SMALL FORM FACTOR PCB-BASED AIR COIL FOR CUBESATS

A Thesis

by

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SMALL FORM FACTOR PCB-BASED
AIRCOIL FOR CUBESATS

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To everyone who supported me at any point in this study...

ABSTRACT

Space missions using Earth's magnetic field to achieve effective attitude determination and control (orientation) is becoming more and more popular at relatively low altitudes, Low Earth Orbit (LEO). CubeSats (U-class spacecraft) are deployed in LEO and rely on miniaturizing technology without significant performance degradation. They use magnetic torque generator (magnetorquers) within the Attitude Determination and Control Systems utilizing the Earth's magnetic field, which is still strong enough to create a functional level of torque with a well-known distribution map around the sphere model. This thesis presents a small form factor air coil and magnetorquer design in the form of a PCB, considering the miniature CubeSat dimensions. Although several studies have shown the torque's effectiveness through simulation-based evaluations, it has not been evaluated in a real environment. In this thesis, we propose a test bench for the torque measurement that can be implemented in a real environment using a simple low-loss pendulum analogy due to the lack of air bearing. The measurement results demonstrate the small form factor PCB-based magnetorquer design's effectiveness.

ÖZETÇE

Etkili pozisyon belirleme ve kontrol (yönlendirme) elde etmek için Dünya'nın manyetik alanını kullanan uzay görevleri, nispeten düşük irtifalarda, Alçak Dünya Yörüngesinde (LEO) giderek daha popüler hale geliyor. CubeSats (U sınıfı uzay aracı), LEO'da konuşlandırılır ve önemli performans düşüşü olmadan minyatürleştirme teknolojisine dayanır. Pozisyon Belirleme ve Kontrol Sistemleri içinde, küre modeli etrafında iyi bilinen bir dağılım haritası ile işlevsel bir tork seviyesi oluşturmak için hala yeterince güçlü olan Dünya'nın manyetik alanını kullanan manyetik tork üreteci (magnetorquer) kullanırlar. Bu tez, minyatür CubeSat boyutları dikkate alınarak, PCB formunda küçük form faktörlü bir bobin ve magnetorquer tasarımı sunmaktadır. Birkaç çalışma ve simülasyona dayalı değerlendirmeler yoluyla torkun etkinliğini gösterse de, gerçek bir ortamda değerlendirilmemiştir. Bu tezde, sürtünmesiz rulman olmaması nedeniyle basit bir düşük kayıplı sarkaç benzetmesi kullanarak gerçek bir ortamda uygulanabilen tork ölçümü için bir test tezgahı öneriyoruz. Ölçüm sonuçları, küçük form faktörlü PCB tabanlı magnetorquer tasarımının etkinliğini göstermektedir.

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

CHAPTER I

INTRODUCTION

So far, 33722 active artificial satellites orbit the Earth and human beings takes the everyday benefits of space for granted, whether it can be for communication, navigation, Earth observation, and weather forecasting. Recent years have seen an increase in the number of satellites developed at universities, government agencies, and commercial entities around the world, that adhere to the CubeSat Standard [1] for over a decade. CubeSats are a class of research spacecraft called nanosatellites made up of multiple cubic modules of 10 cm × 10 cm × 10 cm standard dimensions (Units or "U"). They can be 1U, 2U to 12U in size, and typically weigh up to 2 kg per unit [2]. They often use Commercial Off-The-Shelf (COTS) components for their electronics and structure. They are used for various purposes space applications such as earth observations, atmosphere experiments, communication purposes, and even scientific experiments with unproven underlying theories because their low cost can justify higher risks. The major challenge for CubeSats is to have lots of equipment such as payload, Attitude Determination and Control System (ADCS), power source, and other subsystems packaged together effectively. A more complex payload and payload add-ons as well as a more durable power supply can be carried when the parts such ADCS are as small and light as possible. ADCS is the control system of a satellite that provides attitude, direction, and movement information. The satellite gets aligned to the desired direction or located to the desired position via ADCS thanks to several actuators. For example, an antenna needs to point to its ground station, the solar panels need to point to the sun, or the payload needs to point to a particular target.

When a CubeSat is carried to space by spacecraft, there is a tumbling session after it is deployed to mission altitude. The satellite should be stabilized with its mission requirements like position and movement. The tumbling session is an unwanted motion, and any actuator can be used to slow down this process, called detumbling, which consists of damping all angular velocity components of the spacecraft to zero. Zero angular velocity and angular acceleration rate are desired other than an orbital motion to obtain a stable mission position. Various types of actuators, such as thrusters, reaction wheels, and magnetorquers inside the ADCS may be used for this purpose. In a fully actuated system using thrusters, three-axis control is available and detumbling is rather straightforward. At first look, thrusters are effective, but they are heavy and expensive systems, according to others. Moreover, they have a limited lifetime due to their capacity of propellant gas. Reaction wheels are reliable actuators within their mechanical complexity and they can be used with the lifetime of the satellite's power source. Using magnetorquer for detumbling is the most popular and common actuators in low-level orbit, since they are lightweight, low power, and low cost. They have no moving parts used during the mission and they are easy to control by adjusting the current of the coil. The torque of the coils' magnetic dipole moments interact with the ambient Earth's magnetic field magnitude and direction; therefore, the magnetorquer produces a smaller amount of torque compared to other actuators.

1.1 Scope

The thesis aims to explore how the magnetorquer of the satellite control system can be designed as a planar PCB. Although we can see various control methods, the main purpose is to create a compact and effective actuator. Volume restriction and the rotational motion of the satellite needs enough magnetic moment to achieve smooth stabilization with minimum space occupation of the satellite. We followed these requirements and designed a planar PCB coil. Following the Introduction, the next sections explain the working principle of magnetorquer coils, design details, simulation, and measurement results. The final section summarizes the study, provides concluding insights, and future work.

1.2 What is the motivation of this work?

Different types of actuators can be used on satellites, such as thrusters, reaction wheels, magnetorquers. At first look, thrusters are effective, but they are heavy and expensive systems according to others. Moreover, they have a limited lifetime due to their capacity of propellant gas. Reaction wheels are reliable actuators within their mechanical complexity, and they can be used with the lifetime of the satellite's power source. Magnetorquers are popular actuators, thanks to them having no moving parts and being easy to control through the current of the coil. The magnetic moment of the coil is related to the current and surface area of the closed part of the current-carrying loop. The moment of the magnetorquer is also related to Earth's magnetic field magnitude and direction, which can be a handicap for the desired moment. This field is not uniformly distributed around Earth. It is represented as the International Geomagnetic Reference Field (IGRF) [3], and the IGRF is updated 5 years periods. According to all these inputs, a complete ADCS can be established effectively. In this thesis, the main target is proofing our magnetorquer design effectiveness of the PCB coils.

If we check the situation of using small satellites, the number of statistics quite excited. Figure 1 [4] shows the prevalence of these satellites. The rapid growth leads to new technologies and improvements in current designs. Furthermore, expected forecasts of satellite missions take the stage for future studies.

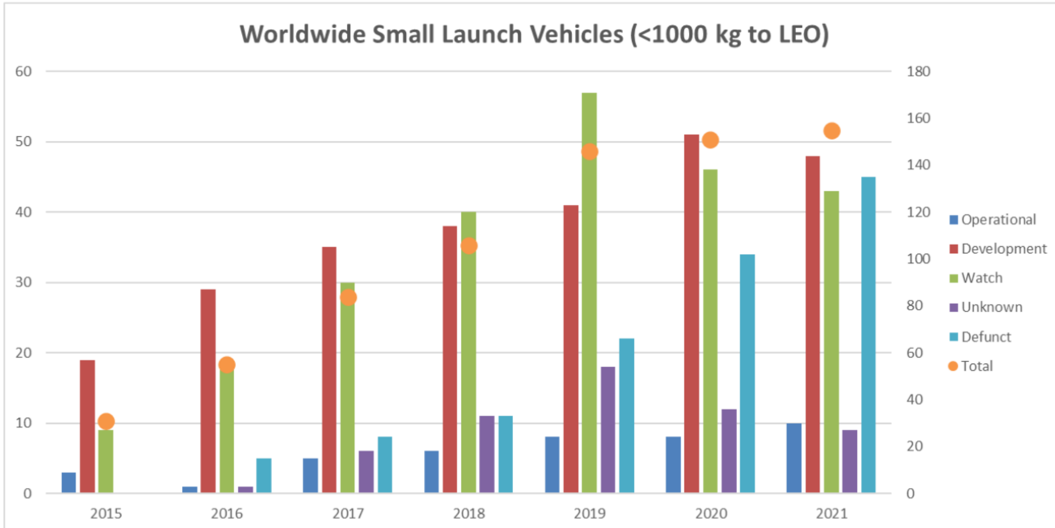

Figure 1: Small satellite launches

1.3 The physics behind this study

The basic principle of the study is the interaction between the magnetic moment of a coil and Earth's magnetic field. The designed coil will be interacted with the magnetic field according to satellite motion and alignment to Earth's magnetic field. The torque of the coil can be controlled in the opposite direction of the motion of the satellite.

