ATTITUDE CONTROL OF CUBESAT IN SINGLE AXIS BY FUZZY LOGIC CONTROLLER

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by

ÖZLEM GÜLSÜM KILIÇKAYA

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ATTITUDE CONTROL OF CUBESAT IN SINGLE AXIS BY FUZZY LOGIC CONTROLLER

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Approval of the Graduate School of Natural and Applied Sciences, Atılım University.

Prof. Dr. Ibrahim K. Akman

Director

I certify that this thesis satisfies all the requirements as a thesis for the degree of Master of Science.

Prof. Dr. Abdulkadir ERDEN

Head of Department

This is to certify that we have read the thesis “Attitude control of cubesat in single axis by fuzzy logic controller ” submitted by “Ozlem Gulsum Kilickaya” and that in our opinion it is fully adequate, in scope and quality, as a thesis for the degree of Master of Science.

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I declare and guarantee that all data, knowledge and information in this document has been obtained, processed and presented in accordance with academic rules and ethical conduct. Based on these rules and conduct, I have fully cited and referenced all material and results that are not original to this work.

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ABSTRACT

ATTITUDE CONTROL OF CUBESAT IN SINGLE AXIS BY FUZZY LOGIC CONTROLLER

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M.S., Mechatronics Department

Supervisor: Assoc.Prof.Dr. Sedat Nazlıbilek

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In this thesis, attitude control of a cubesat in a single axis by means of a reaction wheel with fuzzy control is investigated.

A cubesat is a type of miniature satellite for space research that usually has a volume of exactly one liter (10 cm x 10 cm x 10 cm) and a mass of approximately 1 kilogram which is called 1-Unit or 1U shortly.

Although cubesats are introduced for only academic purposes in recent years, they have various missions such as taking photo from space, earthquake detection, detection of cosmic dust, climatology purposes like prediction of rain and tornado, ect today.

Many academic papers on the methods and techniques for attitude control are researched during this study and related information about these are given in the literature survey part.

In this master thesis main interest is concentrated on the attitude control of a Cubesat in a single axis by the application of the reaction wheel.

In this study, the reaction wheel itself and the testbed are designed, implemented and manufactured. The testbed is designed for simulating the behavior of the cubesat in a single axis. The reaction wheel and the testbed are integrated in such a way that all measurements and tests are carried out using this compact system.

A MATLAB based fuzzy control software together with an Arduino Mega microprocessor is developed and applied to the system as the control method.

Keywords: Cubesat, Reaction wheel, attitude control, Cubesat missions, miniaturized satellites.

ÖZ

KÜPSAT UYDUSUNUN BULANIK MANTIK KONTROLCÜSÜYLE TEK EKSENDE YÖNELİM KONTROLÜ

Kılıçkaya Özlem Gülsüm

Yüksek Lisans, Mekatronik Mühendisliği Bölümü

Tez Yöneticisi: Doç. Dr. Sedat Nazlıbilek

Nisan 2016, 83 sayfa

Bu tezde, bir küp uydunun bir tepki tekeri vasıtasıyla bulanık mantık kontrolcüsü kullanılarak tek eksendeki yönelim kontrolü incelenmiştir.

Küp uydu minyatür bir uydu olup uzay araştırmaları için kullanılmaktadır, hacmi yaklaşık 1 litredir (10 cm x 10 cm x 10 cm) ve kütlesi yaklaşık 1 kilogramdır, bu cisme 1-Birim veya kısaca 1B adı verilmektedir.

Küp uydular son yıllarda sadece akademik amaçlar için geliştirilmiş olmalarına rağmen, günümüzde bunlar uzaydan fotoğraf çekme, deprem tespiti, kozmik toz tespiti, yağmur ve tornado gibi iklimsel tahminler vb. pek çok alanda kullanılmaktadır.

Bu çalışma sırasında, yönelim kontrolü ile ilgili yöntem ve teknikler hakkında pek çok akademik yayın taranmış ve konuya ilişkin bilgi tezin literatür incelemesi bölümünde verilmiştir.

Bu yüksek lisans tezinde esas ilgi, küp uydunun tek eksendeki yönelim kontrolünde bir tepki tekeri kullanımı üzerinde yoğunlaşmıştır.

Bu çalışmada, tepki tekerinin kendisi ve test düzeneği tasarımlanmış, gerçeklenmiş ve imal edilmiştir. Test düzeneği, küp uydunun tek eksendeki davranışının benzetimi için tasarımlanmıştır. Tepki tekeri ve test düzeneği tüm ölçümlerin alınması ve testlerin yapılması gerçekleştirilebilecek şekilde bütünleşik bir sistem olarak entegre edilmiştir.

Arduino Mega mikroişlemcisi ile birlikte çalışan bir MATLAB tabanlı bulanık mantık yazılımı geliştirilmiş ve sisteme kontrol yöntemi olarak uygulanmıştır.

Anahtar Kelimeler: Küp uydu, Tepki Tekerleği, Yönelim kontrolü, Küp uydu görevleri, minyatür uydular.

To my parents Hatice and Reşat Kılıçkaya, my brother Cihan Kılıçkaya

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LIST OF SYMBOLS AND ABBREVIATIONS

MEMS : Microelectronic Mechanical Systems

GPS: Global Positioning System

J_p :platform inertia around the vertical axis

ω : platform's angular rate

T_d : disturbance torque

T_w: Reaction torque of the wheel (difference between torque of the motor and wheel's friction torques)

$\dot{\omega}_w$: angular rate relative of wheel to plate

J_w: Inertia of the reaction wheel

J_r :mean inertia

T_m or τ: motor torque

b: viscous coefficient

c: Coulomb torque (static torque)

k_m : motor constant

I: current

J: combined inertia of motor + load

i_a :armature current

e_a: generated emf

T_L: Load torque

DC Motor: Direct Current Motor

PC: Personal Computer

PWM: Pulse Width Modulation

CHAPTER 1

INTRODUCTION

Cubesats are first introduced by California Polytechnic State University and Stanford University by 1999. Nowadays satellites are getting smaller. Miniature satellites are getting more favorable. They are much more cost effective than the other widely used satellites both in production and launching actions.

A cubesat is a type of miniature satellite for space research that has a volume of exactly one liter (10 cm x 10 cm x 10 cm) and their mass is approximately 1 kilogram which is called 1-Unit or 1U shortly. By combining several U's, a Cubesat can be enlarged as 2U,3U,etc.

Nanosatellites by their launch years are shown in Figure 1. As seen, very few satellites had been launched from 1999 to 2011. The trend has increased after 2012 sharply. There are 431 Cubesats launched in total by the year 2016 [6].

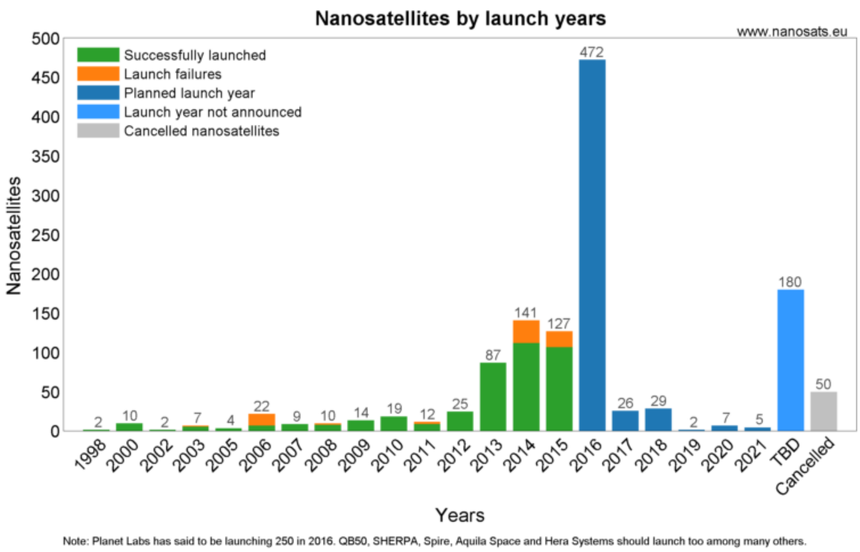

Figure 1: Nanosatellites by launch years

Cubesats have various missions such as taking photo from space, earthquake detection, detection of cosmic dust, climatology purposes like prediction of rain and tornado, etc. Due to their missions and other requirements in space their position must be controlled. A cubesat's orbit cannot be changed in space however its attitude can be controlled using reaction wheels or any other actuators such as magnetotorkers or small thrusters.

In satellite communications the attitude control is the term used to describe the orientation of the satellite in relationship to the earth and the sun. Despite of there is no move and change in placement of the Cubesat, its orientation can be controlled.

Attitude control is applied in three orthogonal axis in Cubesat. Our aim is to apply attitude control in single axis.

Controlling methods of Cubesats may be applied by several ways such as:

- Magnetorquers (Magnetic torquers or torque rods) : Magnetorquers are based upon the main idea that creating magnetic field interfacing with Earth's magnetic field. By this way necessary torque is created by counter-forces.
- Reaction wheels : Reaction wheels are used for attitude control. Attitude control is provided without using fuel. Also differing from other choices attitude control can be maintained as 3-axis stabilized (for every axis, in this thesis it is focused on single axis) and precision for attitude control is higher.
- Thrusters: Thrusters are changing spacecraft attitude by generating external torque. Limitation of thrusters is they depend on limited fuel supply. Once fuel is consumed attitude control ability will be lost if there is any other actuators present.

This thesis is concentrated on reaction wheel. As it is mentioned before reaction wheel is a device such that an electrical motor rotates a wheel to orient the Cubesat (related surface) through its axis.

The reason for selecting the reaction wheel is depending upon its performance in stabilizing the surface and accuracy, it is not using fuels and precision for control is higher [21].

1.1.Aim &Scope

Scope of the thesis focused on the development of:

- Reaction wheel concept
- Controller design

The Objective of this thesis:

- Design of a reaction wheel
- Attitude control of the single-axis of a Cubesat by reaction wheel.

Goals in Attitude Control:

A CubeSat is needed to be controlled because of the reason why that it may lose its attitude by external disturbances by the space conditions. Another reason is that Cubesat is needed to be oriented into desired positions (Example: taking photo from space). Briefly:

- Attitude Correction Due to External Disturbance
- Attitude Correction to Commanded Position

In this thesis controlling the single axis will be achieved for both of these reasons.

CHAPTER 2

LITERATURE SURVEY

2.1. General Information

Attitude can be described as orientation of the vehicle (for our case it is Cubesat) with respect to a definite reference frame.

Attitude control is maintenance of determined and specified attitude within a related tolerance. By the help of the attitude control:

- Cubesat can be stabilized.
- Cubesat can be oriented in desired directions.
- Orientation of the Cubesat can be determined.

There are design requirements and constraints in Attitude Control. Briefly:

- Pointing accuracy: sensor and actuator accuracy.
- Disturbing Environment: disturbance in space conditions that effecting Cubesat's orientation during its mission.
- Mass and Volume
- Power
- Reliability
- Cost

There are different control strategies to maintain Attitude Control. Such as:

- Gravity-gradient stabilization: It can be defined as coarse pitch and roll control. There is no yaw control. It is limited to near Earth satellites.
- Spin Stabilization: It is only suitable for cylindrical geometry.
- Dual Spin Stabilization :This strategy is only suitable for cylindrical geometry. Upper section is not rotating (de-spun) but however lower section is rotating for gyroscopic stability.
- 3-Axis Stabilization : In this strategy active stabilization of three axes is considered. Reaction wheels can be used for that purpose. Accuracy in

pointing is an advantage of this strategy. Disadvantages can be their complexity and extra mass [24].

In this thesis 3-axis stabilization strategy is applied for a single axis. Attitude control by reaction wheel is maintained in each axis by the same manner [21].

Attitude control is an iterative process. That means one output will be used as input in the next step.

Defining of expected disturbance torques is needed for attitude control design as space conditions that Cubesat can deal with. Typical disturbances may be:

- Magnetic torques: It can be induced by residual magnetic moment. It is only related with magnetosphere.
- Solar Radiation: This can be classified as induced by center of mass and solar center of pressure. Reaction wheels can be used to deal with it.
- Gravity Gradient: Force related with extended bodies. (combined vehicles, shuttles)
- Aerodynamic Drag: It is only taken into consideration as a factor in Low Earth Orbit. This is well known term in Aerospace Engineering as “Weathervane Effect”.
- Internal Effects: It is related with equipment such as wheels, pumps, machinery, etc. There is no significant effect to be mentioned for but however inner momentum can affect the attitude.

2.2. Actuators

Actuators are given at the following and detailed description for these are provided afterwards.

- Reaction wheels
- Thrusters
- Magnetotorquers
- Control moment gyros

2.2.1. Reaction wheels: Reaction wheels are mainly used for providing required torque by their rotors with their high inertia. Reaction wheels can turn in both directions. Each axis can be controlled with a reaction wheel [21].

They are useful on Cubesats. Reaction wheels run on electricity and this can be generated by using solar panels of the Cubesat. Reaction wheels can provide high accuracy in attitude control.

Due to their favorable properties, Reaction Wheels are the most popular actuator among the others. As it is mentioned before, in this thesis, Reaction Wheel is chosen for actuator. The Reaction Wheel that we manufactured and used in this study can be seen in Figure 2 as an example.

Figure 2: Reaction Wheel

2.2.2. Thrusters: Thrusters are generating external torque to change the attitude. These are gas jets in which they can create thrust by ejecting propellant. Thrusters can be classified in two categories as cold gas thrusters and hot gas thrusters. Cold gas thrusters can produce thrust by the expansion of the propellant in which it is compressed in the storage tank. This kind of thrust is called as impulse. Hot gas thrusters produce thrust by a chemical reaction. Rocket engines can be a good example for thrusters [16] [17] [18] [19] [20].

A third type of thruster is electrical thruster that differing from other main two categorized thrusters. Electrical thrusters are used for attitude control in special conditions. Propulsion for electrical thrusters are provided by magnetic, electrostatic fields or magnetic fluids to create required reaction force on the space craft [24].

Limitations about the thrusters: they are limited with consumables such as Cold Gas (Freon) or Hydrazine (N2H4). Also they can disrupt orbit determination studies by this limiting factor of it. There can be plumes of discharged matter in which may affect the surface of the spacecraft by heating or contamination [24].

2.2.3. Magnetotorquers: Magnetotorquers are operating by interacting with the earth's magnetic field to provide required torque to rotate the space vehicle. Because of their electromagnets magnetic field disappear when power is extracted from control system. After that torque will be disappeared. Torque rods are providing torque to three axes by their arrangement. Torque rods can be used in systems that reaction wheel is used and in which are stabilized by this way for momentum damping. When reaction wheels are reached to their maximum rotational speed momentum damping may be needed to be performed. Such stored momentum can be damped by the help of the wheels as spinning down or decelerating. By the reason of conversation of angular momentum related body (in our case Cubesat, it can be any kind of spacecraft) will rotate back again to its original attitude (orientation). During momentum damping magnetotorquers are turned on before the reaction wheels are started to spin. By this way a spacecraft can be held in its original attitude (orientation) while reaction wheels decelerate [16] [17] [18] [19] [20] [24].

As it is mentioned above magnetotorquers use the Earth's natural magnetic field and this field reduces while moving from the Earth's center. So that magnetic torquers are less effective at higher orbits [24].

Other disadvantages of magnetotorquers are their lower accuracy than its alternatives in related category and high current.

2.2.4. Control moment gyros: Control moment gyros are similar to the reaction wheels. They both have electric motors in which are used to accelerate the mass. Control moment gyros are single or double gimbaled wheels that are spinning at constant velocity. By rotating the gimbal axis an output torque can be obtained. This torque depends upon the speed of the rotor and rotation rate of the gimbal. The use of control moment gyros needs complex control laws and management of the momentum must be done carefully to avoid saturation of the wheel. Control moment gyros are combining a short life with high cost, power needs and weight.

