SMALL FORM FACTOR CUBESAT ADCS SYSTEM WITH MICROMOTORS

A Thesis

by

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Submitted to the

Graduate School of Sciences and Engineering
In Partial Fulfillment of the Requirements for
the Degree of

Master of Science

in the
Department of Electrical and Electronics Engineering

Özyeğin University
October 2020

SMALL FORM FACTOR CUBESAT ADCS SYSTEM WITH MICROMOTORS

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To My Parents,

Faik and Belma Kahyaoğlu

for their patience and support in all aspect of my life.

And most of all,

I owe my deepest gratitude to my wife, Mrs. Merve Kahyaoğlu,

for her affection, encouragement, understanding and patience.

ABSTRACT

In this study, rather smaller many reaction wheels are distributed in the body frame of CubeSat to perform attitude control while occupying minimal volume. Due to the limited space in a CubeSat, the role of each component's weight and volume is critical. Hence, use of high-efficiency reaction wheels is very important. A set of small ten reaction wheels are mounted on the proposed CubeSat body surfaces to allow the system to point to the correct target in the orbit emulation experiment. Each axis has two reaction wheels that spin in the same direction to increase the total moment. The body is divided into two identical sections where the symmetric upper body to the lower body is set to be in 45 degrees offset with respect to each other. Along with this particular physical formation, the moments of the system change considerably, and hence the new design requires a new set of calculations. The proper operation of the system is verified on a test bench. A mildly loaded 3D printed prototype tumbling with 145 rad/sec angular speed could be stabilized in the desired position in just 250 seconds consumption average power of 540 mW.

ÖZETÇE

Bu çalışmada bir 3U uydu içerisinde yönelim sağlayacak mikro motorlar ile küp uydunun yüzeylerinde yer alacak reaksiyon çarklarının çalıştırılması test edilmiştir. Bir küp uydudaki sınırlı alan nedeniyle, her bileşenin ağırlığı ve hacminin rolü kritiktir. Bu nedenle, yüksek verimli reaksiyon çarklarının kullanılması çok önemlidir. Sistemin yörünge yönelimi deneyinde doğru hedefte durması için düşünülen, bir küp uydu gövde yüzeylerine küçük 10 adet reaksiyon çarkı monte edilmiştir. Her eksenin, toplam momenti artırmak için aynı yönde dönen iki reaksiyon çarkı vardır. Gövde, alt gövdeye simetrik üst gövdenin birbirine göre 45 derece ofset olacak şekilde ayarlandığı iki özdeş bölüme ayrılmıştır. Bu özel fiziksel oluşumla birlikte tasarlanan sistem bir test düzeneği ile testleri yapılmıştır. 3 boyutlu yazıcıdan basılan küp uydunun dışarıdan uygulanan bozucu torkun ilk yüksek değeri 145 rad / sn açısal hıza sahipken ve 540 mW'lık ortalama güç tüketerek yaklaşık 250 saniyede uydunun sabitlenebilirliği test düzeneğinde ölçülmüştür.

ACKNOWLEDGMENTS

I would like to acknowledge Mr. Dr. Ahmet Tekin for his efforts and support during all the time of my studies.

I wish to thank various people for their contribution to this project; Mr. Ahmet Sayar for their valuable mechanical design support on this project.

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CHAPTER I

INTRODUCTION

Nowadays, significant cost reductions are being observed in Micro/Nano satellite launch services due partly to the advances in space transport technology and due partly to the increase in the number of service providers globally [1]. Universities and research companies develop cube satellites (CubeSat) thanks to the lower cost of the small size satellites that perform more specialized tasks and the ease of testing during design stages. Reduction in the cost of rockets used to launch this equipment into space was remarkable over the last decade. In this study, CubeSat dimensional standards set by Cal Poly Tech University are followed to reach a custom multi-section deployable 3U aircraft with the dimensions of 100mm x 100mm x 300mm [2].

The standardized criteria for cube satellites are weight and size. As seen in Table 1, the weight range increases with the satellite size. These standard values have made it easier for cube satellite developers to make appropriate designs.

Table 1: Cube satellite sizes. [2]

Cube Satellite	**Dimensions (mm)**	**Weight Range (kg)**
1U	100x100x100	0 - 1.3
2U	100x100x200	0 - 3
3U	100x100x300	0 - 4

Table 2: List of small CubeSat satellites. [3]

Name	Type	Institution	Mission	Launch Date (GMT)	Rocket	COSP AR	Status
QuakeS at	3U	Stanford University	Earthquake prediction	2003-06-30, 14:15	Rocket	2003-031F	Active
GeneSat -1	3U	NASA/Sa nta Clara University	Biological research Technology demonstrati on	2006-12-16, 12:00	Minota ur	2006-058C	Active, primary mission complet e
ION	2U	Illinois University		2006-07-26, 19:43	Dnepr	N/A	Failed - launch failed
CanX-1	1U	UTIAS	Technologic al show	2003-06-30, 14:15	Rocket	2003-031H	Fail - no signs
DTUsat-1	1U	Denmark Technical University	Tether research	2003-06-30, 14:15	Rocket	2003-031C	Fail - no signs
AAU CubeSat	1U	Aalborg University	Imaging	2003-06-30, 14:15	Rocket	2003-031G	Failed - Battery problem s. It was closed on [[2003-09-22].]
CUTE-I (Oscar 55)	1U	Tokyo Institute of Technolog y	Amateur radio	2003-06-30, 14:15	Rocket	2003-031E	Active

CubeSat XI-IV (Oscar 57)	1U	Tokyo University	Amateur radio	2003-06-30, 14:15	Rocket	2003-031J	Active

Table 1.2 provides detailed information about the missions for which tasks and when and with which rocket launch date. It also shows the activity status according to the date the thesis was written. [3]

Limited volume of CubeSat body posed significant challenges for the particular communication mission CubeSat where the payload didn't leave much space for attitude determination and control system (ADCS). The proposed distributed planar multi-angle multi-wheel system hence required thorough engineering calculations and tests. The solution proposed in this work allows to fit more payload in the space saved by these planar reaction wheels with respect to a standard off-the-shelf ADCS block. Reaction wheels are chosen to be as small as possible to occupy a small headroom at the lower and upper surfaces of the body. Mini low power reaction motors are placed at each axis in the body frame to have reaction wheels' moment in all axes with 45 degrees' fine distribution resolution. The inner body frame is designed 50mm x 50mm x 300mm in size. The reaction wheels remain inside as the deployable solar panels and antennas are placed on the outer surfaces. Figure 1 shows the drawing of the proposed structure in this study within the 3U standard exterior view.

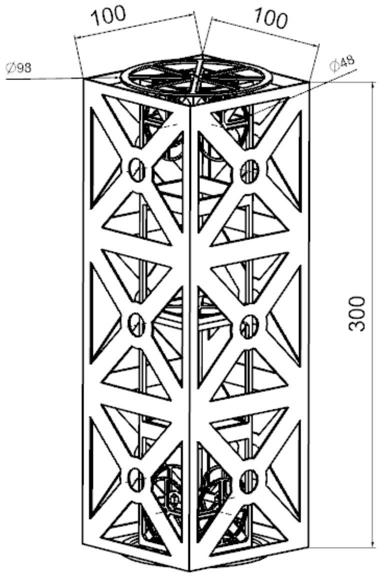

Figure 1: Proposed 3U distributed multi-wheel CubeSat body

Euler's moment equations indicate that any external torque acting on the rigid body turns into an angular momentum to the spacecraft. Active attitude control is carried out using the reaction wheels, the mechanical momentum is converted into a force acting on the main axes of the rigid body of the spacecraft [4].

Some internal and external factors create undesired momentum that disrupts CubeSat's movements [5]. The reaction wheel works using angular momentum principles and thus reduces the tumbling of the CubeSat while keeping it in balance.

Environmental effects are considered while orbiting a spacecraft. The angle with which it points to the ground station can change unintentionally. There are two main types of factors that affect the balance and control of a spacecraft. One group of fundamental effects relates to the interplanetary space; such as solar radiation pressure, gravity gradients, aerodynamic, magnetic forces, meteorite, and man-made debris. The second group of factors is related to the control mechanisms provided ADCS control mechanisms related to the interior of the spacecraft such as rotating wheels, circulating fluids, dredging devices, etc. [6-8].

Solar radiation pressure is generally having a major effect at high altitudes of 1000 km and above. Low Earth Orbit (LEO) CubeSat's may suffer from the disturbance torque sources such as Solar Radiation Pressure (4.487x10^-10 N-m), Aerodynamic Drag Torque (4.723 x10^-9 N-m) and Gravity Gradient Torque (7.98 x 10^-10 N-m) [9]. In order to prevent unintended CubeSat movements due to such external torques that may occur in LEO, reaction wheels' stabilization technique has become a popular solution.

1.1 The CubeSat Concepts

In the last century, there has been a lot of interest in space technologies. Interest in space accelerated especially in the 1950s and 1960s, which are called space racing. Satellites are designed to be used for many different purposes such as remote sensing, communication, scientific experiment, navigation, and exploration, with the technology that has developed since the first satellite sent to space. Large investments are also made for these designs. Thanks to these investments, developments in other engineering fields have accelerated in parallel.

Due to the size and cost of the first satellite structures, it is desirable to use more specific structures for special purposes. In large systems, there are advantages to only sending specific payloads separately rather than having multiple payloads. These special structures are more compact than previous satellites. They are smaller in size and can be used for a variety of purposes. Another reason for reducing the dimensions and weight is the reduction in launch cost. Due to the high launch cost of large-sized satellites, a mistake that may occur after the launch means more money to be thrown than small-sized satellites.

