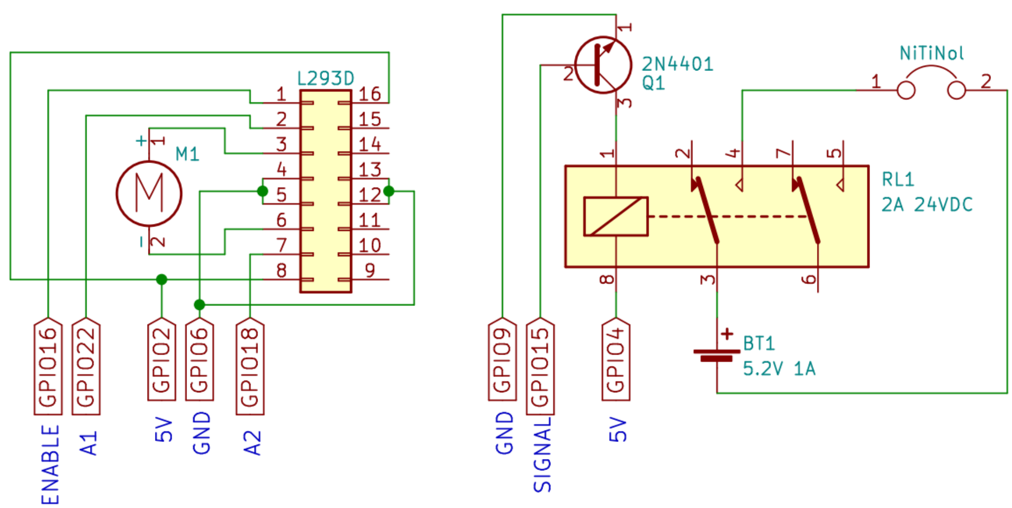

Figure 9: Control Circuit Diagram

After designing the circuit, it was implemented on a solderable breadboard PCB to reduce weight and size. The final implementation is shown in Figure 10 below.

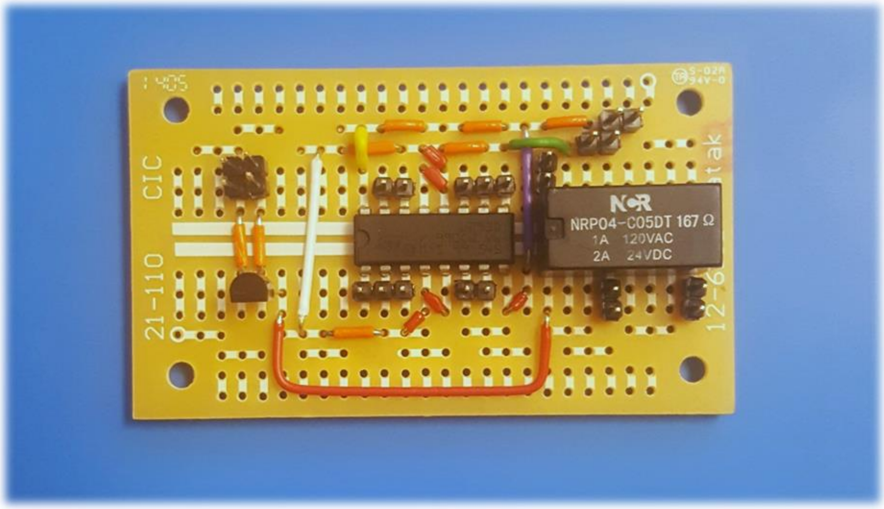

Figure 10: Control Circuit PCB Implementation

6 Software

6.1 OpenCV

Previous work done on this project used geometric asymmetrical, or fiducial, markers to keep track of the orientation of the disk and magnet. This tracking was accomplished in LabView, but the codes that were used previously were not ready to run upon opening and required setup unknown to the researcher. Instead of picking apart the existing code to make it work, the researcher elected to start from scratch to expand their own knowledge. As an alternative to LabView Vision, the researcher discovered OpenCV, an open source computer vision suite written in C++ that included libraries for the tracking of fiducial markers. The library is known as ArUco and, following a tutorial series, code was developed to use a webcam to track ArUco markers [8]. The tutorial series demonstrated the very basics of using the ArUco library to track markers. Two examples of these ArUco markers are shown in Figure 11 below, and these are the two markers tracked in the project.