So that they are generally used only on very large spacecraft and only for certain mission goals in which control moment gyros are absolutely necessary [24].

Due to these considerations they are not chosen as alternative for Cubesat attitude control to reaction wheels. As it is mentioned before Reaction Wheels are chosen due to stabilization by creating torque with the help of rotational dynamics (for every axis and in 3-axis). Also they have high accuracy. Power requirements for the Reaction Wheel can be provided from sun panels of the Cubesats.

2.3. Sensors

Sensors are given at the following and detailed description of them are provided afterwards.

- Gyroscopes
- Magnetometers
- Sun sensors
- Star sensors
- Earth sensors (horizon sensors)
- GPS Receivers

2.3.1. Gyroscopes: Gyroscopes are used for measuring the rotation of the spacecraft in 3 body axes. They are for attitude propagation. This is involving the tracking the changes in orientation from a determined point. By using a gyroscope changes in attitude at a starting point can be measured and by this way attitude information can be taken [16] [17] [18] [19] [20].

Generally gyroscopes are mechanical devices in which has a spinning mass rotating 3 or more axes. Gimbal is the joint part where the rotation is occurred. The rotating mass provides constant angular momentum vector in the spin axis. When spacecraft attitude is changed it can be possible to determine angular changes by the help of the spinning of gimbals [19].

Due to power and mass limitations for Cubesats it is not feasible to use large mechanical gyroscopes. Maybe MEMS (Microelectronic Mechanical Systems) gyroscopes can be used for such purposes. These gyros can give an angular rate output in which is integrated to determine the attitude of the spacecraft. These

MEMS gyros are using a miniaturized piezoelectric oscillating mass. Motion caused by this centrifugal force disturbs the mass and this can be related by angular motion [16] [17] [18] [19] [20].

Despite of their advantages such as low power consumption and miniaturized structure they have the problem known as drift. It is caused by thermal changes in mechanic properties of thermal mass that oscillates over time. This can cause systematic errors.

2.3.2. Magnetometers: Magnetometers are another widely common used sensors due their reliability and simplicity. They can measure both of the directions and Earth's magnetic field. Magnetometers are providing outputs that can help the establishment of spacecraft orientation relative to the local magnetic field. By this way related data can be used with magnetic field models and orbit information in order to determine orientation relative to the inertial reference frames and Earth. But their accuracy cannot compete with other sensors such as star or Earth sensors [24].

A magnetometer is essentially a compass that measures the current direction of the earth's magnetic field. Assuming the spacecraft knows it's location in space, through either an onboard GPS or accurate knowledge of the time and the spacecraft's orbital parameters, the earth's magnetic field can be calculated. As explained before comparing measured magnetic field to calculated field can provide attitude knowledge [16] [17] [18] [19] [20].

2.3.3. Sun sensors: Sun sensors are infrared or visible-light detectors that can measure the angles between their mounted base and sunlight. Sun sensors are popular because of their accuracy and reliability but however they require clear view. So that means if there is eclipse and spacecraft is in that eclipse, sun sensors cannot provide meaningful data [24].

Sun sensors can be either analog or digital devices. Analog sensors have a slit and a photo diode that detects the sun. The output current from the photo diode generally varies with a cosine relationship to the incident angle with the sun. Digital sun sensors contain a slit with an array of photo detectors beneath, with each pixel representing a single digital bit [16] [17] [18] [19] [20].

Sun sensor implementations on CubeSats are often staring type sensors. These sensors normally involve multiple discrete photo diodes on each face of the CubeSat. These photodiodes have overlapping fields of view, and thus overlapping response curves. Comparing the outputs from each sensor on a face mathematically establishes the sun's position. This sensor type was demonstrated on orbit on Boeing's CubeSat Testbed 1 in 2007 [16] [17] [18] [19] [20].

2.3.4. Star sensors: Star sensors are the most common sensors when high-accuracy required for the related mission. Star sensors may be both scanners or trackers.

Scanners can be used for spinning of the spacecraft. Light coming from various stars can pass through multiple slits in the scanner's view. When stars are crossed space vehicle's attitude can be determined [24].

Star trackers are mainly used for tracing one or more than one star to obtain 2 or 3 axis attitude data. Main idea for the design of the star trackers nowadays are similar with digital cameras. So that they are called as *star cameras* [24].

Star sensors are usually used on larger satellites and they are useful. Star sensors can provide a complete attitude determination solution and additional angular rate measurements [16] [17] [18] [19] [20].

Star sensors are very accurate but they must be used properly. In conditions that space vehicle is rotating so fast even the most accurate star cameras cannot obtain a meaningful data [24].

In order to make sure that trackers are operating effectively the related vehicle must be stabilized at first. That means alternate sensors are needed. Because of that total system cost will be increased. If related mission requires highest accuracy than star trackers and gyroscopes combination is generally used [24].

2.3.5. Earth Sensors: Earth sensors are attitude determination sensors. These can work by detecting the presence of the earth in the sensor's field of view [16] [17] [18] [19] [20].

Earth sensors are also named as horizon sensors. They are infrared devices in which can detect the difference between deep space coldness and heat of the atmosphere of Earth. Sensed band can be 40 km above from the surface [24].

Existing earth sensors are generally very large and requires too much power. However, these devices may be appropriate for Cubesat's due to their form. One of the greatest advantage of the Earth sensors is they work independently from the eclipse differing from Sun sensors [16] [17] [18] [19] [20].

2.3.6. GPS Receivers: GPS receivers are known as devices used for navigational purposes. They have high accuracy. But however they can also be used for attitude detection. If a space vehicle is large enough to place multiple antennas that can be separated from each other than attitude can be detected by obtaining the differential signals from separate antennas. These sensors offer lower costs. They can obtain attitude data 0.25-0.5 degrees for antenna baselines on the degree of 1 meter. Due to these they can be used for low accuracy applications or back-up sensors. But related space vehicle must be large enough to place multiple antennas with sufficient separation. So that Cubesats are not the case here [24].

2.4. CONTROL OF CUBESAT

As it is mentioned before, a CubeSat may be needed to be controlled because of the reason why that it may lose its attitude by external disturbances by the space conditions. Another reason is that Cubesat is needed to be oriented into desired positions.

Some controllers that can be used for Cubesat’s control are provided at the following and their brief descriptions are provided afterwards:

- Proportional (P) Controller
- Sliding mode controller
- Proportional Integral (PI) Controller
- Proportional Derivative (PD) Controller
- Proportional Integral Derivative (PID) Controller
- Fuzzy Logic Controller

2.4.1. Proportional (P) Controller:

Proportional Control is complex when compared to on-off control systems but its less complex then PID Controller. It is easiest to implement. Steady state error tends to be in relation with error inversely. So that means when gain is made larger then error goes down [32].

2.4.2. Sliding Mode Controller:

Sliding Mode control is a nonlinear control technique featuring remarkable properties of accuracy, robustness and easy tuning and implementation [33].

There are two main advantages of sliding mode control. First one is that dynamic behavior of the system may be tailored by the particular choice of the sliding function. Secondly, the closed loop response becomes totally insensitive to some particular uncertainties. This principle extends to model parameter uncertainties, disturbance and non-linearity that are bounded [33].

2.4.3. Proportional Integral (PI) Controller:

PI Controller eliminates the forced oscillations and steady state error resulting in operation P controller respectively.

However, using the integral mode has a negative effect on speed of the response and overall stability of the system [32].

As a result of that PI Controller will not increase the speed of response. So that it can be expected that PI Controller does not have means to predict what will happen about error in near future.

2.4.4. Proportional Derivative (PD) Controller:

PD Controller can be chosen because of its stabilizing effect caused by D (derivative). Also there is no negative effect on speed of the response and overall stability of the system, like PI Controller [32].

2.4.5. Proportional Integral Derivative (PID) Controller:

PID Controller has all the necessary dynamics: fast reaction on change of the controller input (D), increase in control signal to lead error towards zero (I) and suitable action inside control error area to eliminate oscillations (P) [32].

2.4.6. Fuzzy Logic Controller:

Fuzzy logic is first proposed by Lotfi Zadeh in 1965. Fuzzy logic is a new approach for soft computing. Too complex or badly defined quantitative terms can be defined by words and/or sentences instead of numbers.

Fuzzy logic firstly proposed for linguistic computing (soft computing) by Lotfi Zadeh but it is started to be used in many branches of science. Control applications are one of that. It is started to be applied in 1990's.

In this thesis Fuzzy Logic Controller is chosen to be used as controller. Fuzzy Logic Controller is chosen because of its less complexity then other controllers. Also its advantage of overcoming the uncertainties caused by the forces that Cubesat is exposed with. Less complexity while studying on non-linearity is another advantage of Fuzzy Logic Controller. Another advantage of Fuzzy Logic Controller is that its power on overcoming with white noise. As a result of these and which are all must be considered in space environment and Cubesat control, Fuzzy Logic Controller is chosen.

2.5. FUZZY LOGIC CONTROLLER

Fuzzy logic is first proposed by Lotfi Zadeh in 1965. Fuzzy logic is a new approach for soft computing. Too complex or badly defined quantitative terms can be defined by words and/or sentences instead of numbers.

Fuzzy logic firstly proposed for linguistic computing (soft computing) by Lotfi Zadeh but it is started to be used in many branches of science. Control applications are one of that. It is started to be applied in 1990's.

In the scope of this thesis fuzzy logic will be applied into a control problem. In this thesis fuzzy logic is used for attitude control for Cubesat. By controlling the speed of the Reaction Wheel attitude control of the Cubesat will be tried to realized. In this thesis Fuzzy Controller will be used.

2.5.1. Theoretical Information About Fuzzy Logic Controller

2.5.1.1. Fuzzy set: Fuzzy set is characterized with membership functions that assign to each element a grade of membership ranging between one and zero. Briefly they are sets that have degrees of membership. Operations for fuzzy sets can be union, intersection, relation, etc.

2.5.1.2. Membership functions: Membership functions are representing the degree of truth with valuation. Degrees of truth means true or false which are defined as 1 and 0. It can be considered as more or less true rather than just simply true or false. Degrees of truth can be confused with probabilities but it is not probability at all.

Fuzzy logic looks like probability at first glance but it is different from probability. As an example for this fuzzy logic says that a man entering into place is tall. He is tall but it is not known that how tall he is. Probability theory says that the man entering place is %70 tall. But he is not tall %30. So that he is not exactly tall but there is probability of %30.

Fuzzy set can provide a point of departure for establishing a cognitive framework which can be used for ordinary sets. Fuzzy sets have wider scope of application especially for pattern classification and information processing. Also this framework can provide ease when dealing with problems that source of imprecision is valid which means there is absence of sharply defined criteria for a class membership and there is presence of random variables is considered.

In recent years, fuzzy logic has started to be used to solve control problems just like methods used by humans. In this thesis fuzzy logic will be applied in control system of the Reaction Wheel.

2.5.1.3. Linguistic Variables: Linguistic variables are linguistic words or objects that are used instead of numbers. The sensor input is a noun such as velocity, speed, displacement and so on. The fuzzy variables are adjectives like “negative” error, “zero” error and so on that modifying the variables.

2.5.1.4. If Then Rules: Fuzzy Logic uses IF X AND Y THEN Z approach to solve problems rather than attempting to model the system mathematically. As an example for this, Fuzzy Logic is not dealing with speed control in terms like “Set Point, SP=20 rpm” or “V<30 rpm”. Fuzzy Logic uses more likely the terms like “IF (speed is too low) AND (speed is getting slower) THEN (the vehicle must increase its speed).

2.5.2. How Fuzzy Logic works? Fuzzy Logic needs numerical parameters to determine significant error and significant rate of change in error. For example a speed control system can use a single feedback sensor whose data is subtracted from the command signal to compute error and differential of error to time as rate of change in error and it is called as error-dot ($\dot{e}$).

2.5.3. Advantages of Fuzzy Logic

- Fuzzy logic is easy to understand: The mathematical background behind fuzzy reasoning is very simple.
- Fuzzy logic is flexible: It is functional that there is no need to start again from scratch.
- Fuzzy logic is based on natural language: It is based on basis of human communication. This underpins many other statements of the other statements about fuzzy logic. Because of its everyday language, fuzzy logic is easy to use.
- Fuzzy logic is tolerant of imprecise data: Everything is imprecise if you look closely enough. Fuzzy reasoning builds this reasoning into the process [25] [26] [27] [28] [29] [30] [31].

CHAPTER 3

THEORY&CONTROL SYSTEM

Reaction wheels are preferred in Cubesat attitude control because of their low energy consumption, torque capacity and high reliability. In spite of all these, Reaction Wheels have some restrictions.

They can be classified in two main groups:

1. Space Environment hazards:
- Fast and high changes in temperature
- Vacuum
- Radiation
2. Launch Requirements:
- Noise
- Vibration
- Chokes

3.1. DESIGN OF REACTION WHEEL AND TESTBED:

3.1.1. Mechanical Design of Reaction Wheel

Two types of reaction wheel systems are designed and manufactured during the studies on this thesis. The first one is designed for light-weight loads with completely electrical feedbacks and the other is designed for heavy loads with electro-optic feedbacks.

The first type of reaction wheel system together with the testbed simulating the floor of the cubesat that is designed and manufactured for this study is shown in Fig.3. The design details of the reaction wheel system are given in Appendix-B. The compact Reaction Wheel system is composed of (1) the brass reaction wheel, (2) the DC Motor (brushed), (3) the motor holder, (4) the plate that representing the Cubesat floor, (5) the plate support, (6) the plate rotation shaft, (7) the bearing of the shaft, (8) the base, (9) the potentiometer for plate position feedback. The rotation speed of the wheel is obtained by a dc generator connected mechanically to the top of the wheel as can be seen in Figure 4.

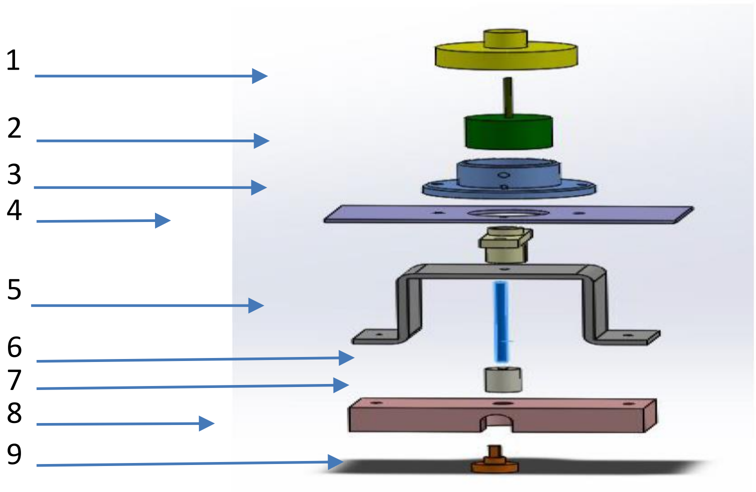

Figure 3: Design of Reaction Wheel and Test bed

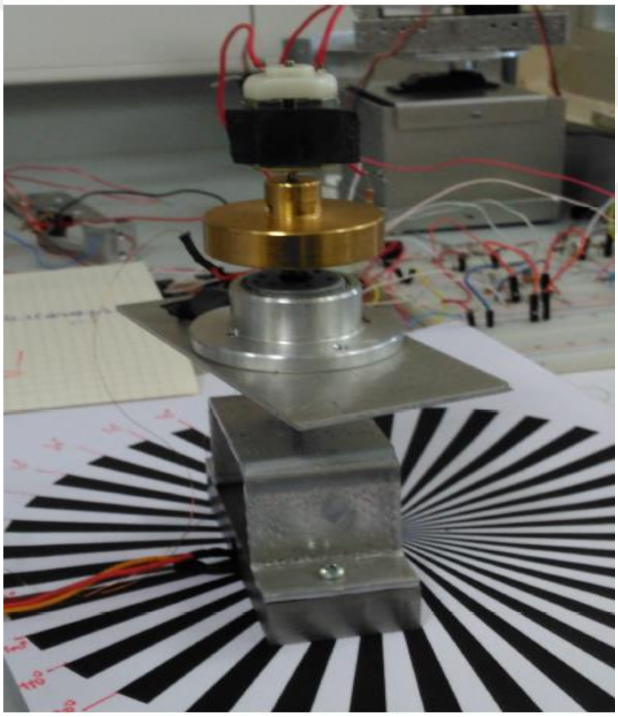

Figure 4: Reaction wheel system used in measurements and tests.