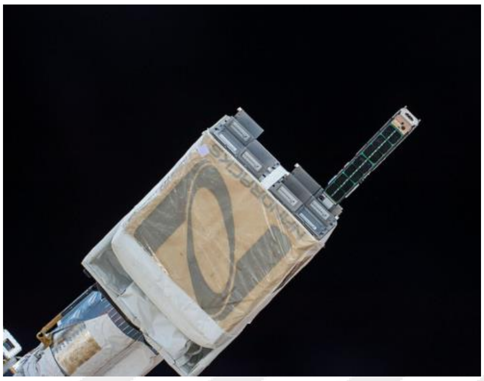

Figure 2: The Nano Racks CubeSat Deployed deploying the SHARC satellite from the ISS [10]

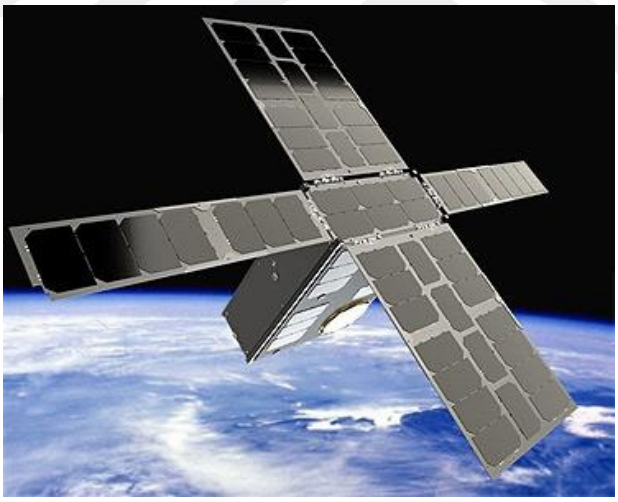

Figure 3: TARS (Kepler 3, IOD 5) [11]

Figure 2 and Figure 3 show the departure of a 6U satellite from the rocket. Satellite standards can be changed after leaving their dimensions. After leaving the satellite carrier almost all satellites subsequently turn on solar panels to use the renewable energy source solar energy.

1.2 Attitude Determination and Control System

Orientation determination is the process of controlling the position and movements of a CubeSat. For this process, the position of the CubeSat must be determined and then its movements must be managed. Orientation control systems are vital in most modern technology applications such as spacecraft, aircraft, and underwater vehicles and play an important role in their correct operation. If the orientation of the spacecraft cannot be accurately predicted, the control of the spacecraft, the transfer of information to the earth, or other mission goals cannot be met. The angle of sunlight in the spacecraft directly affects the efficiency of the solar panels, and the efficiency of antennas used for communication is directly affected by the angle to the ground station. Commonly used reference vectors are specific vectors directed at the sun, the center of the earth, a known star, or the earth's magnetic field [12].

The information received from the sensors is combined with the orientation determination system to continuously provide the best orientation estimation. Depending on the mission requirements, orientation can be determined in real-time on the spacecraft or by evaluating the data transferred to the ground. Orientation control systems are designed for autonomously operating systems with little or no human control and have played an important role in the production and development of both underwater and unmanned aerial vehicles. Autonomous directional control systems require numerical calculations to provide continuous feedback to the vehicle's directional actuators. There is a wide variety of orientation systems, but basically they all require measuring systems that contain enough sensors to provide adequate accuracy of orientation information.

There are basically three necessary of orientation control in low earth orbit (LEO). Firstly, environmental distortion effects can be given as examples of irradiation forces from the sun, incorrect orientation operation, etc. or to eliminate the unwanted rotation caused by the launcher. The second is to keep the satellite's orientation constant with respect to a reference system so that it can always look at the world. Lastly, it needs orientation to get high efficiency from solar panels. The most advanced application of directional control systems is to point the satellite in the direction of interest with inertia. Orientation control is the orientation of the satellite in a certain direction. There are a wide variety of techniques for controlling orientation. The need for precision and maneuverability in directional control, along with cost, weight, reliability, orbital motion, and life span, are important in deciding which technique to use. Control techniques can be grouped according to whether the applied torque is passive or active. The advantage of passive control techniques is that they do not require any control input from the satellite. The passive control method does not need a control input, which means that the passive control torque cannot be controlled. Therefore, it is necessary to use active control methods that can be adjusted continuously at every point in the orbit of the satellite in precise directional and three-axis directional control applications.

Active heading control combines all of the ADCS operations listed below to make the necessary correction in the satellite's orientation. With the orientation information from the sensors, the movements of the satellite are determined and the force is obtained from the actuators to set the target point. This operation is repeated continuously, the forces coming from external factors are weakened and the satellite is constantly locked to the target. The next section describes the sensor types and actuator types.

1.2.1 Sensors

There are basically two types of sensors (also sometimes called detectors) that are frequently used in the direct determination of satellites. The first type comprises the reference sensors, the other is the inertia detectors. Reference sensors measure the direction according to known vectors. At least two measurements are required to obtain complete orientation information. Inertial detectors measure rotation and/or translational acceleration with respect to an inertial system. Sensors are subject to drift and yaw errors and there is no limit to these errors. Constant updates should be made according to references such as the sun, star, or earth to ensure precise orientation. The positions of the sensors within the satellite are important for correct referencing. The correct operation of the sensors is important for the vital activity of the satellite. In this study, magnetometer, acceleration sensors are used. The magnetometer is used to refer to the satellite, while the acceleration sensor is used to detect the satellite's inertia [12].

1.2.1.1 Sun Sensor

The sun provides a well-defined precise reference vector. Sun sensor are visible light detectors that measure one or two angles between the location and the sun's rays. As the name suggests, solar sensors are used to track the sun and check the position of the spacecraft in relation to the sun. The angle of incidence of the sun is obtained from detectors mounted on the surface of the satellite. While the sun sensors are mounted on the satellite surface, care should be taken that the antennas and mechanisms are not in the detector's field of view. While solar detectors are very popular, reliable, and accurate, they require a clear field of view. Solar sensors are a widely used sensor type in the orientation detection and control system of the spacecraft. Because the angular radius of the Sun depends on the orbit and has a very small value of 0.267 degrees for 1 AU (Astronomic Unit) [13]. The sensitivity range of solar sensors is between 0.25 degrees and 6 degrees depending on the number and type of sensors. There are basically three types of solar sensors and these are analog sensors, digital sensors, and solar presence detectors. Major disadvantage of solar sensors is that they occupy a large area within the satellite.

1.2.1.2 Star Tracker

Star tracker provide orientation information by determining the position of the stars according to the coordinate system of the spacecraft and comparing these coordinates with the coordinates known as the stellar directions from the star catalog. Star sensors can obtain accurate information in arc seconds. However, they are heavy, expensive, require a lot of power, extremely light-sensitive sensors, and are affected by light reflected from the sun, the moon, and the earth. For this reason, it is generally not preferred in CubeSat satellites [12].

1.2.1.3 Magnetometer

Since the earth's magnetic field is well-defined and strong in the low earth orbit of the cube satellite, magnetometers can be used as sensors to detect satellite orientation. A magnetometer is very suitable for satellite orientation detection due to its lightweight, small size, low energy consumption. Disturbances in measurements should be taken into account when the magnetometer is on the CubeSat, especially when placed inside the satellite, surrounded by other subsystems and their electromagnetic field. The caliber of the magnetometer is required to reduce the effect of these disturbances. Moreover, when the electromagnetic coils of the satellite are di activated, their use on the satellite (on-board) is restricted. [12-14]

1.2.1.4 Accelerometer

Speed gyros are available in small sizes and light. Speed gyros have low energy consumption and provide useful information about the angular velocities of the satellites. It is very useful when combining information with reference sensors, and especially when stabilizing or preventing the satellite. Based on this fact, it is used as a sensor for speed gyros, Pico satellites, and Cube satellites. The use of speed gyros will increase the time required for development and hardware testing. Speed gyros will take up space within the satellite and increase the time needed for integration. [15]

1.2.1.5 Gyroscope

Gyroscopes determine the orientation by measuring the rotation rate of the space device. Gyroscopes are internally placed inside the space device and operate at all points in the orbit. Since gyroscopes do not give precise accuracy, they should be used with other pointing equipment for full accuracy. They are affected by drag and are complex devices as they have moving parts.

1.2.2 Actuators

Actuators used in the satellite are mechanisms that generate control torque for directional control systems and are also sometimes called torque generators. They enable the satellite to rotate in 3 axes. There are two types of directional control actuators, active and passive. Active actuators need an energy source. The most common active actuators are thrusters, magnetic torque coils, and reaction wheels. Passive control systems use environmental energy sources in order to maintain the orientation of the spacecraft. The gravitational gradient bar and solar winds are examples of general passive actuators. Once the location of the spacecraft has been determined the next step is to decide how to change it. For instance, there may be a need to dampen distortion torques or turn the spacecraft to a new point, and actuators are needed for this. The actuators provide the necessary torque to turn the spacecraft in order to take the required picture, to transmit data, to meet the antenna efficiency or other mission needs. A wide variety of orientation actuators are available for spacecraft designers. The torque to be produced should be created for 3 axes and its movement in space should be ensured. Often different types of sensors are used together to accurately measure the orientation. Typically, two or more actuators are used together to achieve the desired position. Passive actuators use little or no additional torque to maintain the spacecraft's position after the spacecraft has reached the desired position. Active actuators, on the other hand, need constant feedback and correction. Passive actuators typically cannot achieve the same level of accuracy as active actuators, but in some cases they are adequate. The decision to use the passive or active method is made according to the purpose of the task and the determination of direction, strength needs, and reaction time. Passive actuators should be preferred in cases where long response time is acceptable, does not require precise directional control, and when energy resources on the satellite are limited.

When choosing the actuator to be used in the satellite, the volume calculation to be created by the system is important. For example, if it is desired to stabilize in a fast time, the actuators to be used will need to have more space in the satellite. In this thesis, the placements of the actuators have been made with a mechanism that will have the least space for a satellite. Commonly used actuators will be briefly mentioned below. [12-16]

1.2.2.1 Magnetic Torquer

Magnetic torque generators are used to create dipole momentum for directional control. They apply torque to the satellite by generating a magnetic field that interacts with the earth's magnetic field. Magnetic torque generators are usually long copper wire wrapped in a coil or piece of metal with high permeability. It is used to compensate spacecraft yaw and drift caused by environmental distortion torques. They are highly preferred because they are reliable and use less energy. On the other hand, they are only effective in low earth orbits and their applicability is restricted by the direction of the external magnetic field. In addition, they are suitable for long-term use because they are not mechanical.