Figure 11: ArUco Marker ID's 14 (left) and 36 (right)

Each marker has a unique ID in the library. The marker IDs used in the project are 14 (above left) and 36 (above right). Once translational tracking of multiple markers in the webcam's field of view was achieved, the researcher developed code to provide angular tracking using two markers. A vector was created from the origin of marker 14 to the origin of marker 36. This vector is shown as **V** in Figure 12 below. Figure 12 is a drawing of the webcam's field of vision and the method used to calculate angular orientation. Markers 14 and 36 can be seen near the center.

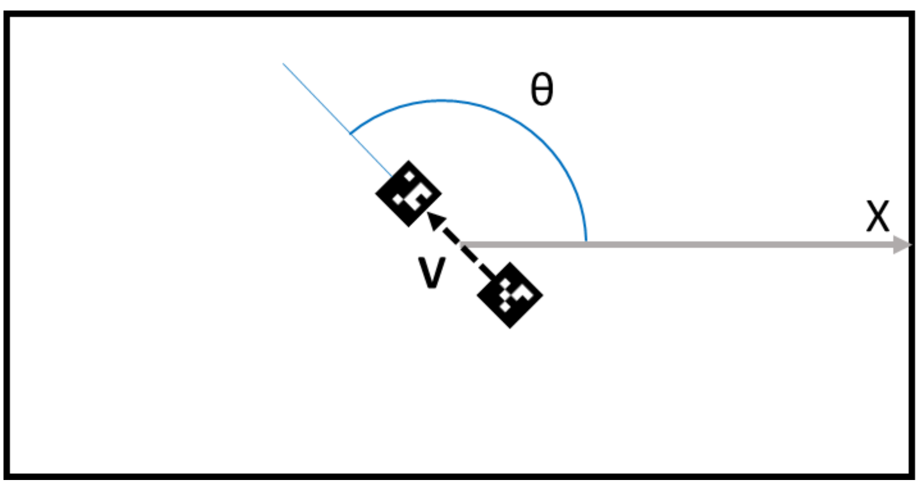

Figure 12: Webcam View Drawing with Angle Calculation Method

The X-axis is labeled and originates from the center of the webcam's field of view. The X-axis is positive in the rightward direction. **V** can then be normalized and the angle θ it makes with the X-axis calculated. By placing the two markers on an object in view of the webcam, this method can be used to track the rotation of the object over time.

7 Testing

7.1 Testing Environment

The testing environment is the same as the one used in 2015. A webcam is suspended on rails above a shallow tray of water, looking vertically down at the water. A metal weight with a hole drilled in it is placed in the water directly below the webcam so that it is submerged several inches under water. The hole in the weight interfaces with a long pin on the underside of the test vehicle to keep the vehicle from drifting while still allowing free rotation. The webcam is connected directly to a laptop, which is on a private Wi-Fi network for communication with the Raspberry Pi on board the test vehicle. The full test environment is shown in Figure 13 below.

