Radio Amateur Satellite Corporation

Attitude Determination and Control

Design Group 03

Michael K. Boice, CoE

Arna T. Friend, EE

Corey T. Janisch, EE

Mark B. Gervais, ME

Troy R. Lynch, ME

Sidney T. Malak, ME

Sponsor: Radio Amateur Satellite Corporation

Faculty Advisor: Mark Fowler

Industrial Advisor: Alex Harvilchuck

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Thomas J. Watson School of Engineering and Applied Science

State University of New York at Binghamton

**Abstract**

The Radio Amateur Satellite Corporation is a non-profit organization that operates many satellites for the purpose of communicating with amateur radios on the ground. To maintain optimal power and spatial components within theses satellites, AMSAT set requirements that their new standard 1U CubeSat satellite design shall have a simple passive control system to orient the unit for optimal communication. In order to maintain these requirements, an Attitude Determination And Control (ADAC) system was designed to implement a solid core magnetorquer to orient the satellite through a restoring torque along the Earth’s magnetic field. To determine the exact linear and angular dynamics of the satellite, the system uses a GPS and a gyroscope to measure the CubeSat’s current motion. The data is stored on the common board and then sent back to ground stations. After several design iterations, the ADAC system has chosen the ITG-3200 gyroscope and the ISM300F2 GPS.

The satellite’s metal structure combined with its motion through the Earth’s magnetic field leads to the formation of eddy currents in the metal body. The formation of eddy currents requires energy, which slows down the natural rotation of the unit. The slower rotation can lead to orbital instability, causing the satellite to move into an uncontrolled tumble. In order to increase the spin of the satellite (re-stabilizing it), the ADAC system flips the satellite by reversing the poles of the magnetorquer. The precision measurements come from running the sensor data through a Kalman Filter allowing for more accurate determination of the satellite’s motion and position during orbit.

**Table of Contents**

List of Figures 1

List of Tables 2

1. ADAC Block Diagram 3

2. Orbital Dynamics 4

2.1. GPS 6

2.2. Gyroscope 9

2.3. Magnetic Field Interaction 9

3. Satellite Damping 10

3.1 Magnetic Damper Charicteristics………………………………………..……………..12

4. Sensor Selection 13

4.1 GPS Antenna…………………………………………………………………….15

5. Kalman Filtering 17

5.1. State Model and State Variables 17

5.2. Model Defects 23

5.3. Linearization 23

5.4. Error and Tuning 23

5.5. Kalman Results 25

5.6. Limitations 27

6. ADAC CPLD Design 28

6.1. I2C Slave Design 28

6.2. Register File 30

6.3. ADAC Control Logic 31

6.4. I2C Master 32

6.5. ADAC CPLD Testing 32

7. Magnetorquer Design and Construction 33

7.1. Maximizing Magnetic Field 33

7.2. Core Material Considerations 35

7.3. Comercial Magnetorquer Option/Magnetorquer Moment Requirement 35

7.4. Magnetic Material Testing 36

7.5. Core Winding Procedure 44

7.6. Mounting Magnetorquer Within Satellite 44

8. ADAC Circuit Design 45

8.1. Magnetorquer Circuit 46

8.2. Power Shutoff 48

9. ADAC Testing 49

10. AMSAT Integration 50

11. Budget 51

12. Schedule 52

13. Future ADAC Development 52

Works Cited 54

Appendix 1. ADAC Circuit Diagram 55

Appendix 2. ADAC Table of Components 57

Appendix 3. Slave Controller Design……………………………………………......................…….58

Appendix 4. T2C Master Controller……………………………………………...…………………..59

Appendix 5. Companies Contacted for Magnetorquer Core material…………...……………………60

Appendix 6. Magnetorquer Moment Testing………………………………………………..………..66

Appendix 7. Core Test Matrix………………………………………………...………………………69

Appendix 8. Circuit Test Matrix………………………………………………………………………70

Appendix 9. Kalman Filter Flow Chart……………………………………………………………….71

Appendix 10. ADAC Requirements………………………………………………………………......72

List of Figures

Figure 1. ADAC Block Diagram………………………………………………………….3

Figure 2. Orbital Inclination Measured from the Equator………………………………...4

Figure 3. Image of a Circular Polar Orbit…………………………………………………5

Figure 4. Orbital Radius vs. Orbital Period……………………………………………….6

Figure 5. GPS Receiver Determines the Distance from the First Satellite……………..…7

Figure 6. GPS Receiver Forms a Circle at the Interface…………………………………..8

Figure 7. GPS Receiver then gets the Distance from a third Satellite………..…………...8

Figure 8. Tumbling Motion of the Satellite from its Magnetic Interactions……………..10

Figure 9. Orbital Rotation………………………………………………………………..10

Figure 10. Damping Ratio on Control System…………………………………………...12

Figure 11. Dome Antenna………………………………………………………………..16

Figure 12. ACTPAT254 Active GPS Antenna…………………………………………..16

Figure 13. Magnetic Dipole Moment Approximation of Earth’s Field………………….17

Figure 14. Ideal Latitude Trajectory for a 2700s Period…………………………………19

Figure 15. Ideal Longitude Trajectory for a 2700s Period………………………………20

Figure 16. Ideal Angular Velocity about Nadir as a Function of Time………………….20

Figure 17. Satellite offset from Nadir due to Earth’s non-circular Magnetic Field……..21

Figure 18. Antenna Rotation………………………………….………………………….21

Figure 19. Total and Radial Components of Earth’s Magnetic Field………………...….22

Figure 20. Precession, Angular Velocity, and Radial Magnetic Field Strength...…….....22

Figure 21. Latitude……………..………………………………………………………...25

Figure 22. Longitude……………………………………………………………………..26

Figure 23. Precession……………………….……………………………………………26

Figure 24. Angular Velocity………………………………………………………..……27

Figure 25. ADAC CPLD………………………………………….…………………..…28

Figure 26. AMSAT Register File………………………………………………………...31

Figure 27. Test Bench Setup…………………………………………………...………...32

Figure 28. H-Field vs. Wire Gauge…………………………………………….………...34

Figure 29. Picture of 1045 Carbon Steel Magnetorquer (5 Layer Wraps)………..……...38

Figure 30. Picture of 1090 Carbon Steel Magnetorquer (5 Layer Wraps)…………..…...38

Figure 31. Magnetic Decay of the 1045 Steel Core over a 180min Period……………...39

Figure 32. Magnetic Decay of the 1090 Steel Core over a 100min Period……………...39

Figure 33. D2 Tool Steel Magnetorquer (five wire layer wraps) with Duct Tape to Maintain the Wrap Integrity During Testing………..………………………………...…41

Figure 34. Magnetic Decay of the D2 Steel Core over a 100 min Period……………….41

Figure 35. Orientation of Magnetorquer in Satellite……………………………………..45

Figure 36. Magnetorquer Flip Circuit…………………………...……………………….46

Figure 37. Shutoff Circuit………………………………………………………………..48

List of Tables

Table 1. State Error……………………………………………………...………………24

Table 2. ADAC Commands……………………………………………...………………29

Table 3. Instruction Register……………………………………………………………..30

Table 4. Results of Magnetic Tests for A36 Steel Sample………………………………37

Table 5. High Carbon Steel Data from Matweb…………………………………………37

Table 6. Results of Magnetic Tests for the 1045 and 1090 Steel Samples………………40

Table 7. Tool Steel Data (from Matweb and other sources)……………………………..40

Table 8. Results of Magnetic Tests for D2 Steel Sample and Neodymium Sample…….42

Table.9. Results of all Magnetic Tests for Magnetorquer Core Materials……………….43

Table 10. Physical and Magnetic Characteristics of Materials for Magnetorquer Core…43

Table 11. Projected and Actual Budget………………………………………………….51

Table 12. ADAC Schedule………………………………………………………………52

# ADAC Block Diagram



Figure 1: ADAC Block Diagram.

AMSAT ADAC system uses a permanent magnet to passively control the orbit of a standard 1U sized CubeSat. Using the torque between the magnetic field of the magnet and the magnetic field of the Earth, the satellite will orient itself to allow the antenna array of the satellite to point towards a specific point on the earth; this allows for maximum communication (the primary function of the satellite). The system also includes hardware to reverse polarize the magnet, allowing the satellite to flip 180 degrees on command. Flipping the satellite resets the eddy currents induced in the satellite’s main structure, allowing for increased rotation, and in turn, a more stable system. Other system hardware includes a sensor array that measures the orbital dynamics of the satellite, and control hardware that utilize the rest of the ADAC hardware. The ADAC system, which is to be mounted on a separate PCB, also uses this control hardware to communicate between the common processor board and the rest of the system. The last remaining component of the ADAC system is a power saving mode that shall cut off power to the circuit when the CubeSat’s power is low.

Figure 1, shown above, is the system block diagram for the CubeSat. As seen in the figure, main command prompts come from the common processor board and enter the CPLD via an I2C interface. The device then looks up the received signal in a bank of registers, and follows the command of the sent signal. From there, the CPLD has a power shutoff/turn on, measurement signal to every sensor, and flip communication signals. If the command is to measure the orbital dynamics of the satellite, the sensor will receive the command signal and proceed to measure data, which is sent back to the CPLD. Included sensors are a gyroscope to measure the rotational dynamics, and a GPS to determine the linear motion. The CPLD will store the data received from the sensors, and send them back to the common processor board when the ADAC system routine is called again. A circuit diagram of the ADAC system is shown in Appendix 1.

# Orbital Dynamics

In order to fulfill the ADAC system requirements of measuring and filtering the system’s dynamics, the satellite’s actual orbital dynamics must be understood. The satellite will orbit the Earth at a distance in the range of 500 km to 800 km from the surface of the Earth. The CubeSat's general orbit will put the satellite at an orbital inclination in the range of 95 to 99 degrees, making its orbit a roughly polar orbit. This is shown in Figure 2.

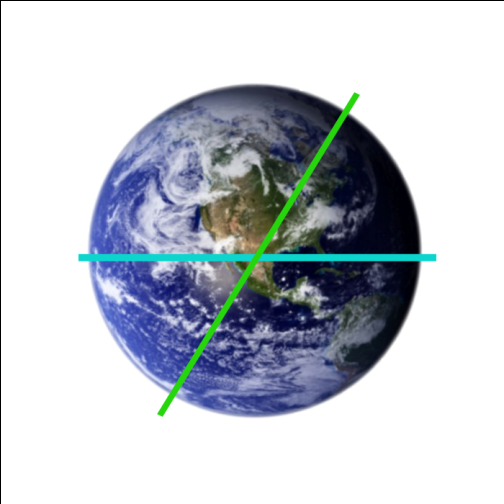


Figure 2: Orbital Inclination Measured from the Equator.

This angle can be calculated once the satellite has been launched and is transmitting data back to the command center. However, the previous values were determined from data collected from different CubeSats launched from different sites around the world. For ADAC’s purpose, the angle can be approximated as being 90 deg from the equator of the earth to the orbital plane of the satellite. With this said, the characteristic of the satellite's motion around the earth will be assumed to be both circular and polar. This idea is demonstrated in figure 3.

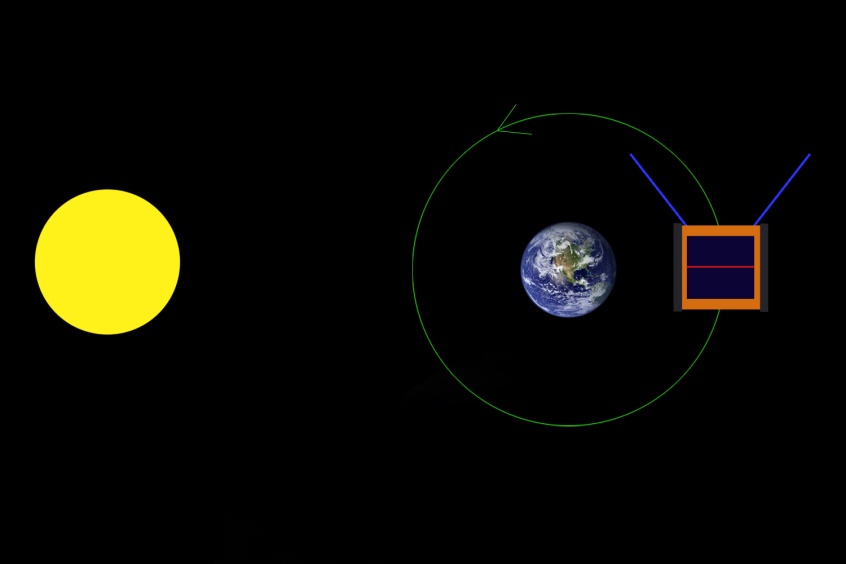


Figure 3: Image of a Circular Polar Orbit.

A polar orbit simply means that the satellite will be passing through the earth's geographic poles for the span of its orbit life. This makes the orbit more complicated in reference to the magnetic field of the Earth because the Earth’s magnetic field is non-circular and switches as the CubeSat passes over the poles. More details are provided in section 2.3.

It is possible to calculate a range of potential orbital periods for the satellite using Kepler’s Third Law for circular orbits and a range of possible radii:

(1)

In equation 1, r equals the radius from the center of the Earth, G equals the gravitational constant 6.6730 x 10-11 m3 kg-1 s-2, and ME is the mass of the Earth, ~5.9742 x1024 kg. Figure 4 shows a MATLAB plot demonstrating the relationship between the orbital period and the orbital radius.

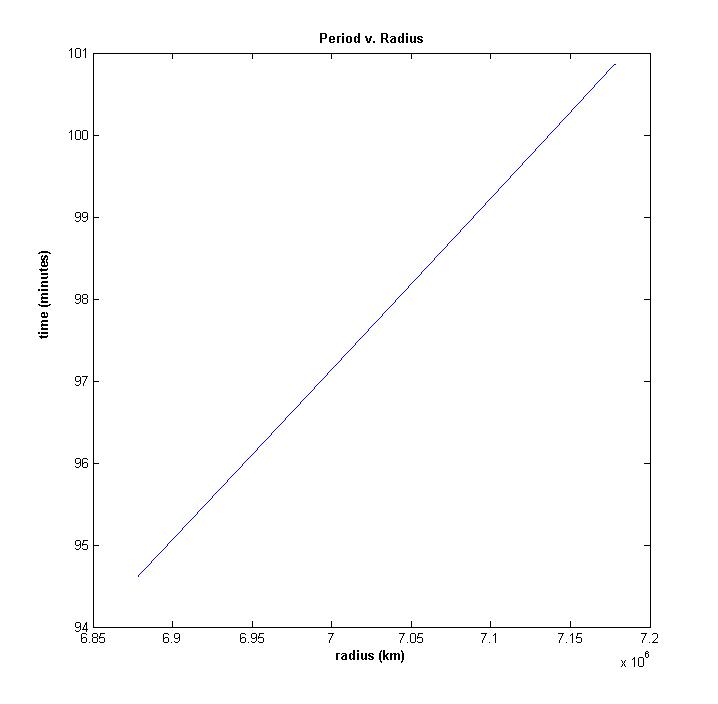


Figure 4: Orbital Radius vs. Orbital Period.

This gives a minimum period of 94.6 minutes at 500 km and 100.9 minutes at 800 km.

## GPS

GPS technology has been implemented in myriad of applications, from pet locators to space stations, as well as existing CubeSat satellites. The CubeSat will be using an IMF300F2 GPS receiver, which will aid with the measurement of the system dynamics. The GPS receiver system onboard works in conjunction with at least four of the twenty seven GPS satellites (three of which are back up). The constellation of satellites orbit the Earth in a pattern where at any given point there are four satellites “visible” to the GPS receiver. The CubeSat's projected orbit is around 800 km which puts it several thousand meters below the 19,300 km operational altitude of GPS satellites. The primary purpose of the GPS receiver is to locate four or more of the orbiting satellites. The satellites constantly send the receiver messages which have the time the message was sent, information on the orbit and the almanac. Disregarding error and assuming that the signals travel at the speed of light, the receiver is able to determine the distance from each satellite and deduce its own location in three dimensional space; this is based on the time it takes for messages from the GPS satellites to reach the receiver.The method used to accomplish this feat of ingenuity is called trilateration.

Each of the three or more satellites communicating with the CubeSat are the center of imaginary spheres with radii (r1, r2, r3) from the GPS receiver. Their intersections in three dimensional space will give one of two possibilities for the location of the GPS receiver (land based GPS receivers will disregard the point in space). Consider being 13 miles (r1) away from the first satellite, which in turn means that the location of the CubeSat can be anywhere on an imaginary sphere with satellite one at its center. When the GPS receiver receives information that the second satellite is 15 miles away, a second sphere from satellite two intersects with that of the first satellite forming a perfect circle. The CubeSat can now be at any of the possible points on this circle (not disk). When a third satellite is introduced, the sphere that it forms will intersect the perfect circle at two points, which will both be possible positions for the CubeSat. The fourth satellite is used to intersect the GPS receiver's clock (an error of 0.000 001 second corresponds to a 300 meter error). The following images demonstrate these concepts.