1.2.2.2 Reaction Wheel

Reaction wheels are simple discs that are turned around themselves by electric motors. When the motor applies torque to increase or slow down the disk speeds, it produces reaction torque in the body of the satellite. Since the satellite is basically a closed system, the sum of the total angular momentum of the satellite body with the reaction wheel is constant. Therefore, any change in the angular momentum of the reaction wheel causes the angular momentum of the satellite body to be in the same and opposite direction. Reaction wheels are effective active control elements. They are especially good for variable rotation ratio control. Active control of the spacecraft using the reaction wheel is a fast, flexible, and precise way of directional control. On the other hand, it needs fast-moving parts that cause support problems and friction. A second control system may be needed to control all angular momentum in response to changes in circumferential torques. The main difference between momentum wheels and reaction wheels is that reaction wheels work with momentum without deviation. [17-18]

Reaction wheels use rotational variance, which is Newton's 3rd Law. If the speed of the wheel inside the satellite increases, the satellite also accelerates in a different direction. Normally, three reaction wheels with the wheel axis aligned with the principal body axis are used to control the satellite. The use of the fourth spare wheel is also common practice in some satellites. Response wheels are the most accurate behavior control actuators for satellites. On the other hand, excess weight is the main disadvantage of reaction wheels. In this thesis, reaction wheels in the satellite were used by distributing them to the surfaces. The reaction wheel is used in 10 different locations within the satellite.

A reaction wheel can affect the satellite's momentum in only one axis. At least three reaction wheels are needed to control the satellite along three axes. The four response wheel system can be used to provide redundancy and also allows us to change wheel speeds without generating net torque.

The advantage of using reaction wheels is that it is an advantage in control systems as the speed is easily controlled. In addition, since the earth is not dependent on magnetic field lines like magnetorquer, it has the ability to move in 3 axes in all situations.

For instance, if we examine the reaction wheels on sale commercially on the

CubeSat market. There are many models available, but these are mostly large in size and have high power consumption. There are reaction wheel systems that occupy almost 1U volume in a 3U system.

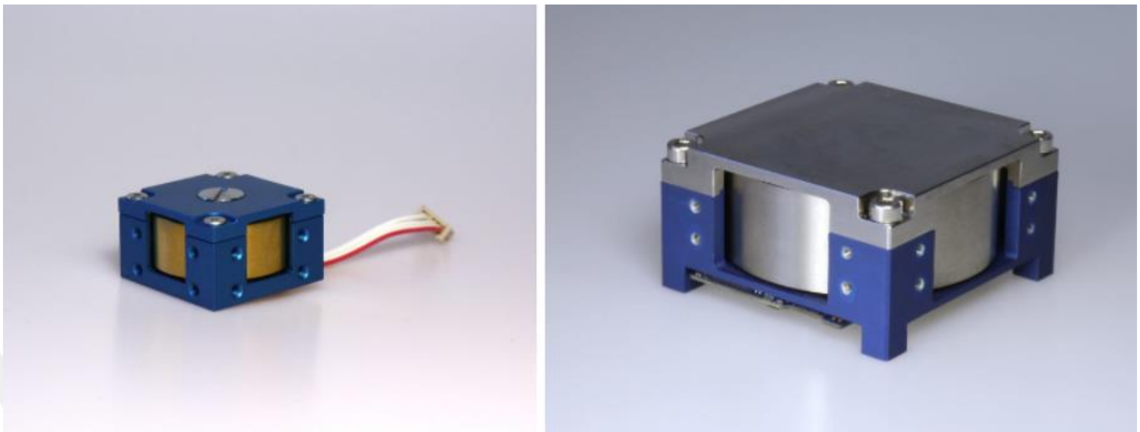

Figure 4: RW210 and RW400 reaction wheel for CubeSat [29]

The RW210 and RW400 series reaction wheels are aimed at applications in 1-3 U CubeSat's and 6-12 U CubeSat's (or similar platforms) respectively. It is shown in Figure 4. Both systems feature a small envelope (of 25 x 25 x 15 mm for the RW210 and 50 x 50 x 27 mm for the RW400) that includes a dedicated controller, offering simple fire-and-forget control to the user [29].

1.2.2.3 Momentum Wheel

Momentum wheels are similar to reaction wheels except that their spin rate does not change or reverse. The concept behind this device is powered by or adding energy from the flight wheel and torque is applied to the single axis of the spacecraft. On some satellites, horizontal scanners are included as an integral part of the momentum wheel assembly.

1.2.2.4 Thruster

The jets and propellants used for active direction control generate a thrust force in the opposite direction by gas jet. Gas jets can use cold or hot gases. If the thrust force is obtained from a physical phase change, it means that cold gas is used, if it is obtained from a chemical reaction, it means that hot gas is used. The received torque and power-ups behavior can be used to control the rate of rotation, the speed of the momentum wheel, and to adjust the trajectories. Gas jets and magnetic coils can be used for the same purpose in LEO. The magnetic torques generated by the magnetic coil depend on the local magnetic field. The local magnetic field changes as the spacecraft move in its orbit. On the other hand, jets do not change their behavior according to the environment. The main limiting factor in jet use is the sprayer needed. In the use of gas jets, the fuel budget is an important part of mission planning. Gas jets have complex and expensive plumbing systems. In higher orbits, gas jets momentum is used to exchange with the environment. In recent studies, researches are ongoing to reduce the cost and size of these systems [19].

CHAPTER II

PURPOSE OF THE STUDY

In this thesis, the effect of nonlinear controllers on the system has been investigated in order to control the motion of a low-orbit satellite. In this context, the performances of the nonlinear controllers obtained are compared with those obtained by using linear controllers. The purpose is to evaluate and measure the effect of the operation of reaction wheels on theoretically calculated surfaces and to lead the satellite design study that is planned to be carried out in the future. The design started with the selection of the ideal small-sized motor, and the whole body was designed according to 3U standards keeping in mind price limitations.

2.1 CubeSat System Structural Design

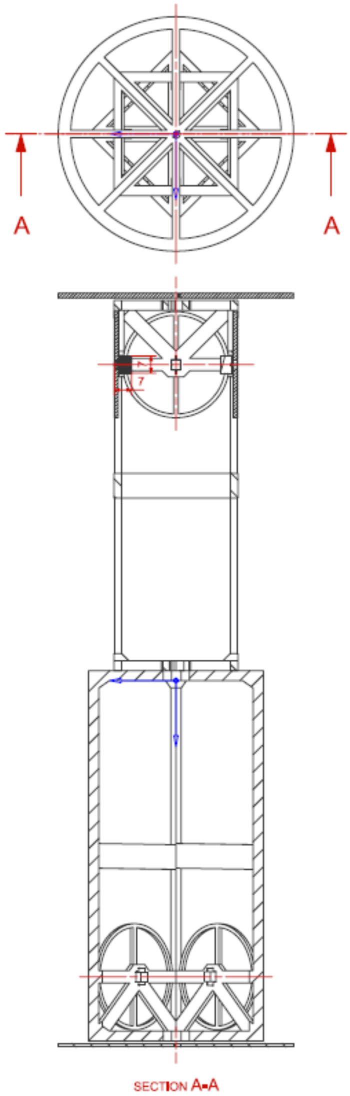

Figure 5: Shows the locations of the reaction wheels

Figure 5 shows the locations of the reaction wheels. The design of the outer body is according to the body frame 3U specifications. However, the inner structure is fully customized, considering the volume to be created for deployable solar panels along with a panel opening technology. The dimensions of the design for the core body are 50mm x 50mm x 300mm. After CubeSat enters the desired orbit, the panels are launched outward on the 4 surfaces, and 45 degrees of rotation is made from the midpoint of CubeSat's length. The reason for this is that the reaction wheels that will be used to stop the potential spin after the CubeSat orbit can have a much finer resolution to pour the actuation energy into the most suitable set of wheels, and hence save power which is an invaluable resource for such a small structure. The body frame was also designed to accommodate the wheels, the very small motors and at the same time provide housing for the remaining aircraft electronic systems like communication and power management. It is specially designed for the engines to be used on the surfaces. The design given in Figure 6 shows the exact locations of the reaction wheels and M represented angular momentum. Reaction wheels are controlled by edge-connected 3-Volt micro DC motors.

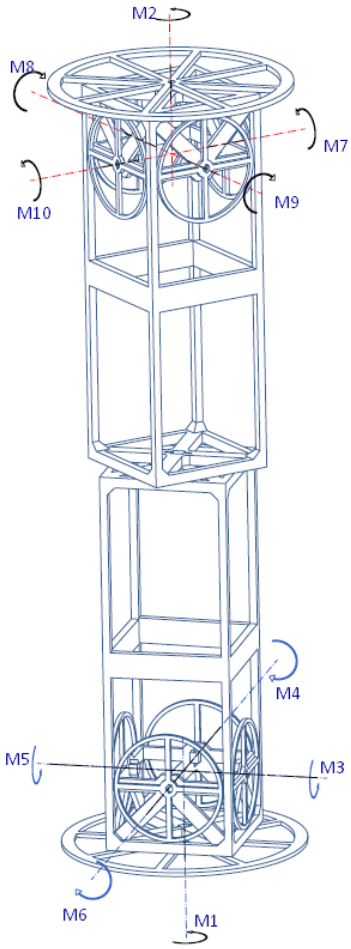

Figure 6: Locations of the reaction wheels

2.2 Reaction Wheel Design

Reaction wheels are a kind of flywheel used for the attitude stability of a cubesat. By adding or removing energy from the flywheel, torque is applied to each axis of a spacecraft, causing it to react by rotating. Stability of cubesat is controlled by the change in speed. By maintaining file rotation, called momentum, a single axis of a spacecraft is stabilised. For instance, it is the YAW axis stabilized by M1 and M2 as shown in Figure 6. Newton’s third law that we all know, that for every action there is equal and opposite reaction. Hence, if the reaction wheel is accelerated counterclockwise, it creates an internal torque on the spacecraft clockwise.