The first step is creating a magnetic moment on a coil with a current. The current will create a magnetic moment towards the coil plane normal according to the "Right Hand Rule", as shown in Figure 2. The created magnetic moment calculated by below formula:

$$\mu = I \times \vec{A} \tag{1}$$

We know that the effective torque of a coil in a magnetic field is a cross product of two vectors: the magnetic dipole moment of the coil and Earth's magnetic field. Figure 3 shows the relation between two vectors.

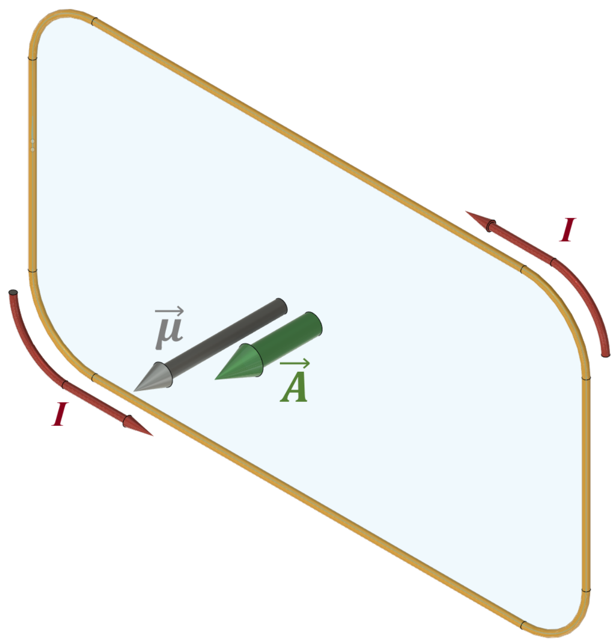

Figure 2: Right hand rule for magnetic moment

$$\tau = \mu \times \vec{B} \tag{2}$$

If we combine the equations (1) and (2) we get:

$$\tau = I.\vec{A} \times \vec{B} \tag{3}$$

$$\tau = I.A.B.sin(\theta) \tag{4}$$

Re-writing the equation with area of the rectangular coil with a and b, which are length and width, respectively:

$$\tau = I.a.b.B.sin(\theta) \tag{5}$$

If we dealing with a coil, we should organize the equation with the number of turns of the coil N:

$$\tau = N.I.a.b.B.sin(\theta) \tag{6}$$

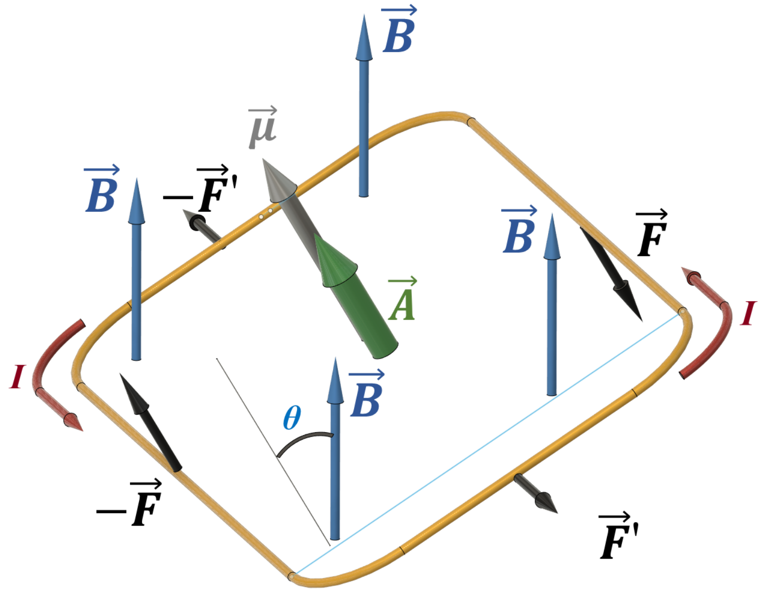

Figure 3: Current loop in magnetic field B

We can see that the magnetic moment of the coil can be changed with its area and number of turns in design phase. The current can also be adjusted considering current capacity of the coil.

1.4 Detumbling

Detumbling is damping the rotation motion of the satellite with actuators such as thrusters, reaction wheels, and magnetorquers. The main objective is to get the angular velocity to zero. The detumbling process is usually performed by magnetorquers in small satellites because thrusters have limited sources, and reaction wheels may consume more power than magnetorquers. Detumbling time may become longer with magnetorquers, but it may be acceptable compared to the overall mission duration. Figure 4 shows the modes of detumbling.

CHAPTER II

CONCEPTUAL FRAMEWORK

Firstly, we would like to mention general information about the systems and components used in space applications. All of these materials creates a fundamental system for a satellite operation. Additional components and different methods may also be applied according to mission goals. We use these fundamental components and basic control systems for checking our coil PCB design effectiveness.

2.1 What is an ADCS?

ADCS is the control system of satellite that provides attitude, direction, and movement information. The satellite can be able to align to the desired direction or locate to the desired position with ADCS. The satellite gets aligned to the desired direction or located to the desired position via ADCS thanks to several actuators. An ADCS subsystem is shown in Figure 5. For example, an antenna needs to point to its ground station, the solar panels need to point to the sun or the payload needs to point to a particular target. Power sources may be selectable according to mission requirements and the payload because they are related to each other. However, creating a small and efficient ADCS can be achieved by avoiding unnecessary weights and focusing on compact dimensions of actuators. The critical point of ADCS is performing the satellite mission to perform the mission objectives in a planned way with keeping the satellite in its position. This state will be the most efficient state of the satellite for its purpose.

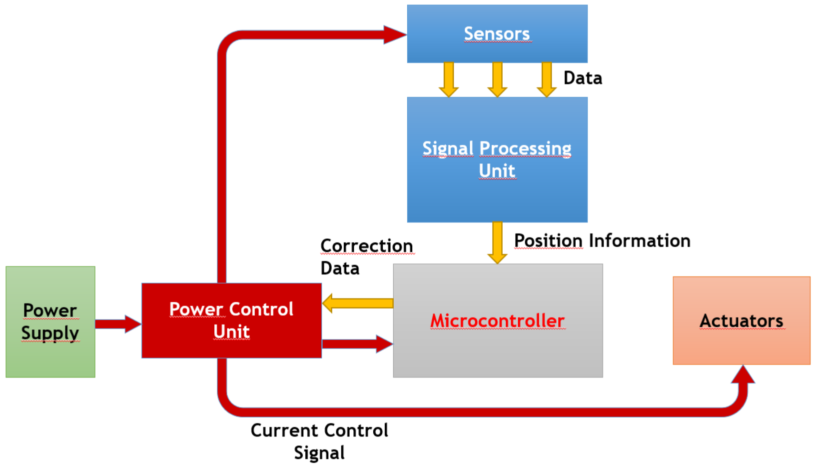

Figure 4: ADCS with subsystems

2.2 The CubeSat

The CubeSat has appeared at California Polytechnic State University and Stanford University first. The objective of the CubeSat project was to provide affordable studies about space in their universities. Nowadays, lots of universities can achieve space studies quickly, thanks to the CubeSat program. Additionally, the system can be used by lower educational levels such as high schools. We should not forget to mention the other special groups like commercial groups or government agencies. All these groups are able to perform their scientific investigations and technical developments.

While typical satellites are very large, CubeSat has specific physical properties. This standardization helps keep the costs lower together with carrying them into space and deploying them at the desired location. The fundamental physical property of the CubeSat is multiple volume step units as 1U, 1.5U, 2U to 12U. 1U CubeSat dimensions are 10 cm × 10 cm × 10cm cubic shape as shown in Figure 6. The allowed weight is approximately 2 kg. These values are related to the dispenser system of a CubeSat launch vehicle. The dispenser helps the connection between the launch vehicle and the CubeSat module. Detailed information can be found at www.cubesat.org.

2.3 Actuators

The motion of a satellite can be made by actuators on it. Thrusters, reaction wheels and magnetorquers are the most common actuators on satellite missions. Every system has pros and cons to each other. These options drives the designers and engineers to select different actuators for different manoeuvres.