The type with optical encoders is shown in Fig.5 for illustrative purposes. It also operates as we needed. However, we preferred the first type because of the reason that the optical sensors cannot give precise measurements when they are not isolated enough from the environment. Also the resolution of feedback information is not enough for precise control.

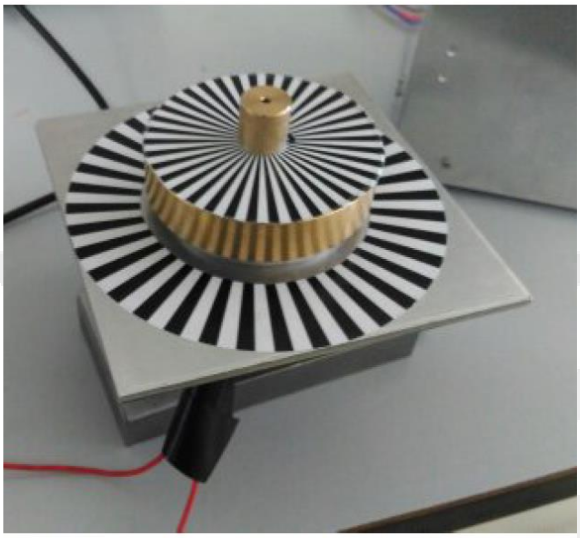

Figure 5: Reaction wheel system with testbed using optical encoders for feedback information.

In the system that we preferred in our study that is shown in Fig. 4, the dimensions are determined based on the standards of the cubesat applications. The parameters of both systems are provided in Table 1.

Table 1: Parameters for test beds

Parameters	Units	System 1	System 2
Mass	gram	39,68	226.93
Diameter(2R)	cm	2	4
Moment of Inertia, J	gcm^2	19,84	453,86
Plate mass and dimensions	cm	10cmx5cm	10cmx10 cm
Power necessary to rotate Reaction Wheel	Watts	0,1	0,33
Torque	mN m	0,4	2,23

3.1.2. Equations for Control of Cubesat:

Cubesat control mainly depends on Newton's law of energy conversation. The law of conversation of energy states at the following:

In a closed system, a system in which is isolated from its surroundings the total energy of the system is conserved.

Rotational kinetic energy can be described by the following formula:

$$\frac{1}{2} J \omega^2 \tag{1}$$

And also angular momentum can be described by the following formula:

$$L = J\omega \tag{2}$$

Energy is conserved and that includes also conversation of angular momentum. From Eq.(1)and Eq.(2), it can be said that when Reaction Wheel rotates in any direction, Cubesat will rotate on the other direction. This is the main idea of using the reaction wheels for attitude control of a Cubesat..

In this thesis Cubesat's control is applied on single axis. Single axis platform (representing the Cubesat) can be considered as an inertia component for disturbance torque and reaction wheel torque. The following relations describes the behavour of the system.

$$J_p\ \dot{\omega} = T_d - T_w \tag{3}$$

$$J_w(\dot{\omega} + \dot{\omega}_w) = T_w \tag{4}$$

$$\dot{\omega} = \frac{Td}{Jp} - \frac{Tw}{Jp} \tag{5}$$

And

$$\dot{\omega}_w = \frac{Tw}{Jr} - \frac{Td}{Jp} \tag{6}$$

Where J_r (mean inertia) is defined as

$$J_r = \frac{Jp\ Jw}{J} \tag{7}$$

The reaction wheel's DC motor characteristics are unknown, there can be a relation between motor torque and applied electric current as given below:

$$T_m = k_m I \tag{8}$$

Kinematics of the single axis platform is very simple and given below:

$$\dot{\theta}_w = \omega_w \tag{9}$$

3.1.3. Mathematical Model for DC Motor Coupled with Reaction Wheel (Load):

The reaction wheel that we implemented uses a permanent magnet dc motor. Fig.6 shows the equivalent circuit for a permanent magnet dc motor.

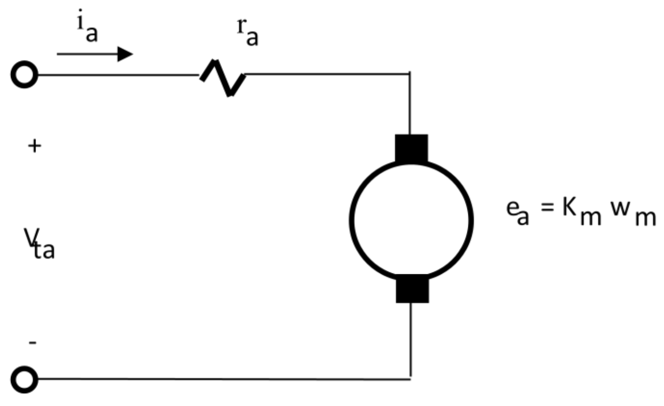

Figure 6: Equivalent circuit of a permanent magnet dc motor.

The closed-loop model for DC Motor coupled with a load (that is, Reaction Wheel) is shown at Figure 7.

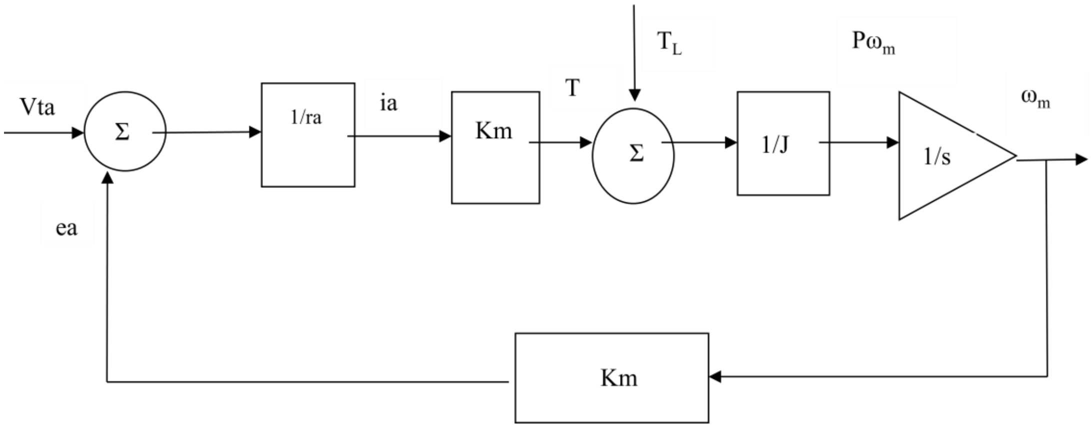

Figure 7: Model of dc Motor with load

As it can be seen in Fig. 7, when voltage is applied to the DC motor coupled with load gives the speed ω_m. The mathematical equations for the variables of the dc permanent magnet dc motor can be written from the equivalent circuit in Fig.6 as in the following:

$$T = K_m \, i_a \tag{10}$$

$$e_a = K_m \, \omega_m \tag{11}$$

$$i_a = (v_{ta} - e_a)/r_a \tag{12}$$

Where $K_m = K_a \, \Phi_d$ is called as the torque constant of the motor and is a function of motor geometry and magnet properties. The torque in Eq.(10) is the mechanical torque. As seen the torque of a permanent magnet motor is given by the product of the torque constant and the armature current.

3.2. CONTROL SYSTEM

The overall system is shown in Figure 8. As it is described in Section 3.1, the reaction wheel system is composed of both reaction wheel and its driving motor and the testbed simulating the cubesat floor. In order to control the attitude of the plate (cubesat's floor), we have to get two feedbacks from the system. One of the feedbacks is the speed of the dc motor, and the other is the position feedback of the plate orientation. The controller is implemented in the laptop by MATLAB with Arduino Mega routines. The controller is a fuzzy logic controller. Arduino Mega is the processor that implement receiving both feedback signals and transmitting PWM signals driving the motor in CW and CCW directions. The position feedback of the plate is received by a potentiometer connected mechanically to the rotating shaft of the plate. The speed feedback of the motor is received by a dc generator connected mechanically to the center of the reaction wheel. The feedback signals are used to calculate the error and the derivative of the error signals by comparing them with the desired set points. The control signal is produced by the fuzzy controller based on the IF THEN RULES linguistically and the output of the fuzzy controller is converted to crisp values (numbers rather than linguistic variables) and also converted into PWM signals. The motor is driven by these PWM signals transmitted from the related outputs of the Arduino processor. These signals are powered by the H-Bridge up to a level of driving the motor and the brass reaction wheel with enough torque. When the motor reaches a reasonable speed level, the plate begins to rotate in reverse direction of the motor. When the plate takes the desired angle, the motor speed is lowered by the fuzzy controller. The plate points the desired target position afterwards.

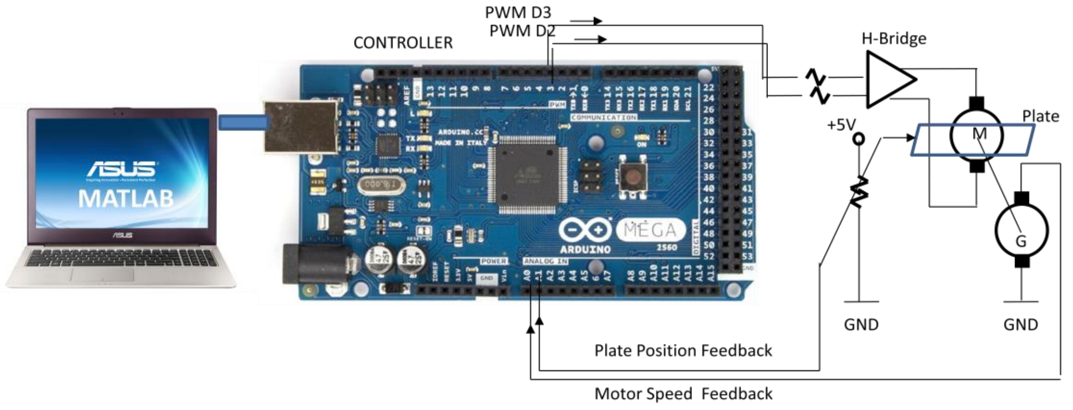

Figure 8: Overall reaction wheel control system

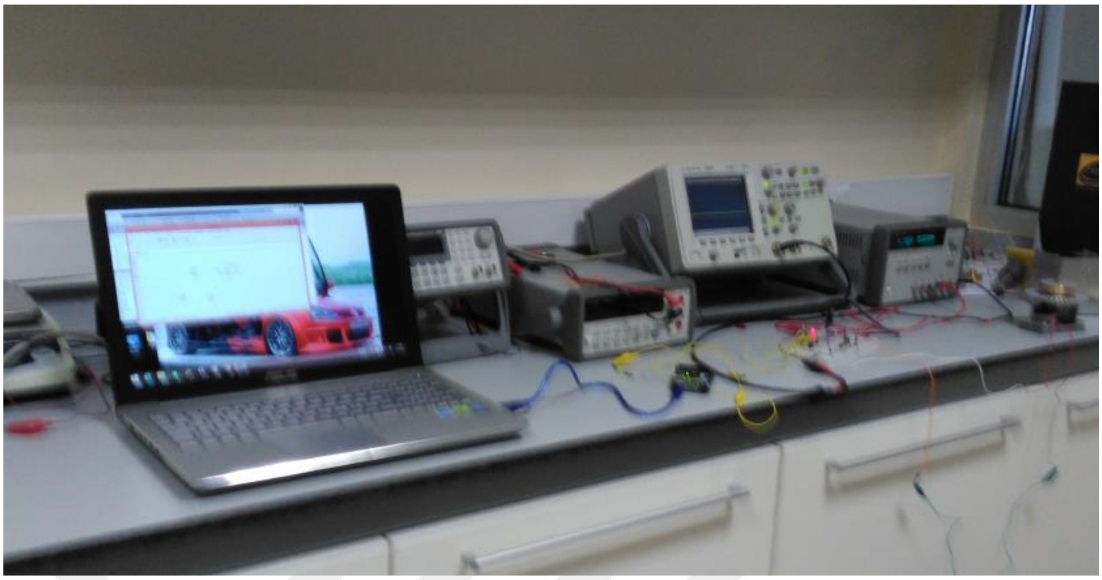

Figure 9: Photo representing the control system

Fig.9 depicts the measurement system established in the laboratory. The variables such as feedback signals and output PWM signals are measured both by the oscilloscope and multi-meter connected to the appropriate terminals. The signals are also displayed in the laptop by MATLAB program.

In the scope of this thesis Arduino is used as microprocessor in our control system. Pulse Width Modulation (PWM) signals are given to the system in accordance with the feedback data (voltage). The well known “duty cycle” is used by combining with Fuzzy Logic.

As lower percentages of duty cycle means the lower value of voltage and higher percentages means higher voltage, in which corresponds to speed of the motor.

The feedback voltage coming from potentiometer provides data for plate’s position, direction and speed. By this way fuzzy rules can be applied in system. Feedback data and Pulse Width Modulation are used together. As an example for a fuzzy rule is as follows:

"If error<0 and error-dot<0 then speed must be LOW."

Here error means difference between desired (commanded) and actual data (feedback data) and error-dot is first derivative of the error signal. Therefore speed must be LOW means that Fuzzy Logic output must be LOW. This means low duty cycle values that corresponds to lower values of output from the system that fed to the motor. Rules for satisfying all conditions of this system are given at the next section. This explanation is only for describing the system in general.

3.2.1. Fuzzy Logic Controller:

Fuzzy Logic Controller is briefly shown in Figure 10. As seen, the fuzzifier stage implements the input membership functions of error and error-dot. The if-then-rules are implemented based on the membership functions. The output is obtained from one of the appropriate if-then-rule and converted into a crisp value by defuzzifier. The linguistic variable obtained as the output such as slower the speed or increase the speed etc. is then converted into a PWM signal with appropriated width. The width of the PWM signal is a percentage called the duty cycle. The details of the fuzzy control are explained in the next section.

Figure 10: General schematic for fuzzy logic controller

3.2.1.1. Fuzzy Control Theory :

The details of the Fuzzy Logic Theory and Fuzzy Control are explained in this section. First of all, the general definitions are given and then the implementation of fuzzy controller is described.

Granularity is an important term to resolve details. Sensory organs have finite abilities. In order to resolve detail, partitioning of objects (points) into granules is necessary.

A granule is an aggregation of objects (points) drawn together by indistinguashibility, similarity, proximity, of function. Perceptions are both fuzzy and granular, in short f-granular. Measurements are crisp and granular, that is, c-granular. Information granularity plays key roles in both human and machine intelligence.

Let's take *age* as a property (variable) and see the meanings of f-granularity and c-granularity. Fig.11 shows the two types of granularities and realted functions.

3.2.1.1.1. Fuzzy Granular (F-granularity)

Perceptions are F-granular. Boundaries of perceived classes are "un-sharp" and the values of attributes are granulated with a granule being a clamp of values (points, objects) drawn together by indistinguishability, similarity, proximity and function.