Reaction wheels can rotate a spacecraft only around the center of mass with high pointing accuracy. However, they are not capable of moving the spacecraft from one place to another. There are some advantages and disadvantages of the reaction wheels the pros of the reaction wheels are that they do not consume fuel and relatively power efficient unlike the magnetorquers. They do not rely on a magnetic field and suitable for deep space missions they also store angular momentum. The main disadvantage is that the reaction wheel is a mechanism and the mechanism is not preferred in space. Since, it generates microvibrations and if it fails the mission can fail too. Another disadvantage of a reaction wheel is that over time reaction wheels’ may build up enough stored momentum to exceed maximum speed of wheel called saturation which will need to be stopped. That is why the reaction will system are supplemented with attitude control mechanism such as magnetorquers. The wheel speeds are independently precision adjusted by 10 different the pulse width modulation method [18].

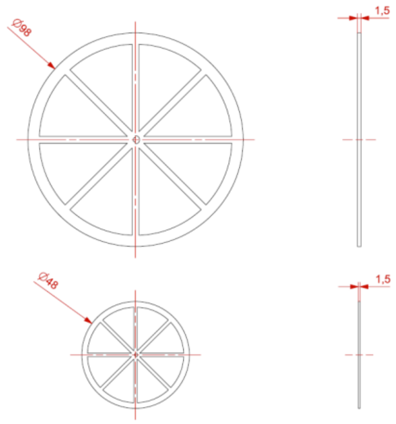

Figure 7: Reaction wheel thickness dimensions

The reaction wheel's outer cap dimensions are limited by the CubeSat body frame. For this reason, those used on the side surfaces are 48mm, and those used on the upper and lower surfaces are 96mm. The reaction wheel's outer cap and thickness dimensions are shown in Figure 7.

The total stored momentum in the reaction wheel depends on the speed of the motor and the inertia of the flywheel. The most important design parameters used for the reaction wheel design are motor speed, wheeler mass, and wheel diameter. It should be noted that the reaction wheel cap dimensions are restricted due to the CubeSat body frame size limitations [2]. In Table 3 provides details on the dimensions and general properties of the reaction wheels.

Table 3: Dimension parameters of reaction wheels and micro motors

Reaction Wheel Number	M3, M4, M5, M6 M7, M8, M9, M10	M1, M2
Wheel Outer diameter	48mm	98mm
Wheel Thickness	2 mm	2 mm

Wheel Mass	4 gr	10 gr
Max speed	3000 rpm	3000 rpm
Motor Rating Voltage/Ampere	3Volt/10mA	3Volt/20mA
Motor Size (length width height)	11 x 7 x 3 mm	11 x 7 x 3 mm
Motor Mass	3 gr	3 gr

According to the target CubeSat design, the largest wheels are placed at the top and bottom and enable the M1 and M2 yaw movements. All other small wheels are placed for pitch and roll accordingly. In normal designs, when running three loops, the CubeSat body is rotated 45 degrees from its mid-point, so there are 5 loops and 5 drive models. Top and bottom wheels are still symmetrical and are driven by the same signal to create more symmetric and stable rolling around the center of mass. The reference inputs of the 45-degrees offset loops that need to be locked would also be 45-degree offset with respect to each other whereas the systems are otherwise identical. For instance, when one defines a target position where it wants to stop at an absolute position as 0-deg, this would correspond to a 45-deg angle target in the upper half of the CubeSat body. Figure 8 shows the top view of the CubeSat body.

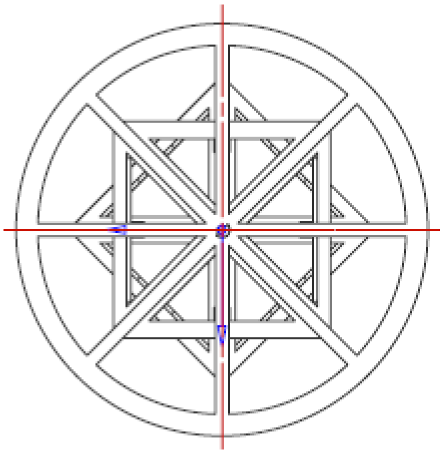

Figure 8: Top view of CubeSat Body

The following assumptions were made for simplifying the theoretical calculations. The CubeSat body frame is assumed a rigid body with the center of mass and origin of the body-fixed frame located at its geometric center. All reaction wheels are assumed to yield the same output when fed with the same PWM. The systems operate with a closed loop PID control. Based on the above assumptions the torque generated by each wheel is calculated using angular momentum equations. This also allows to calculate the total torque they collectively generate for every possible position. Since the system is assumed to have a close loop PID controller, the torque can be easily estimated and the loop parameters can be determined accordingly.

2.3 Kinematic and Dynamic Model

The CubeSat's dynamic and kinematic models show the attitude and angular velocity of the satellite as a function of time. The following assumptions have been made for creating the dynamic modeling of the satellite. It is assumed that the satellite acts as a solid object. It is assumed that the spacecraft acts as a point mass model for orbital dynamics. Kinematic equations as given Equations 1 and 2 that are represented in quaternions [20-21].

$$\dot{q_0} = -\frac{1}{2} W^T q_v \quad (1)$$

$$\dot{q_v} = -\frac{1}{2} W \times q_v + \frac{1}{2} q_0 W \quad (2)$$

In Equation 1 and 2, $\dot{q_0}$ and $\dot{q_v}$ are vector components and scalar respectively and W is the angular velocity of the CubeSat. Equation 3 is obtained when the kinematic equations are simplified.

$$\begin{vmatrix} \dot{q}_1 \\ \dot{q}_2 \\ \dot{q}_3 \end{vmatrix} = \frac{1}{2} \begin{vmatrix} q_0 & -q_3 & q_2 \\ q_3 & q_0 & -q_1 \\ -q_2 & q_1 & q_0 \end{vmatrix} \begin{vmatrix} W_1 \\ W_2 \\ W_3 \end{vmatrix} \quad (3)$$

According to the Newton-Euler law formulation varies depending on the torque applied angular momentum. T^b, the dynamic model of this CubeSat with these assumptions, is given in Equation 4 [20]. Here I is the moment of inertia W_{bi}^b is the angular velocity of the body frame relative to the inertial frame in the body frame.

$$T^b = I\dot{W}_{bi}^b + W_{bi}^b \times \left(IW_{bi}^b\right) \quad (4)$$

CHAPTER III

ATTITUDE CONTROL SYSTEM OVERVIEW

This section presents the general description of the system and the introduction of the electronic circuit board used. Also, the algorithm developed for the satellite's ADCS system will be mentioned.

3.1 System Description

Attitude analysis can be divided into the following steps determination, prediction, and control. Attitude determination is achieved by processing the data from sensors located in the CubeSat. The custom design collects raw data from an accelerometer, gyroscope, and, magnetometer sensors. Attitude prediction is implemented by dynamic modeling of the future orientation of the CubeSat, whereby the current position and orientation of the aircraft are carefully weighted. Attitude control is activated to direct the CubeSat body to the target position and orientation. The wheel-based actuation mechanisms are implemented to move it from one attitude to another attitude [22].

The dynamic rotational movements, namely tumbling of the body, are measured using an accelerometer sensor and a gyroscope. These movements are analyzed and the feedback actuators are controlled with a Pulse-Width-Modulation signal from the central controller.

The rotational wheel concept is extended to a distributed counter action multi-wheel structure in order to enable attitude control without using the large standard power-hungry reaction wheels. The proposed design comprises a total of 10 reaction wheels located on the body frame shown in Figure 6. The advantage of this system is that it increases the torque by a factor of two symmetrically around the center of mass. This is due to the fact that each reaction wheel has an additional at same axis that works in the same direction to duplicate the moment. Moreover, placing the reaction wheels at the furthest points in the structure, away from the center of gravity, allows to maximize the moment produced. It is a directly proportional to the distance of the mechanism from the center of gravity. This is the reason why the reaction wheels were placed at the extreme end-points in the CubeSat body. The weight-wise symmetric 5-wheel half body sections with single-lane manufacturing are assembled with a 45 degrees offset resulting in 10 distinct injection points with finely separated actuation control.

3.2 Hardware

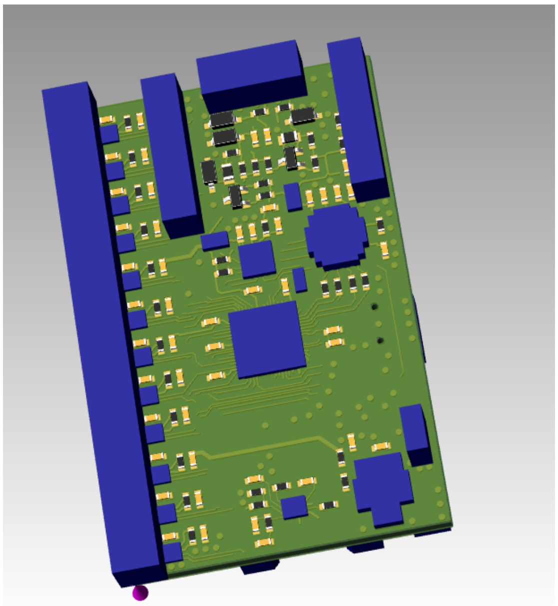

Figure 9: Photograph of the controller mainboard 3D view.

The systems required for the entire electronic system were combined on a single control card, called the mainboard. The power management system, the onboard processor, the attitude sensors and actuator control have all been integrated onboard. The mainboard design is realized in FR4, 4 layers. There are 12 optional H-Bridge motor driver outputs. The desired high-voltage drive for the reaction wheels' activation is generated by a step-up converter also integrated on the same ADCS controller card. The main system power supply is a 3.7-V Li-Ion pack; the sensors processors are fed from a 3.3V LDO for good isolation from the motor drivers. A calibrated small form factor magnetometer is directly plugged on to this system card in order not to introduce errors due to misalignments related to custom assembly of the sensor coils. Figure 9 and Figure 10 show the top view of the complete electronic system.

Figure 10: Photograph of the controller mainboard module.