2.3.1 Thrusters

Thrusters have gas of liquid containers under pressure. The working principle releases the pressure desired amount and direction, generating torque in its opposite direction of release. Comparing the other two actuators that we mentioned, thrusters are the most effective actuators regarding torque generation. However, they are heavy, bulky and not reusable because of their limited source.

2.3.2 Reaction wheels

Reaction wheels are motors that have a special shape and design with a flywheel. The motors rotate the flywheel and generate angular momentum. This angular momentum creates torque in the direction of the rotor axis. The torque depends on the shape of the flywheel. Placing several reaction wheels into the satellite helps to create torques for different directions. They are also effective with respect to torque. Nevertheless, they are heavy and also bulky. They need significant power for the motors related to their size. They are usually used in combination with magnetorquers to provide wheel desaturation.

2.3.3 Magnetorquers

Magnetorquers are magnetic coils that create a magnetic moment. This moment interacts with Earth's magnetic field. The moment can be controlled with the current of the coil and orientation in the magnetic field. They are lighter, compact and need less power. However, their torque is smaller than two other actuators. They also have limited usage up to low-level orbit, because Earth's magnetic field gets weaker as the altitude increases. Using magnetorquer for detumbling only seems less likely to achieve, but for example, studies like [5] and [6] present it is applicable.

2.4 Contribution of this study

If Equation (5) is checked, coil area, number of turns and the current can be modified for mission needs and satellite design, because of the limited power source of the satellite, current variation may not be so increased. Nevertheless, the coil area and number of turns can be increased by using the outer edges of the satellite. In our design, we focused on increasing the area and maximize the number of turns thanks to aim foldable planar PCB design. Thanks to embedded PCB design, its open-air design for heat dissipation, compact, and lightweight structure leads to the best choice for ADCS compared with current systems [7]. its See the conceptual design of PCB coils on satellite body in Figure 10.

Magnetorquers are popular actuators thanks to they have no moving parts and easy to control with controlling the current of the coil. The torque of the magnetorquer is depended to Earth's magnetic field magnitude and direction, which can be a handicap for the desired moment. The torque is product of magnetic dipole moment $\vec{\mu}$ of the coil and Earth's magnetic field.

The magnetic moment of the coil is related to the current and surface area of the closed part of the loop. To simplify the design, we can focus on limited variables as shown below equations. If we take as a reference Equation (6), we can adjust current, number of turns, and area of PCB coil on design stage, but we cannot manipulate the magnetic field.

Note that the increasing of the current is limited because of current capacity of loop's wires and power source. When we increase the current, the lifetime of mission duration will decrease according the limited power source of the satellite.

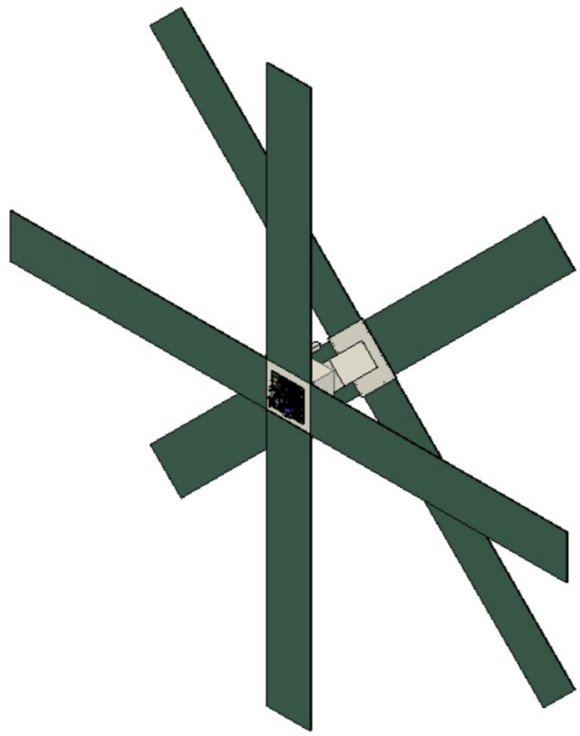

Figure 5: Deployed planar PCB coils

So, increasing these values will gain more magnetic moment for the loop. However, focusing on a design that maximizes the number of turns and area provides more magnetic moment while keeping the current low.

We reflect on the concept, and we design a planar coil on PCB. The PCB can be placed on the surfaces of the CubeSat. So, the inside volume will not be occupied by the coils. PCB coil design can be found below in Figure 11. Manufactured samples of the coils are in Figure 12 and Figure 13.

We will implement the design to check the effectiveness of the coil PCBs. We will measure the experimental rate of slowing down the satellite motion by laboratory setup. There is a control board that includes three main measurement units which are an accelerometer, gyroscope, and magnetometer. The control board drives the coils with PWM signals to adjust the coil current.

For four layers, there will be 100 turns for one PCB. There are ground planes

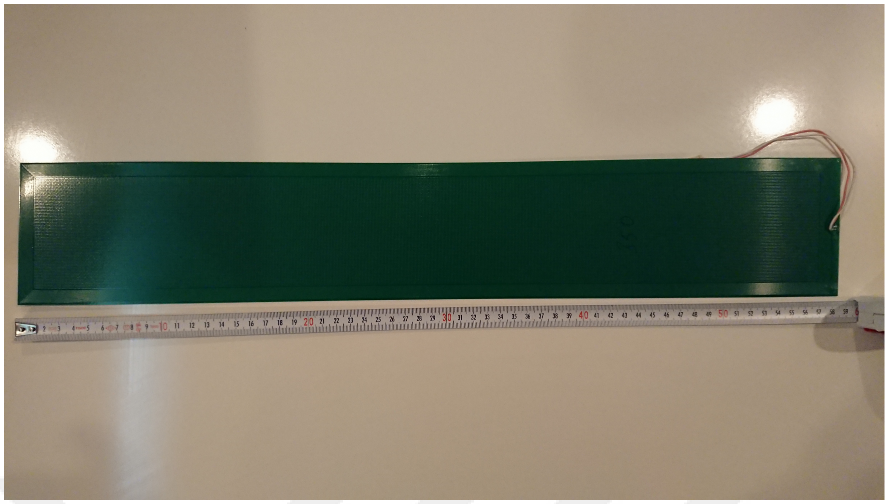

Figure 6: Concept PCB design

for eliminating electrical fields at the first, second, and third layers as shown in Figure 14. There are coils inside the edge coil loop at fourth layer for magnetometer design in future work as shown in Figure 15.

With basic mathematics, the coil PCB is four layers PCB that includes 25 turns every layer and the turns have placed the edges of the PCB. Using Equation (3) without a direction vector, the magnetic moment will be below at the centre of the coil.

$$\mu = N.I.a.b$$

$$\mu = 100 turns \times 0.036A \times (0.585m \times 0.1m)$$

$$\mu = 0.21 \quad A.m^2$$

This value is for one coil. With DC booster, there is 12.7 V_{max} on every coil. Each coil has approximately 350 ohm resistance. So maximum current of any coil will be around 0.036 A.

If the coil is placed on a given magnetic field which is around 40 μT on Earth's surface, the torque of a current-carrying loop will be:

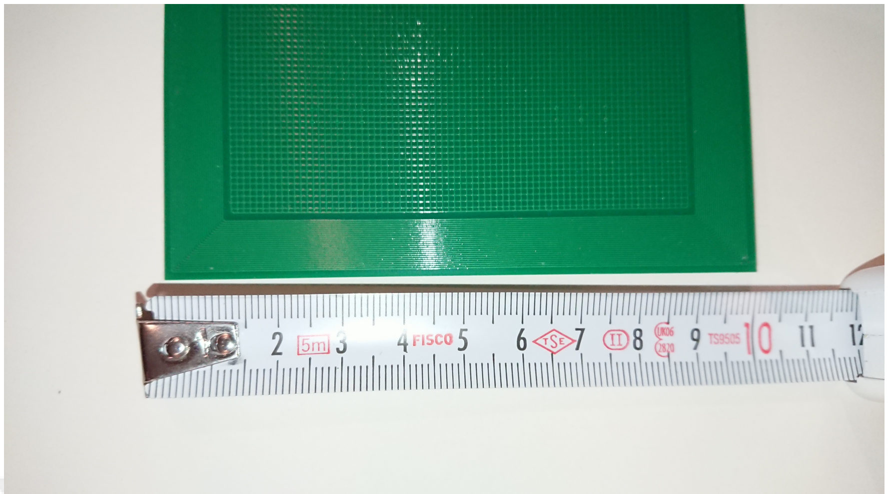

Figure 7: Concept PCB design

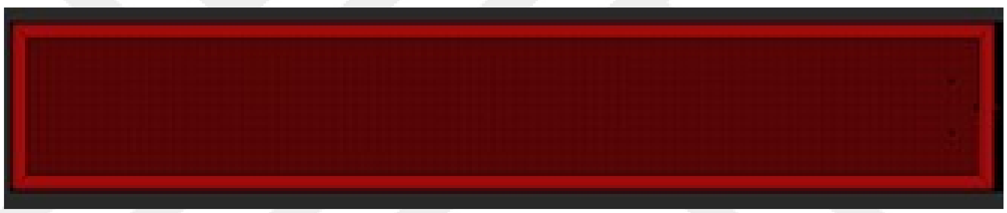

Figure 8: 1st, 2nd, and 3rd layers drawing

$$\vec{\tau} = I.\vec{A} \times \vec{B} = I.A.B.sin(\theta) \quad (7)$$

$$\vec{\tau} = 100turns \times 0.036A \times (0.585m \times 0.1m) \times (40.10^{-6}.1) \quad (8)$$

$$\vec{\tau} = 8.4.10^{-6} \quad N.m \quad (9)$$

In addition to magnetic moment efficiency, the final leaf of the coil PCB can be able to fold onto CubeSat's surfaces in the final design. When it is deployed, the coil PCBs will be opened like leaves.