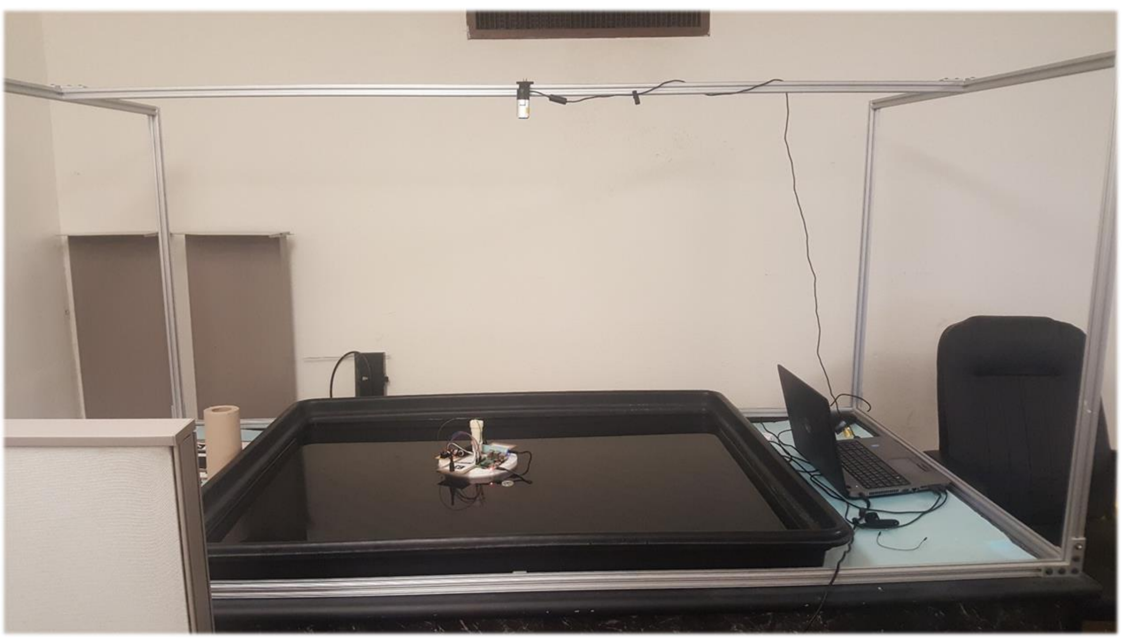

Figure 13: Testing Environment with Webcam, Pool, and Laptop

7.2 Test Vehicle

The test vehicle consists of all previously mentioned hardware mounted on a Styrofoam disk with a few added components and the ArUco fiducial markers. The test vehicle is shown in Figure 14 below.

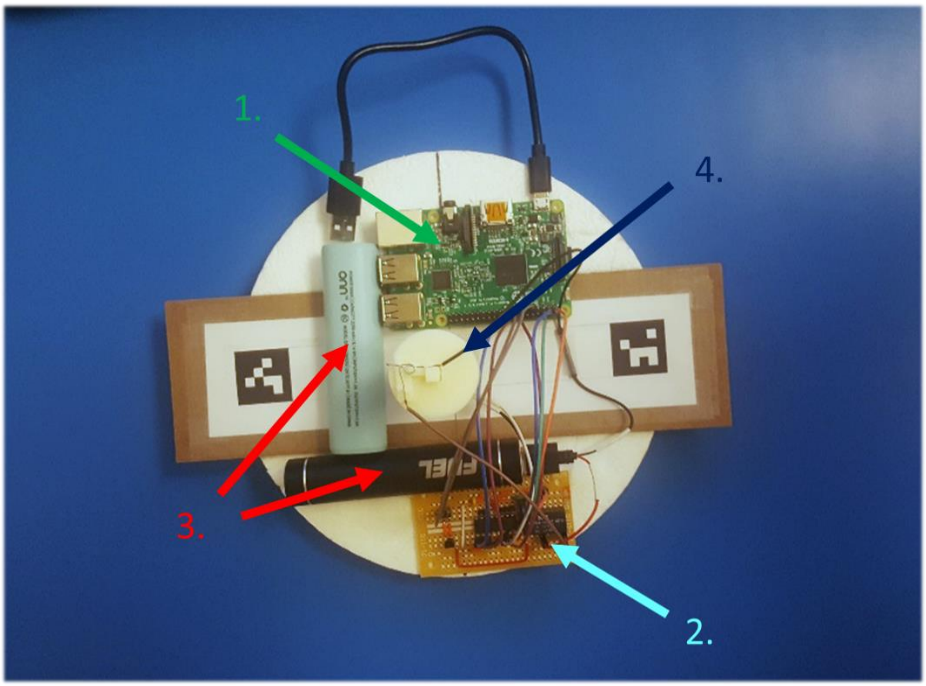

Figure 14: Test Vehicle

The numerical labels in Figure 14 refer to the following components:

1. Raspberry Pi 3 Model B
2. Control Circuit Board
3. Power Bank Batteries
4. Magnet Control and Shield Assembly

The Pi 3 is connected to the same Wi-Fi network as the laptop and is commanded from the laptop by Secure Shell. The power bank batteries each provide 5V and a maximum continuous current of 1A. One battery powers the Pi 3 and the motor and the other is dedicated to providing power to the NiTiNol. The magnet control and shield assembly is mounted upright in the center of the disk so that the torque generated by the magnet rotates the disk when it is placed in the water. The ArUco markers are printed on paper and then secured to cardboard to ensure that they lie completely flat, as any distortion would result in a loss of accuracy during tracking. The markers are placed seven inches apart and aligned with the center of the disk. Not shown is the thin wooden pin that interfaces with the weight at the bottom of the water pool. This pin pierces the bottom of the Styrofoam disk vertically at the center of the disk. Friction is sufficient to hold it in place.

8 Results

During the following tests, motor control was achieved by regulating the amount of time that the motor was on. Because the motor has a planetary gearbox, the out shaft rotates slowly. Through experimentation, it can be determined how long the motor needs to be powered on for to rotate the shaft approximately 90°. Because precision control is not critical to the testing of the magnetic shield, this level of control is sufficient for the scope of this research.