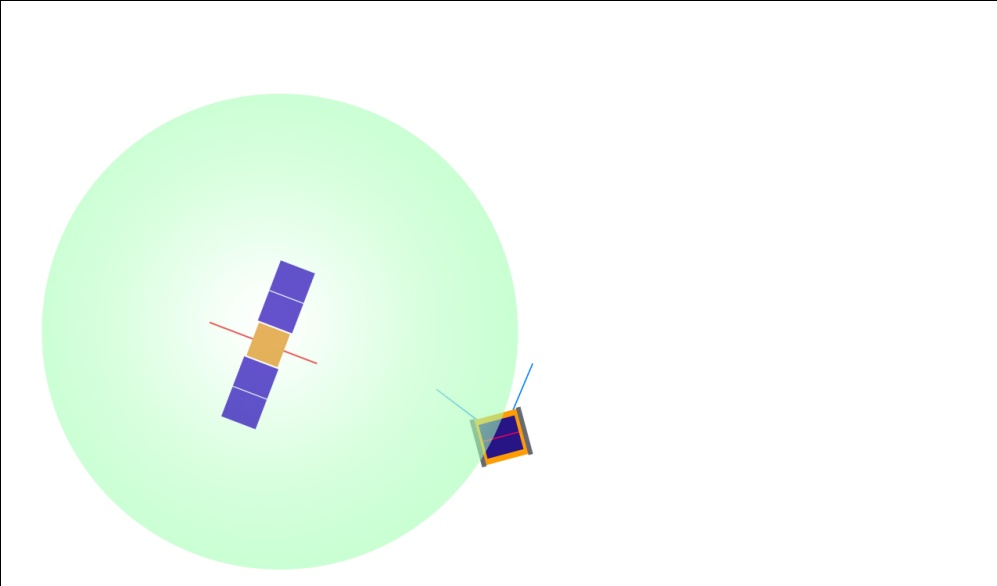


Figure 5: The GPS receiver determines the distance from the first satellite.

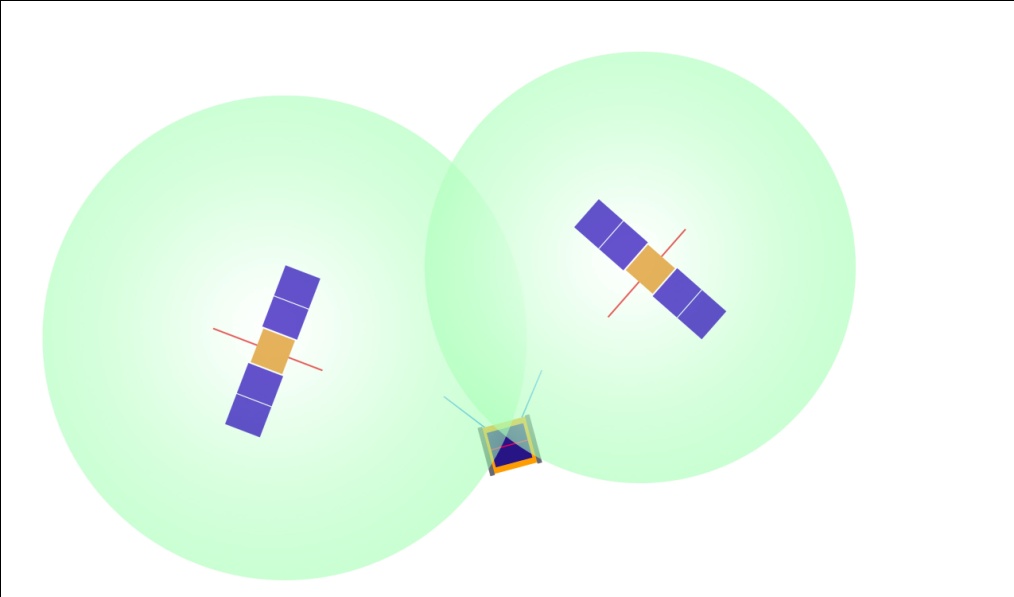


Figure 6: The GPS receiver forms a circle at the interface.

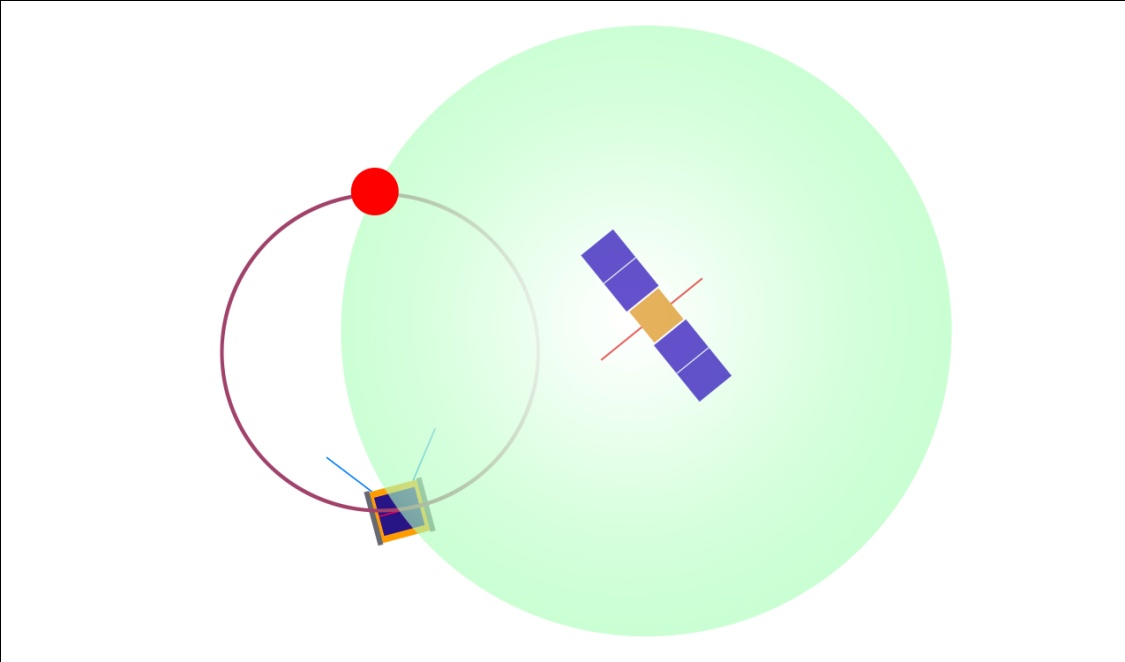


Figure 7: The GPS receiver then gets the distance from a third satellite.

At this point an Earth based GPS receiver will have a point on the surface of the earth and the other in outer space. It is able to eliminate the point in outer space by utilizing the fourth satellite.In the case of accuracy information from a fourth satellite, as mentioned previously, can eliminate one of the points. Information, such as velocity and heading, can all be deduced from having the satellites position updated instantaneously with each new position being compared to the last.

By choosing a GPS, the ADAC system obtains the position of the satellite in orbit. Knowing the satellite’s linear dynamics can be used in conjunction with the Kalman filter to improve the signal-to-noise ratio and improve the system measurements. However, the GPS does not provide ample information about the satellite’s angular motion. The satellite’s angular motion is required to know when the satellite’s spin has decreased (due to eddy currents) to such an extent that substantial tumbling may occur. At this point the satellite would be sent a command to flip, causing its spin rate to increase, leading to improved stabilization.

## Gyroscope

The gyroscope is used to determine the angular velocity of the satellite system in outer space. The satellite will use a three axis gyroscope to acquire the angular velocity of the satellite about the x, y, and z axes. The z-axis angular velocity will give the ground team an idea of how fast the satellite is spinning (for its spin stabilization system). As the eddy currents slow the satellite’s angular velocity about the z-axis, the satellite’s orbit becomes more unstable, signaling that the magnetorquer should be flipped to reset the rotational dynamics. Therefore, using a GPS in conjunction with a gyroscope allows the satellite to determine both the linear and angular dynamics, giving a complete picture of the motion of the satellite’s orbit

## Magnetic Field Interaction

The motion of the CubeSat is also being influenced by two other major factors; the Earth's gravity gradient and its magnetic field. However out of the two, the magnetic field will be the major contributor to the satellite's motion due to the onboard magnetorquer. The magnetorquer's interaction with the magnetic field will produce a tumbling action as the magnetic moment of the magnetorquer tries to align itself with the magnetic field of the earth. This tumbling motion is pictured in figure 8**.**

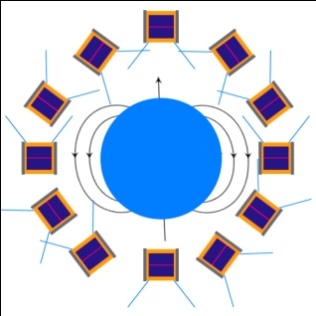
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Figure 8: Tumbling Motion of the Satellite from its Magnetic Interactions.

There will also be a spinning action about the z-axis of the satellite, as shown in figure 9.

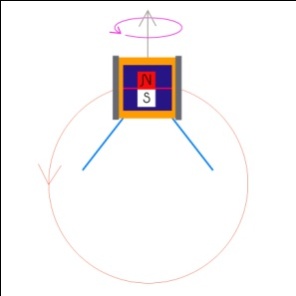


Figure 9: Orbital Rotation.

# Satellite Damping

The satellite will be experiencing a nutation like motion from its spin axis due to separation from its launch vehicle and environmental torques. The damping of this motion will increase the efficiency/accuracy of the onboard sensors and aid in the antenna nadir pointing when the satellite is in prime mode. However this motion can be advantageous when scanning the surface of the earth. A passive nutation damper is one that does not rely on power from the system or information from the onboard sensors and is driven by the motion of the satellite itself and seeks to dissipate energy. Conceptually the passive damper resembles a fluid-filled ring positioned around the z-axis (major spin axis). Upon the conditional acceleration of the CubeSat when launched from the transport vehicle, the damper will resist the acceleration when the viscous fluid creates a drag force on the walls of the tube; thus creating the damping effect.The dynamics of the satellite are complicated, and due to the delay in the construction of the satellite, the damping system was not constructed. However, the following theoretical calculations were derived.

The system can be acknowledged as a control system who’s settling time and maximum overshoot must be minimized. The natural oscillation frequency of the system can be modeled as the following equation:

(2)

In order to minimize the settling time the system should be underdamped (an underdamped system tends to settle more rapidly than a critically or overdamped system), having a damping ratio between 0.5 and 0.8.

However the system will be complicated, since the Earth’s magnetic field is not constant or circular. This in turn will create a range of possible natural frequencies for the satellite. Disregarding this in order to explain the concept, the settling time of the motion can be modeled as the following:

(3)

Connecting ts with wn, it is possible to deduce that one way to minimize the settling time is to maximize the magnetic moment of the magnetorquer.

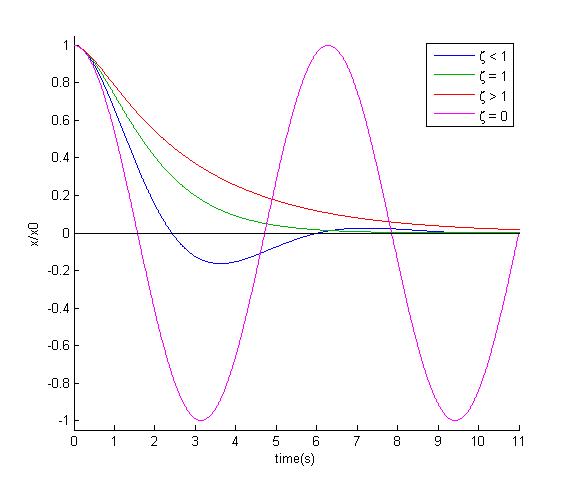


Figure 10: Dampling Ratio on Control System.

Making a linear approximation for the system at very small oscillations, one can then define the damping ratio as the following:

(4)

This will give us an approximation of what the damping coefficient should be for the theoretical damper. However, due to the inconsistency in the Earth’s magnetic field, the final calculations for the damper were left unfinished.

## Magnetic Damper Characteristics

The noncircular nature of the earth’s magnetic field and the satellite’s circular orbit will cause the satellite to oscillate about the earth’s magnetic field lines as it traces out its orbit. The absence of any substantial atmosphere will allow this oscillation to continue unhindered. An effective solution can be achieved through magnetic damping strips (this method has been utilized on other satellites) [2][4].Magnetic damping strips are thin, ferromagnetic strips of metal which are magnetized and re-magnetized through their movement through the earth’s magnetic field. The damping occurs because it takes energy to flip the direction of the magnetic domains within the magnetic material. This energy is obtained from the oscillatory kinetic energy of the satellite [3]. Ideally the movement of the magnetic damping strips causes damping only in the oscillation plane (the plane about the earth’s magnetic field lines) and little to no damping of the satellite’s rotation (the rotation helps stabilize the satellite).

Determining the appropriate composition, size, and mass of the damping strips can be very difficult and was beyond the investigation of this group within the time frame provided. However, the material should exhibit certain general characteristics [3].

1. The material should have a low magnetic coercivity (≈ Hearth = 23.9 A/m) (allowing the magnetic strips magnetic field direction to switch easily).
2. The material should have a large magnetic permeability in order to maximize the amount of energy required for each magnetic field switch (allowing for maximum damping effect for a given magnetic coercivity).

A soft ferromagnetic material such as low carbon steel may be a good place to start the material search.

# Sensor Selection

Attitude determination and control involves a complex system designed to stabilize a satellite orbiting freely in space. This requires a specific sensor array that samples and determines the satellite’s attitude or position relative to the earth. This data is then sent to the stabilization system which in turn adjusts the satellite to its desired position. In order to maintain the desired position this process is constantly repeated throughout the orbit.

In most large scale satellites, exact positioning is crucial and stabilization systems consist of thrusters that can adjust the satellite to any position. With small scale satellites such as the 1U CubeSat this is not always the case. One reason for this is that the size of the CubeSat satellite does not allow for the implementation of complex stabilization systems. Another reason is that these small scale satellites are used mostly for experimentation and the data being communicated is not as imperative as that for a manned satellite. Therefore a smaller more conservative stabilization system is needed. A solid core magnetorquer was chosen to work as the stabilization system for this satellite. This system uses the Earth’s magnetic field to re-orient itself when it deviates from the desired or prime position. However, the same attitude information is needed for any stabilization system to work properly.

This information can be gathered using a gyroscope and a GPS sensor for reasons discussed earlier. A magnetometer was originally considered as part of the sensor array due to the type of stabilization being used in this satellite. With Earth’s magnetic field as the only way to adjust the satellite’s position, knowledge of its strength and direction is needed and a magnetometer can provide this. Despite this, a problem arises when a solid core magnetorquer and a magnetometer are in close proximity to each other. The magnetometer’s data will be affected by the magnetorquer’s magnetic field and will not be able to correctly sense the Earth’s field. One solution to this problem would be to extend the magnetometer out on a collapsible boom, sufficiently away from the solid core magnetorquer. Again, due to CubeSat standards and restraints this boom solution would become more of a problem than a solution. The 1U CubeSat is simply too small for this to be implemented which means the use of a magnetometer is impractical.

Without a magnetometer, information on Earth’s magnetic field must be known before hand and implemented directly into the system. This means that without being able to determine the strength and direction at each instant, a theoretical model is needed so that the motion of the satellite through orbit can be predicted. This is done with a Kalman filter, which will be discussed later.

Due to the application of these sensors in space, only specific models can be used. First of all, due to extreme conditions in space a temperature range of -40˚C to 85˚C is necessary for the sensors to remain in working order. Another specific parameter that needs to be considered is the altitude at which the satellite will be orbiting. Due to the p-pod launching mechanism that will be used, each CubeSat is launched at a standard altitude of 500 to 800km. This requires high altitude sensors because most ground based sensors would not operate at these altitudes. The last major parameter that needs to be considered is the orbiting velocity. At this altitude the average orbital velocity is calculated to be 7500m/s which will introduce a problem when selecting sensors.

While researching the different builds and brands of sensors most requirements were able to be met except for the orbital velocity. Due to a government restriction, no GPS sensors are sold to the public with an operating velocity higher than 515m/s. This restriction is set to prevent the public from building any self guided weapons. This prevented the sensor array to be fully functional in orbit. A new direction was taken so that the ADAC system could be designed and built using the sensors that are commercially available for testing. This would allow the complete design of the system and only require the more powerful sensors to replace the commercially available ones before space worthy implementation.

Due to space and weight considerations, only MEMS sensors were chosen, as they are the most size and power efficient sensors available. Furthermore, communication interface limitations narrowed our search for only sensors that contain serial or I2C communication, as these types of interfaces are either already in development (I2C) or simpler to implement (serial). The last important parameter that was considered is power consumption. With only limited power available, the most power efficient sensors were chosen. After narrowing a long list of gyroscope sensors, the ITG-3200 three axis MEMS gyroscope was chosen. This was chosen because of its operating speed, size and compliance with the other required parameters discussed previously. The ITG-3200 was purchased on a breakout board for approximately $50 which was within the budget’s allotted amount for this sensor. This gyroscope allows for the rotational velocity and acceleration to be measured up to a speed of 2000˚/s and can output a maximum of 8000 samples per second and a minimum of 3.9 samples per second. This allows for a very flexible sensor, with low power, weight, and size.