A RF communication module is used to allow real time data transmission when testing the system's operation. A computer with proper interface is used as a ground station that allows visualizing the collected data. Rotational movements of the satellite are both displayed and recorded. More detailed information is given in the section presenting the testing of the system.

3.2.1 Sensors

Magnetic meter, accelerometer, and gyroscope are used to determine the orientation. More detailed information about the sensors used is explained in the following subsections. The sensory data reading frequency is 1 kHz.

3.2.2 RM3100 Magnetometer

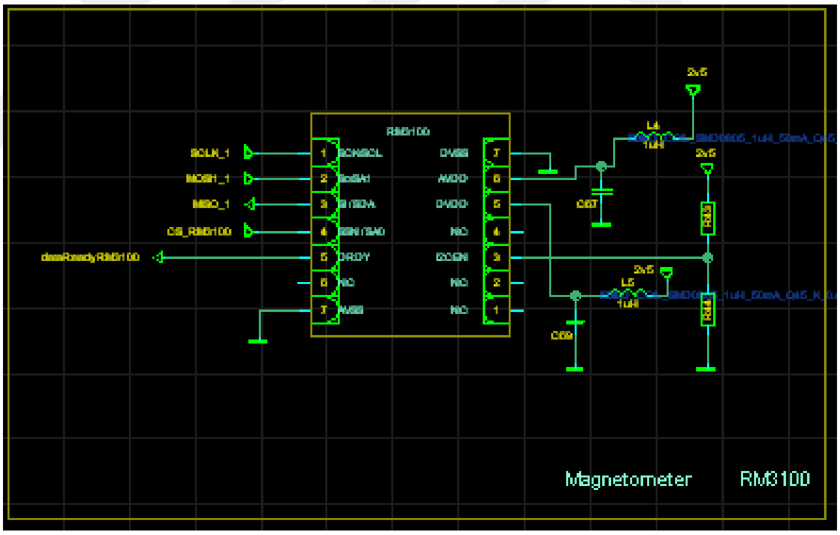

Figure 11: Magnetometer schematic circuit

The magnetic meter measures the magnetic field flux density of the environment it is in. With the RM3100 module to be placed on the satellite, the 3-axis magnetic meter gives information about the magnitude and direction of the Earth's magnetic field. Figure 11 shows the magnetometer schematic circuit. Although magnetic meters are not very sensitive sensors (0.5 - 3 degrees), they are used in almost every space mission as cheap, light, and reliable reference sensors. The accuracy of the magnetic meters depends on their calibration on the ground to reduce the effects of electromagnetic disturbances caused by many electronic components in the subsystems of the satellite, as well as in space during the mission. The fact that the magnetic field model of the Earth is not accurate also reduces the accuracy of the orientation data obtained from the magnetic meters. In addition to being used for orientation determination, these sensors are also used in some control methods such as the B-dot algorithm to calculate the control signal to be sent to the magnetic torsion. In this mode, magnetic wires must be closed while measuring with magnetic meters. Figure 12 shows the view of the magnetometer breakout board.

In this study, RM3100 magnetometer from PNI Sensor Corporation was used. PNI‟s 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. The primary components of the RM3100 Testing Boards are two Sen-XY-f sensor coils, one Sen-Z-f sensor coil, and PNIs MagI2C ASIC controller. They also incorporate resistors, capacitors, and connectors, all mounted on a PCB, to provide a complete magnetic-field sensing module. The RM3100 Testing Boards incorporate both I2C and SPI interfaces for system design flexibility. [23]

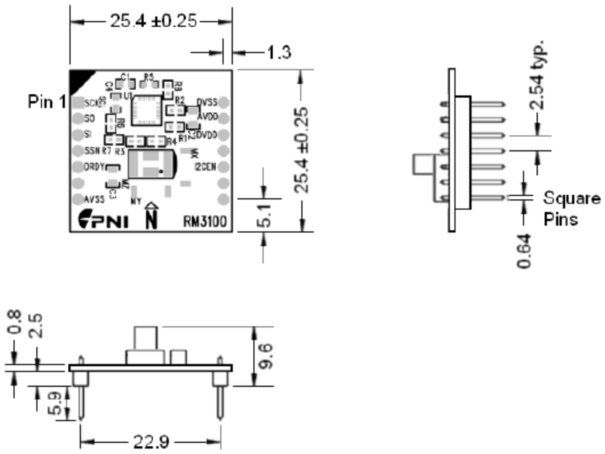

Figure 12: RM3100 Evaluation Board Mechanical Drawing

3.2.3 Gyroscope I3G4250D

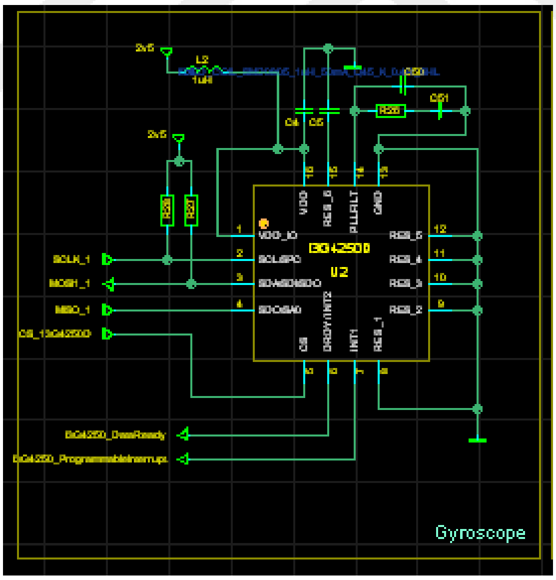

Figure 13: Gyroscope schematic circuit

Gyros measure angular velocity; they need to be integrated for orientation data. Therefore, errors increase over time and need to be calibrated. They are suitable for use with other sensors and for measuring rapid changes in orientation. In Figure 13 the gyroscope schematic circuit is shown.

I3G4250D sensor selection was made for the use of 3-axis digital gyroscope. The I3G4250D is a low-power 3-axis angular rate sensor able to provide unprecedented stability at zero-rate level. Figure 14 presents the pinout of the I3G4250D.

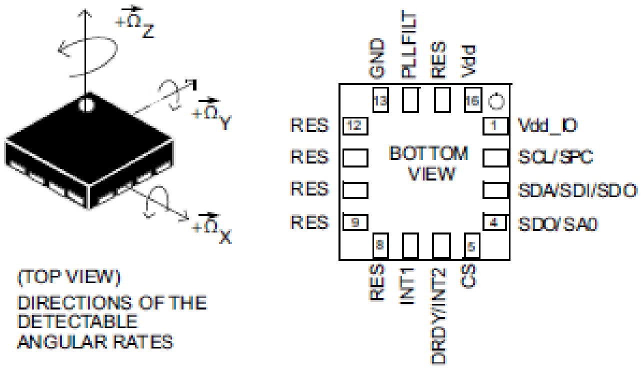

Figure 14: Pin output and view of axis [24]

3.2.4 Accelerometer ADXL356

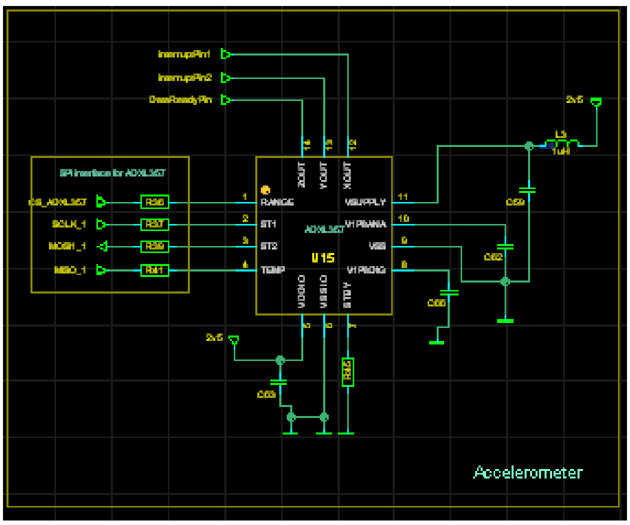

Figure 15: Accelerometer circuit diagram

In this study, ADXL357 IC is used as accelerometer because of its high sensitivity. Data is received from the sensor using SPI communication infrastructure. The accelerometer circuit diagram is shown in Figure 15 and Figure 16 provides the Pin configuration of the ADXL357.

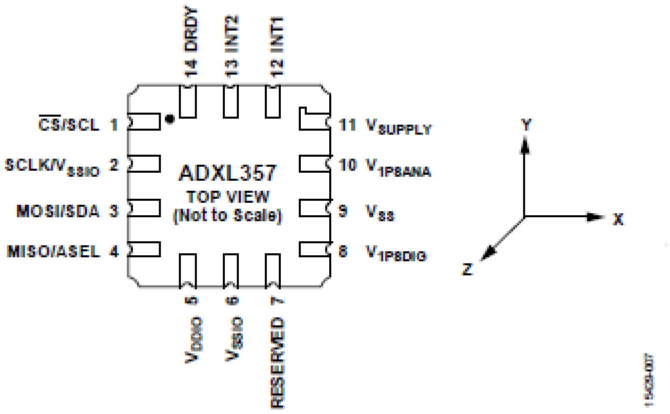

Figure 16: ADXL357 Pin configuration [25]

3.2.5 Motor Driver DRV8838

A first stage converts the input voltage to 3 V and Figure 17 shows buck converter circuits. The motor driver comprises discrete components and DRV8838 by Texas Instruments was selected for this project. Figure 18 gives an overview of the schematics. Motor driver’s controller is a low voltage driver. The reason to select this model is the small size of the reaction wheel and the fact that motor working voltage is 3 V.