8.1 Shield Up Test

For an initial test, the shield remained in the open position while the magnet was rotated to various positions in order to slew the disk. This is analogous to the previous research done and ensures that the shield does not interfere with the magnet as an attitude control device when the shield is open. The test vehicle was placed in the water and rotation tracking was started. As the magnet attempted to realign itself, the disk began to slew towards and oscillate about -50°. This angular position (-50°) would be the orientation of the disk if the magnet were perfectly aligned with the Earth's magnetic field. When the magnet is rotated, this equilibrium position would change accordingly. In actuality the disk tends to overshoot and oscillate around this equilibrium position as a result of its own momentum. Thus, each result contains two plots, one for the equilibrium disk rotation, and one for the true disk rotation. This is the convention that will be used to explain the control maneuvers from here forward. A plot using this convention for the Shield Up test is shown below.

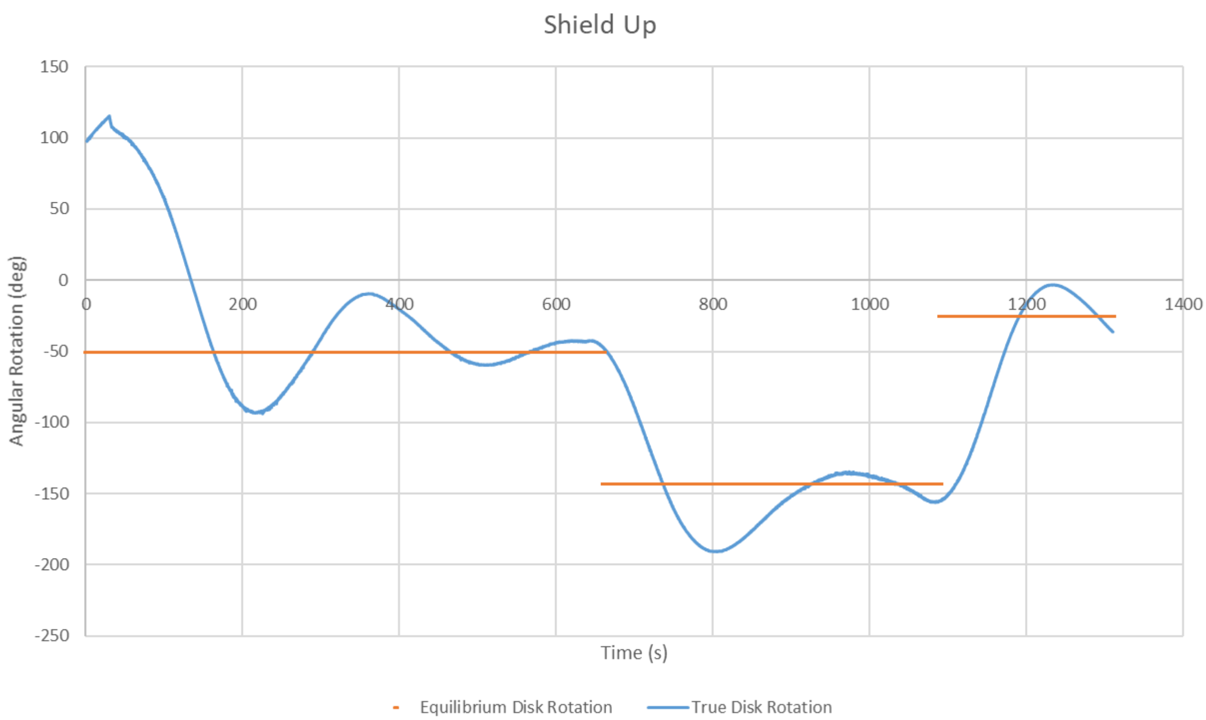

Figure 15: Shield Up Test Plot Over Time

As mentioned previously, at the start of the test, the disk began to slew toward and oscillate about -50° as the magnet attempted to align itself. Then, about 650 seconds in, the motor was commanded to rotate the magnet 80°. This resulted in a new disk equilibrium position of around -140°. The disk began its second slew toward this new heading and oscillated about it until the motor was commanded to rotate the magnet -120° at around 1100 seconds in. This change resulted in a new equilibrium disk rotation of -25°. The disk began its third and final slew toward this heading and the test was concluded shortly after the disk reached it.