Linguistic modifiers can be: very, quite, more or less, extremely, essentially, completely, etc.

3.2.1.1.2. Crisp Granular (C-granularity)

Measurements are crispy values. (numerical or c-granular)

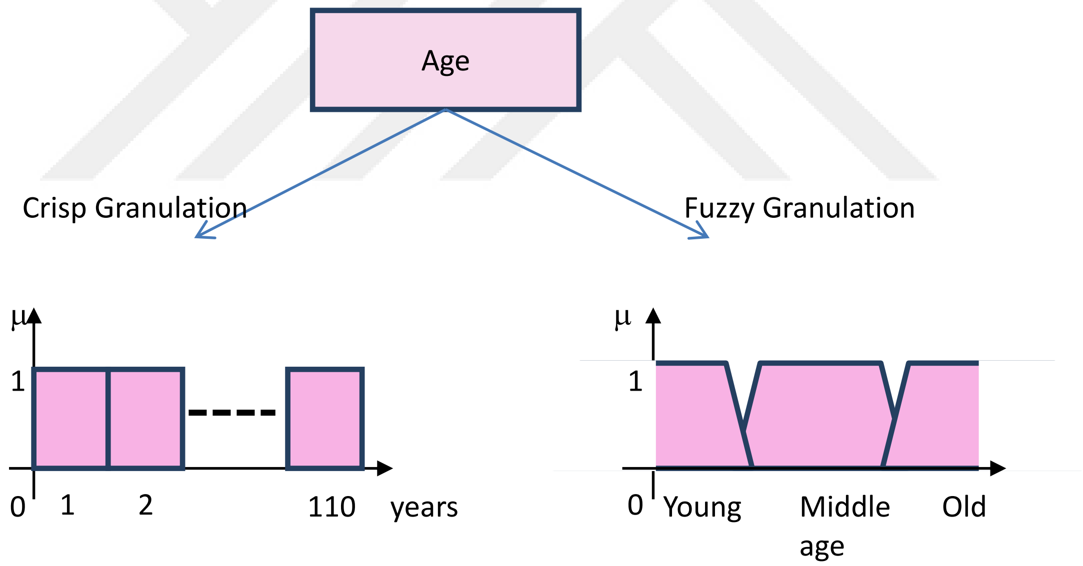

Figure 11: F-granulation and C-granulation

Difference between F-granulation and C-granulation is shown in Figure 11.

The granules can be determined based on the application. In our case, we use slow, no-change, and fast instead of young, middle and old for example. In control systems, the following terms could be used.

- Sensor input is a noun: Temperature, Pressure, Flow, Displacement, etc.
- Error is just the "difference".
- Fuzzy variables are adjectives like:

- Large positive error
- Small positive error
- Zero error
- Small negative error
- Large negative error

3.2.1.1.3. Fuzzy set:

Fuzzy set is characterized with membership functions that assign to each element a grade of membership ranging between one and zero. Briefly they are sets that have degrees of membership. Operations for fuzzy sets can be union, intersection, relation, etc.

3.2.1.1.4. Membership Functions:

Membership functions are representing the degree of truth with valuation. Degrees of truth means true or false which are defined as 1 and 0. It can be considered as more or less true rather than just simply true or false. Degrees of truth can be confused with probabilities but it is not probability at all.

Fuzzy logic looks like probability at first glance but it is different from probability. As an example for this fuzzy logic says that a man entering into place is tall. He is tall but it is not known that how tall he is. Probability theory says that the man entering place is %70 tall. But he is not tall %30. So that he is not exactly tall but there is probability of %30.

Fuzzy set can provide a point of departure for establishing a cognitive framework which can be used for ordinary sets. Fuzzy sets have wider scope of application especially for pattern classification and information processing. Also this framework can provide ease when dealing with problems that source of imprecision is valid which means there is absence of sharply defined criteria for a class membership and there is presence of random variables is considered.

In recent years fuzzy logic has started to be used to solve control problems just like methods used by humans. In this thesis fuzzy logic will be applied in control system of the Reaction Wheel.

An example for Error membership function is given in Figure 12.

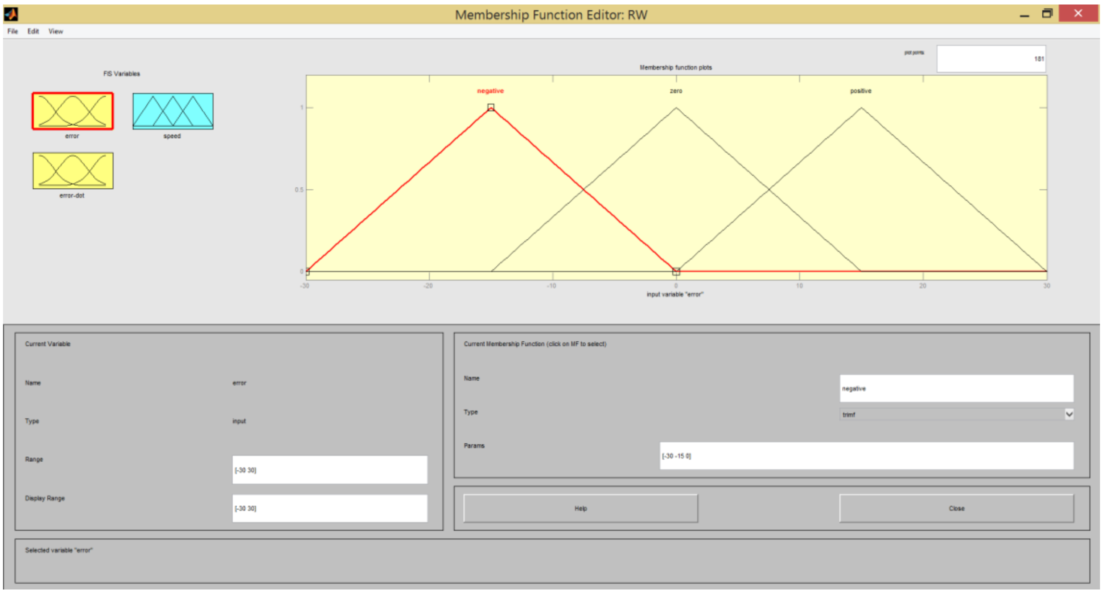

Figure 12: Example for Error Membership Function

3.2.1.1.5. Linguistic Variables:

Linguistic variables are linguistic words or objects that are used instead of numbers. The sensor input is a noun such as velocity, speed, displacement and so on. The fuzzy variables are adjectives like “negative” error, “zero” error and so on that modifying the variables.

3.2.1.1.6. If Then Rules

Fuzzy Logic uses IF X AND Y THEN Z approach to solve problems rather than attempting to model the system mathematically. As an example for this, Fuzzy Logic is not dealing with speed control in terms like “Set Point, SP=20 rpm” or “V<30 rpm”. Fuzzy Logic uses more likely the terms like “IF (speed is too low) AND (speed is getting slower) THEN (the vehicle must increase its speed).

3.2.1.2. Use of Fuzzy Logic in Control

Fuzzy Logic can be used in control with several steps as indicated at the following:

1) Define control objectives.
2) Determine input and output relationships and choose a minimum number of variables for input to the Fuzzy Logic Controller (as in Figure 10). Typically it can be error (e) and error-dot ($\dot{e}$).
3) Break the control problem into a series of IF X AND Y THEN Z rules.

4) Create the Fuzzy Logic Controller Membership functions that define the meaning (values) of I/O terms used in the rules.
5) Create the necessary pre- and post- processing Fuzzy Logic routines.
6) Test the system.
7) Evaluate the results.
8) Tune the rules and membership functions.
9) Retest the system until satisfactory results are obtained.

3.2.1.3. The Rule Matrix (Rule Structure):

The fuzzy parameters of error (command-feedback) and error-dot (rate-of-change-of-error) were modified by the adjectives "negative", "zero", and "positive". To picture this, imagine the simplest practical implementation, a 3-by-3 matrix. The columns represent "negative error", "zero error", and "positive error" inputs from left to right. The rows represent "negative", "zero", and "positive" "error-dot" input from top to bottom. This planar construct is called a rule matrix. It has two input conditions, "error" and "error-dot", and one output response conclusion (at the intersection of each row and column). In this case there are nine possible logical product (AND) output response conclusions.

Table 2: Rule Matrix (Rule Structure)

Error-dot \ Error	**NEGATIVE**	**ZERO**	**POSITIVE**
NEGATIVE	LOW	HIGH	HIGH
ZERO	LOW	NO CHANGE	HIGH
POSITIVE	LOW	LOW	HIGH

In Fuzzy Logic, membership functions must be designed for controller as a first step. The membership function is a graphical representation of the magnitude of each input. Membership functions are in process by associating with each of inputs as overlapping with inputs and output response is determined by this way for the Fuzzy Logic Controller. Membership functions used within the scope of this thesis are provided at the following:

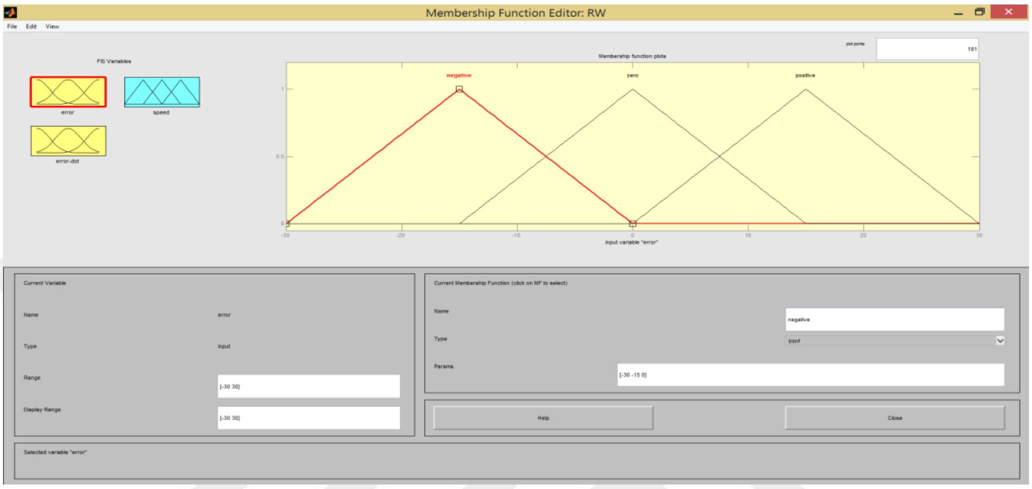

Figure 13: Membership functions-Error

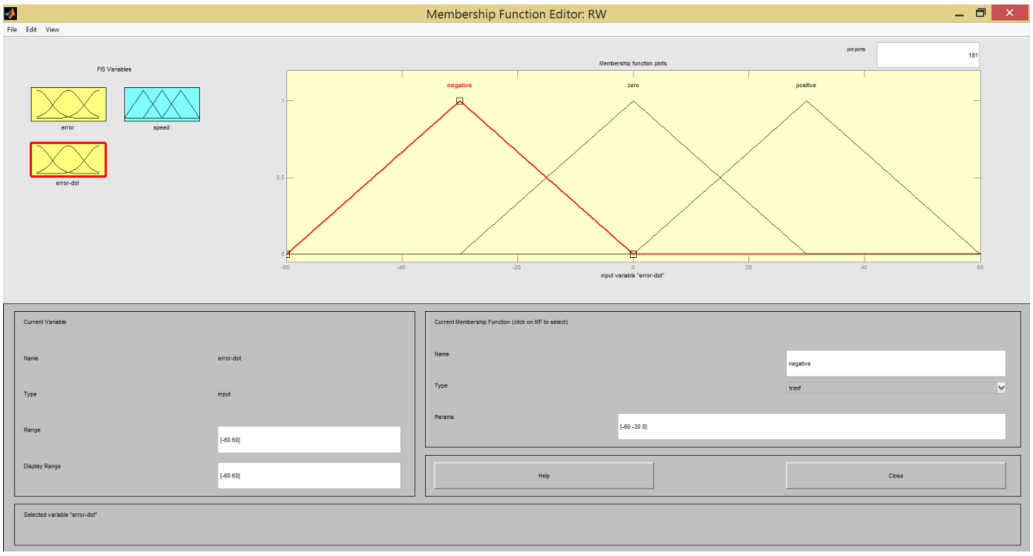

Figure 14: Membership functions-Error dot

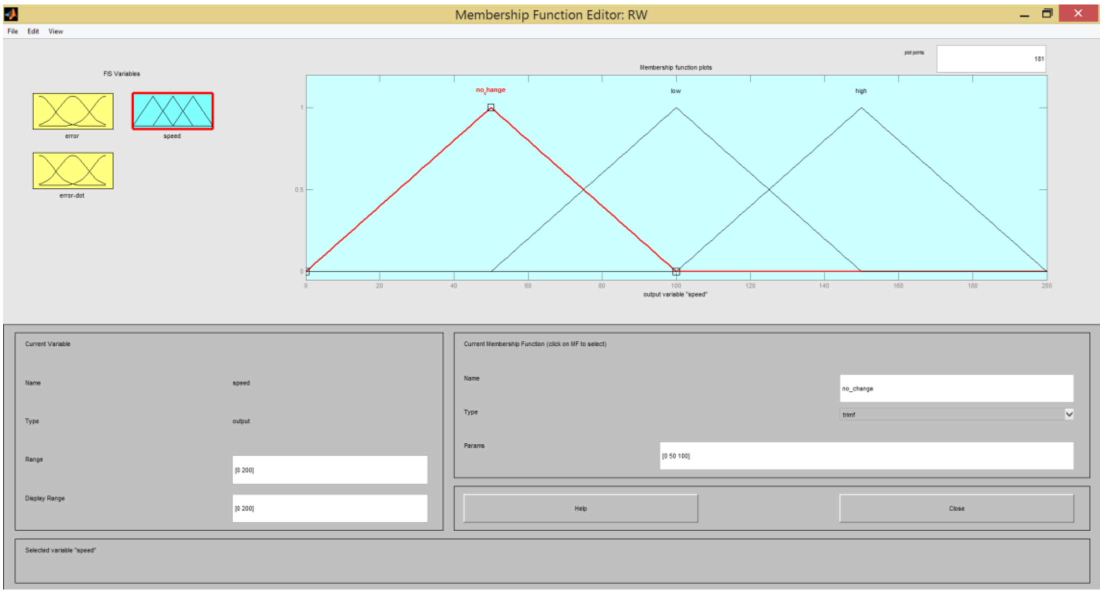

Figure 15: Membership function-speed

As it can be obtained from Table 2, Fuzzy Logic Rules Ri's, i=1,2, …,9 are given at the following:

1. If error<0 and error-dot<0 then speed must be LOW. (R1)
2. If error=0 and error-dot<0 then speed must be HIGH. (R2)
3. If error >0 and error-dot<0 then speed must be HIGH. (R3)
4. If error <0 and error-dot=0 then speed must be LOW. (R4)
5. If error =0 and error-dot=0 then speed is NO CHANGE (no change in speed).(R5)
6. If error >0 and error-dot=0 then speed must be HIGH. (R6)
7. If error <0 and error-dot>0 then speed must be LOW. (R7)
8. If error =0 and error-dot>0 then speed must be LOW. (R8)
9. If error >0 and error-dot>0 then speed must be HIGH. (R9)

These rules are used by input membership values to determine how fuzzy output sets will be influenced and final output is concluded. Once these functions are resulted, scaled and combined they are defuzzified to crisp values that driving the controlled system.