There are ground plane grids on the 1st, 2nd, and 3rd layers in order to minimize the electrical field element of any electromagnetic wave or additional coulombic

Figure 9: 4th layer drawing

charge. Additionally, these ground planes prevent the solar winds by neutralising them on itself.

Heat dissipation of the coil is also considered while designing our magnetometer. Today's common usage, when the magnetorquer coils are placed inside the CubeSat body, the heat generated by the energized coils will be spread over the payload or the other parts of the control system. In our proposed design, thanks to coils are placed outside the CubeSat: there will be negligible heat dissipation from the coils to the payload or CubeSat body.

2.5 Control methods

Through by years, many control system concepts were developed step by step. Every single improvement and different method achieved by developers with keeping the main purpose which is keeping the satellite desired position. With fearing of missing some of them, we can put some popular methods worth mentioning on the table. Using an LQR with or without linearized dynamics, PD or PID control with a proper feedback and gain coefficients, cross-product method and B-Dot method etc. can be regarded as comparable ones. Because our aim is not to compare these methods, we would like to consider a more applicable method, the B-Dot method, in the sight of us for detumbling. The method was reviewed by different studies.

There are different control techniques to orientate the satellite in the desired position. There are also different magnetic moment creators like magnetic coil rods, frame winding coils, and PCB coils inside a circuit board. In this study, the coils' magnetic dipole moments interact with the ambient magnetic field, which is Earth's magnetic field. All these parts are attached to the satellite body to apply a necessary torque calculated by the control system. The rods and frame coils are generally limited to the dimension of the used CubeSat. In order to control the satellite in 3 dimensions, the coils are placed specific positions on the satellite to meet maximum efficiency and performance.

While determining the spacecraft motion model, we assume there is no gravity gradient disturbance torque and atmospheric drag torque. This is useful for the test the design fundamentally. The non-coupled Euler angels provide a fundamental determination of the satellite's motion relative to Earth's frame.

For higher angular speeds like 1 rad/sec, the B-Dot method [8] can be used effectively. This method was compared with other control methods in various studies like [9] and [10]. The magnetorquer coils generate magnetic dipole moments m_i (i=x, y, z). The magnetic moments should be aligned opposite signs of the geomagnetic field vector with respect to satellite body frame ($\frac{dB_i}{dt}$) where (i=x, y, z). Maximum torque will be applied until the angular rates below specified values (i.e <1 deg/sec). With a defined maximum dipole moment value μ, applied magnetic moment of each m_i can be expressed as:

$$m_i = -\mu \ . \ sgn\left(\frac{dB_i}{dt}\right) \qquad (i = x,\ y,\ z) \tag{10}$$

If we analyse the mission phases, the control system of the satellite will be active after take-off from the carrier of the satellite. The motion of the satellite will start at this phase after deployment so that the very first motion will have the highest rates of angular momentum as expected. At this stage, it is aimed to slow down the satellite as soon as possible by applying the highest torque.

In normal conditions, the maximum angle rate occurs while the deployment phase is separated from the launch of CubeSat from the carrier. Thus, before determine and control the attitude, the rotation velocity should be small enough for sensitive control of the CubeSat alignment. The B-Dot method is a handy and straightforward way to achieve small rotation velocity with respect to the CubeSat body frame. Because it uses a simple algorithm to control and maximum possible torque value to reduce the rotational speed quickly.

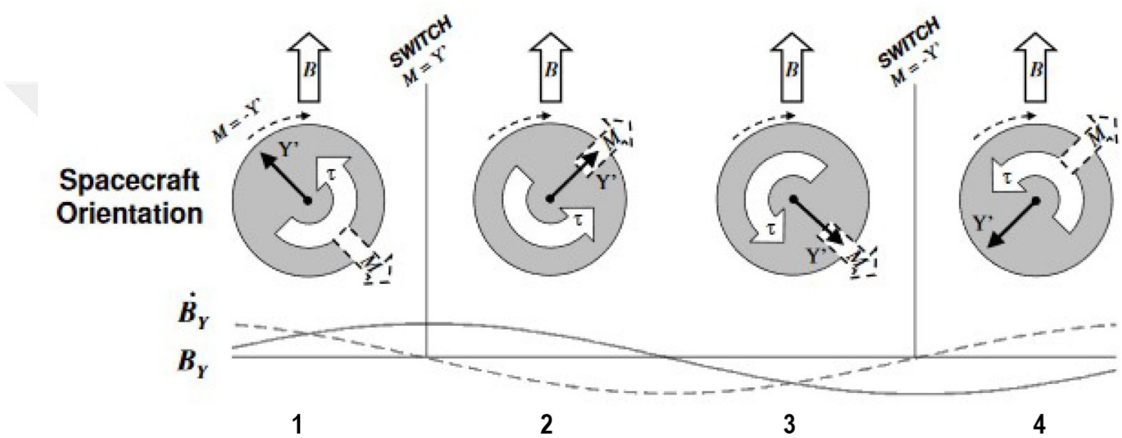

Figure 10: Example of the B-Dot algorithm applied to the Weber State University's satellite

Explanation of the B-Dot method briefly with respect to (1) and (4) in Figure 16 is summarized as below;

- The magnetorquer is aligned along to Y-axis and fixed to the satellite body, body,

- While Y-axis pointing to the direction of the Earth's magnetic field with rotating satellite, projection of B or its derivative will be positive

- The opposite signed signal will be applied to the magnetorquer coil, which has the magnetic moment μ, points to the direction -Y,

- If the Y pass across the B direction or derivative of B is negative, the signal will be reversed and applied to the coil. That provides that the dipole moment of the coil will be reversed, and the same signed torque will be applied to the coil.

CHAPTER III

CONTROL SYSTEM HARDWARE

According to space mission standards, the semiconductor parts of any system used in space should be immune to external disturbances such as solar winds, the sun's magnetic field, Earth's magnetic field, etc. Many components are compatible with related standards to use in space with their reliability. Nevertheless, to achieve this kind of immunity, the price of these parts is increasing dramatically. Before establishing the final design, the concept parts can be used to prove the system structure is working as project requirements. With respect to this kind of view, the parts have chosen for providing fundamental requirements.

3.1 Sensors

To control the CubeSat, we first need to measure the variables that we can get from sensors. Several sensors can be used to get the motion information of the satellite. Fundamental sensors are magnetometer, gyroscope, accelerometer, horizon sensor, sun sensor, star sensor, GPS, etc. We wanted to proceed with a magnetometer to measure the angle between Earth's frame and satellite body frame. A gyrometer to measure the angular velocity of the satellite. An accelerometer to measure angular acceleration of the satellite with respect to the body frame. All these sensors can be used in combination or may be used alone for special purposes, such as in [11].

3.1.1 Magnetometer

A magnetometer is a unit that measures the magnetic field properties around itself, such as magnitude and direction. The measurement principle may vary for the selected component, but our aim is not a detailed study on magnetometers. In this study, we use the 3-dimensional magnetometer to measure the magnetic field of Earth. We chose STMicroelectronics LIS3MDL magnetometer. LIS3MDL magnetometer specifications can be found in Figure 17. LIS3MDL geomagnetic sensor technology provides high resolution, low power consumption, large signal noise immunity, a large dynamic range, and high sampling rates. Measurements are stable over temperature and inherently free from offset drift. There is sufficient sensitivity for achieve the effectiveness the designed planar PCB coil. We use digital interface of the sensor via SPI. So the measurement steps on software will be more manageable compared to an analog interface. Additionally, we avoid manual assembling due to the risk of damage the coils and measurement unit. Therefore, the magnetometer unit is used with its breakout board. More information can be found on manufacturer website.