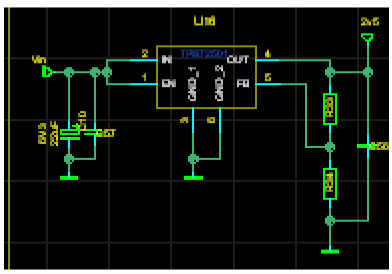

Figure 17: Buck converter circuit diagram

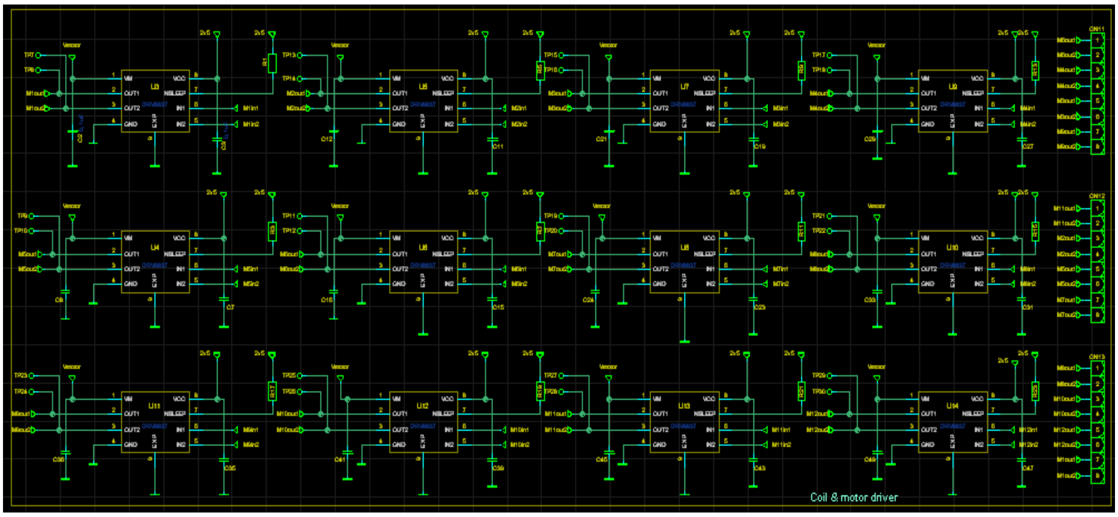

Figure 18: Schematics of the implemented motor driver.

3.3 Layout Design & Assembly

Once the circuit diagram was determined, the layout design was made. Layout work is done in Mentor Expedition program. PCB is designed as four layers, FR4, double-sided. Its dimensions are 39mm x 61mm. The pallet design is multiplexed in six pieces. For ease of assembly, the materials in the small and sensitive cover are arranged in a top layer. Figure 19, Figure 20, and Figure 21 are show the layout design of mainboard and stencil solder before the pick and place electronic component.

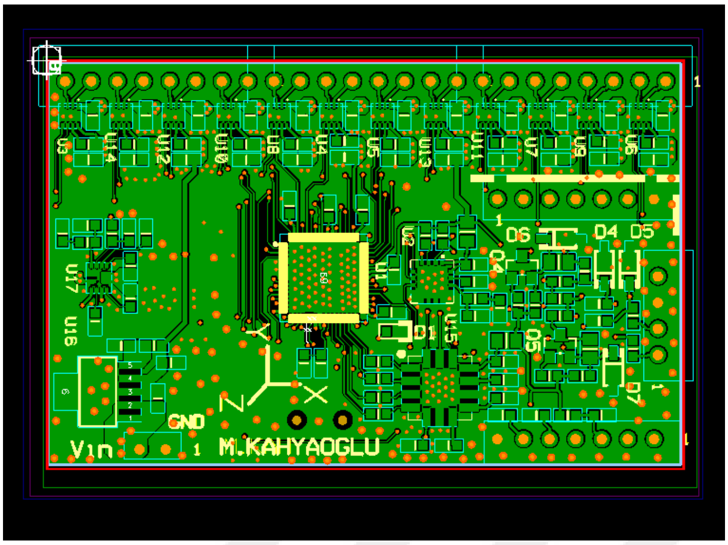

Figure 19: PCB Layout top side

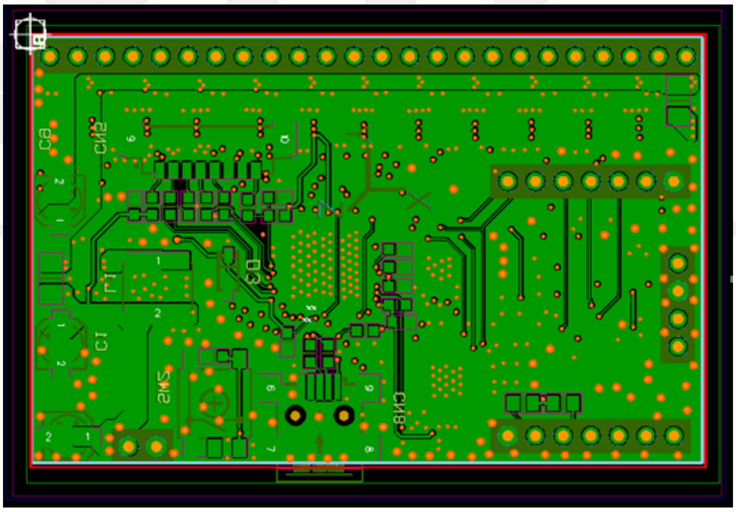

Figure 20: PCB Layout bottom side

In order to be able to produce PCBs in automatic placement machines, the reflow method was used. Stencil production is also made with PCB, and after the materials were placed with auto assembly, the assembly of the materials on the card was completed with the baking process.

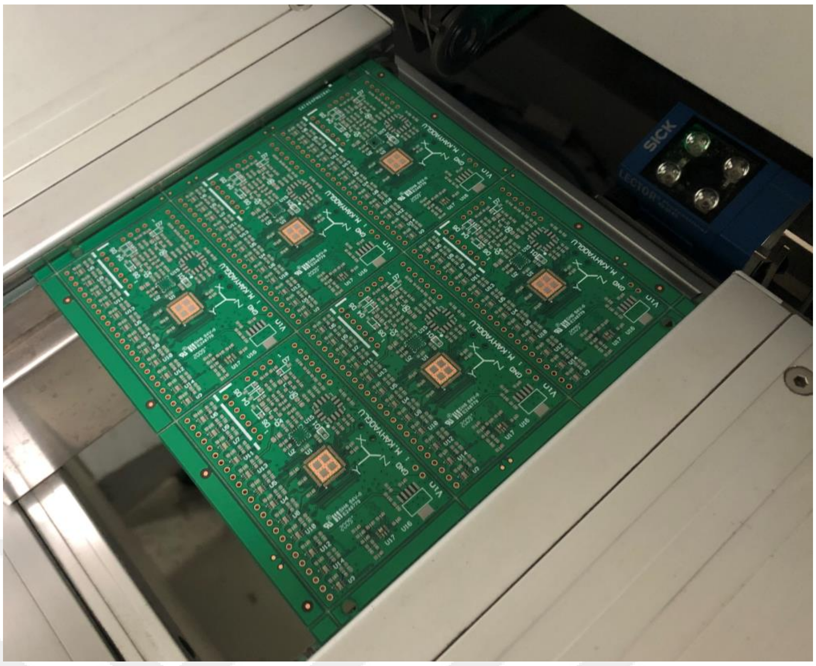

Figure 21: Auto assembly machine

CHAPTER IV

ATTITUDE CONTROL SOFTWARE ALGORITHM

In the CubeSat Attitude Determination and Control System (ADCS) system, motion analysis is done in 3 axes. Firstly, the instantaneous position, orientation, and angular speed of the CubeSat body are determined. The difference between the target and current orientation is fed into the central system that produces an error signal. After determining the current position and sending an error signal into the feed-forward PID algorithm, a feedback action is determined by which the proper torque wheel will be activated along with the corresponding direction by pulling the data from the look-up table according to the distance to the target. The B-Dot controller is run until angular rates fall below 5 deg/sec on all three axes. Then, the closed-loop PID algorithm is used to determine the torque with an angular difference. Figure 22 shows the Matlab/Simulink block diagram for PID controller.

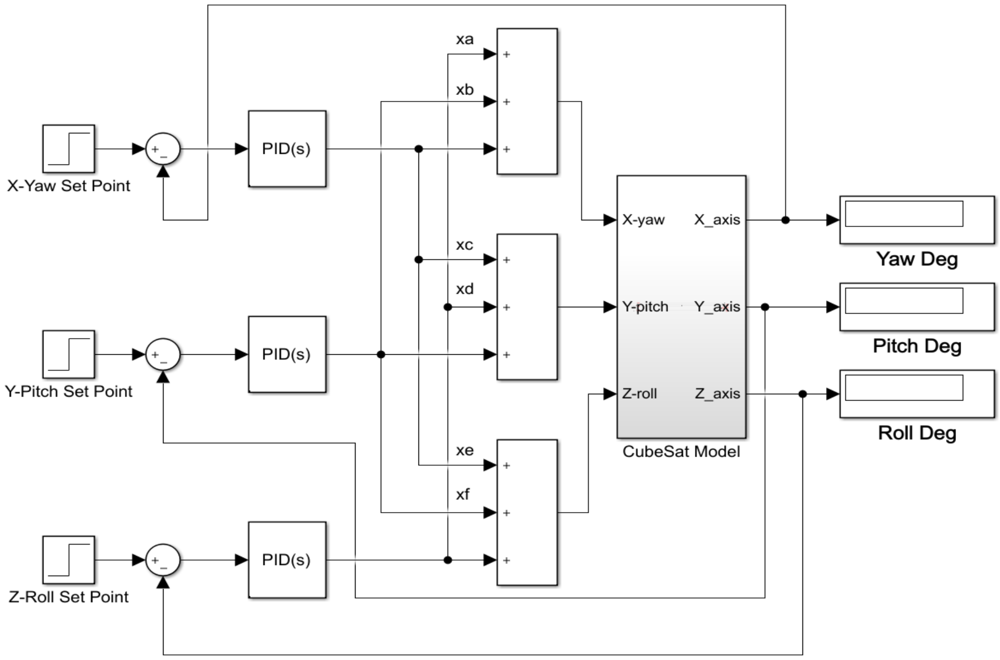

Figure 22: Simulink block diagram of CubeSat model with PID controller

The system is locks in all 3-axis thanks to the feedback action with high PID gain. The feedback signal from each path is proportionally scaled and forced into the other actuation branch with proper dynamic scaling for each of the possible positions. This allows to achieve the overall stability of the system. The key contribution here is a coefficient look-up table that provides a perfect set of coefficients relating the actuation level in the target reaction motor to the torque in the other relative directions.