3.2.1.4. INFERENCING

There are several inference methods:

- MAX-MIN method that selects the highest one.
- MAX-DOT or MAX-PRODUCT method, scales each membership function.
- AVERAGING method
- ROOT-SUM-SQUARE (RSS) Method: combines the effects of all applicable rules, scales the functions at their respective magnitudes and computes the "fuzzy" centroid of the composite area.

3.2.1.5. DEFUZZIFICATION-CRISP NUMBERS

RSS Method is chosen to inference. The respective output membership strengths (range:0-1) from the possible rules (R1-R9) are :

Negative "low" = (R1^2+R4^2+R7^2+R8^2)^0.5 (slowing) (13)

Zero "no-change"=(R5^2)^0.5 (no change) (14)

Positive "high" = (R2^2+R3^2+R6^2+R9^2)^0.5 (accelerating) (15)

Every rule is chosen that effecting the related case in accordance with their effect. In accordance with the case related rules are used and taken into account.

Example: error=20

Negative= (R1^2+R4^2+R7^2+R8^2)^0.5 =(0.00^2+0.00^2+0.00^2+0.00^2)^0.5 =0

Zero= (R5^2)^0.5= (0.00^2)^0.5=0

Positive= (R2^2+R3^2+R6^2+R9^2)^0.5

= (0.5^2+0.5^2+0.5^2+0.5^2)^0.5= 1

3.2.1.6. A FUZZY CENTROID ALGORITHM

The defuzzification of the data into a crisp output is accomplished by combining the results of the inference process and then computing the “fuzzy centroid” of the area.

The weighted strengths of each output member function (0.5, 0.866 and 0) are multiplied by their respective output membership function center points and summed.

Finally this area is divided by the sum of weighted member function strengths and the result is taken as the crisp output.

$$Output = \frac{(neg_{center} * neg_{strength} + zero_{center} * zero_{strength} + pos_{center} * pos_{strength}}{(neg_{strength} + zero_{strength} + pos_{strength})} \quad (16)$$

The output is converted to a duty cycle of PMW signal as follows:

$$Duty\ Cycle = \frac{Output}{255} * 100 \quad (17)$$

3.2.1.7. Implementation of Fuzzy Logic Control

The controller is implemented in the laptop by MATLAB with Arduino Mega routines. The Simulink implementation for the reaction wheel system controller is shown in Fig.16. MATLAB uses Ardunio routines such as reading feedback signals from potentiometer and the dc generator. It also realizes fuzzy control membership functions. The fuzzy controller needs error and the derivative of error signals to produce the fuzzy rules. As it is explained before, there are nine fuzzy rules for controlling the system. MATLAB calculates the crisp fuzzy output and convert it to the duty cycle value of the PWM driving signals. The interface between the MATLAB and the reaction wheel system is an Arduino Mega processor. The PWM signals are transmitted from the PWM pins of the Arduino Mega to the H-bridge that it drives the motor with enough power. MATLAB Simulink has some advantages to monitor the input/output signals both in values and shapes through its visual displays on the laptop screen.

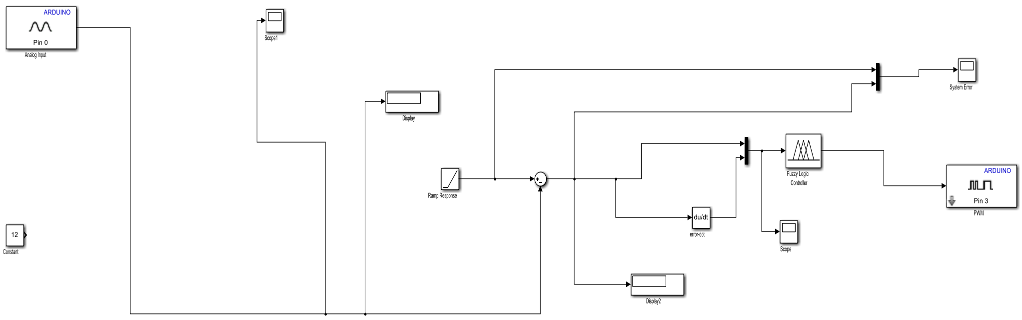

Figure 16: Simulink implementation for the system controller

During experimental studies we have tried to obtain the control of the plate by means of position (angle), speed and direction. For this brushed DC Motor Control is applied. Speed and direction control is maintained for motor. Plate (representing the Cubesat) is turning the reverse direction of the Reaction Wheel. In accordance with the voltage applied to motor it gets faster and slower.

To control the voltage applied to the motor, Pulse Width Modulation (PWM) is used. Pulse Width Modulation signals are provided from Fuzzy Logic Controller for every related case. As a well known concept, Pulse Width Modulation is a system that depends on production of waves in accordance with the voltage needed for the related case. Width of the pulses is directly proportional to the related command loop. The PWM signal is a kind of signal composed of pulses with duty cycles corresponding to the average value of the overall signal. The applied PWM signal to an analog motor rotates the motor based on the duty cycle. The motor sees the average value of the signal and rotates as if a dc voltage equal to the PWM signal average value applied to it. In this case this is the voltage applied to the motor.

As examples, Fig.17 and Fig.18 depict the oscilloscope screens giving PWM outputs for different Duty Cycles that corresponds to voltage in which are applied to the motor. Fig.17 shows a PWM signal with 20% duty cycle and Fig.18 shows a PWM signal with 56% duty cycle respectively.

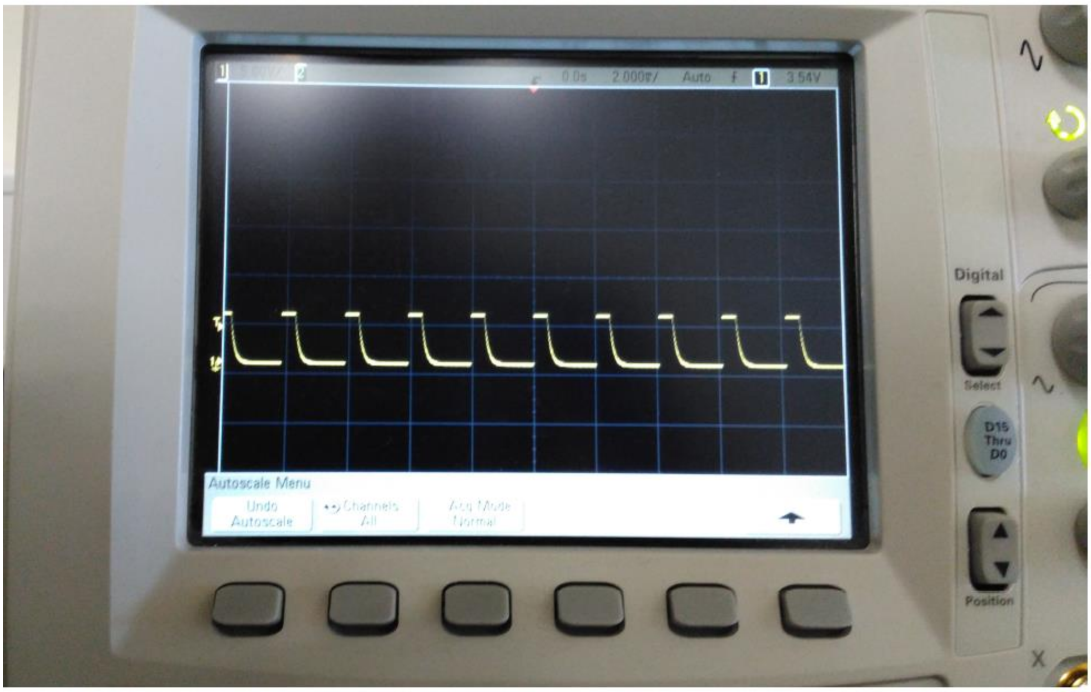

Figure 17: Scope output for 22% duty cycle

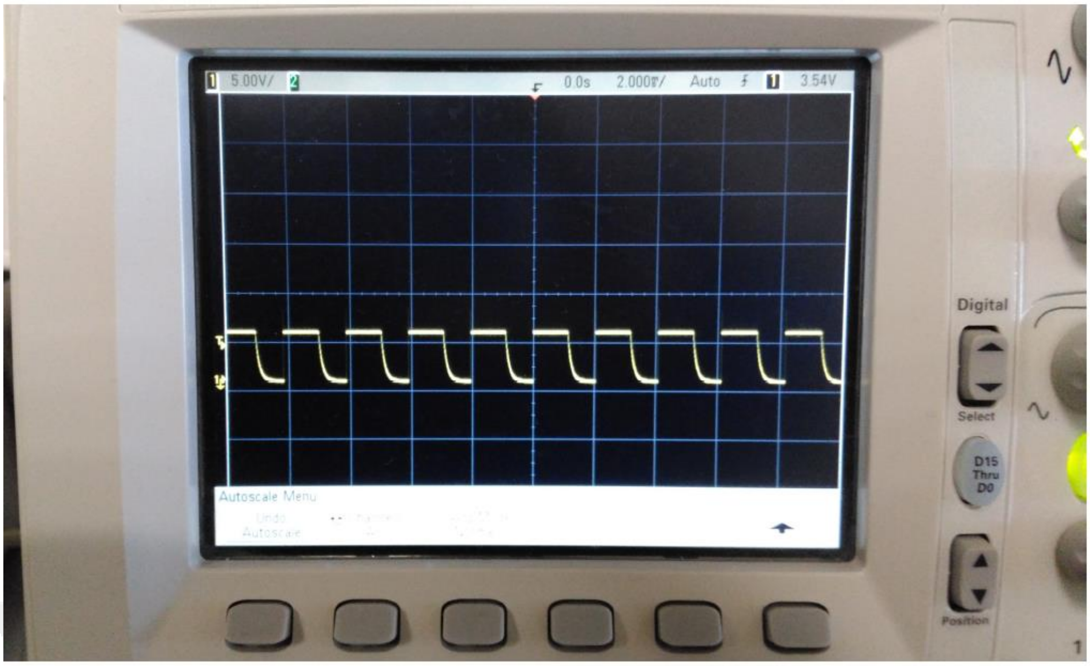

Figure 18: Scope output for 56% duty cycle

By using Pulse Width Modulation (PWM), the Fuzzy Logic Controller can control the plate (representing the Cubesat) in accordance with the inputs (error and error-dot). Because Fuzzy Logic Controller can decide in accordance with the error value in which is the difference of desired and actual values and it can determine the output signals in accordance with the error and error-dot values. Scope outputs for different values of error and error-dot values are submitted at the following:

- Case 1: In this case error=0 and error-dot>0. Because of that reason related rule is applied by the Fuzzy Logic Controller as designed in previous section. In this case following rule is applied by the Fuzzy Logic Controller:

“If error =0 and error-dot>0 then speed must be LOW.”

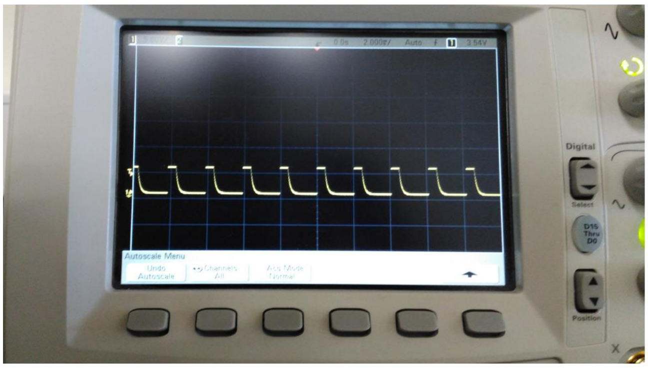

Figure 19: Scope output for Case 1

- Case 2: In this case error>0 and error-dot>0. Following rule is applied by the Fuzzy Logic Controller:

"If error >0 and error-dot>0 then speed must be HIGH."

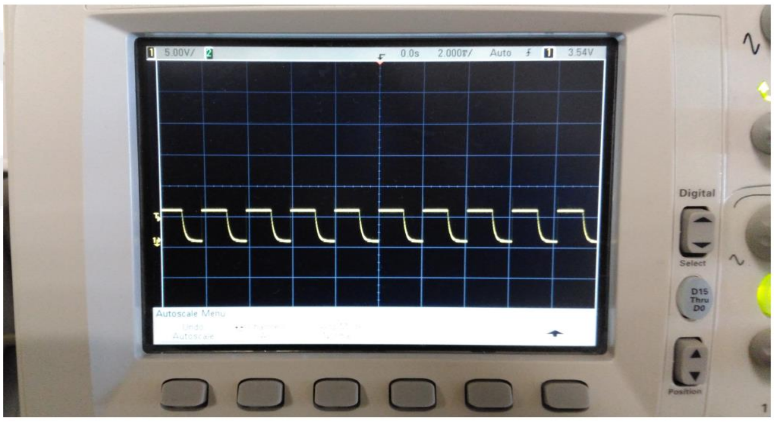

Figure 20: Scope output for Case 2

3.2.1.8. Discussion on System Responses

Before giving the experimental resuls in Chapter 4, it is better to discuss some of the observations on controlling the reaction wheel system here. As it is given in mathematical model and physical descriptions of the system, there are some frictional forces acting on the system working in Earth's environment. However, as it is a well known fact that, there is no friction on cubesat in space environment. A cubesat moves on an orbit passing thorough a vacuum condition. So when our tests are considered about the Reaction Wheel plus the plate representing the Cubesat system, it is important to consider this situation. We tested the system by two different test inputs. One of them is a step input representing a sudden change in forces applied to the cubesat and the other is the ramp input representing gradually changing forces applied to it.

When step function is applied to system, there is a sudden movement of the plate. It rotates immediately and stuck to the maximum ending of the potentiometer. Optimal value for applied voltage here is 2,75 V. This situation is an undesired condition in space since the movement of the system is very fast and sudden, despite of the friction. This undesired and sudden movement of the plate is found inconvenient. Because of this reason we decided to apply a ramp function to adjust the position of the plate to the desired position.

Details about system response and comparison for step and ramp function will be provided in next chapter, Experimental Results section.

CHAPTER 4

EXPERIMENTAL RESULTS

In this chapter, we give the experimental results on our study. During the experiments, we utilized the sensors to measure the inputs and responses. There are mainly two sensors giving the data on the system namely a potentiometer that is used to obtain the position angle of the plate representing the floor of the cubesat, and a dc generator giving the rotation speed of the reaction wheel. Both quantities obtained from the sensors are in volts. The characteristics of the potentiometer and the dc generator are given in Fig.21 and 22 respectively.