3.1.2 Gyroscope

A gyroscope is a unit that measures the angular velocity magnitude and direction of the object. The measurement principle may vary for the selected component, but our aim is not a detailed study on a gyroscope. In this study, we use the 3-dimensional gyroscope to measure the satellite's angular velocity with respect to its body frame. We chose STMicroelectronics L3GD20H gyroscope. Sensor specifications can be found in Figure 18. The L3GD20H is a low-power three-axis angular rate sensor. It includes a sensing element and an IC interface able to provide the measured angular rate to the external world through a digital interface (I2C/SPI). The L3GD20H has a full scale of ±245/±500/±2000 dps and can measure rates with a user-selectable bandwidth. There is sufficient sensitivity for achieving the effectiveness the designed planar PCB coil. We use the digital interface of the sensor via SPI. So the measurement steps on software will be easier compared to analog interface. More information can be found on manufacturer website.

3.1.3 Accelerometer

An accelerometer is a unit that measures the acceleration magnitude and direction of the object. The measurement principle may vary for the selected component, but our aim is not a detailed study on the accelerometer. In this study, we use the 3-dimensional accelerometer to measure the satellite's acceleration with respect to its body frame. We chose Analog Devices ADXL357 accelerometer. Sensor specifications can be found in Figure 19. The ADXL357 is a low-power three-axis angular rate sensor. The digital output ADXL357 is low noise density, low 0 g offset drift, low power, 3-axis accelerometers with selectable measurement ranges. The ADXL357 supports the ±10.24g, ±20.48g, and ±40.96g ranges. The ADXL357 offers minimal noise, offset drift over temperature, and long-term stability, enabling precision applications with minimal calibration. The low drift, low noise, and low power ADXL357 enable accurate tilt measurement in high vibration environments, such as airborne IMUs. The ADXL357 multifunction pin names may be referenced only by their relevant function for the SPI or limited I2C interface. There is sufficient sensitivity for achieving the effectiveness of the designed planar PCB coil. We use the digital interface of the sensor via SPI. So the measurement steps on software will be easier compared to an analog interface. More information can be found on manufacturer website.

3.2 Microcontroller

As brain of the system Microchip dsPIC33EP512MC806 microcontroller has chosen. The main specs that focused in this study are ”up to 7 PWM pairs with independent timing”, popular communication interfaces are supported, such as SPI, I2C, and others. Independent PWM pairs helps to control 7x2=14 coils separately. The microcontroller has enough to more additional features. More information can be found on manufacturer website.

3.3 Control board

We collected the above sensors and microcontroller, then designed the control board according to the system needs. The coils are controlled via H bridges to flip the magnetic moment direction of the coil. Additionally, the control board can be upgradable via software. The sensors, microcontroller, and other control board elements have more capabilities than we used in this study. Photo of the control board is shown in Figure 20.

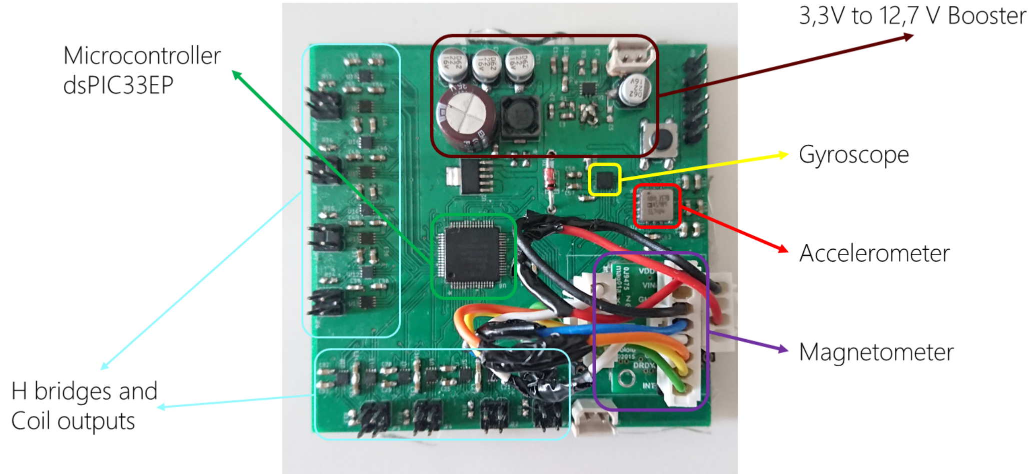

Figure 11: Control board

CHAPTER IV

CONTROL SYSTEM SOFTWARE

With the selected method that B-Dot design, there will be relatively simple control algorithm may be used. The fundamental steps of the algorithm will lead the system to work as a closed-loop until the angular rates of the satellite meet the desired rates. The flowchart of the method is shown in Figure 21.

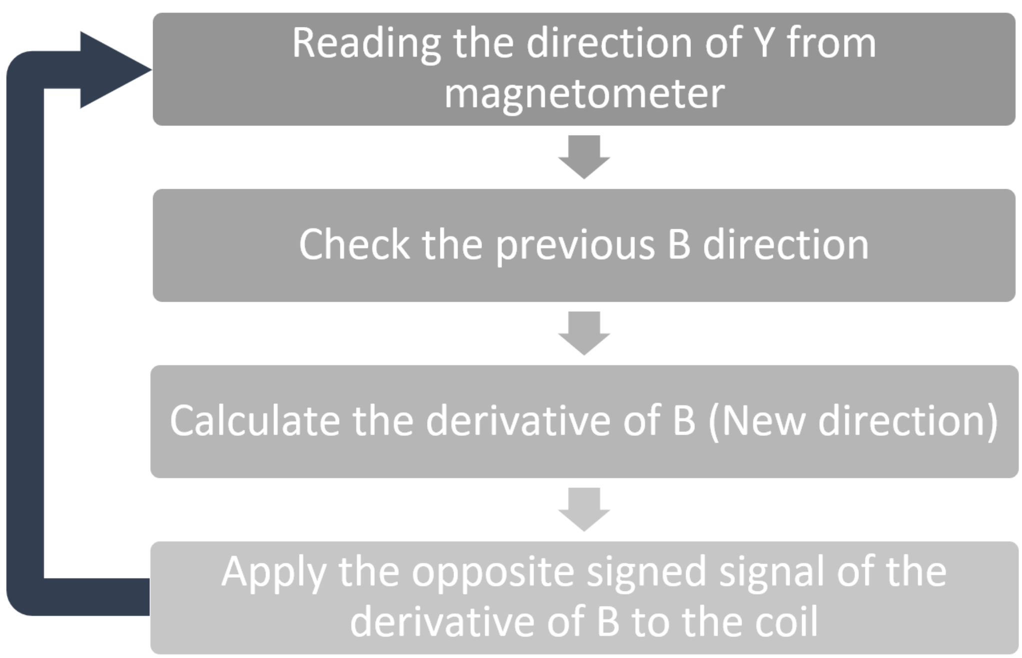

Figure 12: Flowchart of B-Dot control algorithm for detumbling

4.1 Reference mission scenario

We assume that putting the satellite into orbit is divided into steps that are almost independent of each other, from loading to launcher and separation from the launcher. These steps can be considered as a waterfall process that every operation is performed in order. Therefore, there should be no created torque on the magnetorquer coil until the launcher's separation is performed successfully to avoid any interference. When the satellite leaves the launcher, the CubeSat module will be opened itself, and the satellite is deployed. Our proposed planar PCB coil design will be opened up with the help of a mechanical system where the coils were planned to place the edges of CubeSat. To test the coil PCB, we thought about the effect of slowing down the motion of CubeSat. To test this effect, their test systems were evaluated. The first and second test scenarios have not been performed due to their restrictions.