The 6-degree-of-freedom (DOF) motion tracking system is used in many applications with the 3-axis gyroscope and 3-axis accelerometer to determine the incremental movements of the CubeSat body frame. Figure 23 shows the block diagram of the main algorithm.

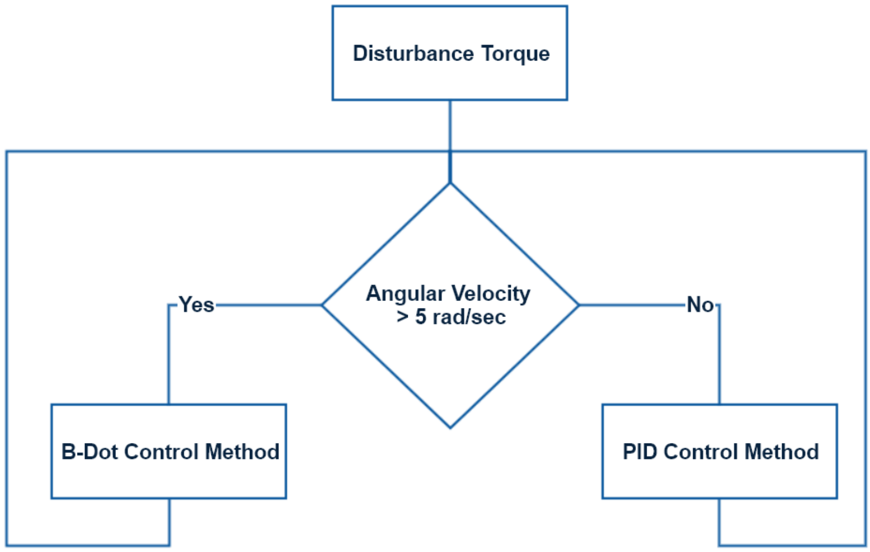

Figure 23: Software Flow Diagram

While the system is stable with an underdamped response, external moments will constantly affect the CubeSat body trying change its course. In order to overcome the undesired torques, ADCS is kept active, and external disruptive effects are absorbed to ensure the system's lock in the desired orientation.

4.1 B-Dot Control Method

After a satellite leaves the rocket, it must first do a de-tumbling, i.e to reduce the angular momentum. To do this, a force against the direction of rotation is continuously generated and the rotation of the satellite is damped. In addition, the B-Dot rule is applied not only for de-tumbling but also for cases where angular acceleration is increased. The B-Dot algorithm operation is as follows. According to the values read from the Gyroscope sensor, the forces that will act in the opposing direction are determined. In this study, the reaction wheeler in the forces against the direction of rotation of the satellite was activated. When the angular transformation remained below 5 deg/sec, the PID algorithm was activated and locked on the target was achieved. [26]. The general flow diagram of the B-Dot algorithm operation is shown the Figure 24.

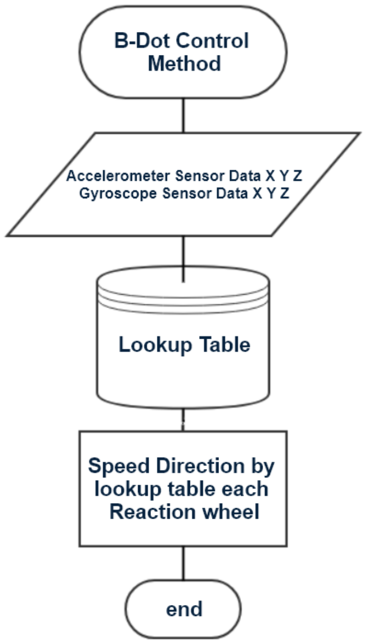

Figure 24: B-Dot Flow Diagram

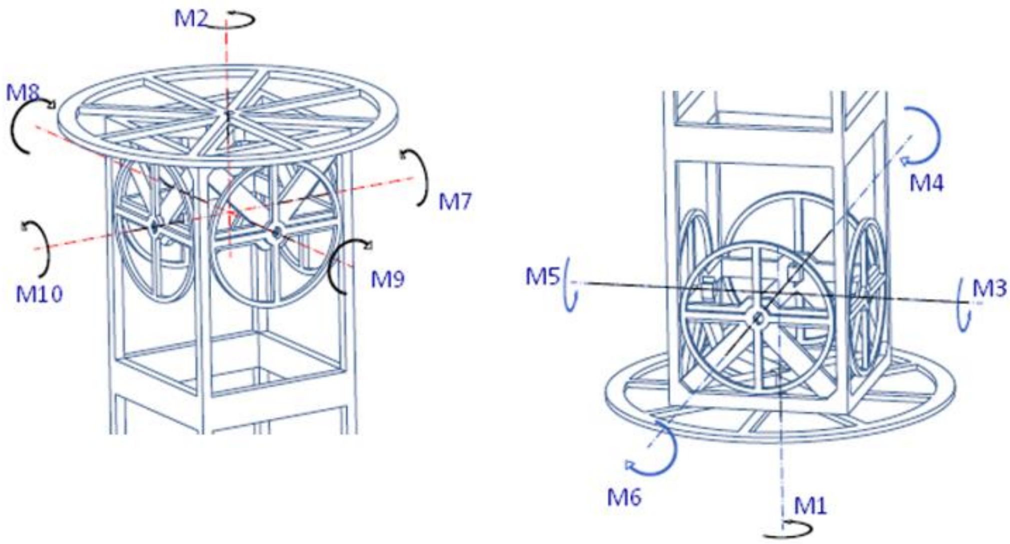

Figure 25: Top and bottom reaction wheel are shown.

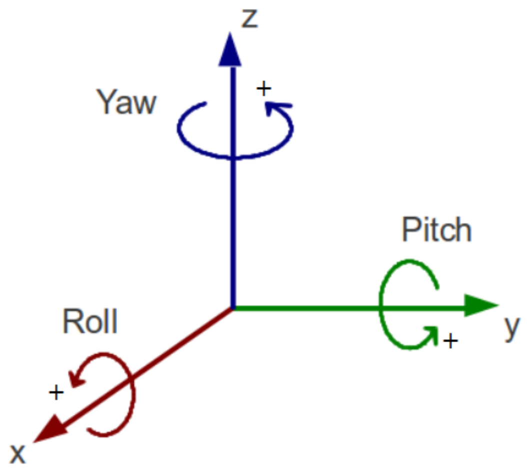

Figure 26: Direction of Euler angels

Figure 26 shows general Euler motion is used determine the motion characteristic for each axis. For instance, if Cubesat body needs to Yaw motion in the + direction as shown in Figure 26, M1 and M2 must move in the same direction to generate angular momentum that show Figure 25 with M. Also, these return movements are mentioned in section 2.2. When the reaction wheel is accelerated counterclockwise, it creates an internal torque on the cubesat clockwise.

Figure 26 shows the Euler angels with direction. First, it is necessary to identify the movement orientation of the satellite to be made to use this kind of moves to do to the current position and the target yaw, pitch and roll movement of the direction of + or - as after determining that corresponds to each power + or - will move in that direction.

4.2 PID Control Method

"PD" control law, also known as proportional derivative control law generates the proportional law by adding a derivative term. The purpose of this differential term, allowing more refined control is to provide the oscillating motion of the proportional damping law. With this dampening, the satellite is less likely to overshoot its desired attitude. With this damping, the satellite is less likely to go out of the desired state. [27]

Proportional integral derivative control laws, or simply "PID", constitutes the legislation by adding an integral term “PD”. This integral term allows the elimination of the error accompanying the continuous degradation such as external torque on the spacecraft. In this study, first model analysis was performed in Matlab / Simulink which allowed to determine the PID coefficients for the structure along each of the three axes. The reason for this situation was made in order to affect the rotations of other axes in every axis movement and to increase the stability of this situation. PID parametric coefficients were found by iteration experimentally. [21]

CHAPTER V

EXPERIMENTAL RESULTS

The proposed CubeSat design and ADCS was experimentally tested using a custom made setup. The application was made on examining the effect of external disturbing torque application. The stability of the study was increased with repeated experiments for the analysis of the working state of the system.

5.1 Test Results

The prototype was hung with a fishing line on the axis of gravity and rotated by applying external disturbing forces. Two cases were considered without ADCS and with the proposed ADCS. The operation of the system was first tested in a laboratory environment. All movements of the CubeSat body were emulated while it is hung with a piece of fishing line. For the experiment, reaction wheels were placed on 50mm x 50mm x 300mm body frame surfaces. These reaction wheels were controlled by the mainboard designed for this experiment and an image of the test bench is given in Figure 27.

In the software-supported test setup, the orientation determination is controlled by the mainboard inside the satellite and it only transmits the information from the orientation sensing sensors via wireless communication. The computer acts like a ground station and displays the values on the interface according to the information from the satellite.

The data received for the computer interface are observed with the interface written in the Processing language. Gyroscope and acceleration values of the satellite are projected in three axes.