Choosing the GPS sensor was similar to that of the gyroscope in that there are hundreds of models, with only minor differences. The ISM300F2 GPS module was chosen due mainly to its small size and start up speeds. This model is a high altitude build that allows data acquisition up to 18km which is a lower altitude than needed. This is alright due to the fact that most GPS modules are not designed for satellites, but it has been proven that higher altitude builds do operate at the altitude that our CubeSat will be orbiting. This model was purchased for $35 and comes equipped with a UFL series antenna connector. The ISM300F2 consumes blank power and can track GPS signals with a sensitivity of -159dBm.

However, the ADAC team was unable to implement this GPS into the system in the given time allotment. This was for two reasons. First, the GPS did not come with a breakout board, something that was required for mounting in the protoboard. This will not be an obstacle in future PCB designs and it was too late in the design process to design a breakout board for the chip to use on the protoboard, so the GPS was not mounted onto the circuit. However, the GPS was purchased, and future design iterations will have immediate access to the sensor. Secondly, the ISM300F2 uses serial communications that would take extra time to develop. Due to the availability of only one team programmer, the team decided to finish the I2C communication interface, rather than to code a serial interface, leaving to communication interfaces with bugs, rather than one I2C interface that works.

## GPS Antenna

One major concern that arose while choosing the GPS sensor was which antenna to choose. Originally a dome antenna was proposed as shown in Figure 11 to ensure the reception of signals. This would require it to be mounted on the exterior of the satellite so that it could be visible to the GPS satellites that would be communicating with it. The first problem with this option is that the solar panels of the satellite completely cover all surfaces of the satellite before it is launched into space, requiring it to be deployed following the deployment of the solar panels. The second problem is the connecting interface between the antenna and the ISM300F2. After discussing these problems with an Inventek employee, he proposed the ACTPAT254 active GPS antenna which is the recommended antenna for the ISM300F2 and is shown in Figure 12. This is a patch antenna as opposed to the dome shape and can be mounted within the satellite avoiding any interference with any external components. This patch antenna can connect directly to the U.FL series connector on the GPS module which avoids the need for an adapter.

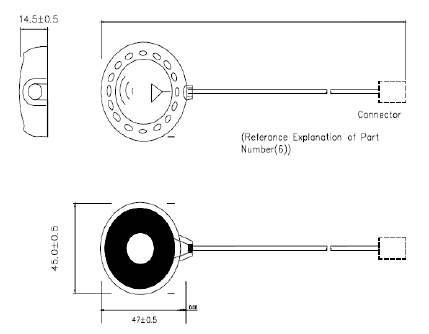


Figure 11: Dome Antenna.



Figure 12: ACTPAT254 Active GPS Antenna.

The only downside to this patch antenna is the reception quality it would receive. Without any current information about the reception strength of a patch antenna mounted underneath a solar panel or within an aluminum structure custom testing is needed. A test was designed to monitor the signal strength of the antenna while under various materials. The antenna would be enclosed with various combinations of aluminum and solar panel and evaluated with respect to a completely exposed control configuration. Due to time constraints this test was only theoretical and was not preformed.

# Kalman Filtering

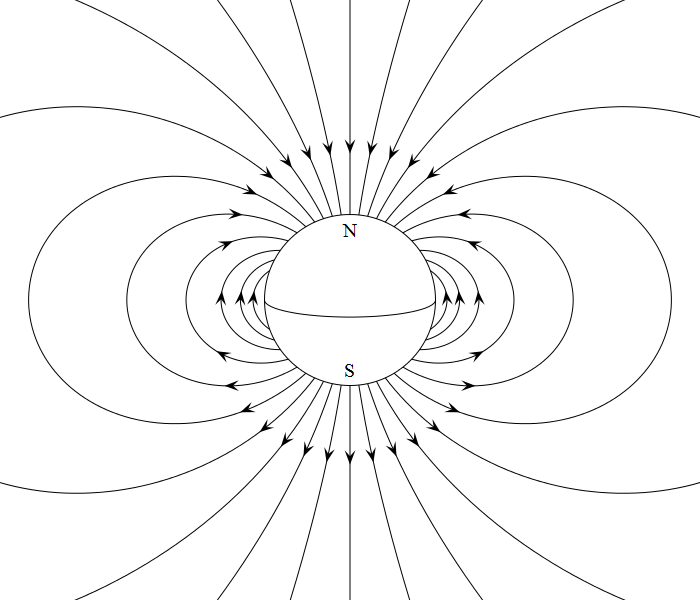
The 1U version of the satellite utilizes a Kalman filter to filter noise from the measurements and to provide optimally estimated values for the state variables for each instant of time. The filter for this project is really intended to serve as a proof of concept for a more sophisticated 3U filter. As will be discussed below, there are serious barriers to implementation for the 1U version, which are due primarily to the lack of a magnetometer in the sensor array. Also the Kalman filter is more useful when active control is required.

## State Model and State Variables

The state model for the filter made the following simplifications:

* The Earth’s magnetic field is modeled as a dipole (current loop) whose North and South poles are directly in line with the geographic North and South Poles. In reality the field can be modeled fairly accurately as a dipole but is tilted at roughly 11 degrees.
* The satellite will maintain a strictly polar orbit. In reality the orbit will be close to polar, but not exactly. The reason a polar orbit makes the model more tractable is that it implies that the latitude changes only according to the orbital angular velocity of the satellite and the longitude changes only according to the angular velocity of the earth.

Figure 13 (below) approximates this model, with the earth being the sphere in the center, the red arrow indicating the component of the magnetic field in the radial (nadir) direction and the orange arrow being the component of the magnetic field tangential to the field line. The diagram does not describe the model as clearly as desired in the sense that it does not convey the assumption that the satellite remains on one field line for its entire orbit.



**Figure 13.** Magnetic Dipole Moment Approximation of Earth’s Magnetic Field

The following fundamental equations govern the model, subscript p indicates prediction:

Magnetic Field, Radial (the red arrow in the above diagram)

Magnetic Field, tangential (the orange arrow)

Total Magnetic field

Precession, φ, as a function of the field

Latitude

Longitude

Angular Velocity of Satellite about its Z-axis

Orbital tangential velocity, g is the universal gravitation constant

Orbital Angular Velocity

This model went through several versions, none of which performed to satisfaction. The following state variables were used, the progression of state vectors shown below is the progression from version to version of the filter.

The first versions had a minimum of state variables. The height, and later the values of the magnetic field, were added in an effort to improve filter performance by accounting for more error. The following graphs illustrate the performance of the model. The graphs were created by running the state generation routine with all mean square error values set to zero.



**Figure 14.** Ideal Latitude Trajectory for a 2700 Second Period.

This figure includes no error. It shows the latitude for 2700 seconds with Fs =1. This affirms that the model is properly calculating latitude. Below is the same graph for longitude.



**Figure 15.** Ideal Longitude Trajectory for a 2700 Second Period.

This graph also affirms the validity of the model by showing very little change in latitude over half an orbit. Below is a graph of the error free angular velocity for roughly one orbit.



**Figure 16.** Ideal Angular Velocity about Nadir as a Function of Time.

The angular velocity was initially calculated with an analytical derivative, but was later calculated by taking the difference between adjacent gamma values and multiplying by Fs. There are abrupt drops in the angular velocity at three points. There are no extreme discontinuities in the generated data. This is a bug that will need to be addressed in future development of the filter. Below is a graph of precession for roughly one orbit.



**Figure 17.** Satellite Offset from Nadir due to Earth’s Non-Circular Magnetic Field.



**Figure 18.** Antenna Rotation

Below is a graph of the magnetic field versus time. The blue represents the entire field, and the red represents its radial component.



**Figure 19.** Total and Radial Components of Earth’s Magnetic Field

Finally, below is a graph showing the relationship between precession, angular velocity and radial field strength. This graph is especially helpful because it shows that the model reflects the expected dynamics.



**Figure 20.** Precession, Angular Velocity, and Radial Magnetic Field Strength.

## Model Defects

The calculation of angular velocity about z is considerably more complicated than represented above. This filter code is useful for the other variables and the discussion here establishes important conceptual ideas for a future filter. The angular velocity is caused by non-idealities in the model. This could be amended by measuring the angular velocity about all three axes and using Euler angles and a moment of inertia tensor to calculate the angular velocity. The precession gives us a qualitative sense of angular velocity. The greater the precession, the more the satellite is being torqued about the other two axes. This is because the entire magnetic field torques the satellite but only the portion of the magnetic field not perfectly perpendicular to the nadir direction torques it about the x and y axes. Equations for torque about an axis are shown below. I stands for moment of inertia.

## Linearization

The equations that govern the state model, with the exception of those for latitude and longitude, are non-linear. This means that the state transition matrix must be linearized about each point. This was accomplished by calling a routine each iteration of the filter that takes the partial derivative of each variable’s transition equation with respect to each state variable. This produces an 11x11 matrix where each column corresponds to a variable’s equation and each row corresponds to a variable. The variables are still transitioned directly with the transition routine which uses the non-linear equations, but the linearized state transition matrix is necessary for the definition of the Kalman gain. The linearized matrix essentially contains information about how much each state variable is affected by each other state variable, which is necessary to calculate the Kalman gain effectively.

## Error and Tuning

The Kalman filter requires the definition of three covariance matrices. The first, Q, represents the driving noise of the process. This noise is due to small perturbations in the state due to un-modeled variables such as solar wind, and small irregularities in the magnetic field. In this model these errors are very small. The only modeled forces on the satellite are the Magentic force due to Earth’s field and the gravitational force between the satellite and the Earth. Many of the variables are modeled with no error at all. This is because many of the variables are interrelated. Orbital angular velocity, for instance, had no error because the error on the tangential velocity will propagate through the calculations. Putting error on the orbital angular velocity would be redundant and cause excessive error in the model. The latitude and longitude are also ultimately determined by orbital speed but error is included because that is not how they are calculated. The error used in testing to establish Q is shown below.

|  |  |  |
| --- | --- | --- |
| State | Mean Squared Error | Absolute Error |
| Angular Velocity About Z | 0 | 0 |
| Latitude | .1440 x 10-9 | .1200 x 10-4 |
| Longitude | 1 x 10-13 | .0001 x 10-4 |
| Precession about Nadir | 0 | 0 |
| Angular Velocity of Earth about its Axis | 0 | 0 |
| Orbital Velocity of the Satellite | 0 | 0 |
| Tangential velocity of the Satellite | 1 x 10-13 | .0001 x 10-4 |
| Height Above Earth’s Surface | 0 | 0 |
| Radial Component Of the Magnetic Field | 0 | 0 |
| Magnetic Field Component Tangential to the Field Line | .0 | 0 |
| Absolute Value of the Magnetic Field | .002 x 10-9 | .0141 x 10-4 |

**Table 1.** State Error

The second, Cn, is 3x3 and accounts for error in the measurements. Cn is very precisely defined according to the data sheets for the sensors. According to the datasheet for the gyroscope, its root mean square error has a value of .38 least significant bits per degree per second. The satellite is expected to be spinning at between zero and ten revolutions per minute and to have an absolute maximum speed of thirty revolutions per minute. According to the model, the satellite spins much slower than that, showing a maximum speed of about .02 revolutions per minute when unaffected by the passive control effort. The magnetorquer will cause the satellite to spin faster than that, but probably not faster than thirty revolutions per minute. This means that the root mean square error for the angular velocity about z, 2.2236 x 10-9 radians per second, is probably too high. The filter seems able to handle it though and it is better to assume too much error than not enough. The error for the GPS sensor was estimated to be about the same as that for the gyroscope since the GPS unit can be configured to communicate in several ways, which change how much of the output is dedicated to position and hence the error associated with the measurement. As of this writing, final decisions regarding GPS configuration had not been made. The GPS is capable of measuring tangential orbital velocity, as well as altitude in addition to position. The choice of configuration in later design stages will affect the values in Cn. Finally, Cs is 11x11 and reflects the error in the initial state. The greater the terms down the diagonal of Cs, the more the filter weights the measurements over the model. The Kalman filter’s convergence is determined by the interaction of these three covariance matrices, for they determine the Kalman gain, which is the weight assigned to the difference between prediction and measurement to obtain estimation.

## Kalman Results

The following graphs show the performance of the filter for latitude, longitude, angular velocity about the z-axis, and precession from the z-axis. The precession from the z axis shows only state and filter output because it is not directly measured.



**Figure 21.** Latitude



**Figure 22.** Longitude



**Figure 23.** Precession



**Figure 24.** Angular Velocity

## Limitations

The Kalman filtering algorithm is not tractable for this model and sensor array. The work done on it so far, however, provides a solid point from which to proceed in the design of the 3U satellite. The reason it is not tractable is because the simplifications of the model are drastic. The polar orbit is not much of a stretch but the simplification of the magnetic field causes significant deviation from reality in the states produced by the model. The main reason this is a problem is because the driving force behind the change in precession and angular velocity about z is the magnetic field. This in and of itself is not the whole problem. The other aspect is the lack of magnetometer on the sensor array. Without a magnetometer, there is almost no check on the model. This means that were the filter used on actual measurements as opposed to the synthetic measurements generated according to the model, nonsense would likely result. It also means that if sufficient error is included in the model, the filter is fairly powerless to fix it. However, a solid foundation for further work has been established. The next steps for future designers will be to incorporate the tilt into the model of the magnetic field and to include a magnetometer in the sensor array. Graphs of the filter output are not included because the filter has not been correctly tuned.

# ADAC CPLD Design

In order to control the functions of the ADAC circuits, the ADAC system is controlled by a CPLD, as seen in the block diagram in Figure 1. The basic setup of the ADAC CPLD is shown in the block diagram below (Figure 20). There are two sections of the CPLD design, an application independent section and the application specific section. Other teams within the AMSAT project that are going to use a CPLD will use the application independent section which consists of the I2 I2C Slave and the AMSAT Register File as shown in Figure 20. The ADAC CPLD must communicate with the Command & Data Handling (C&DH) system via an I2C Bus. The Command & Data Handling system will send commands to the ADAC system over the I2C Bus. These commands are stored in the Register File. It is up to the application specific logic to decode the commands and provide the necessary functions.

The application specific logic will be placed in another module. For the ADAC system the specific logic is placed in the module called ADAC Logic. The ADAC Logic module must communicate with the 3-axis gyroscope and in the future a GPS module. There are also several control signals that the CPLD must manage. These signals include the magnetorquer control circuitry and the sleep mode signals, which when the signal is high the desired logic is given power. The sleep mode circuitry and the magnetorquer signals are explained in more detail in Section 8- ADAC Circuit Design.



Figure 25: ADAC CPLD

## I2C Slave Design

The I2C bus to the ADAC CPLD is the only input to the ADAC system. The I2C Slave maintains communication with the C&DH system, which sends commands to the ADAC CPLD. These commands are outlined in Table 1 below. The commands are issued by writing a certain value to the Instruction Register at register location 0x00 in the Register File. The I2C slave is also able to send data from the Register File over the I2C bus. The I2C Master, which in this case is C&DH, determines what data they will request and how many bytes they need. The I2C slave was designed to work with either a repeated start or two separate transmissions. This makes the salve module more versatile and allows correct communication with systems that are unable to provide the repeated start functionality. The I2C Slave uses a module from the XAPP333 IP core from Xlinx for the core logic of the I2C bus [1]. The module that was used provides base I2C functionality but still requires a control module to operate. A Slave controller module was designed to provide the necessary controls for the IP core to provide I2C slave functionality. The Slave Controller module also controls the read and write operations to the Register File. The Slave Controller design is provided in Appendix 3.

|  |  |
| --- | --- |
| Command | Function |
| Sleep Mode - GPS | Sets GPS Sleep mode signal High which restores power to the GPS module |
|
| Sleep Mode - Gyro | Sets Gyroscope Sleep mode signal High which restores power to the Gyroscope module |
|
| Sample GPS | Initiates the GPS to start sampling |
|
| Sample Gyro | Initiates the Gyroscope to start sampling |
|
| Magnetorquer Prime | Sets the Magnetorquer Prime signal High which provides the control signal necessary to allow current to flow to the magnetorquer’s prime mode |
|
| Magnetorquer Secondary | Sets the Magnetorquer Secondary signal High which provides the control signal necessary to allow current to flow to the magnetorquer’s secondary mode |
|

Table 2: ADAC Commands

When the C&DH system sends a command, it sets a specific bit in the instruction register in the Register File Module shown in Table 2. The C&DH system would always write to register location 0x00, the instruction register. All of the commands need to be toggled in order to turn then on/off, where 1 would turn on that function and 0 would turn off that function. For example, if C&DH needs to turn on the Gyroscope then C&DH sends 0x04 to register location 0x00. If C&DH then wants to tell the Gyroscope to start sampling, C&DH sends 0x14 to location 0x00. C&DH must write 0x14 to register location 0x00 because if it wrote 0x10 instead then it would turn off the gyroscope.

|  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Register Location |  | Instruction Register | |  |  |  |  |  |  |
| Bit | 7 | 6 | 5 | 4 | 3 | 2 | 1 | 0 |
| 0x00 | Data | 0 | Magnetorquer Secondary | Magnetorquer Prime | Gyro sample | GPS sample | Sleep gyro | Sleep GPS | 0 |

Table 3: Instruction Register

## Register File

The Register File is designed such that any system that needs to use it has one set I/O for their specific logic as well as a dedicated set of I/O from the I2C Slave module. The Register File, as shown in Figure 21 is designed such that there are no write conflicts between the systems. The I2C Slave module can only write to the slave\_ram, but it can read from any of the ram locations. The custom logic would only be able to write to the custom\_ram, but it also can read from any of the ram locations. This separation avoids the situation of conflicting writes on the same register. The read\_address is decoded in the Register File module to determine which ram to read from. The addresses are shown on the right hand side of the figure. Each register location is 8 bits, or 1 byte wide, therefore the DataIn and DataOut signals are also 8 bits wide.