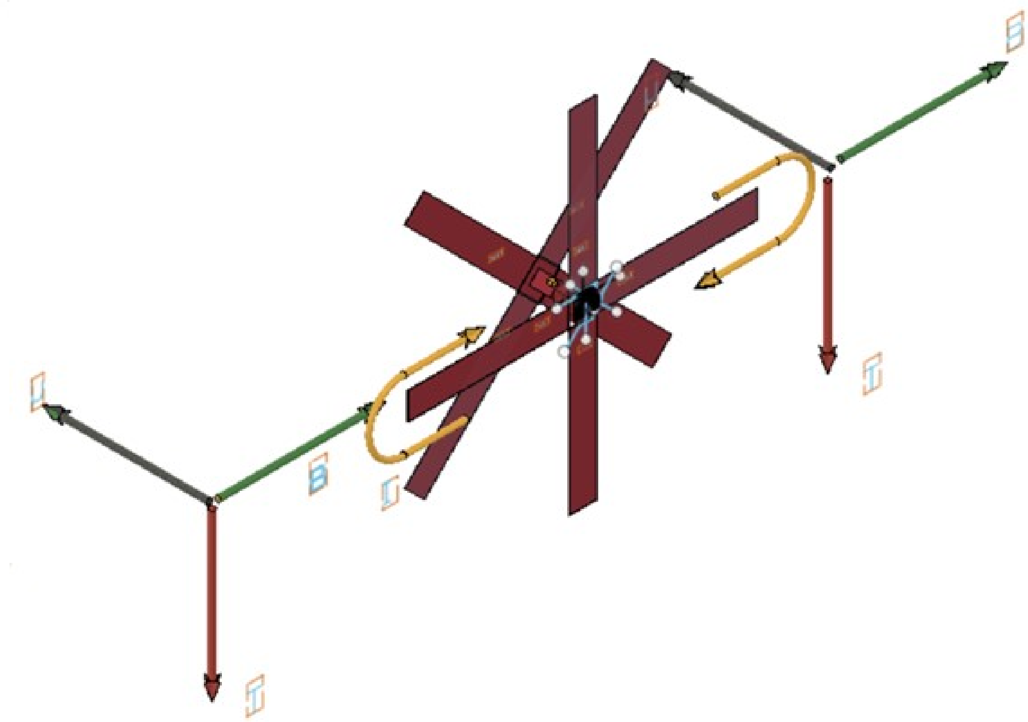

Figure 13: Coil current (I) in yellow, Earth's magnetic field (B) in green, coil PCB dipole moments (μ) in grey, effective torque (T) in red

4.2 Test scenario 1

In this test design, the satellite would hang on a suspension arm with negligible weight as shown in Figure 23. The first satellite would be rotated on the suspension arm axis slowly. After that, the satellite would be rotated again, and the coil PCBs would be actuated. The stop times would be recorded, too. The average of these stop times between "with coil PCB" and "without coil PCB" scenarios would show us the effect of the coil PCBs. As a result, if the coil PCB slows down the satellite, the stop time would be shorter. This result would lead us to the coil PCBs are effective while detumbling. However, in this design, there is a restriction. The restriction is that the Earths magnetic field direction will be near parallel to the surface of the Earth. The torque of the coil PCBs can only be effective when the normal of the coil PCB (surface normal) is perpendicular to Earth's magnetic field direction. However, when we set the test system as in this scenario, the normal of the coil PCBs will be parallel to the Earth's magnetic field.

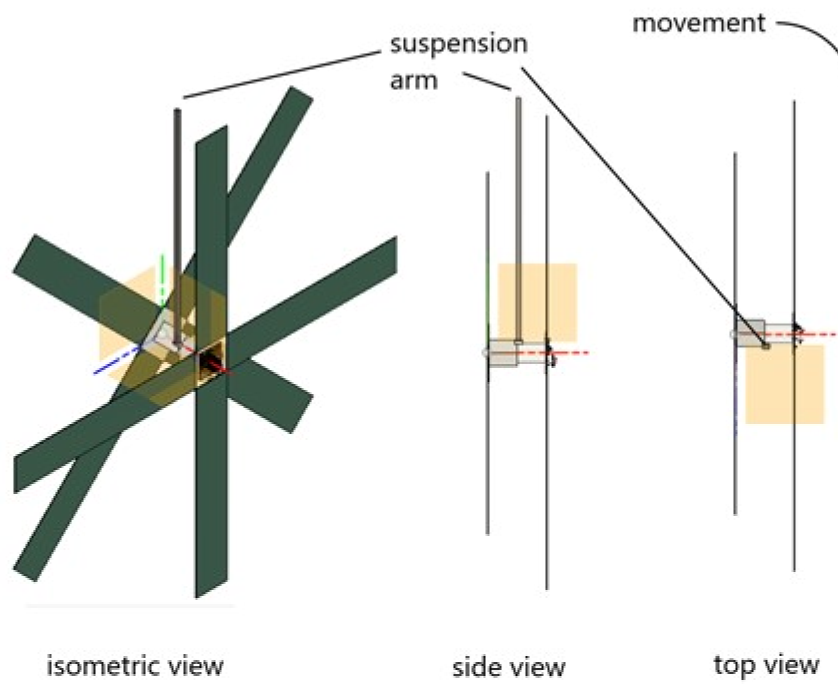

Figure 14: Test scenario 1

4.3 Test scenario 2

In this test design, the satellite would be placed on a hemispherical object and would be left leave its balanced position as shown in Figure 24. Like an inverted pendulum, the satellite would be disturbed with small displacement while keeping the satellite on the test point. The first satellite would be displaced with slight movement on the hemispherical object slowly. After that, the satellite would be disturbed again, and the coil PCBs would be actuated. The stop times would be recorded, too. The average of these stop times between “with coil PCB” and “without coil PCB” scenarios would show us the effect of the coil PCBs. As a result, if the coil PCB slows down the satellite, the stop time would be shorter. This result would lead us to the coil PCBs are effective while detumbling. However, in this design, there are several difficulties. Keeping the satellite on balanced position is a significant difficulty because the dimensions of the opened satellite are quite big. Another difficulty is measuring tiny displacements and movements of the satellite. These motions would be like vibrations. Their measurements and calculations are prone to fault.

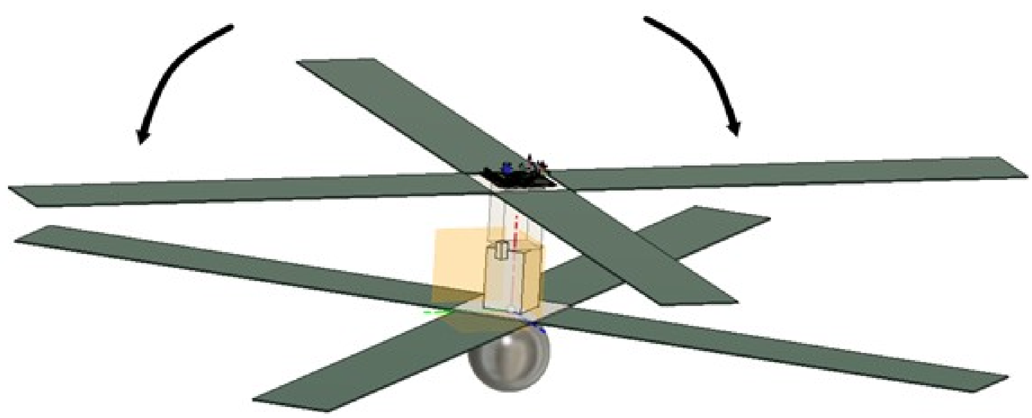

Figure 15: Test scenario 2

4.4 Test scenario 3

In this test design, the satellite would be hung with a suspension arm with a bearing as shown in Figure 27. Opposite to the inverted pendulum, the simple pendulum has been taken as a reference. There is enough displacement and stable movement somewhat then inverted pendulum. With the same concept of the difference between slowing down effects, we can measure the effect of coil PCBs. The main difference in the slowing down effect comes from bearing friction and coil PCBs.

Simple pendulum motion can be explained with Newton's Second Law. Total applied forces are equal to the acceleration of the object times mass of the object. With this expression we can establish a relation between torque effect of magnetometer PCBs and satellite free motion is shown in Equation (9). Alternatively, this expression can be summarized with torque and moment of inertia.

$$\Sigma\tau = J.\alpha \tag{11}$$

if we extend Equation (12) as below according to simple pendulum mechanics are shown in Figure 26:

$$-m.g.L.sin(\theta) - b.\dot{\theta} + K_{coil}.sin(\theta).i(t) = J.\frac{d^2\theta}{dx^2} \tag{12}$$

$$\vec{\tau} = N.I.a.b.B.sin(\theta) \quad \Rightarrow \quad K_{coil} = N.a.b.B \tag{13}$$

The normal of coils are parallel to Earth's magnetic field. See Figure 26 and 27. If we re-organize the equations:

$$\ddot{\theta} = \frac{-m.g.L}{J}.sin(\theta) - \frac{b}{J}.\dot{\theta} + \frac{K_{coil}.i(t)}{J}.sin(\theta) \tag{14}$$

where

$$\frac{b}{J}.\dot{\theta}$$

is damping due to bearing and

$$\frac{K_{coil}.i(t)}{J}.sin(\theta)$$

external torque from magnetorquer coil PCB, respectively.

There are two forces that slowing down the pendulum. The first is friction force on bearing, and the second is the magnetic force generated by magnetorquer coil PCBs. The difference in settling time of pendulum due to these forces can be evidence that the magnetorquer coil PBCs are effective for the detumbling process.