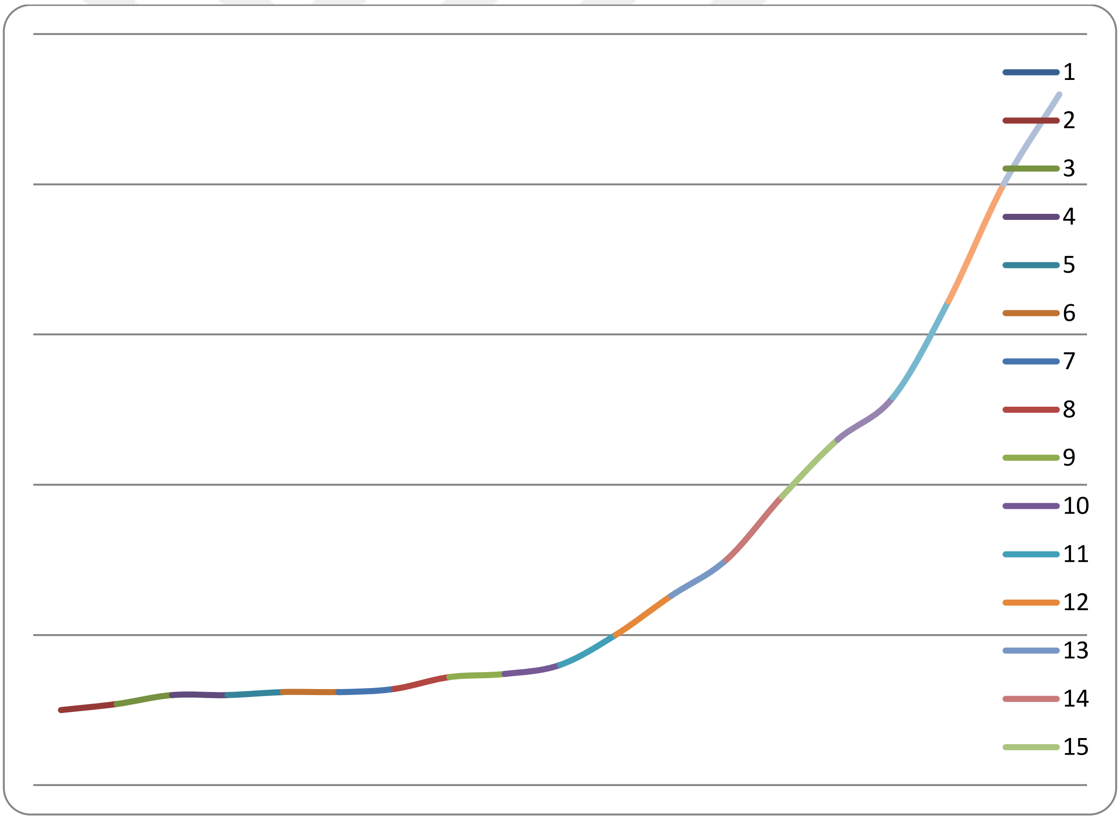

Figure 21: Potentiometer Degree vs mV characteristic

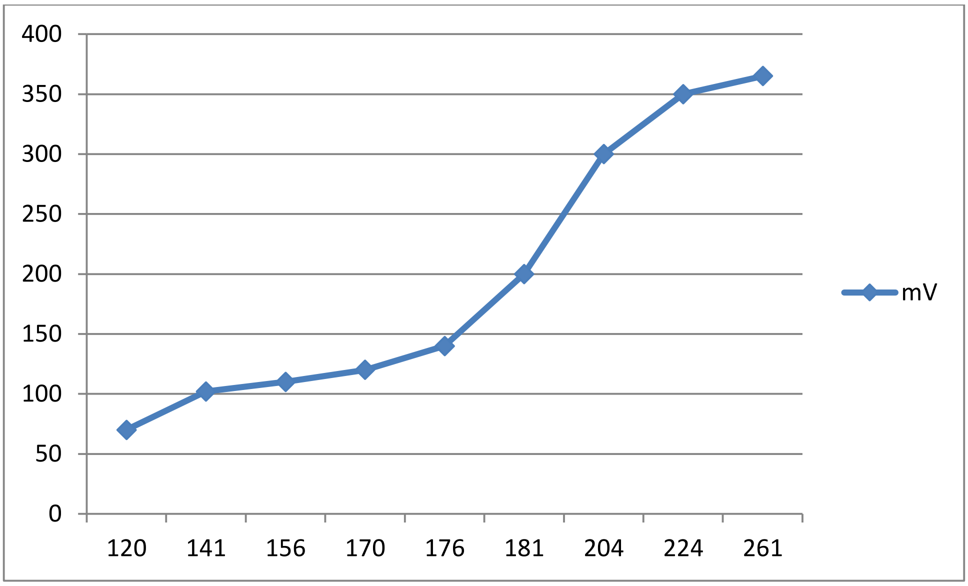

Figure 22: DC generator rpm vs mV characteristic

4.1. Experimental Results

In this frictional environment following system responses are obtained:

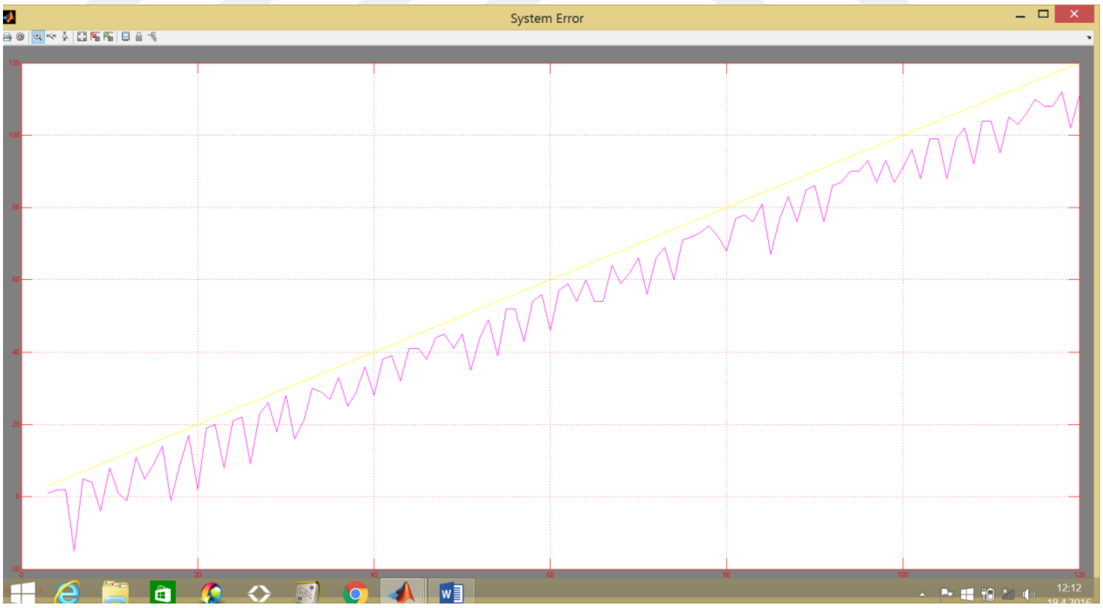

Figure 23: System response for ramp function

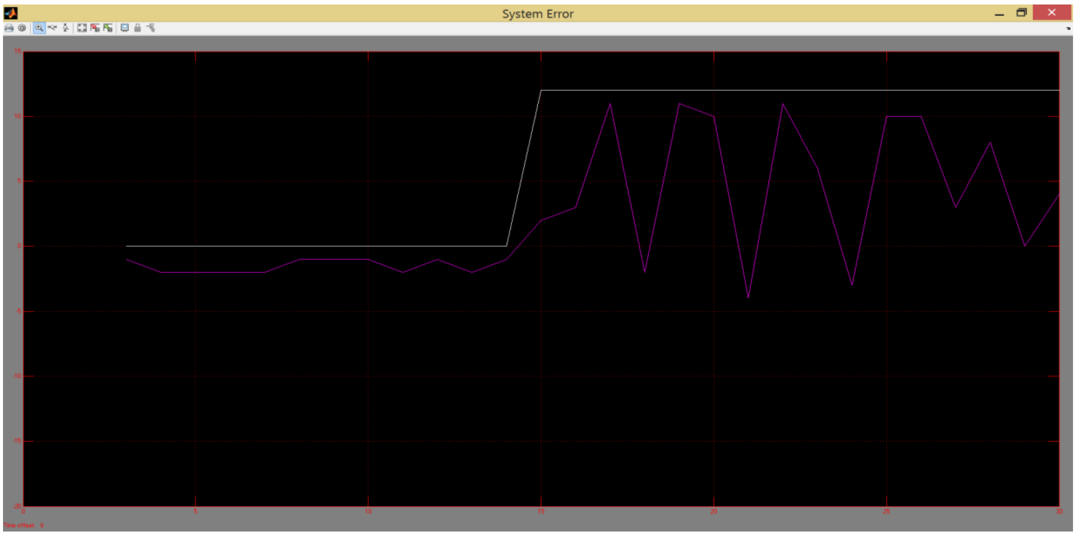

Figure 24: System response for step function

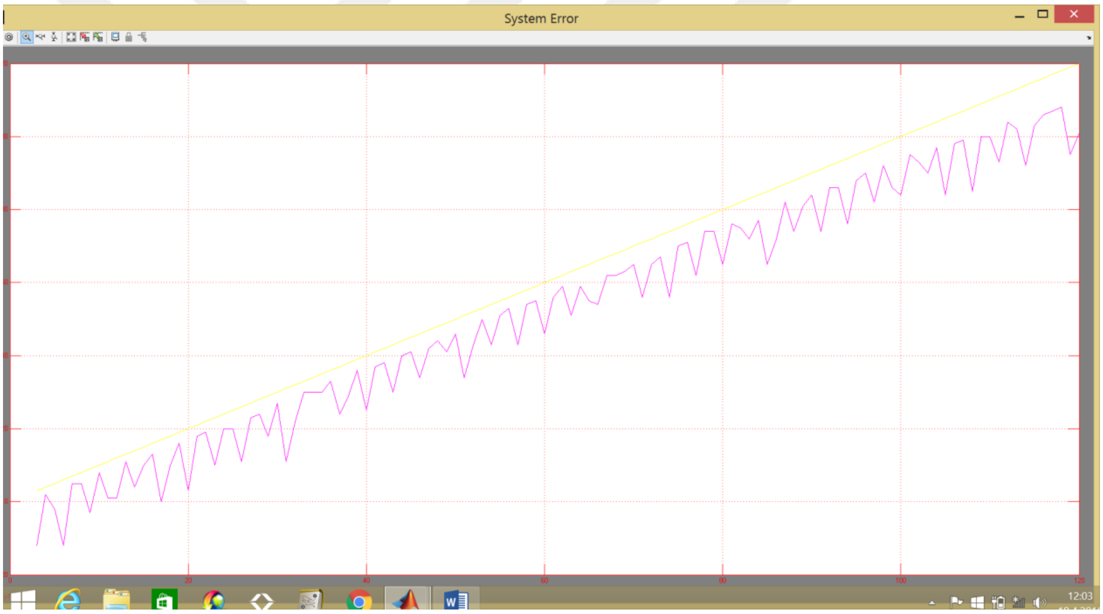

Figure 25: System response for ramp function

In Figure 23 and Figure 24 step function is applied to the system. Approximately 15-20 degrees of error is obtained.

In Figure 25 ramp function is applied to the system. Approximately 3 to 5 degrees of error is found.

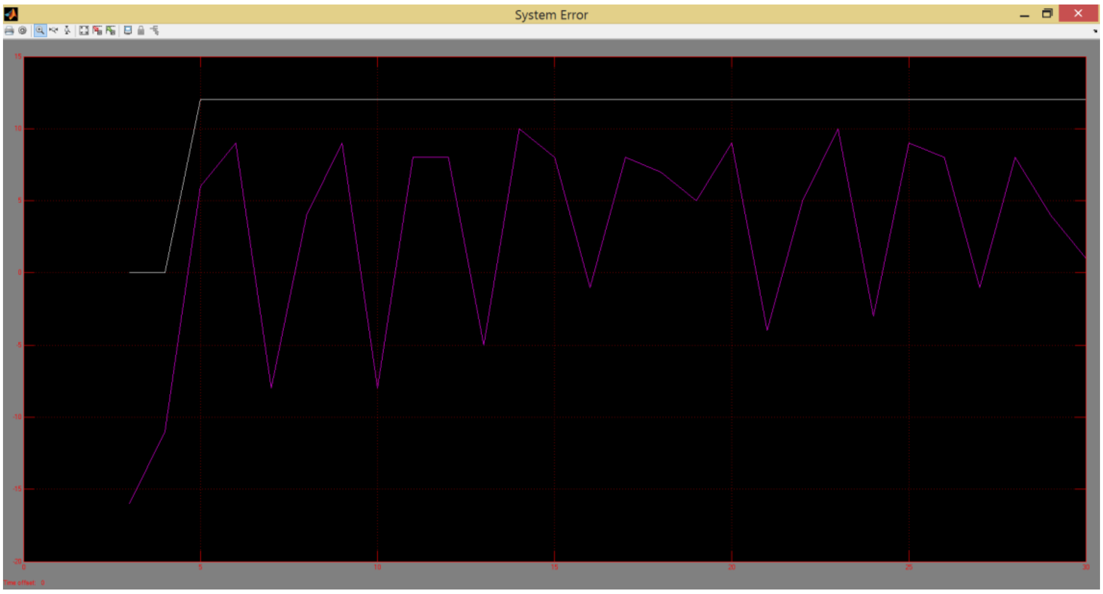

Figure 26:System response for step function

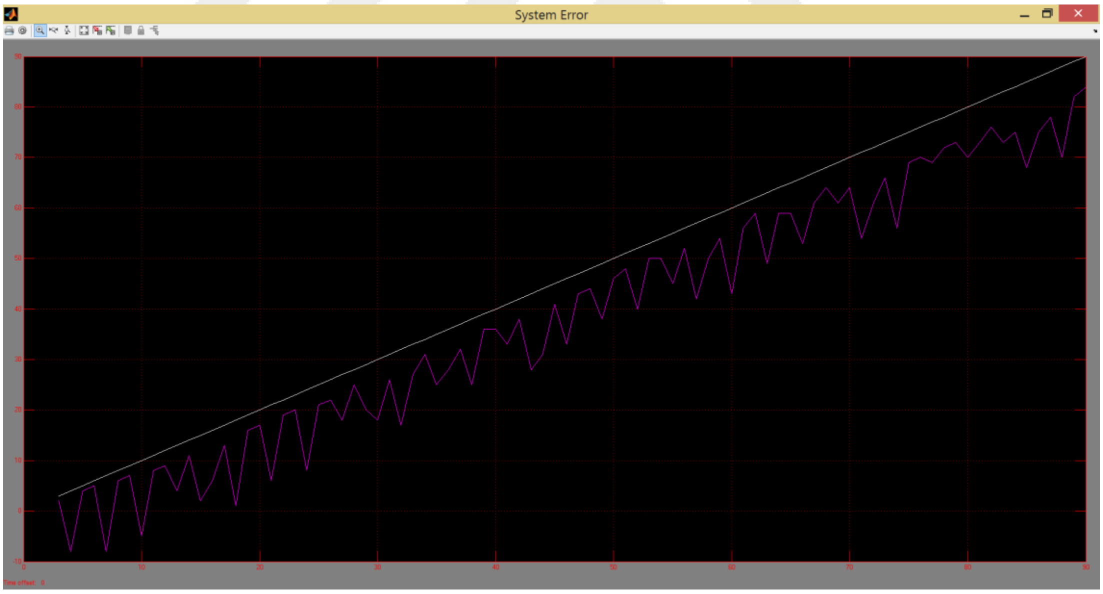

Figure 27:System response for ramp function

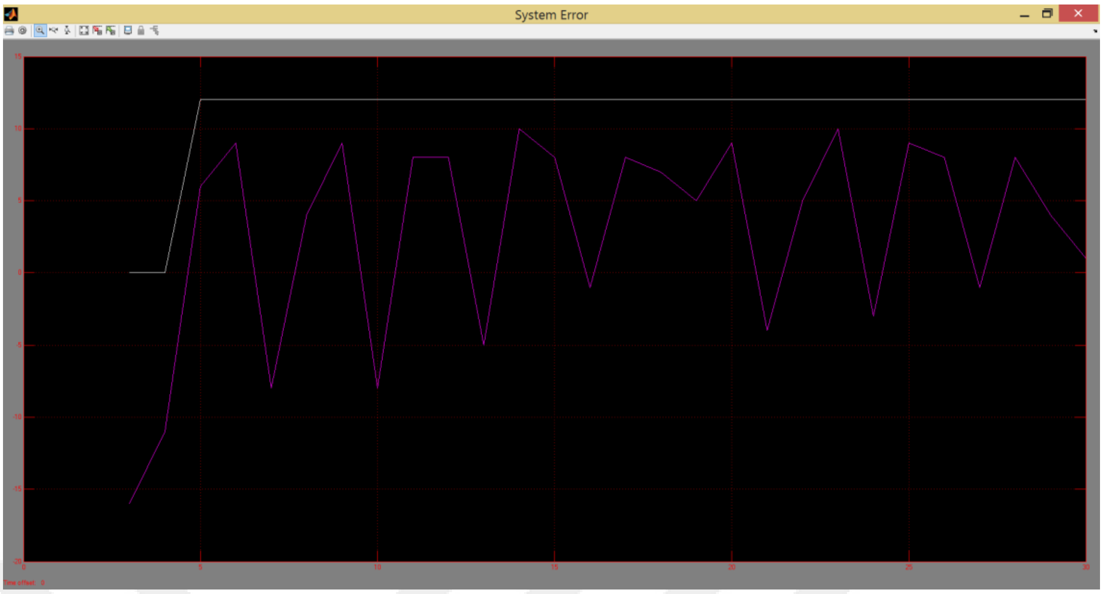

Figure 28:System response for step function

In Figure 26 and Figure 28, step function is applied to the system and nearly 15-20 degrees of error is found. In Figure 27 ramp function is applied to the system and nearly 3-5 degrees of error is found.