Figure 26: AMSAT Register File

## ADAC Control Logic

The ADAC Control Logic as shown in Figure 20 is a module within the ADAC specific hardware on the ADAC CPLD. This module reads the instruction register and depending on the status of certain bits, sets or clears the control signals. The ADAC Control Logic reads the instruction register every clock cycle, and determines if any bits have been altered by a bitwise XOR of the instruction register that was just read in with the last instruction register that was read. If a bit has been altered then the module sets or clears that respective bit in the status register, which is located at 0x00 in the Custom Ram in the Register File. As mentioned in the I2C Slave section, these control bits need to be toggled. The C&DH system needs to write a ‘1’ to the bit location to turn “on” the control signal and then write a ‘0’ to the bit location to turn “off” the control signal. The ADAC Control Logic is designed to be completely autonomous. C&DH will send a command to the ADAC CPLD over the I2C bus and the ADAC CPLD will initiate the function. C&DH can also read from the Register File to retrieve any data that they need.

## I2C Master

The I2C Master Module is the means of communication with the 3-axis Gyroscope. The I2C Master, like the I2C Slave, uses an IP Core from Xlinix for the core I2C logic [1]. There is a Master Control Module that was developed to provide the IP Core with the necessary control signals to provide I2C Master functionality. The specific design for the I2C Master Controller is in Appendix 4. The data that is retrieved from the gyroscope is stored starting at location 0x01 in the Custom Ram in the Register File. The data from the Gyroscope is shown in the designated locations. The specific details as to what data needs to be sent to the gyroscope were detailed in the Fall 2010 Report.

## ADAC CPLD Testing

There were two main segments of testing. The first segment was using multiple test benches. Each of these testbenches were designed to test the hardware for functionality. Once each smaller module was tested independently, a larger system test bench was constructed. The configuration of the system test bench is shown below in Figure 22. The middle three modules are the modules that are under test. There are two other modules on each end of the system that are there for simulation purposes only and provide the necessary I/O to test the system. The I2C Simulation Master was designed to imitate the behavior of the I2C Master from C&DH while the I2C Simulation Slave was used to imitate the behavior of the 3-axis Gyroscope. Overall this test went well, but there were some circumstances that did not allow for a full comprehensive test of the system with this setup. Due to the fact that the I2C Bus requires pull-up resistors to bring the bus to a known voltage this was not able to be done in the test bench without drastically changing the modules under test. Therefore not all of the functions were able to be tested in this manner.



Figure 27: Testbench Setup

The second segment of testing included multiple setups. One setup was with C&DH. The ADAC CPLD design was uploaded on the Basys2 FPGA Development Board. The Basys2 Board was then connected to a level shifter which was connected to C&DH’s Beagle Board. The Beagle Board is the development board that the C&DH team was using to develop the code that would run on the OMAP processor. The level shifter was needed in order to convert from the different voltage levels of the two systems. The Basys2 Board uses 3.3V while the Beagle Board uses 1.8V. C&DH was able to type in commands on the command line that would send over to the Basys2 Board and write in the Instruction Register. C&DH could also request the data that is stored in the Register File. As noted above, the system was designed to be fully autonomous. In theory, when the C&DH team sent a command to the ADAC CPLD, the CPLD should initiate the function. Some of the functions work but due to the time constraints and slight differences in the commands with C&DH there are still some bugs that were unable to be fully resolved.

Another setup for testing used the Proto Board that contained the Gyroscope, the Magnetorquer and its control circuitry. By using switches for the control signals that would be set by the instruction register, the control signals where able to correctly provide the functions that were desired. For instance, the Gyroscope was given power by turning on the Gyroscope sleep mode switch. Then the I2C Master was told to retrieve the data from the Gyroscope by using a pushbutton for this signal. The I2C Master was able to retrieve the data from the Gyroscope and write it to the designated locations in the Register File.

In later tests the signal to retrieve data from the Gyroscope was tied to a clock signal that would assert once every ten seconds. This allowed the data to be continually updated while the enable switch was on.

# Magnetorquer Design and Construction

In order to properly orient itself in orbit, the satellite uses a solid core magnetorquer, as can be seen in Figure 1. This is a solenoid that uses its magnetic moment to act upon the Earth’s magnetic field, allowing the satellite to point at the Earth. The core is designed such that it points towards North America in Prime mode, and away in Secondary mode. To go between Prime and Secondary mode, current can be applied in either the forward or reverse direction through the solenoid. Refer to the ADAC circuit section for applying current to the magnetorquer.

## Maximizing the Magnetic Field

In order to maximize the restoring power of the magnetorquer, its remnant magnetic moment needs to be maximized. This is achieved by selecting a material that has a high remnant field percent (percent of magnetizing field remaining after H-field is removed) and low decay of this field with time. Before a material was selected the solenoid configuration that would yield the highest magnetizing field (H-Field) was examined.

The magnetizing field (H-field) is the field due to the movement of free charges (current). The H-field of a solenoid is given by equation 5 below:

(5)

Where n is the turn density (turns per meter) and I is the current (A) flowing through the solenoid. This equation shows that the H-field can be increased by increasing the turn density or the current of the solenoid. However, it becomes important to recognize that increasing the current means a smaller gauge (larger diameter) wire needs to be implemented to avoid wire/insulation melting and electrical shorting. Therefore, the above equation can be re-written to provide an expression including the diameter (gauge) of the wire.

(6)

Where N is the number of turns, L is the length of the solenoid (m), and D is the diameter of the wire (m). The final expression shows that the H-field can be maximized by maximizing the ratio between the current and the diameter of the wire used. Data was plotted to find the highest current-to-diameter ratio.

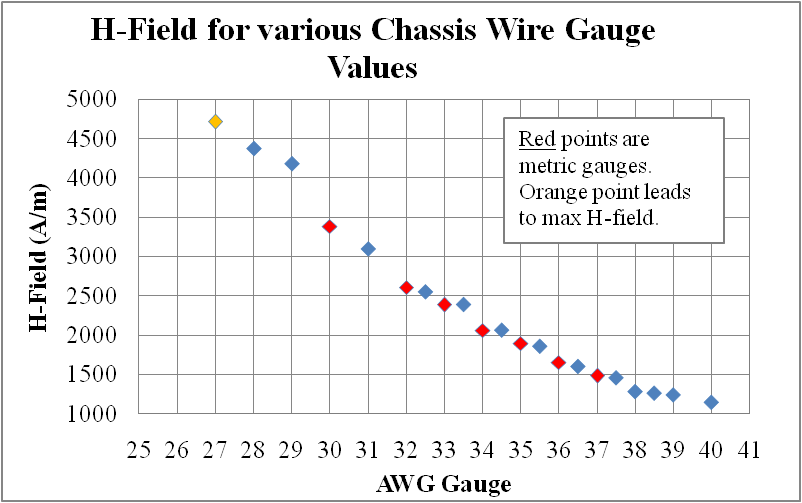


Figure 28: H-Field vs. Wire Gauge

Graph of the maximum H-field for a range of AWG gauge values used to determine which wire gauge to select to maximize the H-field. Figure 15 shows that the maximum H-field is obtained when a smaller gauge wire is used. Smaller gauge values were not plotted because this relationship assumes the maximum amount of current is put through the wire and lower gauge wires had maximum current values above the maximum current allowed by the system constraints (1 ampere). In short, this graph shows that the 27 gauge wire should be used in order to maximize the H-field of the solenoid.

The previous examination regarding the maximizing of the H-field did not take into account the insulation of the wire. Insulation on typical electrical wires can be comparable to the diameter of some of the wire sizes considered in the examination and therefore can lead to a noticeable reduction in the turn density (H-field). For this reason, magnet wire (which has a very thin insulating layer) was implemented in the design of each magnetorquer (except for the A36 sample because we did not have the magnet wire at that point).

## Core Material Considerations

Substantial time and energy were put into finding a suitable core material for the magnetorquer. As a review, the magnetorquer core material should exhibit a number of characteristics:

1. Remnant magnetic moment

A material is needed that can be magnetized by the solenoid after a brief application of the solenoid’s H-field. This minimizes the amount of power needed to orient the satellite because the magnetorquer does not need to be continuously charged during orbit.

1. High remnant magnetic moment (~0.4 A\*m2)

The larger the remnant magnetic moment the stronger the restoring torque for the satellite during its orbit. A stronger restoring torque should lead to a higher nadir pointing accuracy which is needed to ensure communication with satellite.

1. Minimal decay of remnant magnetic moment over orbital period (% decay < 10%)

Ideally the core material would retain its remnant magnetic moment forever. However, some decay will likely be present in the material because of thermal effects and mechanical stress.

1. Ability to flip magnetic field direction (using available solenoid H-field)

There are permanent magnetic materials available that have very high magnetic moments (Neodymium). However, the magnetorquer core material must able to switch is magnetic field when an external H-field (from solenoid) is applied in order to allow for stabilization of satellite. This requirement rules out any permanent magnetic materials (unless physical rotation of magnet is possible) because the H-field necessary to flip is field direction can be orders of magnitude greater than the field the solenoid can provide.

**7.3. Commercial Magnetorquer Option/Magnetic Moment Requirement**

A company called Sinclair Interplanetary has developed a chargeable permanent magnet magnetorquer that fulfills all the requirements mentioned previously. It can attain a magnetic dipole moment of approximately 13 A\*m2. The core material for this device is Alnico-5 (Al-Ni-Co). They have developed a circuit device, in conjunction with a high voltage electrolytic capacitor, which provides a 200 amp pulse for 100 microseconds. This set-up produces a large enough H-field to flip and create the dipole strength mentioned.

This magnetorquer was developed for the LatinSat-A and LatinSat-B satellites which both have a mass of 11 kg and a cube-side-length of 25 cm. They have also performed mathematical dynamics simulations under the 13 A\*m2 magnetic moment throughout an orbital period[4]. Since the AMSAT 1U Cubesat satellite has a smaller mass and cube-side-length than the LatinSat satellites, it does not need a magnetic moment as large as 13 A\*m2 to obtain similar dynamic results. A suitable magnetic moment can be obtained by comparing their moments of inertia, which is shown below.

I is the moment of inertia of a cube (kg\*m2), m is the mass of the satellite (kg), and s is the cube-side-length (m). The 1U CubeSat satellite has a moment inertia shown below.

The mass of the LatinSat-A and LatinSat-B satellite is provided below in terms of the mass and size of the 1U satellite.

The ratio of the 1U CubeSat satellite to the LatinSat satellite is shown below.

This shows that the moment of inertia of the 1U CubeSat satellite is less than 1.5% of the LatinSat satellites. This means the magnetic dipole moment of the 1U cubesat can be scaled down (linearly) to achieve similar dynamic results to the LatinSat satellites. In order to provide a margin of safety of 10 (to take into account any non-linear effects – orbital drag, radiation pressure, etc.) the magnetic moment should be made to be 15% of the LatinSat satellites’ magnetic moments, yielding a suggested value of 1.95 A\*m2.

## Magnetic Material Testing

Much time and effort was put into contacting various magnetic material, steel, solenoid, etc. companies in order to find a material that satisfied the aforementioned requirements. Many tables with the name of companies and their contact information, materials available, and outcome is provided in Appendix 5.

It became apparent that steel might fulfill our requirements. A sample of A36 steel was purchased and tested using the test procedure outlined in Appendix 6. The outcomes of these tests are shown below.

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| **Material** | **Carbon Content (%)** | **Residual Magnetic Moment (A\*m2)** | **Decay Period** | **Flipped?** | **Suitable Material** |
| A36 Steel | 0.25-0.29 | 0 | Instant decay to zero | n/a | No |

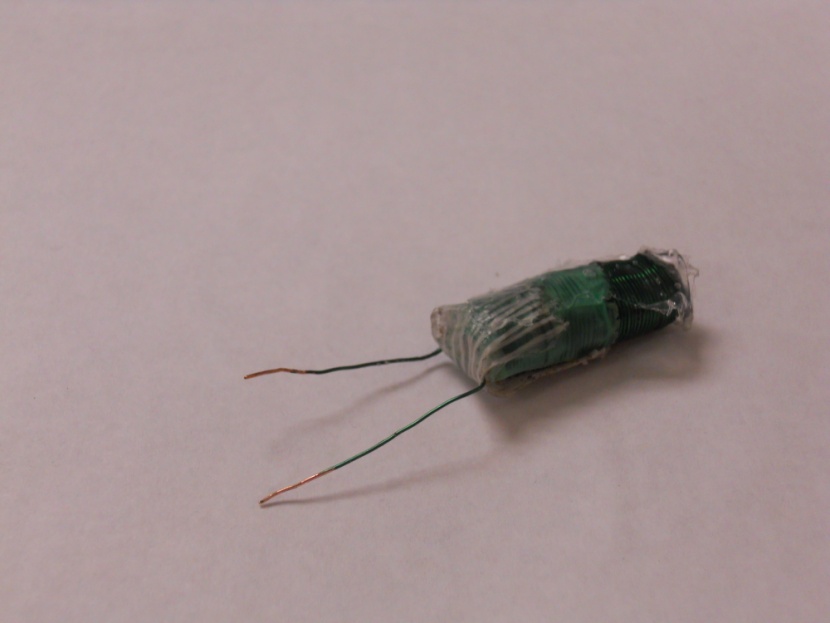
**Table 4:** Results of Magnetic Tests for A36 Steel Sample

Table 1 shows that the A36 steel sample does not fulfill the requirements and therefore is not a suitable material. After this result it was recommended by some company representatives to explore high carbon steel. The higher carbon content in high carbon steel leads to higher remnant fields because the carbon helps impede magnetic domains from relaxing into lower energy states (due to thermal effects and mechanical impulses). A table of high carbon steels is shown below.

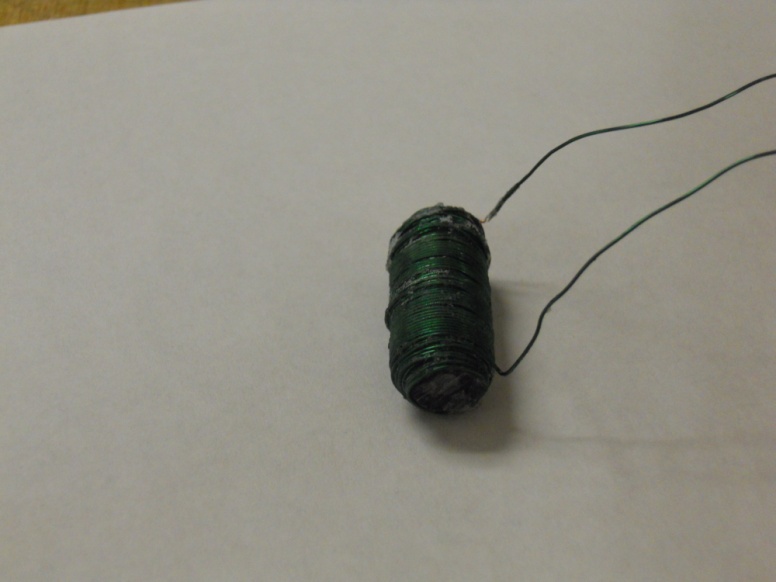


**Table 5:** High Carbon Steel Data from Matweb.

The two highest high carbon steels that were available in the required size, quantity, and price range were obtained. These were AISI 1045 and AISI 1090 carbon steel, which were made into magnetorquers, shown in Figures 15 and 16, respectively.



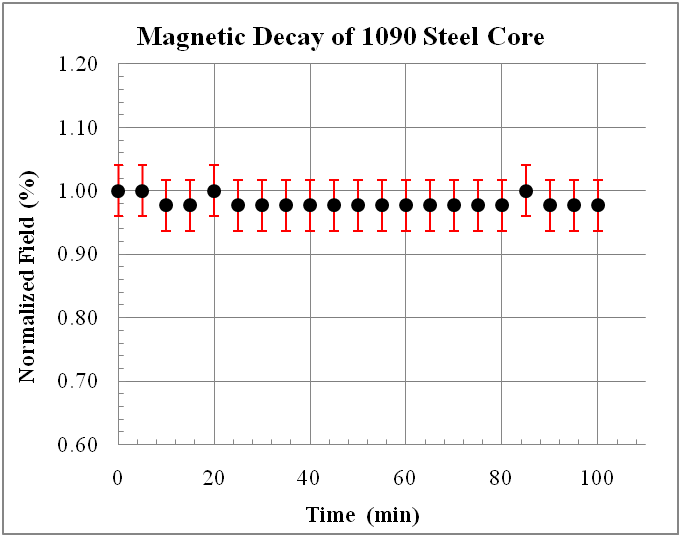
**Figure 29:** Picture of the 1045 Carbon Steel Magnetorquer (5 Wire Layer Wraps).