The rate of the major portion of each slew was found by determining the slope of the position graph at the main part of the slew. The rates at which the disks rotated are tabulated below based on these calculations, along with an average.

Slew Rates for Shield Up Test			
First Slew	Second Slew	Third Slew	Average
1.73°/sec	1.45°/sec	1.66°/sec	1.66°/sec

8.2 Full System Test

Once the initial test was completed, the shielding system could be tested fully. At the start of this test, the shield was left open, and a few slew maneuvers were performed. Then, another slew maneuver was initiated and the shield was dropped in the middle of it. This cancelled the magnetic field of the permanent magnet, and thus the torque on the disk. The disk slowed, and then began to reverse direction and move to a new equilibrium. This new equilibrium is produced due to the uneven loading about the disks rotation axis. Because the disk is not completely level in the water, when no forces are acting on it, it naturally reorients to its lowest potential energy equilibrium position. From here, the magnet is rotated several times inside the shield to new theoretical equilibrium disk positions with no appreciable effect on the true rotation of the disk. Some oscillation can still be seen, but this is not related to the permanent magnet, but rather oscillations about the disk's new equilibrium. Some possible sources are air currents and vibrations in the building. A plot of the disk's rotation during the Full System test can be seen below.

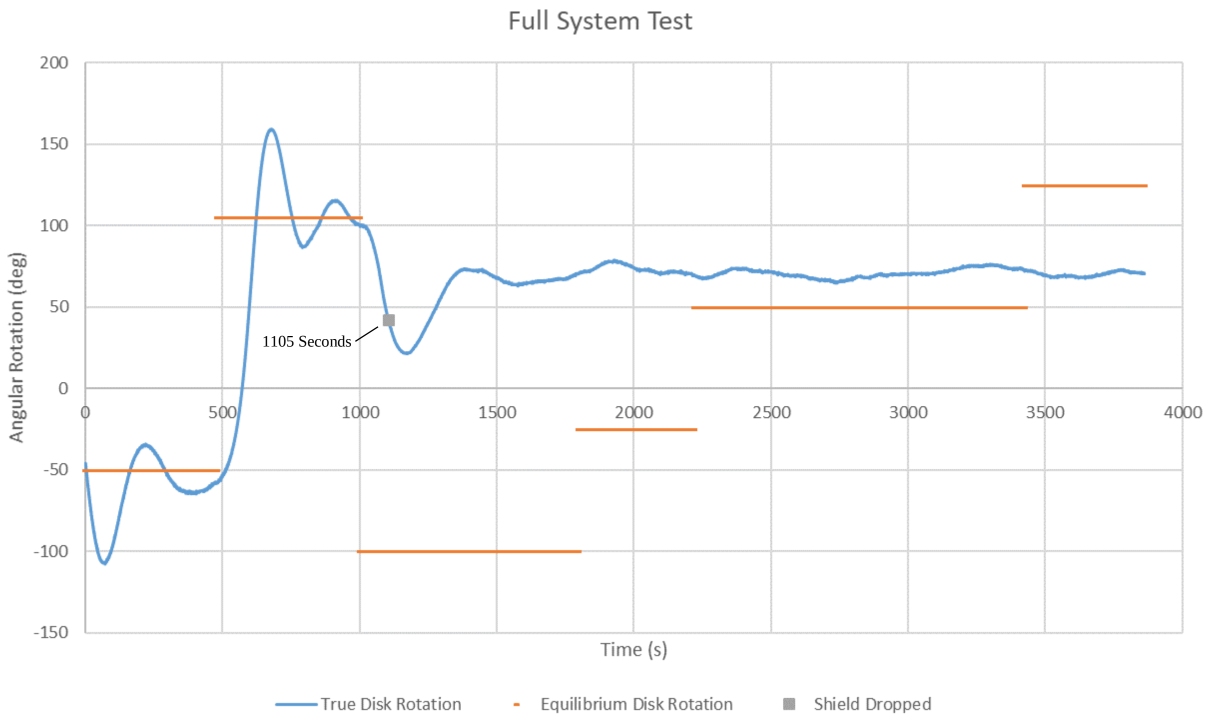

Figure 16: Full System Test Plot Over Time

At the start of the test, the disk rotated again to -50°. At around 500 seconds in, the motor rotated the magnet -155°, resulting in a new equilibrium disk rotation at 105°. The disk responded appropriately, slewing toward and then oscillating about the new heading. At around 1000 seconds, the motor rotated the magnet another -155°. This produced a new equilibrium disk rotation of -100°. The disk began to respond until, at 1105 seconds, the shield was dropped. The grey box on the plot of the True Disk Rotation indicates the position and time that the shield was dropped. From this time, the disk immediately begins to slow down, reverse direction, and move toward and oscillate about its inertial equilibrium. At around 1800 seconds, the magnet was rotated -75° inside the deployed shield. The disk showed no noticeable response, as seen in the plot. The magnet was rotated -75° twice more at around 2220 seconds and 3400 seconds. No noticeable response was recorded and the test was concluded.