Results obtained from step function worse than the others obtained from ramp response of the system. Error for step response is approximately 15-20 degrees and on the other hand error for ramp function is approximately 3-5 degrees.

,

CHAPTER 5

DISCUSSION

In the scope of this thesis our aim is to provide attitude control of Cubesat in single axis by Fuzzy Logic Controller. As it is described in previous chapters Attitude Correction Due to External Disturbance and Attitude Correction to Commanded Position are tried to be realized.

These two are almost the same thing but they are defined separately. Because in application for usage of Reaction Wheel in space these are two different problems for a Cubesat in which may occur.

When attitude correction to commanded position is considered, it can be explained with a Cubesat that takes a photo from space. In this time Cubesat's attitude can be commanded as needed for that purpose.

On the other hand, when attitude correction due to external disturbance is considered it can be explained by another example. Cubesat's attitude can be changed in space due to space environment. This is not desired. So attitude correction may be needed due to these external disturbances. Because of that reason, again Cubesat's attitude can be commanded as needed for another purpose. As a result of that they are defined as two different aims, due to different purposes. In order to prevent confusion, this explanation is considered necessary.

PID Controller is widely used in many control applications and it is well known. Fuzzy Logic Controller is a new concept in Control Engineering applications and it is started to be applied on control problems in 1990's. However, despite of all Fuzzy Logic Controller is chosen within the scope of this thesis. The main reason is same quality control is obtained with less complexity. In this thesis Fuzzy Logic Controller is chosen to be used as controller. Fuzzy Logic Controller is chosen because of its less complexity then other controllers. Also its advantage of overcoming the uncertainties caused by the forces that Cubesat is exposed with. Less complexity while studying on non-linearity is another advantage of Fuzzy Logic

Controller. Another advantage of Fuzzy Logic Controller is that its power on overcoming with white noise. Fuzzy Logic Control method is relatively new method but despite of all it provides more advantages for further improvements. So that it is chosen as Controller for this thesis.

In accordance with the experimental results that given above system responses for step and ramp function can be compared. These experiments are in frictional environment and as it is well known there is no friction in space.

When the results above are considered system error can be seen for both of these functions. It is changing between 10-15 degrees for step function and 3-5 degrees for ramp function. Also during experimental studies there is a fast and sudden movement is observed for step function. This is undesired in space. It increase the error in angle and lowering the control quality, despite of the frictional environment. When space condition is considered and it is a frictionless environment these results will become worse. As a result of all system response for step function is undesired.

On the other hand results obtained for ramp function are more desirable. Because error is lowered and control quality is higher when compared to step function results. When our purpose is also considered and frictionless environment is kept in mind, ramp function response is found more accurate. Therefore it is found that ramp response of the system is better.

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Udit Narayan Student of BE, TIEIT, BHOPAL, MP
Akash Verma Student of BE, TIEIT, BHOPAL, MP

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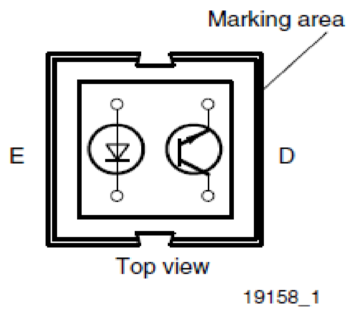
APPENDICES

APPENDIX A

DATASHEETS OF EQUIPMENTS

CNY 70 SENSOR



DESCRIPTION

The CNY70 is a reflective sensor that includes an infrared emitter and phototransistor in a leaded package which blocks visible light.

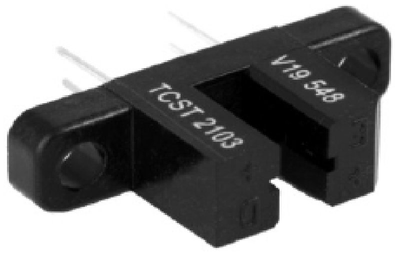
FEATURES

- Package type: leaded
- Detector type: phototransistor
- Dimensions (L x W x H in mm): 7 x 7 x 6
- Peak operating distance: < 0.5 mm
- Operating range within > 20 % relative collector current: 0 mm to 5 mm
- Typical output current under test: I_C = 1 mA
- Emitter wavelength: 950 nm
- Daylight blocking filter
- Lead (Pb)-free soldering released
- Material categorization: For definitions of compliance please see www.vishay.com/doc?99912

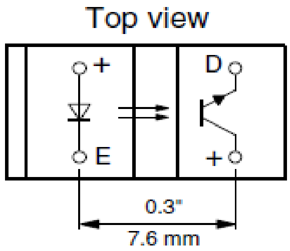
APPLICATIONS

- Optoelectronic scanning and switching devices i.e., index sensing, coded disk scanning etc. (optoelectronic encoder assemblies).

TCST 2103 SENSOR



19180_4



19180_3

DESCRIPTION

The TCST2103, TCST2202, and TCST2300 are transmissive sensors that include an infrared emitter and phototransistor, located face-to-face on the optical axes in a leaded package which blocks visible light. These part numbers include options for aperture width.

FEATURES

- Package type: leaded
- Detector type: phototransistor
- Dimensions (L x W x H in mm): 24.5 x 6.3 x 10.8
- Gap (in mm): 3.1
- Typical output current under test: I_C = 4 mA (TCST2103)
- Typical output current under test: I_C = 2 mA (TCST2202)
- Typical output current under test: I_C = 0.5 mA (TCST2300)
- Daylight blocking filter
- Emitter wavelength: 950 nm
- Lead (Pb)-free soldering released
- Compliant to RoHS directive 2002/95/EC and in accordance to WEEE 2002/96/EC

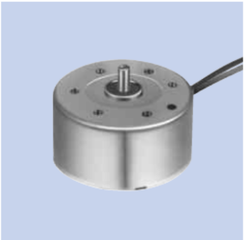
APPLICATIONS

- Optical switch
- Photo interrupter
- Counter
- Encoder

MABUCHI MOTOR RF-300CA

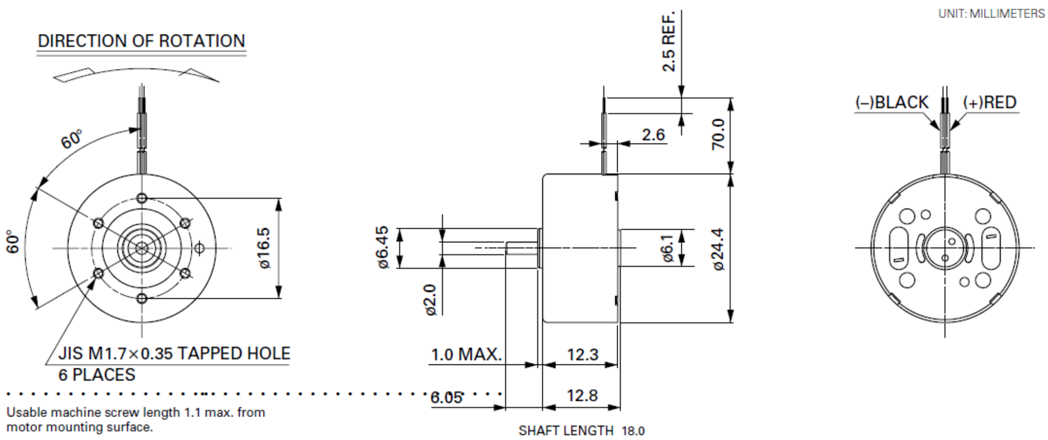
OUTPUT: APPROX 0.1W~0.5W *Precious metal-brush motors*

Typical Applications **Audio and Visual Equipments** : CD Player / Headphone Stereo / Car CD Player / DVD Player
Office Automation Equipments : CD/DVD-ROM Drive



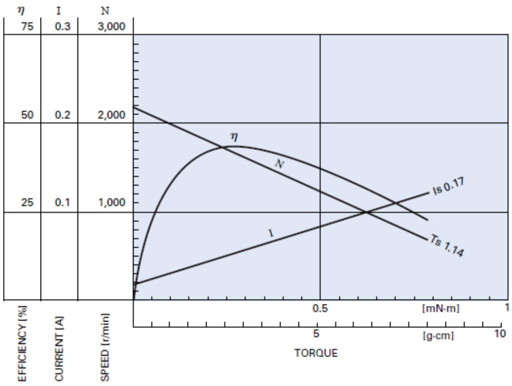
MODEL	VOLTAGE		NO LOAD		AT MAXIMUM EFFICIENCY					STALL		
	OPERATING RANGE	NOMINAL	SPEED	CURRENT	SPEED	CURRENT	TORQUE		OUTPUT	TORQUE		CURRENT
			r/min	A	r/min	A	mN·m	g·cm	W	mN·m	g·cm	A
RF-300CA-11440	0.7 ~ 5.0	2V CONSTANT	2200	0.018	1660	0.055	0.28	2.9	0.049	1.14	12	0.17
RF-300CA-11400	1.2 ~ 6.0	3V CONSTANT	3700	0.018	2970	0.073	0.38	3.8	0.12	1.91	20	0.30
RF-300CA-09550	1 ~ 6	3V CONSTANT	2700	0.012	2100	0.042	0.27	2.8	0.060	1.24	13	0.15
RF-300CA-14270	0.5 ~ 4.0	1.9V CONSTANT	3500	0.032	2740	0.12	0.38	3.9	0.11	1.76	18	0.42

*High temperature specification motor is also available.
*Also available with terminals (without leadwires).

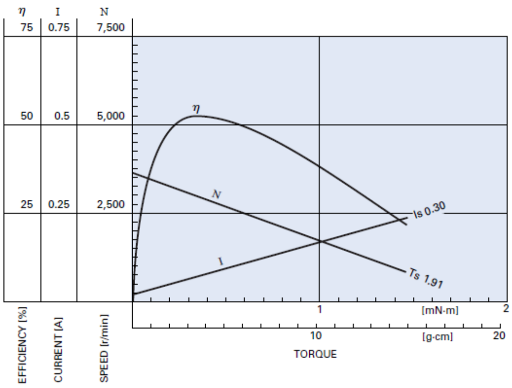


WEIGHT: 22g (APPROX)