**Figure 30:** Picture of the 1090 Carbon Steel Magnetorquer (5 Wire Layer Wraps).

These materials were put through the same tests as the A36 sample. The decay graph for the 1045 and 1090 steel samples are shown in Figure 17 and 18, respectively.

**Figure 31:** Magnetic Decay of the 1045 Steel Core Over a 180 Minute Period.



**Figure 32:** Magnetic Decay of the 1090 Steel Core Over a 100 Minute Period.

As Figure 17 and 18 show, there is little decay over the 100 minute period, approximately 5-10% for the 1045 sample and 2-3% for the 1090 sample. Both of these are within the 10% maximum decay desired. The results of all the magnetic tests are shown in the table below.

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| **Material** | **Carbon Content (%)** | **Residual Magnetic Moment (A\*m2)** | **Decay Period** | **Flipped?** | **Suitable Material** |
| AISI 1045 Steel | 0.43-0.50 | 0.00506 | 5-10% decrease over 180 minute period | Yes | Potentially - Although magnetic moment is much smaller than 1.95 A\*m2 |
| AISI 1090 Steel | 0.85-0.98 | 0.00836 | 2-3% decrease over 100 minute period | Yes | Potentially - Although magnetic moment is much smaller than 1.95 A\*m2 |

**Table 6:** Results of Magnetic Tests for the 1045 and 1090 Steel Samples.

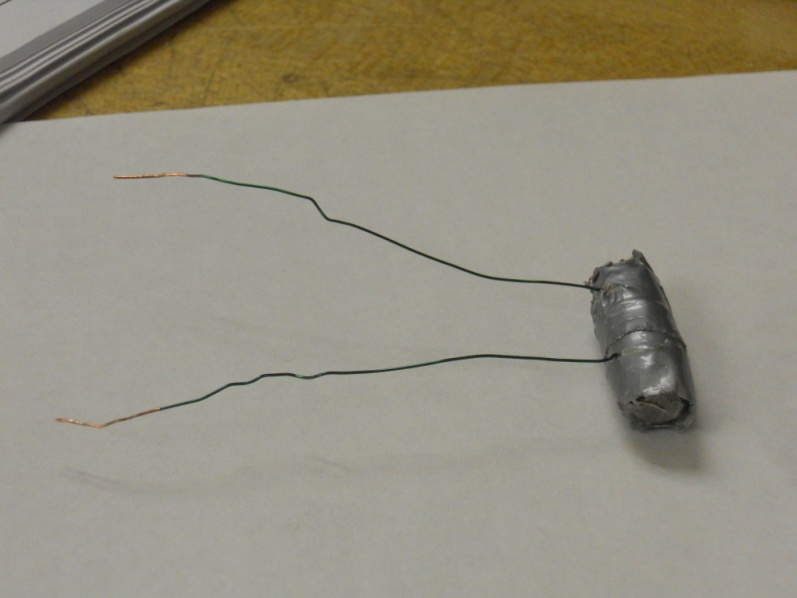
Table 3 shows that these two materials are potential candidates. However, their magnetic moments are quite small which means their ability to torque the satellite into following the Earth’s magnetic field lines will likely be limited.

Tool steel was also investigated because of its high carbon content.



**Table 7:** Tool Steel Data (from Matweb and Other Sources).

A D2 tool steel sample was obtained and investigated because of its high carbon content, along with the permanent magnetic material Neodymium (to provide a comparison). A picture and the results of the D2 tool steel magnetorquer are shown below.



**Figure 33:** D2 Tool Steel Magnetorquer (5 Wire Layer Wraps) with Duct Tape to Maintain Wrap Integrity During Testing.

The decay for the D2 tool steel sample is shown below for a 100 minute period.

**Figure 34:** Magnetic Decay of the D2 Steel Core Over a 100 Minute Period.

As Figure 20 shows, the D2 tool steel sample decays approximately 2-3% over there 100 minute period which is well within the 10% maximum desired.

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| **Material** | **Carbon Content (%)** | **Residual Magnetic Moment (A\*m2)** | **Decay Period** | **Flipped?** | **Suitable Material** |
| D2 Tool Steel | 1.4-1.6 | 0.00397 | 2-3% decrease over 100 minute period | Yes | Potentially - Although magnetic moment is much smaller than 1.95 A\*m2 |
| Neodymium | n/a | 0.559 | Lasts Forever (permanent magnetic material) | n/a | Potentially – Multiple magnets may be required. Also need to be physically rotated. |

**Table 8:** Results of Magnetic Tests for D2 Steel Sample and Neodymium Sample.

Table 7 shows that D2 tool steel has a smaller remnant magnetic moment than both the AISI 1045 and 1090 steel sample even though it has higher carbon content. This is likely due to the fabrication process of the tool steel.

The permanent magnetic material Neodymium has a magnetic moment that is approximately two orders of magnitude greater than the other materials, which would provide a very strong restoring torque for the satellite. Larger samples are available that could likely provide the 1.95 A\*m2 magnetic moment that is suggested. However, as mentioned previously, switching its magnetic field direction would require a magnetizing field more than an order of magnitude greater than what is available. Therefore, if this material was used, physical rotation of the magnet would be necessary in order to change the field direction.

A table showing all the results of the magnetic tests for the magnetorquer core materials is shown below along with a table of the physical characteristics of each magnetorquer. Also, a test matrix of the tests conducted is seen in Appendix 7.

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| **Material** | **Carbon Content (%)** | **Residual Magnetic Moment (A\*m2)** | **Decay Period** | **Flipped** | **Suitable Material** |
| A36 Steel | 0.25-0.29 | 0 | Instant decay to zero | n/a | No |
| AISI 1045 Steel | 0.43-0.50 | 0.00506 | 5-10% decrease over 180 minute period | Yes | Potentially - Although magnetic moment is much smaller than 1.95 A\*m2 |
| AISI 1090 Steel | 0.85-0.98 | 0.00836 | 2-3% decrease over 100 minute period | Yes | Potentially - Although magnetic moment is much smaller than 1.95 A\*m2 |
| D2 Tool Steel | 1.4-1.6 | 0.00397 | 2-3% decrease over 100 minute period | Yes | Potentially - Although magnetic moment is much smaller than 1.95 A\*m2 |
| Neodymium | n/a | 0.559 | Lasts Forever (permanent magnetic material) | n/a | Possibly – Although magnet will need to be rotated. |

**Table 9:** Results of all Magnetic Tests for the Magnetorquer Core Materials.

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| **Material** | **Mass (g)** | **Volume (mm3)** | **Density (g/cm3)** | **Volume Magnetization (A/m)** | **Mass Magnetization (A\*m2/g)** |
| A36 Steel | 12.54 | 2873 | 7.85 | 0 | 0 |
| AISI 1045  Steel | 13.87 | 3313 | 7.85 | 1.53\*103 | 0.000195 |
| AISI 1090  Steel | 20.43 | 3849 | 7.85 | 2.17\*103 | 0.000276 |
| D2 Tool  Steel | 14.0 | 3167 | 7.70 | 1.25\*103 | 0.000162 |
| Neodymium | 5.7 | 924 | 7.45 | 6.05\*105 | 0.081208 |

**Table 10:** Physical and Magnetic Characteristics of the Materials for the Magnetorquer Core

Table 8 shows that each magnetorquer sample falls within suitable volume and mass values. The magnetization (density of the magnetic moment with respect to volume (volume magnetization) and mass (mass magnetization)) were also calculated. The larger the density value, the stronger the magnetic dipole moment that can be obtained for a given volume or mass, respectively. As table 9 shows, neodymium has the highest volume magnetization and mass magnetization (more than two orders of magnitude larger than the other samples). However, one of the other samples has to be chosen since the direction of neodymium’s magnetic field cannot be switched using the solenoid’s H-field that is available. The AISI 1090 steel sample has the next highest volume and mass magnetization so it is the most suitable material out of all the remaining materials that were tested.

All the magnetic materials that might fulfill our requirements (that could be found) have been tested. There may be other more exotic materials in existence. However, even through searches and talks with representatives at many companies, no other suitable materials besides high carbon steel has been located that fulfills the system requirements (chargeable permanent magnet) within the volume, mass, and power constraints that are present.

Final testing of all the high carbon steel samples show that they are unlikely to have the magnetic moment required for high nadir pointing accuracy. At this time the Neodymium sample is the only material that has a suitable magnetic moment. It also has the smallest mass and volume of all the samples and requires no power. However, its magnetic moment direction cannot be switched which means it will have to be flipped either mechanically (small rotator engine) or magnetically (solenoid provides torque).

Obviously introducing a small motor would introduce additional volume and mass. A solenoid would also introduce more volume and mass but could probably be designed to be less than the motor.

## Core Winding Procedure

The procedure for making the magnetorquer is outlined below.

*Materials*

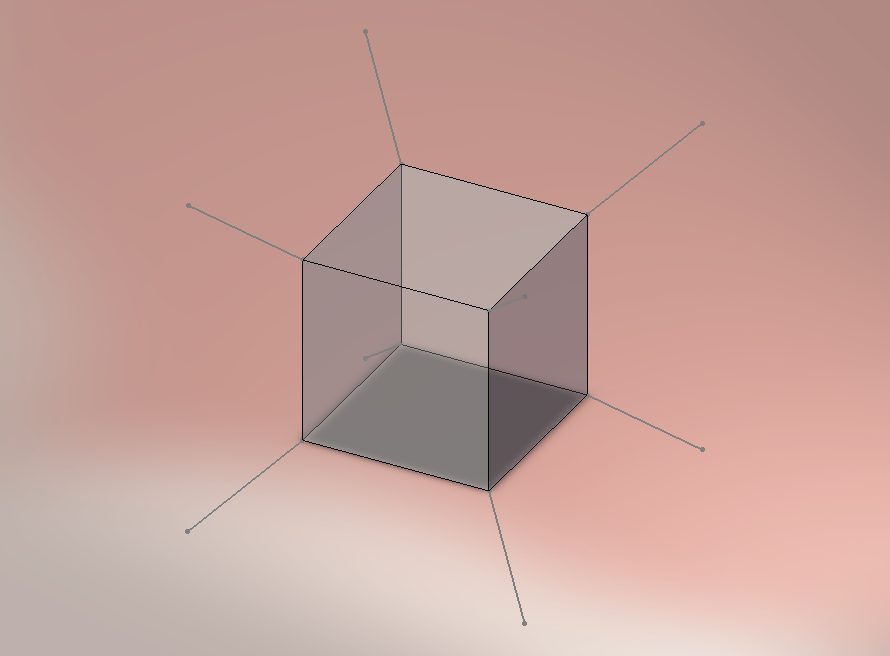
1. High carbon steel piece (see table below for specifications) with approximate dimensions of: *0.25* ***inch diameter, 1 inch length.***
2. 26 Gauge Magnet wire (should be good for direct current <=1.0 Amp)
3. High temperature epoxy (from Cotronics Corp., Daubert Chemical Company, etc.)

*Method*

1. Use a small amount of adhesive to bond a portion of the magnet wire to the high carbons steel piece so the wire does not shift during wrapping. Make sure to leave a 1-2 inch wire portion for the board connection.
2. Begin wrapping the magnet wire at the end of the steel core, ensuring there are no spaces between turns.
3. Have a partner spread the high temperature epoxy on the wire turns once the end of the magnet has been reached (1 layer wrap).
4. Let sit until epoxy has dried fully.
5. Begin wrapping a new layer over the previous layer, wrapping in the same direction (meaning clockwise or counterclockwise) as the previous layer.
6. Have a partner spread the high temperature epoxy on the new wire layer wrap once the end of the magnet has been reached.
7. Let sit until epoxy has dried.
8. Repeat steps 2-4 again until there are 5 (or more) layer wraps.

## Mounting Magnetorquer within Satellite

The magnetorquer should be mounted in such a way that its long axis is perpendicular to the face (or faces) that will be facing the earth (nadir direction). A diagram is shown below:



Nadir Facing Side

Antennas

Magnetorquer Axis

**Figure 35:** Orientation of Magnetorquer in Satellite.

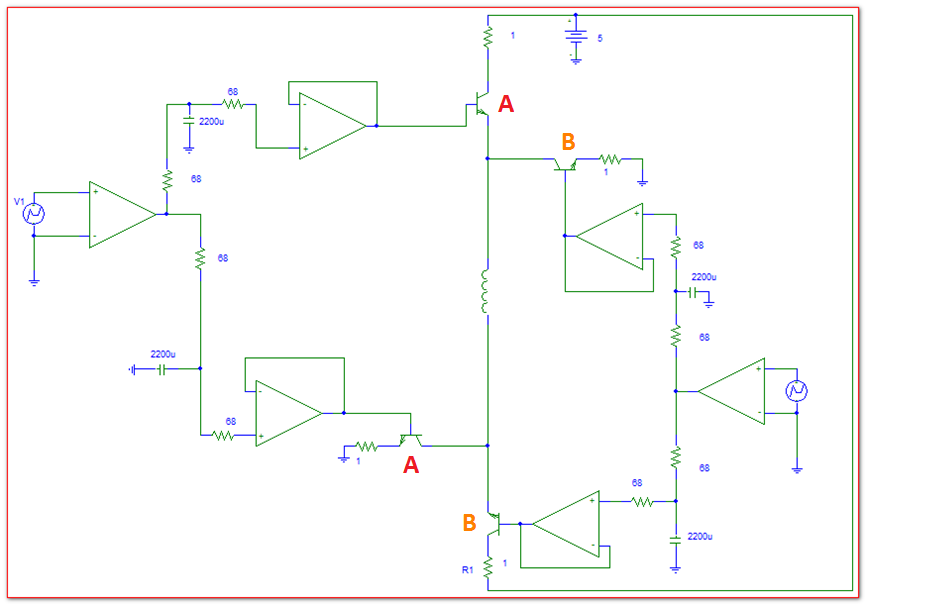
# ADAC Circuit Design

In order to function properly, the ADAC system relies on a complete circuit model of the block diagram (Figure 1). The complete ADAC circuit wiring diagram is seen in Appendix 1. A 5 pin cable comes from the Command and Data Handling board and the Power Generation and Distribution system, as seen in the top left of the image. In this cable, there are two lines from the IHU that are connected to the CPLD/Basys Board. From the power system, there comes in a 3.3V and 5V power lines, as well as the ground line. In the circuit, the 3.3V line powers the GPS and Gyro, as well as whatever potential CPLD would be implemented in the circuit later; the 5 V line is used in the magnetorquer circuit.

The CPLD/Basys Board outputs values to the power shutoff opamps to disable the GPS or Gyro power when not in sampling mode. More of this will be explained in the power shutoff section. It also outputs two values to the magnetorquer circuit, one for forward applied current, as well as one for reverse current. The CPLD/Basys board receives information from the IHU along the SCL and SCA I2C lines. It also receives the output from the Gyroscope via two I2C lines. The GPS unit uses a serial connection, shown here with two transmission lines.

## Magnetorquer Circuit

The magnetorquer charge circuit utilizes an H-bridge configuration to allow the inductor to charge its core in both the forward (prime mode) and reverse direction (secondary mode). This is done utilizing alternating transistors to either pass or allow current in both directions. A better view of the H-bridge is seen below in figure XXX.



Forward

Figure 36: Magnetorquer Flip Circuit

If the CPLD/Basys Board applies current in the forward direction, the top op amp outputs high, turning on the A set of transistors. If the control activates the reverse direction, the B set of transistors will open. A pair of 1 ohm resistors are placed between the transistors and power or ground. Although this seems a waste of power, the inductor would be connected directly to power and ground if they were not in place, effectively shorting the entire satellite’s power system.

Two types of transistors were selected for this circuit. For the high voltage side, the KSD882 NPN BJT transistor from Fairchild Semiconductor was chosen, because it has high current gain, high current capability, and can handle the power of the max current flow. For the pair of transistors leading to the ground path, the STSA851NPN BJT from ST microelectronics was chosen. It has a low gain with high current and proper power requirements. Both of the units also have low gate to threshold voltage, creating a larger voltage drop across the 1 ohm resistors, allowing more current to pass through the magnetorquer. After testing, we verified that the inductor does receive the 1A of current required for its charge cycle.

In order to guarantee that no voltage spikes will feedback from the magnetorquer, additional capacitors are added into the circuit. To decide what values for the parts seen in figure XX, basic equations are used.

(9)

Because the voltage across the transistors and the resistors, the voltage drop across the inductor when active, is approximately 1V.

(10)

This means that the capacitor circuit must have a charge time of over .175 seconds.