9 Conclusions

9.1 Slew Maneuvers

The average slew maneuver rates achieved during this research met or exceeded the previous slew rates recorded. For this research, the average unshielded slew rate was 1.66°/sec. The average slew rate achieved in 2015 was 1.54°/sec. It is likely that in 2015 the tray was not filled sufficiently with water, and drag forces were larger, as this research project placed a greater load on the disk. All other things equal, it would be expected that with a greater load, the disk would rotate more slowly with the same magnet.

9.2 Mu-Metal Shield as a Failsafe

The findings in the results section support the theory of using a Mu-Metal shield to "turn off" the torqueing effect of a permanent magnet as attitude control in the event of a hardware failure. With the shielding apparatus open, the magnet interacted normally with the Earth's magnetic field and slew maneuvers could be performed. When the shield was closed, the magnet induced no attitude control on the disk, regardless of the orientation of the magnet with regard to the Earth's magnetic field. There were problems with the deployment of the shield, particularly in regards to the activation of NiTiNol. While the relay used is sufficient to switch the power, pulse width modulation using transistors would provide power to the NiTiNol in a way that does not risk overheating it. Even at a fast switching speed, the relay would often stay open too long and the NiTiNol would overheat, making it only useful for a few deployments. Further research is necessary to improve the reliability of the shield deployment system.

9.3 Reworking and Documenting

The use of OpenCV and the tutorial found online means that the tracking code written can be easily stored and transferred from computer to computer simply by installing and setting up Microsoft Visual Studio as demonstrated in the tutorial series. It is intended that, by following the setup procedure found in the tutorial and using the code written for this project, the computer vision application will be more "plug and play" for future researchers, and there will be little need for long setup and catch up.

10 Future Work and Ideas

10.1 Extendable and Retractable Shield

For an actual space flight, it would be practical to have a shield that could be opened and closed as desired. If a larger magnet were used, a faster rotation rate could be achieved. This magnet however, may exceed flight maximums for measurable field strength outside the body of the spacecraft at launch. Launching with the shield closed could work around this by attenuating the measurable field produced by the magnet. Then the shield could be opened after launch and still be used as a failsafe. A potential method for opening and closing could be coils of NiTiNol which extend and compress like an electrically controlled spring.

10.2 Precision Control

One of the original proposed goals of the overarching project was to use the magnet to control the spacecraft precisely. This means cancelling out the overshoot observed in the results of this research. In order to do this, determination of the magnet's orientation is required. Because the webcam is unable to see the magnet because of the shield, and that a webcam will not be used to determine orientation in space, a high resolution magnetic encoder is the next step in tracking the magnet's orientation. Using the feedback from the encoder, the slew could be more controlled, managing the overshoot and allowing the satellite to stop precisely on target.

10.3 Minimization

In order for the Mu-Metal shield failsafe to become flight ready on a CubeSat, it must first become much smaller. Currently, the control and shield assembly is almost 9.5cm long. With a one unit CubeSat having nominal side lengths of 10cm, the assembly will need to become considerably smaller to be practical. A redesign of some aspects may also be necessary. This will mean a smaller gearhead motor, smaller Mu-Metal cans, and a deployment system that does not rely on gravity.

11 Acknowledgements

I would like to thank the University of Arkansas Honors College for selecting and funding this research. Without those funds, the material to perform the shielding tests would have been very difficult to acquire.

I would also like to thank Professor Adam Huang, who has been a consistently helpful and reliable presence throughout my undergraduate career. And who without, I would not be nearly as prepared for graduate study. Your time and effort over these years has been appreciated beyond measure.

I would also like to thank Professor Paul Millett, for being a part of my thesis defense committee and helping out in numerous ways over the years.

Lastly, I would like to thank my family and loved ones for all they've dealt with during this long journey through an undergraduate mechanical engineering degree. I could not have done this without your support. On to the next journey.

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