4.5 Test environment

Special studies as ours need special environments to test and evaluate. The effectiveness of the designed magnetometer coil can be tested in a zero-gravity environment by simulating the deployment of the satellite. After deployment, it is easy to see the tumbling of the satellite in that environment. However, it is hard to find a zero-gravity environment all the time. So those practical estimations were already evaluated as above. Test scenario seems the most applicable and reliable test method between the three. To create the test environment, a simple pendulum mechanism was built as a prototype as shown in Figure 25. The satellite prototype was hanged on the suspension arm, and the magnetometer coil PCBs mounted as their settled positions after deployment of the satellite.

Measurements of the tests were monitored via a UART-USB connection. The microcontroller sends every desired value or variable to the computer via UART. The data from the control board were collected on a built-in software of microcontroller manufacturer that is MPLAB Data Visualizer. Built-in software selected because of avoiding any unnecessary conflicts due to 3rd party computer software.

Figure 16: Hanged test system with bearings and cross-bar

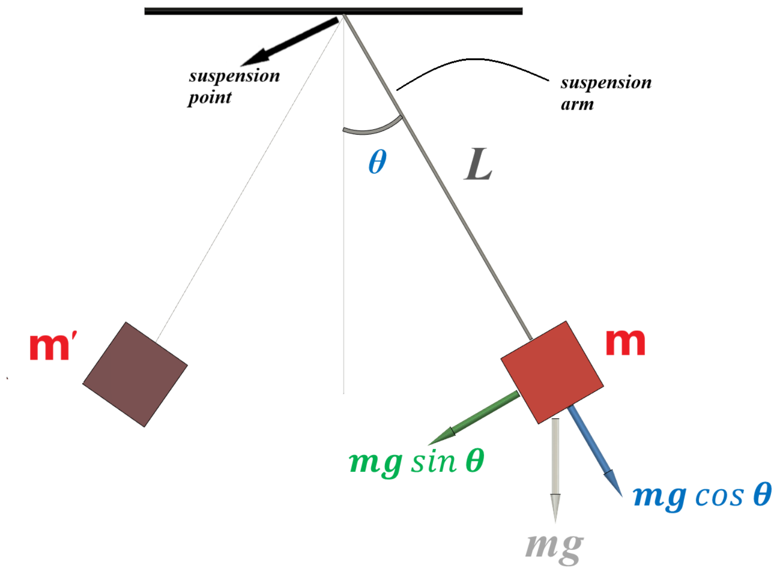

Figure 17: Simple pendulum mechanics

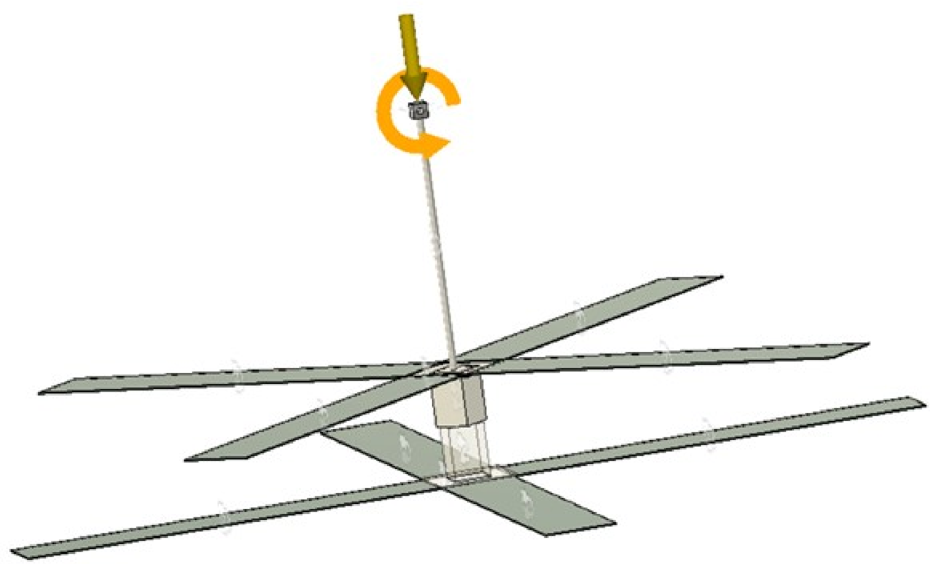

Figure 18: Test scenario 3

CHAPTER V

TEST RESULTS

The results of a simple pendulum analogy can give us the effect of the coils. There are two steps to evaluate the effect as simulation and real life measurements. As expected the real life measurements are slightly different from simulation, but, the overall concept is similar.

5.1 Simulation

Due the lack of air bearings or any zero gravity environment necessary for testing, different approaches are investigated to see the effectiveness of our designed coil on PCBs. Evaluating various different testing systems, the simple pendulum concept was chosen because it is an easy to establish and reliable concept for testing our system. Before creating a testing environment in real life, the concept design is simulated. According to Equation (11) drag coefficient and coil torque were evaluated separately. These two different effects are demonstrated with different colours in Figure 28. Drag coefficient of bearing was indicated red colour and coil torque was indicated with purple colour. We can see that when the coils are in effect, the angular velocity reaches values less than 1 deg/sec (purple) earlier than coils are not in effect (red).

5.2 Measurements

To mimic the experimental detumbling of the CubeSat in the lack of zero gravity test environment, a simple pendulum mechanism was built as a prototype. The CubeSat prototype was hanged on the suspension arm, with the magnetorquer coil PCBs mounted at their settled positions. The test system was released to let it swing independently. The control board that includes three main measurement units: an

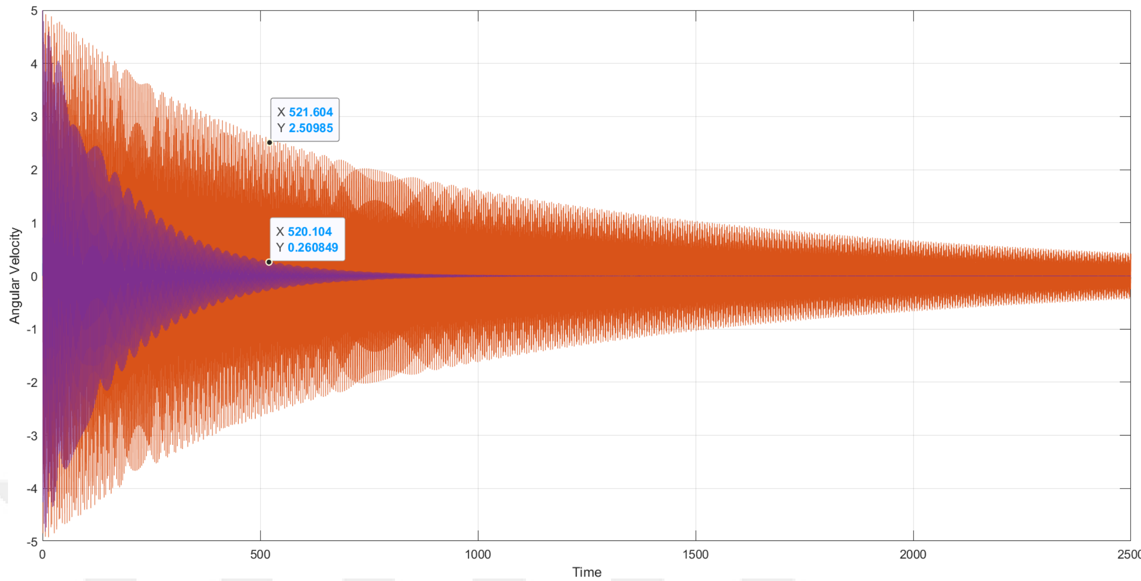

Figure 19: Simulation comparison

accelerometer, a gyroscope, and a magnetometer is used to capture the relevant data such as angular velocity. The control board also drives the coils with pulse width modulated (PWM) signals to adjust the coil current.

The simple pendulum swings in one direction, therefore only X-axis values of the gyroscope sensor without and with the coil torque in place are recorded via a built-in software of microcontroller manufacturer, MPLAB Data Visualizer in real-time. The values are plotted in blue as shown in Figure 29 and Figure 30, respectively. The slowing effect of the coils are summarized in Table 3. Start values and finish values of gyroscope-measured angular velocity are noted. Percent column indicates the amount of drop between the start and finish angular velocities. By averaging the tests, it is concluded that at the end of the five minutes period, the coil torque slowed the CubeSat by 0.0052 percent compared to no coil torque in place.