(11)

Because of the op amp, the voltage is approximately 4.3 V, and the time is the number derived above. Because some current escapes through the BJT, the voltage at the capacitor (the center of the two resistor voltage divider) is 2V. The total resistance is twice the amount of each resistor, because there is a resistor on each side of the capacitor.

sec (12)

In order to fulfill this circuit, many choices could be made for resistor and capacitor values. However, the decision was made to use a low value for R, so the BJT could send in more current to the magnetorquer. Therefore, a large capacitor value would be used. The ADAC team chose to use 2200 uf capacitors because they are a large standard value for capacitors. This equates to a resistor value of approximately 70 ohms. Therefore, a 68 ohm resistor is very close, and it is a standard value, so that was the value chosen for the charge circuit.

Using this configuration allows the inductor to be toggled in either direction without any significant voltage spikes through the system. The capacitor charges in approximately .75 seconds, which is much faster than the .06 time constant for the magnetorquer. This allows the magnetorquer’s inductive effects to be neglected, giving the circuit no residual voltage spikes from the inductor, only the charge time from the capacitor charge.

However, during testing, it was discovered that there was an impedance matching issue between the capacitor and the magnetorquer. This problem was removed with a simple unity feedback opamp, separating the capacitor impedance from the magnetorquer’s inductance, allowing the circuit to switch as desired.

## Power Shutoff

In order to limit the power consumption of the satellite, the ADAC system implements a power shutoff circuit to remove power from the gyroscope and the GPS, allowing the power only when it is time to measure the dynamics of the satellite. The ADAC circuit uses a TLV2463CN operational amplifier to regulate the power. It is manufactured by Texas Instruments, provided a full rail to rail voltage level at both 5 and 3.3 volts, and allows more than 50 mA of current at steady state output. This is enough current to power both the GPS and gyro, making it a great shutoff for power.

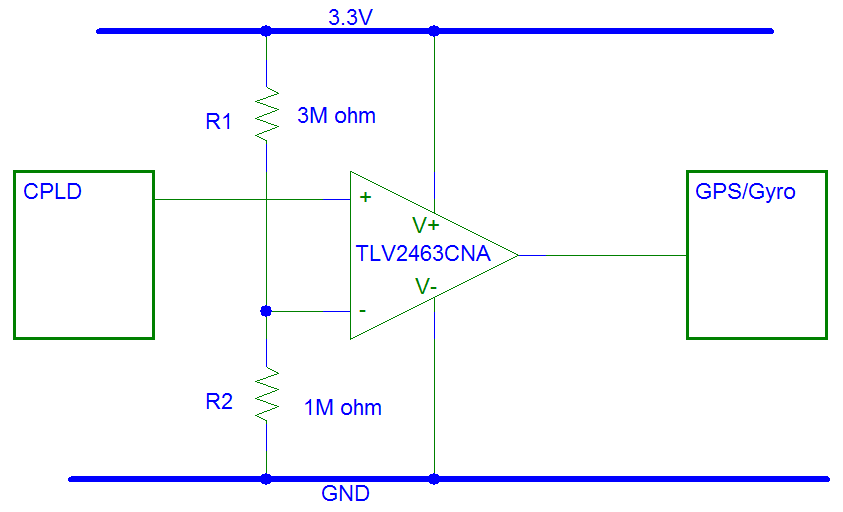


Figure 37: Shutoff Circuit

The basic configuration to the op amp is seen above in figure XXX. The op amp is connected to 3.3V and ground as its V+ and V-. The output is connected to the power pin of the gyro or GPS. The positive input is connected to the CPLD, as we want the output to be driven high when the signal comes from the CPLD. The negative input is connected between a 3 MΩ and 1 MΩ voltage divider. This makes the CPLD voltage lower than the negative input when low, driving the output to 0 V. And, the voltage at the negative input is approximately .825 V, so as long as the CPLD uses more than .9V output voltage, the CPLD will drive the output high no matter what voltage the CPLD drives the output pins at. And, because of the large magnitude of the resistors, the op amp circuit will not use more than 2.7 uW of power, much less than the 20 mW from the gyro or 83 mW from the GPS when in the desired sleep mode. This is more than 3000 percent power efficiency, with only the addition of four resistors and two op amps of space, mass, and cost.

# ADAC Testing

A test matrix and procedure was designed for each major component of the ADAC system and is located in Appendices 6,7,8. The first and most involved testing was that done for the solid core magnetorquer. After preliminary calculations were done to determine the strength of magnetic field needed to flip the satellite and which metals had the ability to have their magnetic field directions reversed, testing commenced. Five different types of metal were wound with wire creating solid core magnetorquers and their magnetic field strengths were recorded with a supply voltage of 5V being applied. The remnant magnetic dipole moment was then measured along with its percentage of decay. The last test for the magnetorquer was its ability to switch magnetic dipole direction. All of these tests resulted in the choice of AISI 1090 for the core material.

After the solid core magnetometer was chosen, it could be tested with the circuit designed to flip the magnetic field. The protoboard was constructed with the magnetorquer and testing began by connecting a power source. Once current was flowing through the magnetorquer the amount was measured using a probe and the respective magnetic field was illustrated with a compass. The power was then connected so that the current would flow in the opposite direction and the same testing was preformed again. This verified that the circuit was in working order as well as a magnetic field was produced while current ran in both directions. The success of this test finished the flipping requirements of the ADAC system.

Power saving mode was tested by first applying a power source and verifying that the CPLD had the correct amount of power (3.3V). The CPLD was then connected to the FET gate and the switch was toggled to put the circuit in high to open power and the voltages were measured at the sources and drains for each case. This test was successful which fulfilled requirements and verified that the circuit is in working order.

The next step in testing this system is testing the communications which is done using a logic analyzer. The first step is to determine if the FPGA is communicating properly with the gyroscope. This is done by verifying that there is 3.3 volts at the SDA line then using the buttons on the FPGA to determine if the information is communicating correctly. The communication between the FPGA and the IHU via I2C is tested next by verifying that the correct voltages are present. Lastly the serial interface between the CPLD and the GPS sensor can be tested. This, unlike the rest of the communications tests, was not preformed due to time constraints. These tests provide that the I2C communication works properly and further testing can be done with the gyroscope.

In order to test the gyroscope, it needs to be in some type of angular motion which inspired a test rig. A rotating platform was designed so that the entire ADAC protoboard and the IHU can be mounted on top along with a battery pack as a power source. This will allow the entire system to spin as it would in space. The platform is connected to a servo motor that is connected to a power source. Using a simple magnetic system to evaluate the rpm of the platform, the accuracy of the gyroscope can be determined. Final testing for the GPS would include connecting it to the CPLD, and verifying that it outputs proper latitude and longitude at various positions.

In order to test the Kalman filter both the simple non-linear filter and the more complex filter need to be analyzed so that all errors are removed. A small number of samples are then input and the output trajectories are studied. The accuracy of the trajectory is evaluated and more samples can be input. The Kalman filter is successful when a quick and accurate trajectory is obtained.

With all of the separate parts tested and verified the entire ADAC system works as a hole when communicating with the common board. First the system is probed to verify that it receives the correct amount of power from the common board. Then the flip command is given and the magnetic field of the magnetorquer is verified. The start and stop sampling commands are tested along with the retrieval of data for the Kalman filter. After the correct amount of data is retrieved for the Kalman filter to work the register file is tested to verify that there is no left over data after the stop sampling command is given.

# AMSAT Integration

The ADAC system is only a portion of the AMSAT satellite project. In order for the satellite to function properly, all components in the satellite must function properly both internally as well as the interactions between systems. This is especially important for the ADAC system, as all of the system’s responsibilities are driven by external signals. Both the magnetorquer flip and the sensor measurement component must be initiated through I2C communication with the command and data handling system (Figure 1). When the signal comes to flip or measure the dynamics of the satellite, the command and data handling system signals to the ADAC system to act. This means all functions of the system, power shutoff, measurement, and motion control, are dependent on the external functions of the command system. Also, the Kalman filter for the data will be implemented on the command system’s processor, further connecting the ADAC and command systems. The information measured by the sensors will be sent to the main processor, where the filter will be implemented. Then, it will be dealt with accordingly by the command system.

Furthermore, the power for the ADAC system comes from the power generation and distribution team, further connecting the satellite. Although the ADAC system is power efficient, the power system has the ability to terminate the ADAC system when the batteries for the satellite are too low and power is unavailable. Therefore, as the ADAC system is not a mission critical function of the satellite, it can be terminated at the discretion of the power system.

The GPS antenna must also be deployed along with the satellite’s antenna. Although the GPS antenna is small, it must be located on the outside of the satellite, making it a concern with the antenna deployment team. The coaxial cable leading from the antenna must be trailed with other wires through the satellite, connecting into the GPS. Therefore, the ADAC system must be integrated with the satellite structure and the antenna systems to properly be located within the satellite, as well as to have a fully functional GPS sensor.

# Budget

Our initial budget was a high estimate of what we would need to spend. During the design process components were emitted and changed (such as a magnetometer and an accelerometer). We no longer needed a boom to mount the magnetometer because we decided to no use the magnetometer at all, which saved money, as well as time. Also instead of purchasing a CPLD and a PCB we purchased a Basys Board and a protoboard, which collectively was more cost effective. The magnetorquer turned out to be less expensive than projected and the sensors cost about as much as was allotted for them. Ultimately the ADAC system came out to be approximately $100 dollars under budget as shown in Figure 25.

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| **Projected** | | | | | |
| **Item #** | **Item Name** | **P/N (if applicable)** | **Cost / unit** | **Quantity** | **Total Cost** |
| 1 | GPS | ISM420 | $25.00 | 1 | $25.00 |
| 2 | Gyroscope | ITG3200 | $50.00 | 1 | $50.00 |
| 3 | Magnetorquer |  | $80.00 | 1 | $80.00 |
| 4 | Boom/Antenna |  | $50.00 | 1 | $50.00 |
| 5 | CPLD |  | $30.00 | 1 | $30.00 |
| 6 | PCB |  | $100.00 | 1 | $100.00 |
| 7 | Logic parts |  | $50.00 | 1 | $50.00 |
|  |  |  |  | **Total** | **$385.00** |
|  |  |  |  |  |  |
| **Actual** | | | | | |
| **Item #** | **Item Name** | **P/N (if applicable)** | **Cost / unit** | **Quantity** | **Total Cost** |
| 1 | GPS | ISM420 | $35.00 | 1 | $35.00 |
| 2 | Gyroscope | ITG3200 | $50.00 | 1 | $50.00 |
| 3 | Magnetorquer |  | $40.00 | 1 | $40.00 |
| 4 | Boom/Antenna |  | $10.00 | 1 | $10.00 |
| 5 | Basys board |  | $80.00 | 1 | $80.00 |
| 6 | Protoboard |  | $15.00 | 1 | $15.00 |
| 7 | Logic parts |  | $53.00 | 1 | $53.00 |
|  |  |  |  | **Total** | **$283.00** |

**Table 11:** Projected and Actual Budget.

# Schedule

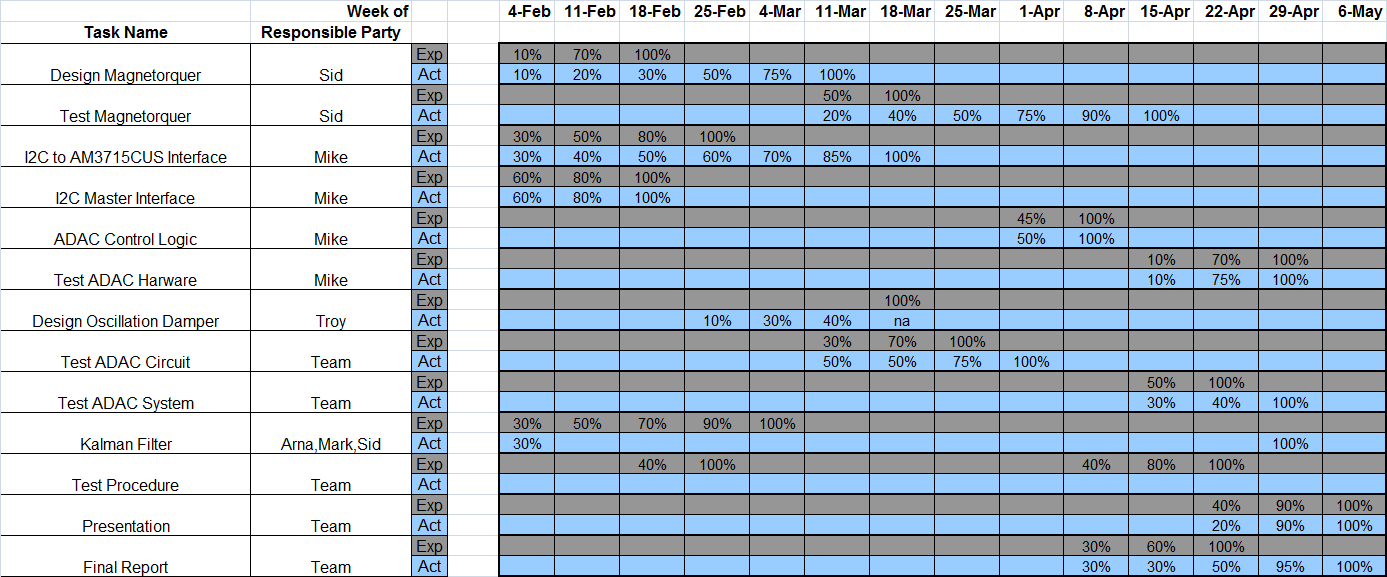


Table 12: ADAC Schedule.

The ADAC team was not on schedule for most of the semester. Elements began to feature creep into the design, and benchmarks were put off due to communication problems with various AMSAT teams. An excellent example of this was the GPS unit. For several weeks, the status of the GPS was in limbo because it was unknown if the GPS would even be purchased, as it was unable to fit into the protoboard design. After some time, an executive decision was made by the team to purchase it anyways, as there was room in the budget this semester.

However, the team was ahead of most of the components for the Engineering Design Process. The test plans and procedures were constructed ahead of time, and elements were worked into the design of the system to make testing easier. Examples of this were to breadboard the circuit before building the protoboard, and the element wise constructing the board to prevent failure. This greatly reduced time in the construction of the project, as the board was constructed overnight, without any failures. The report formulating all the ideas of the ADAC system was begun prematurely from the set dates to allow for more intensive testing schedules with other AMSAT teams.

# Future ADAC Development

# The ADAC system is not a complete design that is ready for satellite deployment. A damping system must be built and tested, a PCB must be designed to house the components, and the GPS must be communicated with the CPLD. Also, the Kalman filter must be tested with the onboard sensors in a realistic test condition, not an environment where the data provides only random location generation. Further system tests must also be run, especially with the power system. The large current draw from the magnetorquer will put large stress on the power generation and distribution system, making these tests crucial to guarantee the satellite to works properly. Also, a CPLD will have to be chosen and introduced to the system, coded, and debugged to run the ADAC system. Overall, the theory of the ADAC system is complete, but much of the implementation for the PCB design needs to be completed.