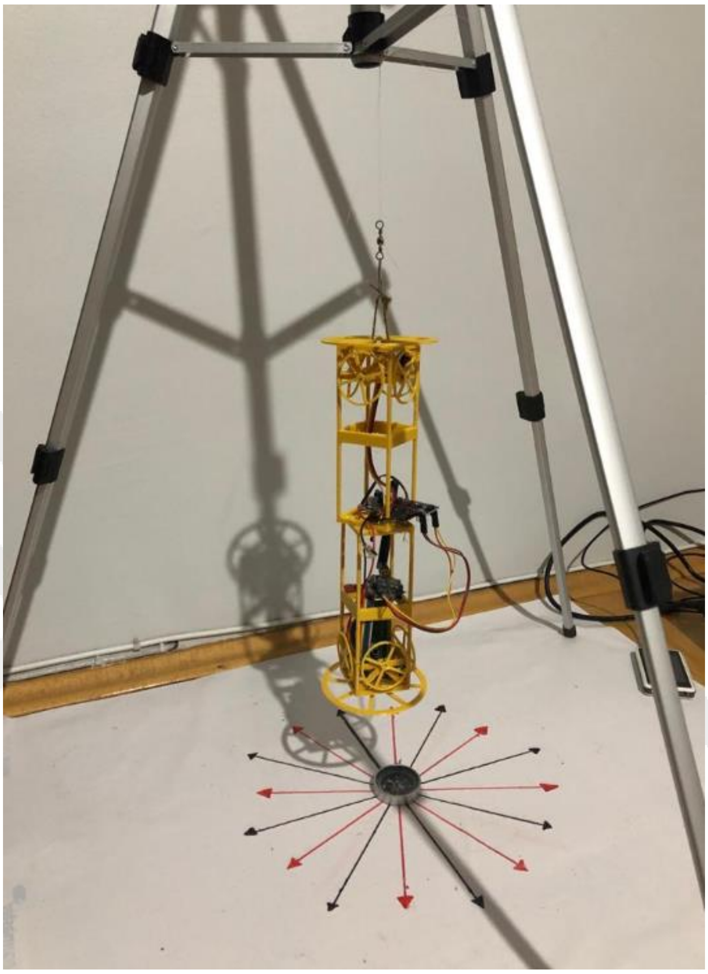

Figure 27: Photograph of the test setup

The Euler angles of the CubeSat are taken to be [-360 360] deg along all the three axes, called Z-yaw, Y-pitch, X-roll. The performance of the reaction wheels placed on CubeSat body surfaces was measured the stable downtime of the system. As a result of this experiment, the reaction wheel of the CubeSat body and the ADCS system showed the time dependent Euler angles against the step disturbances as shown in the graph.

CubeSat distortion force was applied from the outside. The resulting graph shows large changes along the Z-axis together with small changes along the X-axis and Y-axis.

The data in the graph, shows that an external force was applied to the system 2 times. The first of the external forces was applied after 25 seconds. The second one was performed in approximately 300 seconds. After the noise force affecting the CubeSat body, the ADCS system becomes active and the system is brought back into balance at the target set point that the target point is to bring the system to its position before the disturbance torque is applied.

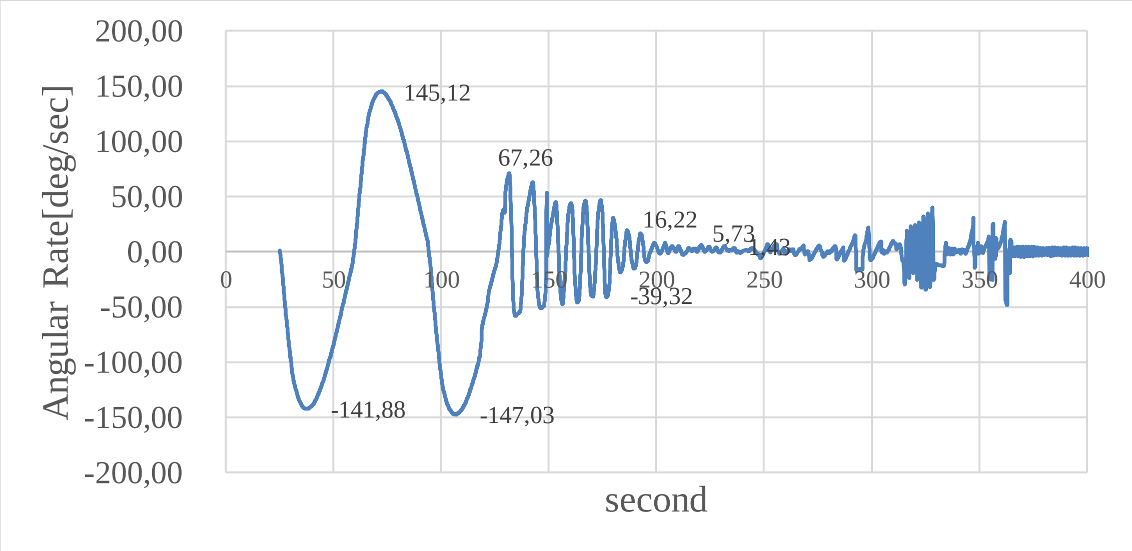

Figure 28: Disturbance torque applied CubeSat body and ADCS system active

If we investigate it as a case study, in the first disturbance torque seen in Figure 28, the external rotation movement was physically applied and continues to move by oscillating. In this case, the rotation angles of the system are shown in the left column and the rotation angles in the time axis are shown. When the system's rotation damping is high, the B-point algorithm works. In addition, the PID algorithm works when the rotation speed becomes less than 5 degrees. The PID algorithm continues until the system stops. This algorithm flow also explained chapter IV. In this case, more force is applied in large swing motions. Hence, this is a disturbing torque was applied in the direction of the Yaw movement and there was only a low impact torque application for the other axes and the oscillations were damped in a shorter time than the Z-Yaw movement.

5.2 CubeSat Angels Viewer

A computer-operated interface software was written to better understand the solutions produced while developing the test and the system and to observe what was done. 3D visualization of the data coming from the serial port was made using the Processing language that is a flexible software sketchbook and a language for learning how to code within the context of the visual arts [30]. The data received from the test satellite were plotted on the computer designated as the ground station. In the graphs, the values rising from the moment when it is stable show Figure 29 the disruptive movements applied externally.

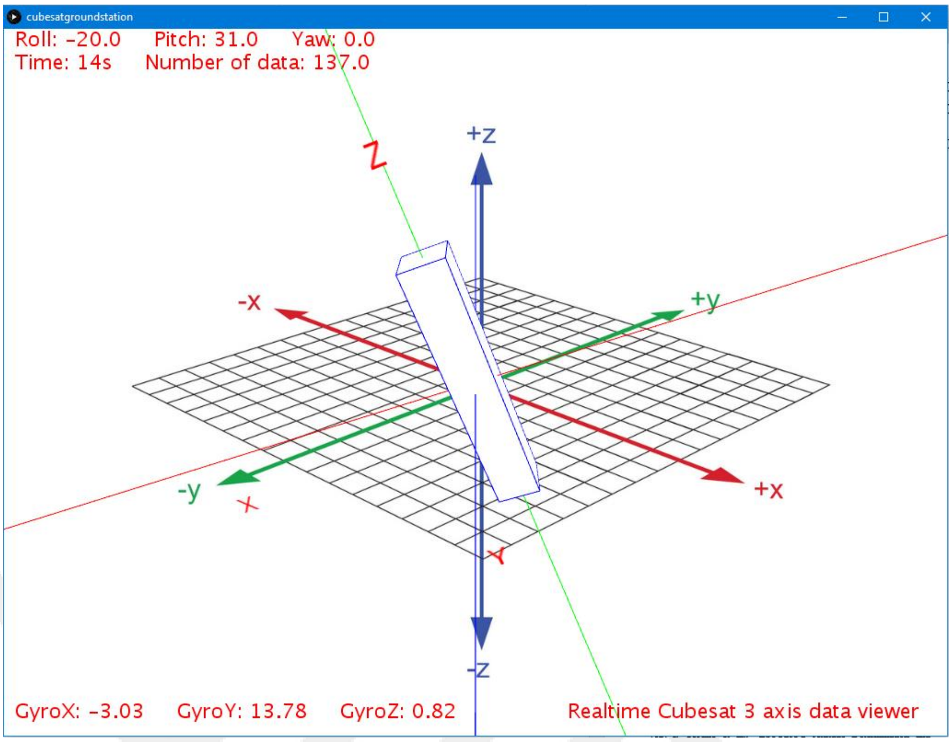

Figure 29: Real-time CubeSat 3 axis data viewer

Figure 29 that is defined as a ground station in the test setup. It has been shown that a real-time Ground Station and bidirectional communication can be achieved.

As a result of this studies, if we state the result of one of the tests applied, a mildly loaded 3D printed prototype tumbling with 145 rad/ sec angular speed could be stabilized in the desired position in just 452 seconds burning average power of 540 mW.

CHAPTER VI

CONCLUSIONS

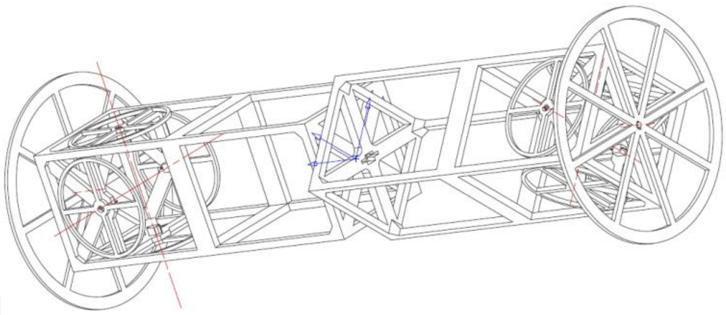

Figure 30: 3U CubeSat body with 10 reaction wheels

This study presents a CubeSat prototype with an attitude detection and control system and the prototype is shown in Figure 30. First of all, similar systems used in CubeSat studies were investigated and trends in this direction were examined. An orientation was proposed with the torques that can be created on surfaces by using reaction wheels mounted on various surfaces of the satellite. Such solutions are very important for microsatellite, where minimizing the dimensions of each component system is of primary importance.

The proposed CubeSat prototype is controlled by 10 reaction wheels carefully designed in different sized and mounted on specific places of the body frame. The design was experimentally tested. Using externally generated disturbance force it was shown that the CubeSat remains fixed in the desired orientation in orbit or points to the desired direction. The proposed control system realized on a PCB occupies minimal space and ensures efficient use of the body frame of the CubeSat in 3U category.

FURTHER

This study can further be elaborated by implementing it on all surfaces where the number of motors with micro motors and reaction wheel caps was limited.

In addition, by optimizing the PID coefficients better, the application results can be improved. Mechanical systems for the placement of the motors can be designed using PCB so that the minimum space can be saved by integrating into the systems to be used as the payload.

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VITA

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