The re-configurable air-coils are compared with the commercially available designs in [12]. While a commercial NCTR-M012 magnetorquer rod provides a very good figure of merit; torque (µNm) to power dissipation (W) ratio of 20.8, it is heavy, expensive, and not space efficient making it not suitable for nanosatellites. On the other hand, a commercial Gomspace Nano Power P110U, offers a very weak torque to power dissipation ratio of 0.2 with the added advantages of being internal to PCB. Comparing this work with the embedded, printed six parallel air-coils in [12], this work provides a torque to power dissipation ratio of 18.3, while [12] has a torque to power dissipation ratio of 8. Our results present the highest torque to power dissipation ratio for a printed magnetorquer coil designed so far.

5.3 Results

The test system was released to let it swing independently. There are two stages, as we mentioned before. Without coil torque and with coil torque. Sensor values were monitored with built-in software in real-time and recorded. The system swung for around nine minutes until it stops. The measurements were recorded between the first stable measurement at the beginning of the movement and the second stable measurement at 300 seconds (five minutes). Start values and finish values of gyroscope X-Axis are indicated in tables. Percent value means how much percentage decrease the corresponding value. The slowing effects of bearings and coils a can be seen in Table 2. The coil torque slowed the system by 0.0052 percent compared to no coil torque condition.

Table 1: Color representations of sensor measurements

$Sensor$	$X - Axis$	$Y - Axis$	$Z - Axis$
Accelerometer	white	blue	green
Gyroscope	orange	red	cyan
Magnetometer	pink	light green	brown

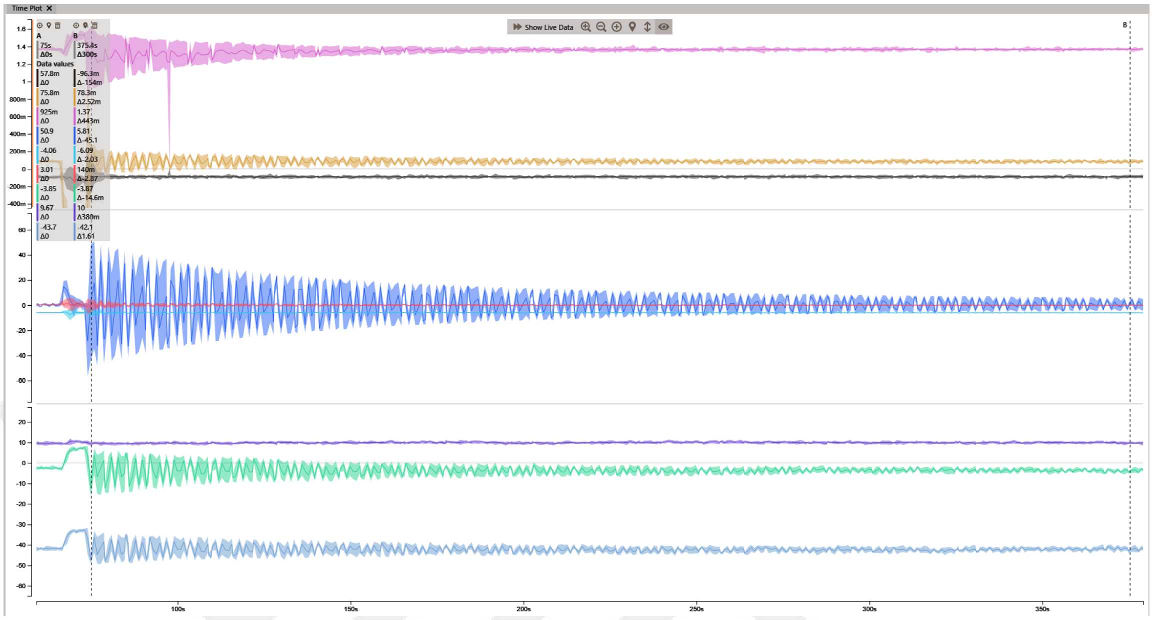

Figure 20: Measurements of sensors without coil torque

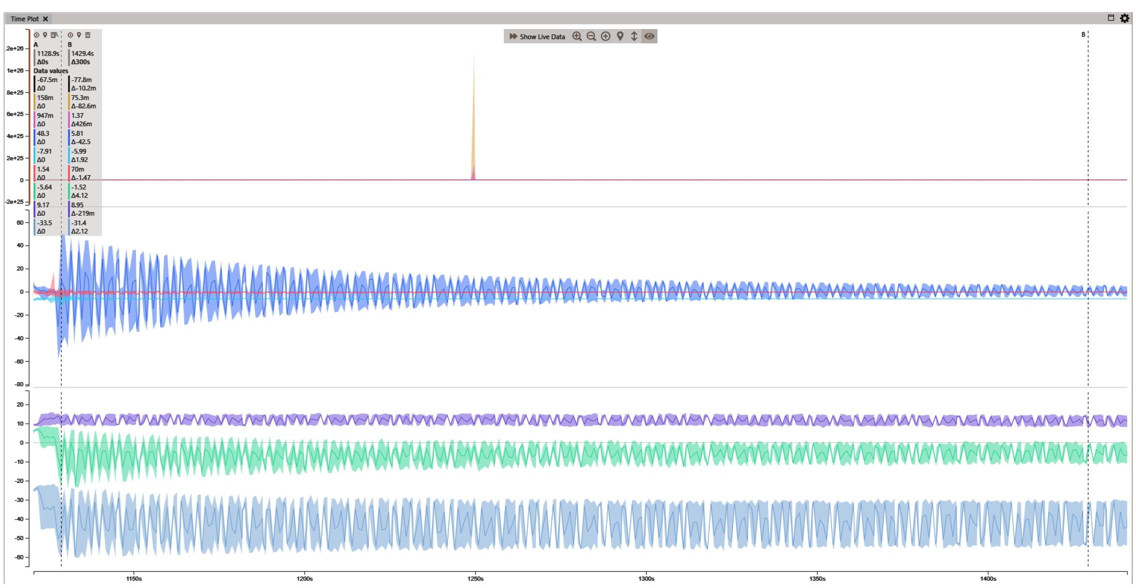

Figure 21: Measurements of sensors with coil torque

Table 2: Summary and comparison of test results

Test No	*Start (deg/sec)*	*Finish (deg/sec)*	*Percent*	*Start (deg/sec)*	*Finish (deg/sec)*	*Percent*	*Diff−erence*
1	48.7	5.88	-0.8793	48.9	5.49	-0.8878	
2	48.2	5.39	-0.8882	52.1	5.59	-0.8928	
3	50.9	5.81	-0.8859	48.3	5.45	-0.8873	
4	50.7	5.74	-0.8868	50.2	5.59	-0.8887	
5	50.3	5.95	-0.8817	49.9	5.52	-0.8895	
6	48.3	5.81	-0.8897	49.6	5.52	-0.8888	
7	48.7	5.60	-0.8850	48.6	5.45	-0.8880	
Avg.	49.4	5.74	-0.8838	49.7	5.51	-0.8890	-0.0052

CHAPTER VI

CONCLUSION AND FUTURE WORK

Air coil magnetorquers are used for the detumbling of CubeSat satellites with miniaturized dimensions, low mass, minimum heat dissipation. They are better choices compared to thrusters, reaction wheels, magnetic rods in terms of space occupation, cost, and weight. In this thesis, a small form factor, innovative PCB-based air coil design for CubeSats is proposed to achieve the desired magnetic dipole moment. This study focused on designing and checking the effectiveness of the coils on PCB. Coils with 0.8mm thickness are designed on four layers PCB, occupying an efficient large loop area on the CubeSat for generating large magnetic dipole moments to slow the tumbling process. A control board is designed to measure the position of the system and control the current of the coils. The system is tested using the low-loss pendulum analogy in the lack of air bearings, and according to measurement results, the air coils on PCB are effective in generating the magnetic dipole moment and torque in the existence of the perpendicular magnetic field with state of the art measurement results.

Further potential research could be done on the presented coil for higher form factor via folding design of coils to increase the area efficiency as well as minimizing the dissipated heat. Furthermore, advanced control algorithms using the developed control board will provide a high resolution magnetic field sensing mechanism via the already built-in magnetometer coils on PCB. Thermal analyses would be done in detail to ensure the feasibility of the proposed coil. For more reliable test results, a convenient testing environment such as a zero-gravity room would be investigated.

More reliable test results may be obtained with more convenient testing environments such as a zero-gravity room. The folding design of coils should be studied according to related CubeSat design. There is an empty torque axis at the Z-axis of CubeSat due to the current placement of coils.

Additional features should also be studied to have a more capable CubeSat. Solar panels may be placed on coils. This helps the power source of CubeSat and so mission duration. Built-in magnetometer coils may be used for sensitive detection of magnetic fields. The control board abilities may be improved with complex software.

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