Works Cited

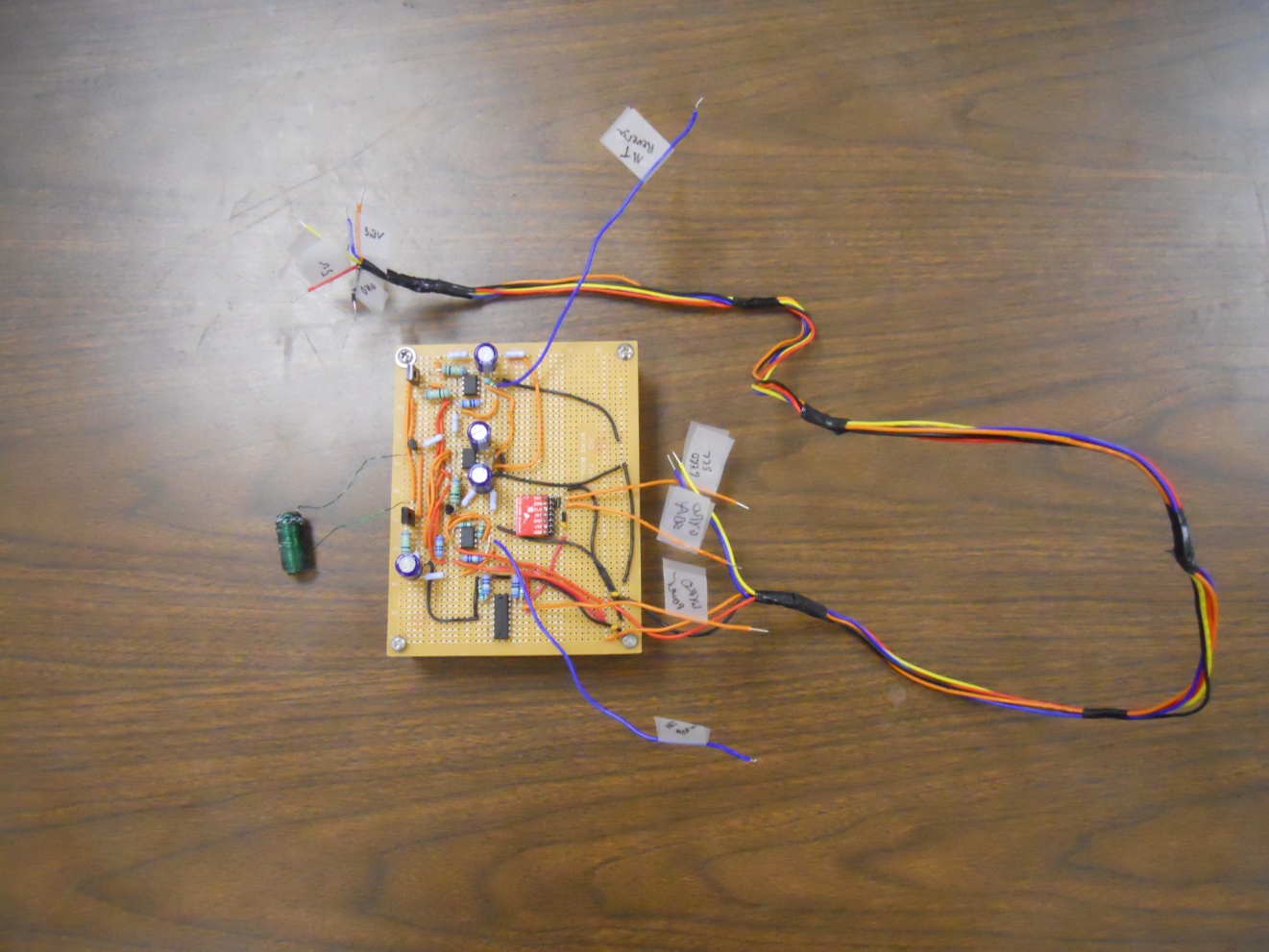
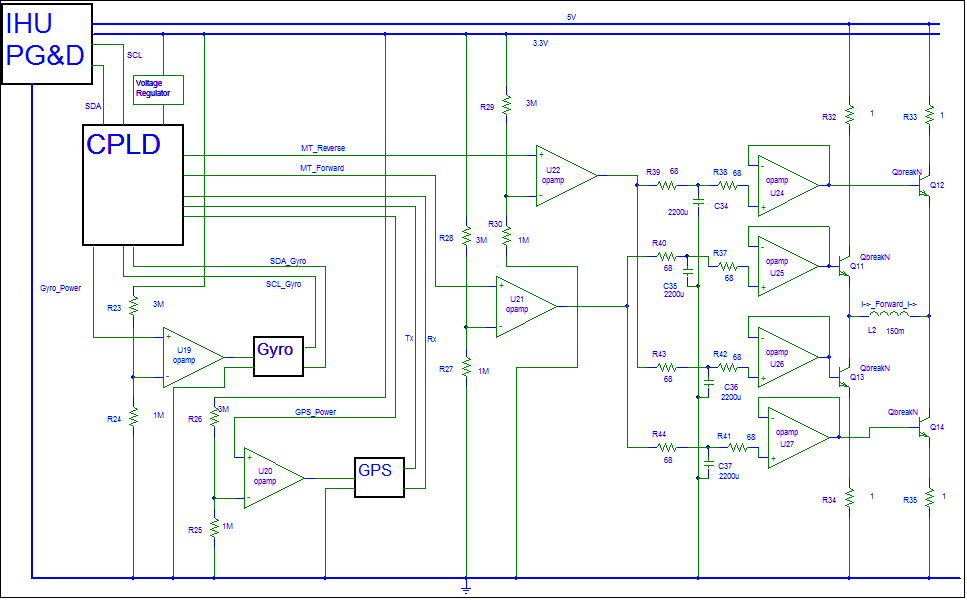
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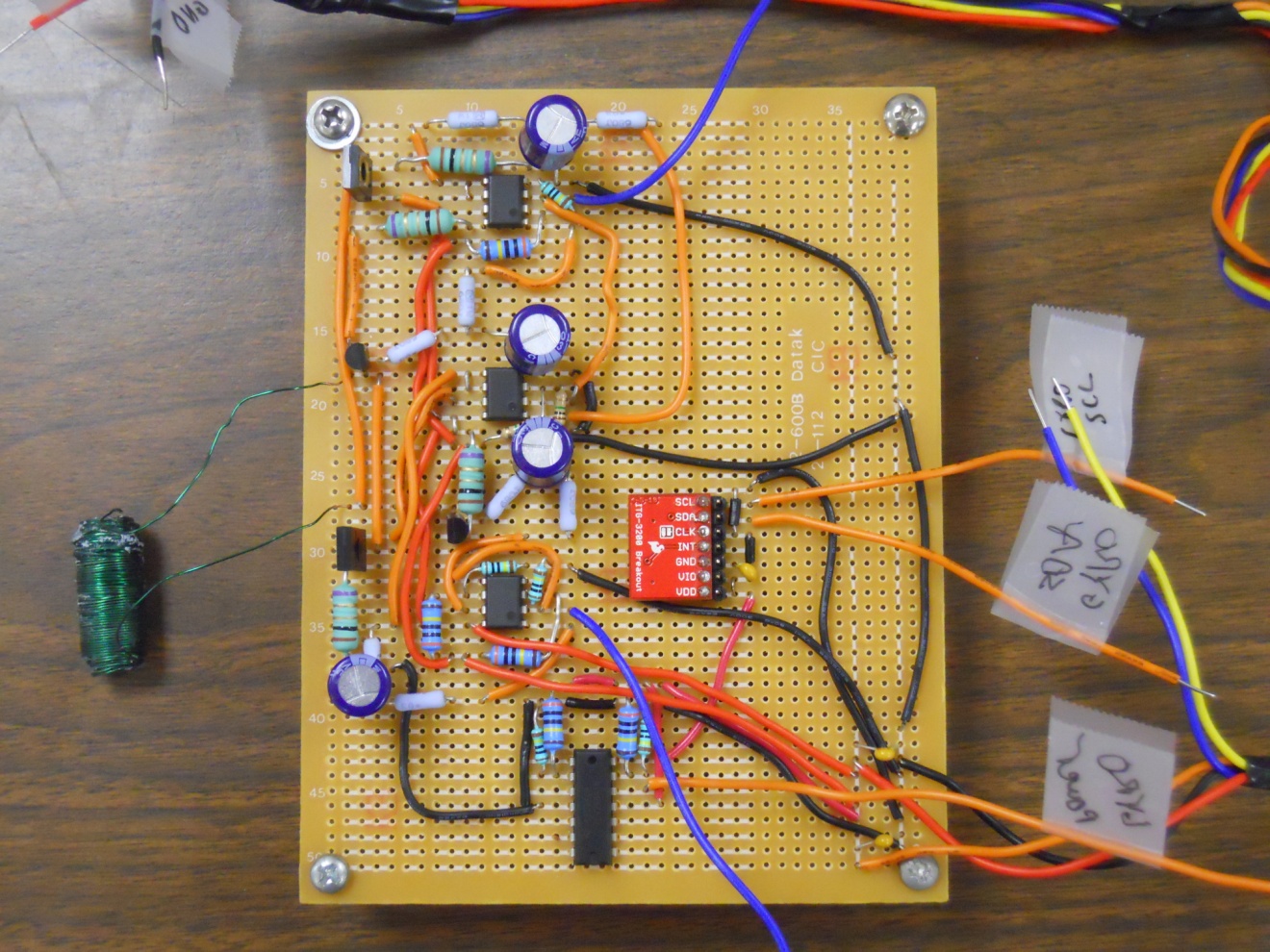
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[3] Rawashdeh, Samir. PASSIVE ATTITUDE STABILIZATION FOR SMALL SATELLITES. December 3rd, 2009. Pg. 34-38.

[4] Sinclair, D.; Damaren C. Flight Results from a Novel Magnetic Actuator on the LatinSat Spacecraft. Sinclair Interplanetary, 17th Annual AIAA/USU Conference on Small Satellites.

Appendix 1 ADAC Circuit Diagram and Picture





Appendix 2 ADAC Table of Components

|  |  |  |
| --- | --- | --- |
| **Function** | **Part Number or Value** | **Number of Components** |
| Basys Board |  | 1 |
| Protoboard |  | 1 |
| Gyroscope | ITG3200 | 1 |
| GPS | IMF300F2 | 1 |
| GPS Antenna | sl1204 | 1 |
| Magnetorquer |  | 1 |
| Power Opamp | Tvl2464 | 1 |
| Control Opamp | Tl3472 | 3 |
| Control Resistor | 3M ohm | 6 |
|  | 1M ohm | 6 |
| Limiter Resistor | 1 ohm | 4 |
| Charge Resistor | 68 ohm | 8 |
| Charge Capacitor | 2200 uf | 4 |
| Filter Capacitor | 100 uf | 3 |
| High Transistor | KSD882 NPN BJT | 2 |
| Low Transistor | STSA851NPN BJT | 2 |
| Board Legs |  | 4 |
| Assorted Wires |  |  |

Appendix 3 The Slave Controller Design



Appendix 4 I2C Master Controller



Appendix 5 Companies Contacted for Magnetorquer Core Material

|  |  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| **Magnetic Material Companies** |  |  |  |  | |  |  | |  | |  | |
|  |  |  |  | ***Suitable material*** | |  | |  | |  | |
| ***Name*** | **Number** | **Location** | **Contacted** | **Yes** | **No** | **Material** | | **Price** | | **Ordered** | |
| **Dexter Magnetic Materials** | (516) 822 3311 | NY | x |  | x | n/a | | n/a | |  | |
| **Dura Magnetics, Inc.** | (800) 773-6891 | OH | x | x |  | Cobalt Stl? | | ??? | |  | |
| **K&J Magnetics** | (888) 746-7556 | PA | x |  | x | n/a | | n/a | |  | |
| **Magnetic Sales & Manufac.** | (800) 421-6692 | CA | x |  | x | n/a | | n/a | |  | |
| **Applied Magnets** | (800) 379-6818 | TX | x |  | x | n/a | | n/a | |  | |
| **Magnetic Incorporated** | (585) 582-2604 | NY | x |  | x | n/a | | n/a | |  | |
| **Magnetic Metals** | (412) 561-4764 | PA | x |  | x | n/a | | n/a | |  | |
| **Carpenter Magnetic Alloys** | (800) 654-6543 | PA | x | ?? |  | ??? | | ??? | |  | |
| **Arnold Magnetics** | none available | many | x | ?? |  | ??? | | ??? | |  | |

|  |  |
| --- | --- |
| ***Name*** | **Comments** |
| **Dexter Magnetic Materials** | Doesn't carry medium magnetic materials |
| **Dura Magnetics, Inc.** | They're going to check on some materials (cobalt steel) and get back to me |
| **K&J Magnetics** | Doesn't carry medium magnetic materials |
| **Magnetic Sales & Manufac.** | Doesn't carry medium magnetic materials |
| **Applied Magnets** | Doesn't carry medium magnetic materials |
| **Magnetic Incorporated** | Doesn't carry medium magnetic materials |
| **Magnetic Metals** | Doesn't carry medium magnetic materials |
| **Carpenter Magnetic Alloys** | Emailed them, awaiting reply |
| **Arnold Magnetics** | Emailed them, awaiting reply |

|  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- |
| **Steel Companies** |  |  |  |  |  |  |  |  |
|  |  |  |  | ***Suitable material*** | |  |  |  |
| ***Name*** | **Number** | **Location** | **Contacted** | **Yes** | **No** | **Material** | **Price** | **Ordered** |
| **Metal Supermarkets** | (866) 867-9344 | Ontario | x | x |  | AISI 1045 | 10.00 | x |
| **McMasterCarr** | (609) 689-3415 | NJ | x | x |  | C1090-1095 | 5.03 | x |
| **Metals Depot** | (859) 745-2650 | KY | x | x |  | AISI 1144 | ??? |  |
| **Ray Morris** | (800) 243-7340 | unknown | x |  | x | n/a | n/a |  |
| **Yarde Metals** | (860) 406-6061 | CT | x |  | x | n/a | n/a |  |
| **Chapain and Bangs** | (800) 972-9615 | CT | x |  | x | n/a | n/a |  |
| **Admiral Steel** | (800) 323-7055 | IL | x |  | x | n/a | n/a |  |
| **Ryerson** | (716) 684-6900 | IL | x | ??? |  | ??? | ??? |  |
| **Hudson Metals** | (800) 996-0411 | CA | x |  | x | n/a | n/a |  |
| **Commercial Metals Co.** | (830) 372-8200 | TX | x | ??? |  | ??? | ??? |  |
| **Sanghvi Metal Corp.** | n/a | India | x | ??? |  | ??? | ??? |  |
| **Alloy Metals** | (800) 681-7363 | MI | x |  | x | n/a | n/a |  |
| **AK Steel Corporation** | (800) 331-5050 | OH | x |  | x | n/a | n/a |  |
| **Queen City Forging Co.** | (513) 321-7200 | OH | x |  | x | n/a | n/a |  |
| **Precision Steel Warehouse** | (888) 490-8296 | NC | x |  | x | n/a | n/a |  |
| **GPI Metal Products LLC** | (414) 406-2051 | WI | x |  | x | n/a | n/a |  |
| **Parker Steel Company** | (800) 333-4140 | OH | x | x |  | ??? | ??? |  |
| **NUCOR Coporation** | (843) 393-5841 | Many | x |  | x | n/a | n/a |  |
| **Central Steel** | (800) 621-8510 | IL | x |  | x | n/a | n/a |  |
| **ONeal Metals** | (205) 599-8000 | AL | x |  | x | n/a | n/a |  |
| **Speedymetals** | (866) 938-6061 | WI | x |  | x | n/a | n/a |  |

|  |  |
| --- | --- |
| ***Name*** | **Comments** |
| **Metal Supermarkets** | Don't carry high carbon steel (1060-1080) |
| **McMasterCarr** | Have (bought) high carbon keystock (square), C1090, cheap, (.25 by .25), 1 ft length |
| **Metals Depot** | Will email me back with quote for 1144 steel, 1 inch pieces |
| **Ray Morris** | Doesn't carry high carbon steel |
| **Yarde Metals** | Doesn't carry high carbon steel |
| **Chapain and Bangs** | Doesn't carry high carbon steel |
| **Admiral Steel** | Don't carry high carbon steel (1060-1080) |
| **Ryerson** | Called them again (Mar 22) - They will call me back |
| **Hudson Metals** | Don't carry high carbon steel (1060-1080) |
| **Commercial Metals Co.** | Emailed them (Mar 22), waiting for response |
| **Sanghvi Metal Corp.** | Emailed them, waiting for response |
| **Alloy Metals** | Don't carry high carbon steel (1060-1080) |
| **AK Steel Corporation** | Don't do small quantities or manufacture rounds |
| **Queen City Forging Co.** | Don't carry high carbon steel (1060-1080) |
| **Precision Steel Warehouse** | Don't manufacture rounds |
| **GPI Metal Products LLC** | Don't carry high carbon pieces that small |
| **Parker Steel Company** | Have 1060 IH in 8mm but cannot only cut to 1 foot, and $85 minimum order |
| **NUCOR Coporation** | Don't do small quantities |
| **Central Steel** | Don't carry high carbon steel (1060-1080) |
| **ONeal Metals** | Minimum Purchase Order of $350 |
| **Speedymetals** | Don't carry high carbon steel (1060-1080) |

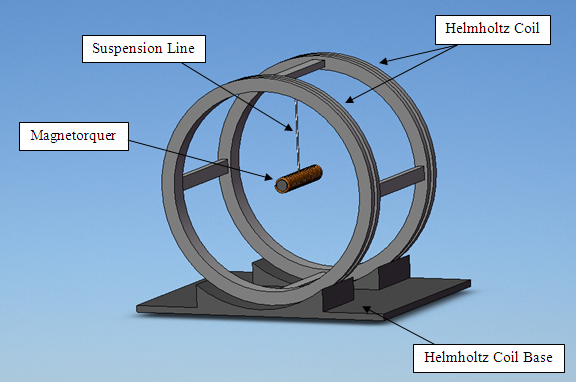
|  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| **Tool Steel Companies** |  |  |  |  |  | |  |  |  |
|  |  |  |  | ***Suitable material*** | | |  |  |  |
| ***Name*** | **Number** | **Location** | **Contacted** | **Yes** | | **No** | **Material** | **Price ($)** | **Ordered** |
| **Hudson Metals** | (800) 996-0411 | CA | x | x | |  | D2, D3 | 55.00 |  |
| **GPI Metal Products LLC** | (414) 406-2051 | WI | x |  | | x |  |  |  |
| **onlinemetals.com** | (800) 704-2157 | WA | x | x | |  | A2 | 18.26 |  |
| **McMasterCarr** | (609) 689-3415 | NJ | x | x | |  | D2 | 9.87 | x |
| **Speedymetals** | (866) 938-6061 | WI | x | x | |  | A2 | 7.00 |  |
|  |  |  |  |  | |  |  |  |  |
|  |  |  |  |  | |  |  |  |  |
| ***Name*** | **Comments** | | | | | | |  |  |
| **Hudson Metals** | Minimum of $55 but they do have D2 maybe D3 | | | | | | |  |  |
| **GPI Metal Products LLC** | Don't do smaller than 6 inch diameter | | | | | | |  |  |
| **onlinemetals.com** | smallest length is 3ft | | | | | | |  |  |
| **McMasterCarr** | Have 0.25 Diameter, 1 ft length | | | | | | |  |  |
| **Speedymetals** | 0.5 inch minimum diameter, can cut to 1 inch | | | | | | |  |  |

|  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- |
| ***Solenoid Companies*** |  |  |  |  |  |  |  |  |
|  |  |  |  | ***Suitable material*** | |  |  |  |
| ***Name*** | **Number** | **Location** | **Contacted** | **Yes** | **No** | **Material** | **Price** | **Ordered** |
| **Magnet-Schultz of America** | (630) 789-0600 | IL | x |  | x | n/a | n/a |  |
| **Jameco Electronics** | (800) 831-4242 | CA | x |  | x | n/a | n/a |  |
| **APW Company** | (877) 627-0644 | NJ | x |  | x | n/a | n/a |  |
| **Bomag USA, LLC** | (860) 589-2098 | ?? | x |  | x | n/a | n/a |  |
| **Satellite Services Ltd.** | UK # | UK | website |  | x | n/a | n/a |  |
|  |  |  |  |  |  |  |  |  |
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|  |  |  |  |  |  |  |  |  |
| ***Name*** | **Comments** | | | |  |  |  |  |
| **Magnet-Schultz of America** | Don't have this type of solenoid | | | |  |  |  |  |
| **Jameco Electronics** | Don't have this type of solenoid | | | |  |  |  |  |
| **APW Company** | Don't have this type of solenoid | | | |  |  |  |  |
| **Bomag USA, LLC** | Don't have this type of solenoid | | | |  |  |  |  |
| **Satellite Services Ltd.** | Designed to have small remnant moment | | | |  |  |  |  |

|  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| ***High Carbon Steel Wire*** |  | |  | |  |  | |  | |  | |  | |  | |
|  |  | |  | |  | ***Suitable material*** | | | |  | |  | |  | |
| ***Name*** | **Number** | | **Location** | | **Contacted** | **Yes** | | **No** | | **Material** | | **Price** | | **Ordered** | |
| **Central Steel and Wire** | (800) 621-8510 | | IL | | x |  | | x | | n/a | | n/a | |  | |
| **Radcliff Wire** | (860) 583-1305 | | CT | | x | x | | x | | n/a | | n/a | |  | |
| **Peterson Steel** | (800) 325-3245 | | MA | | x |  | | x | | n/a | | n/a | |  | |
| **Northeast Steel Corp.** | (203) 774-7500 | | ?? | | x | x | | x | | n/a | | n/a | |  | |
|  |  | |  | |  |  | |  | |  | |  | |  | |
|  |  | |  | |  |  | |  | |  | |  | |  | |
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|  |  | |  | |  |  | |  | |  | |  | |  | |
| ***Name*** | **Comments** | | | | | | | | | | | | | | |
| **Central Steel and Wire** | Don't carry small rounds or high carbon | | | | | | | | | | | | | | |
| **Radcliff Wire** | Deal with special wire cross-sections, going to be expensive (sell by the pound), check website | | | | | | | | | | | | | | |
| **Peterson Steel** | Doesn't deal with high carbon wire | | | | | | | | | | | | | | |
| **Northeast Steel Corp.** | Doesn't deal with small quantities (at least 100 pounds) | | | | | | | | | | | | | | |
| ***Cast Iron*** | |  | |  | | |  | |  | |  | |  | |  | |
|  | |  | |  | | |  | | ***Suitable material*** | | | |  | |  | |
| ***Name*** | | **Number** | | **Location** | | | **Contacted** | | **Yes** | | **No** | | **Material** | | **Price** | |
| **American Iron & Alloys Corp.** | | (800) 544-4800 | | Waukesha, WI | | | x | | x | | x | | Cast Iron | | n/a | |
|  | |  | |  | | |  | |  | |  | |  | |  | |
|  | |  | |  | | |  | |  | |  | |  | |  | |
| **Comments** | | | | | | |  | |  | |  | |  | |  | |
| Have cast iron, 5/8 inch, but $50 minimum purchase order | | | | | | |  | |  | |  | |  | |  | |

Appendix 6 Magnetorquer Moment Testing

1. ***Magnetorquer construction and Helmholtz Coil Verification (3.b.i)***
   * 1. Build magnetorquer by wrapping a cylindrical iron piece with insulated wire (AWG gauge 26 magnet wire)
     2. Measure the physical dimensions of the MT and Helmholtz coil. Use these data to calculate the moment of inertia of the MT
     3. Use a Gauss meter to measure the magnetic field of the Helmholtz coil at a number of currents to insure that it matches up with theoretical predictions (Make sure magnetorquer (MT) is not present or any other object with a strong magnetic field)



**Diagram [2]**. Experimental setup for the Helmholtz coil and the magnetorquer (current source for Helmholtz coil and for magnetorquer not shown).

* 1. ***Measure the remnant magnetic dipole moment of the core (3.b.ii)***
     1. Degauss (remove magnetic field) MT by pulling it in and out of an AC solenoid
     2. Put a direct current of 1.00 A through the MT for 5 seconds and then turn off
     3. Suspended MT at the center of the Helmholtz coil using fishing line or some other very thin, low weight material (see Diagram [2])
     4. Put a constant direct current through the Helmholtz coil
     5. Displace the MT’s axis a small amount (in the horizontal plane) from the Helmholtz coil axis
     6. Count the amount of time required to go through 20 full cycles
     7. Repeat this procedure 5 times without changing the current of the Helmholtz coil
     8. Turn the Helmholtz coil current off
     9. Average the data
     10. Find the magnetic dipole moment of the MT (using equation that relates period of oscillation to magnetic moment)
     11. Degauss MT (remove from suspension string if necessary)
     12. Reattach it to the suspension string.
     13. Repeat steps (iv-ix)
     14. Average the data
     15. Find the magnetic dipole moment of the MT (using equation that relates period of oscillation to magnetic moment)
     16. Subtract the first magnetic moment value (x) from the second (xv).
     17. Compare the measured magnetic dipole moment of the core to the desired magnetic moment
     18. If the measured value is less than desired value MT fails

Note: Steps (xii-xvi) are included because the Helmholtz coil produces an H-field which will magnetize the sample. This effect needs to be considered and removed to obtain an accurate measure of the magnetic moment due solely to the magnetorquer’s H-field.

* 1. ***Measuring the decay of the magnetic dipole moment of the core (after the direct current is removed) (3.b.iii)***

Note: Since the MT core is not a permanent magnet its magnetic dipole moment will slowly disappear when the MT current is removed. Since the strength of the MT during satellite flight is important, the decay characteristics must be measured. Since the previous procedure does not easily lend itself to this type of decay measurement, a different procedure will be used. A Gauss meter will be needed.

1. Degauss magnet.
2. Apply a direct current of 1.00 A to the MT using the power source for approximately 5 seconds and then turn off
3. Measure the magnetic field of the magnetic core at the surface of the MT along its axial axis using the gauss meter
4. Make a magnetic field measurement every 5 minutes for a 100 minute period.
5. Plot the data on a magnetic moment versus time graph
6. Determine best fit line using least-squares fit (likely an exponential)
7. From the graph determine whether the magnetic moment retains at least 90% of its initial value after 100 minutes

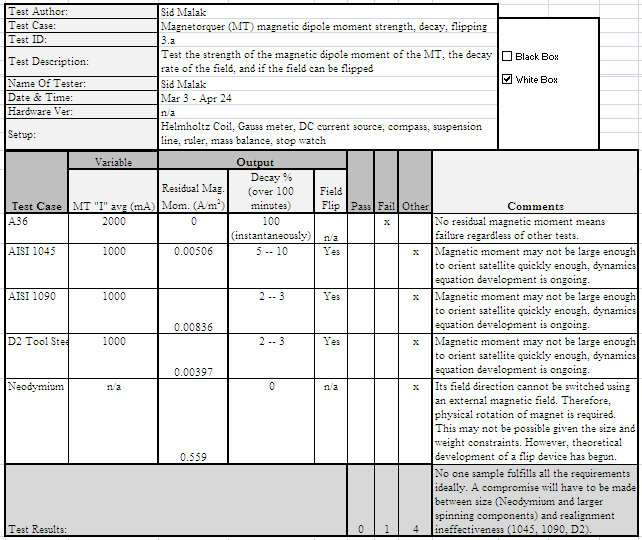
Note: The gauss meter measures the magnetic field of the sample, not its magnetic moment. However, the magnetic field is solely linearly proportional to the magnetic dipole moment so the decay graph for the magnetic field also applies to the magnetic dipole moment

* 1. ***Measuring the ability of the MT core to switch its magnetic dipole direction (3.b.iv)***

Note: A very important characteristic of the MT is its ability to switch its magnetic field direction when a current is applied in a direction opposite to what it was applied to before. A compass will be needed.

1. De-gauss the MT
2. Hook up a mechanical DC current switch from the power source to the MT (so that the current direction can be switched easily)
3. Place magnet near compass
4. Apply a direct current of 1.00 A for 5 seconds and then turn off
5. Observe whether compass north is pointing toward or away from magnet
6. Apply a 1.00 A direct current in the opposite direction for 5 seconds and then turn off
7. Observe whether magnet north is pointing toward or away from magnet
8. If the magnetic field direction of the magnetorquer switched the directions in part (v) should be the opposite of part (vii)
9. If the MT switches direction then it passes

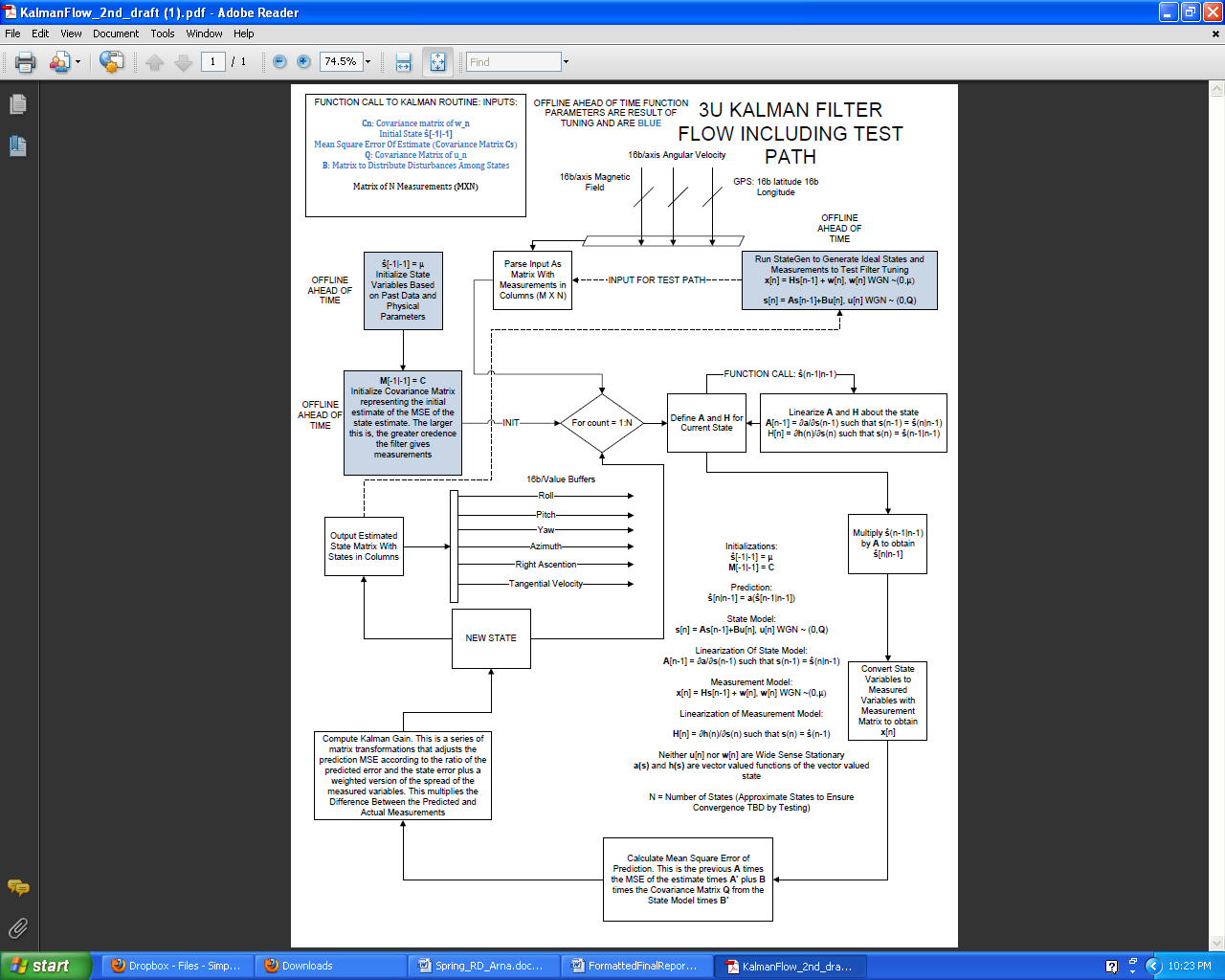
Appendix 7 Core Test Matrix



Appendix 8 Circuit Test Matrix

|  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Test Author: | | Corey Janisch | | | | | |  |
| Test Case: | | Magnetorquer Flip Circuit Test | | | | | |  |
| Test ID: | | 3.a | | | | | |  |
| Test Description: | | Test to see if current flows both directions through inductor | | | | | | clip_image001clip_image002   |  | | --- | |  | | |
|
|
| Name Of Tester: | | Corey Janisch | | | | | |  |
| Date & Time: | | 4/25/2011 0:00 | | | | | |  |
| Hardware Ver: | | 1 | | | | | |  |
| Setup: | | Magnetorquer Flip Circuit with a voltmeter, ammeter, and oscilloscope | | | | | |  |
|  |
| Test #: | Variable: | Output: | | | Pass | Fail | Other: | Comments: |
|  | Voltage | Time |  |
| 3.a.i | T1 Collector | 4.1 |  |  | x |  |  |  |
| 3.a.i | T1 Emitter | 0.4 |  |  | x |  |  |  |
| 3.a.i | T2 Collector | 0.4 |  |  | x |  |  |  |
| 3.a.i | T2 Emitter | 0 |  |  | x |  |  |  |
| 3.a.i | T3 Collector | 4.1 |  |  | x |  |  |  |
| 3.a.i | T3 Emitter | 0.41 |  |  | x |  |  |  |
| 3.a.i | T4 Collector | 0.4 |  |  | x |  |  |  |
| 3.a.i | T4 Emitter | 0 |  |  | x |  |  |  |
| 3.a.ii | T1 Base | 4.3 | 1 |  | x |  |  |  |
| 3.a.ii | T2 Base | 4.32 | 1.1 |  | x |  |  |  |
| 3.a.ii | T3 Base | 4.3 | 1 |  | x |  |  |  |
| 3.a.ii | T4 Base | 4.29 | 1.1 |  | x |  |  |  |
| 3.a.iii | Forward MT I | 3.58 |  |  | x |  |  |  |
| 3.a.iii | Reverse MT I | 3.58 |  |  | x |  |  |  |
| Test Result: | | | | |  |  |  |  |

Appendix 9 Kalman Filter Flow Chart

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Appendix 10 ADAC Requirements

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **Taxonomy** | **Requirement** | **Derived Requirements** | **Derived - Derived Requirements** | **Test Plan Reference Number** |
| Operational | The ADAC Team shall receive commands from the central processor to determine the attitude and RPM of the CubeSat | Communication with the central processor shall occur via I2C based on the clock produced by MDP04 | The communication line shall send and receive data to and from the GPS | 1.a |
| The communication line shall select the operating mode of the GPS | 2.a |
| The communication line shall send and receive data to and from the Gyroscope | 1.a |
| The communication line shall select the operating mode of the Gyroscope | 2.b |
| The communication line shall be a control signal for the magnetorquers | 1.b |
| The ADAC Team shall produce code to run on the central processor. The code shall contain a Kalman Filtering Algorithm to accurately determine the correct attitude of the CubeSat | The algorithm shall be able to be executed in a pre-determined number of cycles allowed for by MDP04 | 1.b, 5.b |
| Create an algorithm to generate "data" from the state model. Then use a Kalman filter to reduce the noise on the data. The algorithm shall be initialized by a best guess of the satellites initial state. | 5.a |
| The ADAC system shall orient the CubeSat by applying current to the magnetorquers upon activation of a control signal | A circuit shall be created to control the flow and direction of current to the magnetorquers |  | 3.a |
| Functionality | The ADAC Team shall implement a sleep mode to turn off ADAC circuitry during power critical stages |  |  | 4.a |
| Energy | The ADAC Team shall adhere to power constraints from Power Generation and Distribution (PG&D) team | The system voltages and clock available to the ADAC board shall be 5 and 3.3 V |  | 6.a |
| Manufacturability | The ADAC Team shall design and mount all control circuitry on separate a Protoboard |  |  | 6.a |