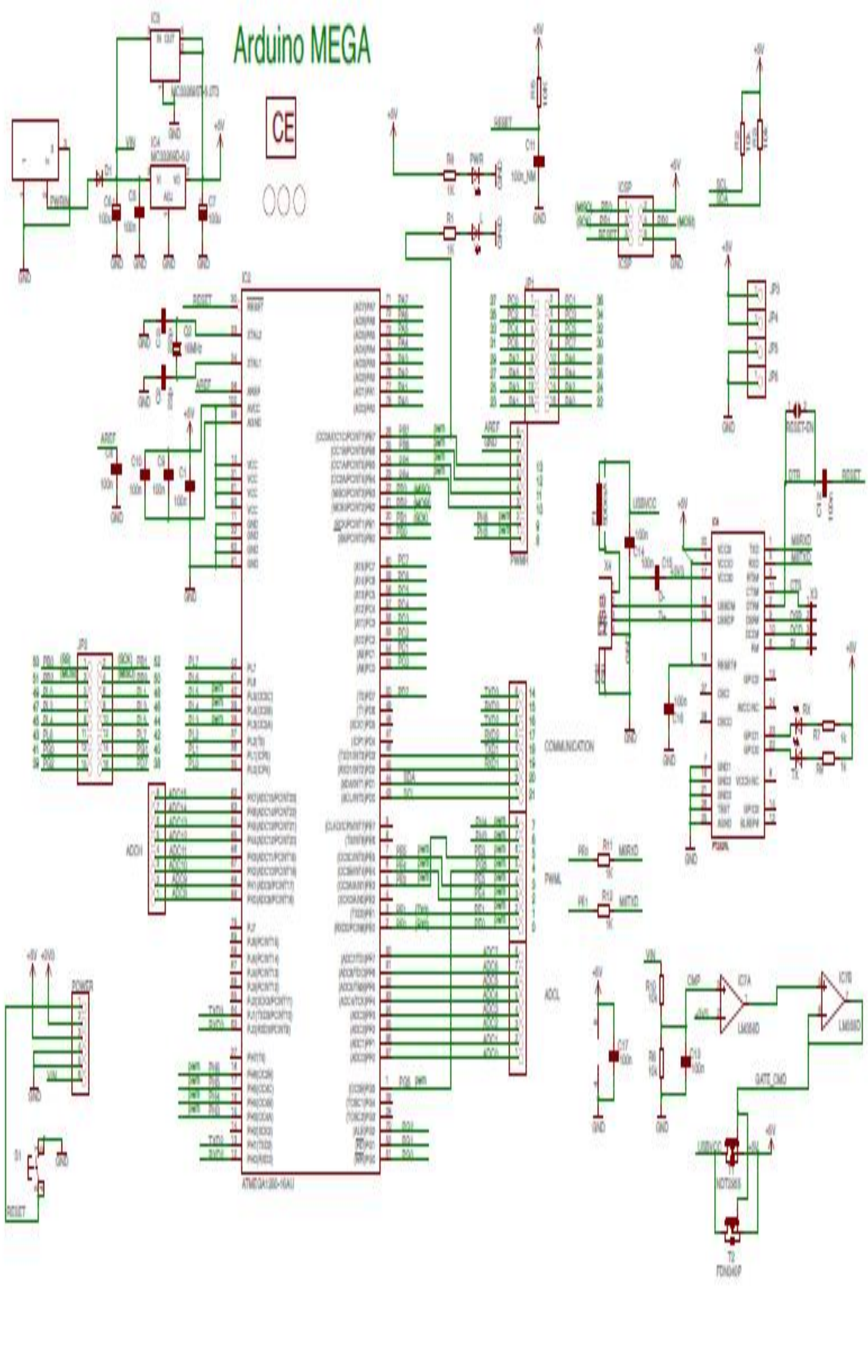
RF-300CA-11440 2.0V



RF-300CA-11400 3.0V

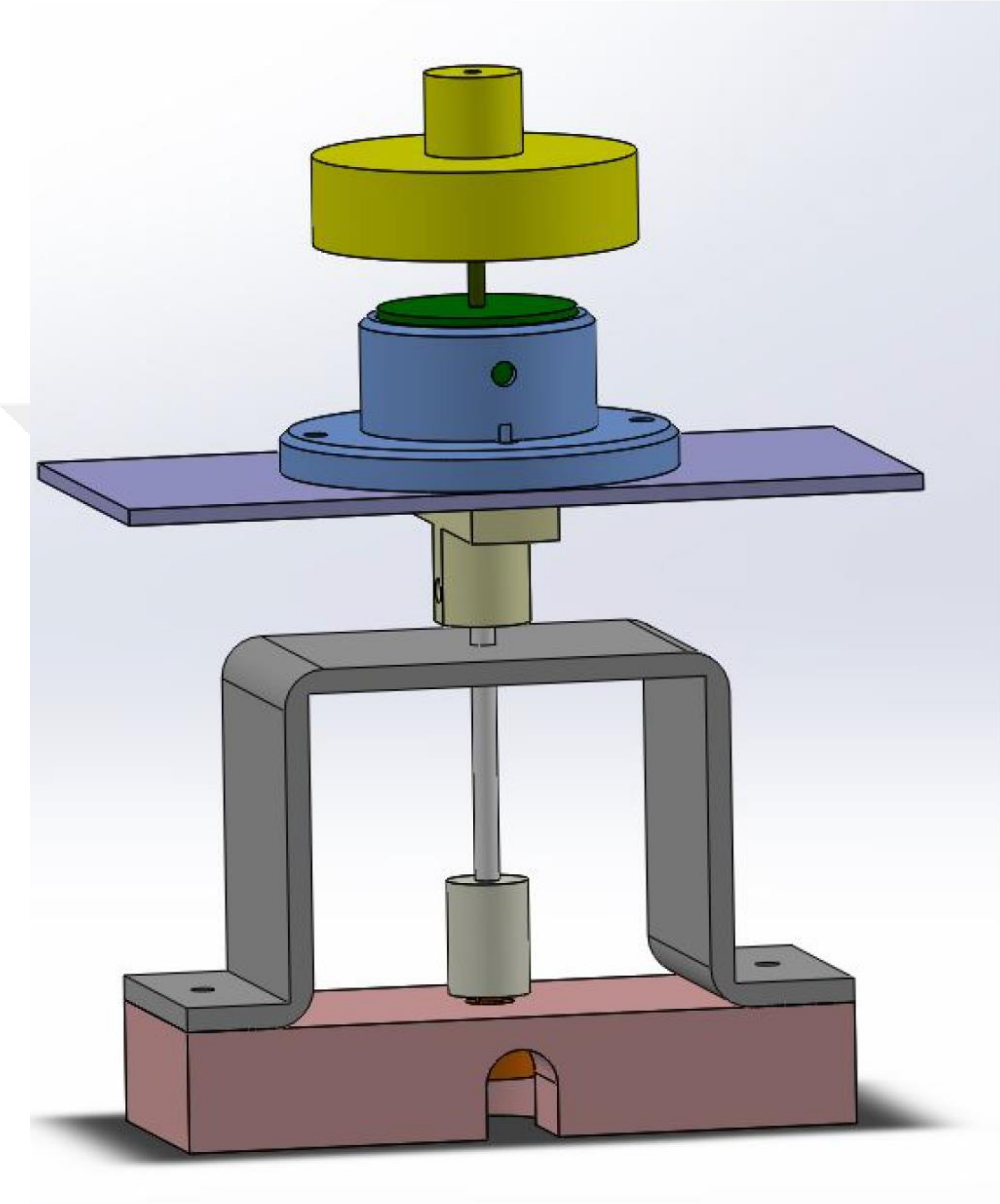


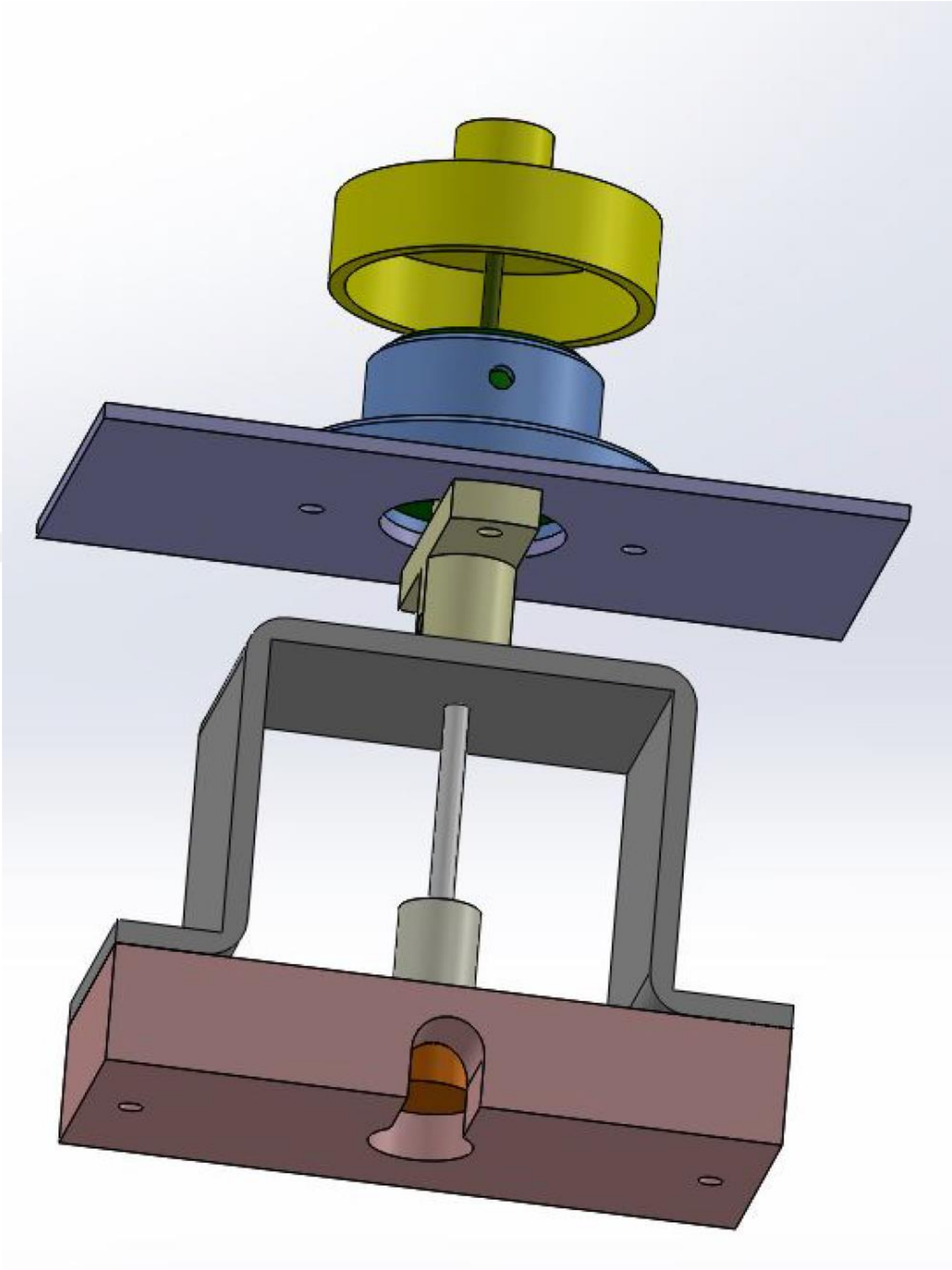
MABUCHI MOTOR CO., LTD. **Headquarters** 430 Matsuhidai, Matsudo-shi, Chiba-ken, 270-2280 Japan Tel:81-47-384-9523 Fax:81-47-385-2026 (Sales Dept.)

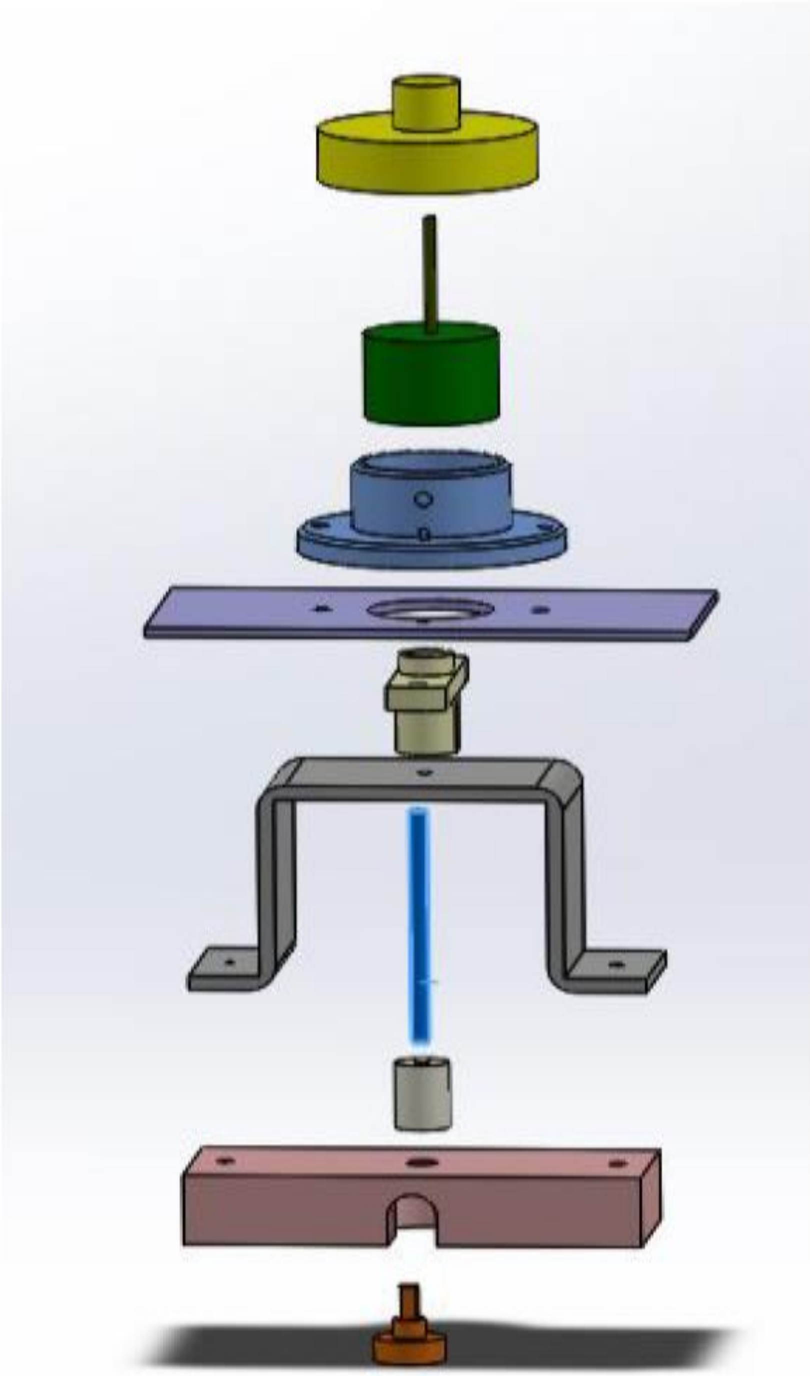

Arduino MEGA
CE
COMMUNICATION
PWML
ADCL
ADCH
POWER
PWMH
ATMEGA1280-16AU

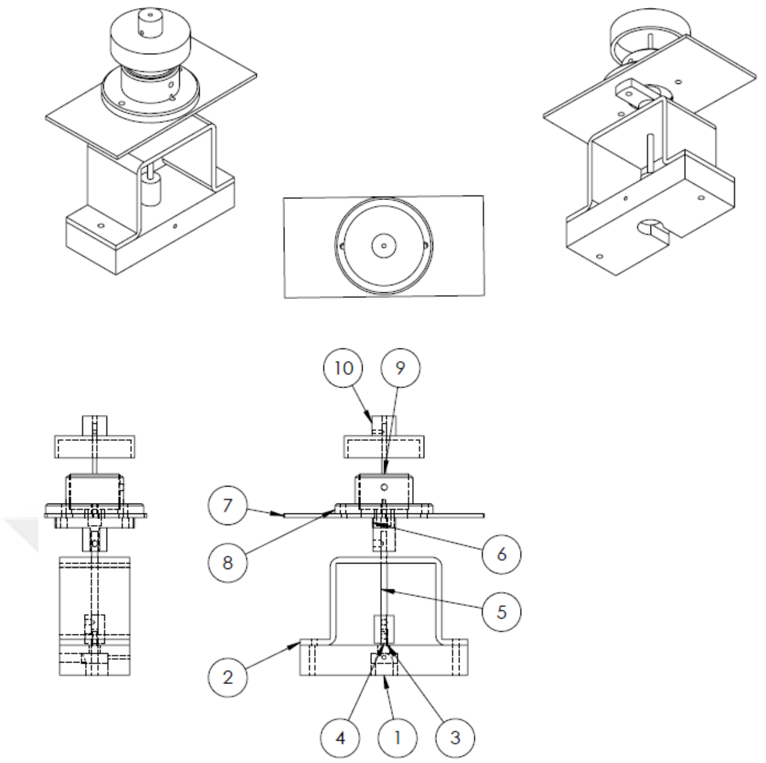
APPENDIX B

REACTION WHEEL AND TEST BED DESIGN

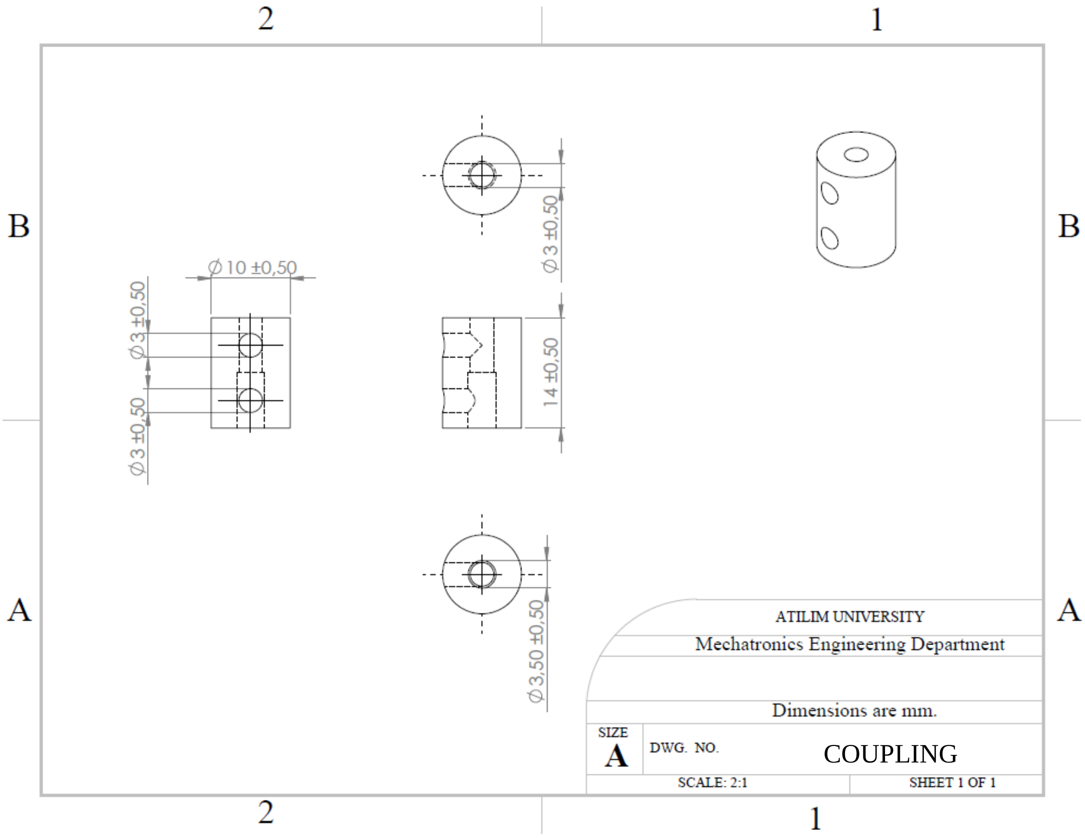




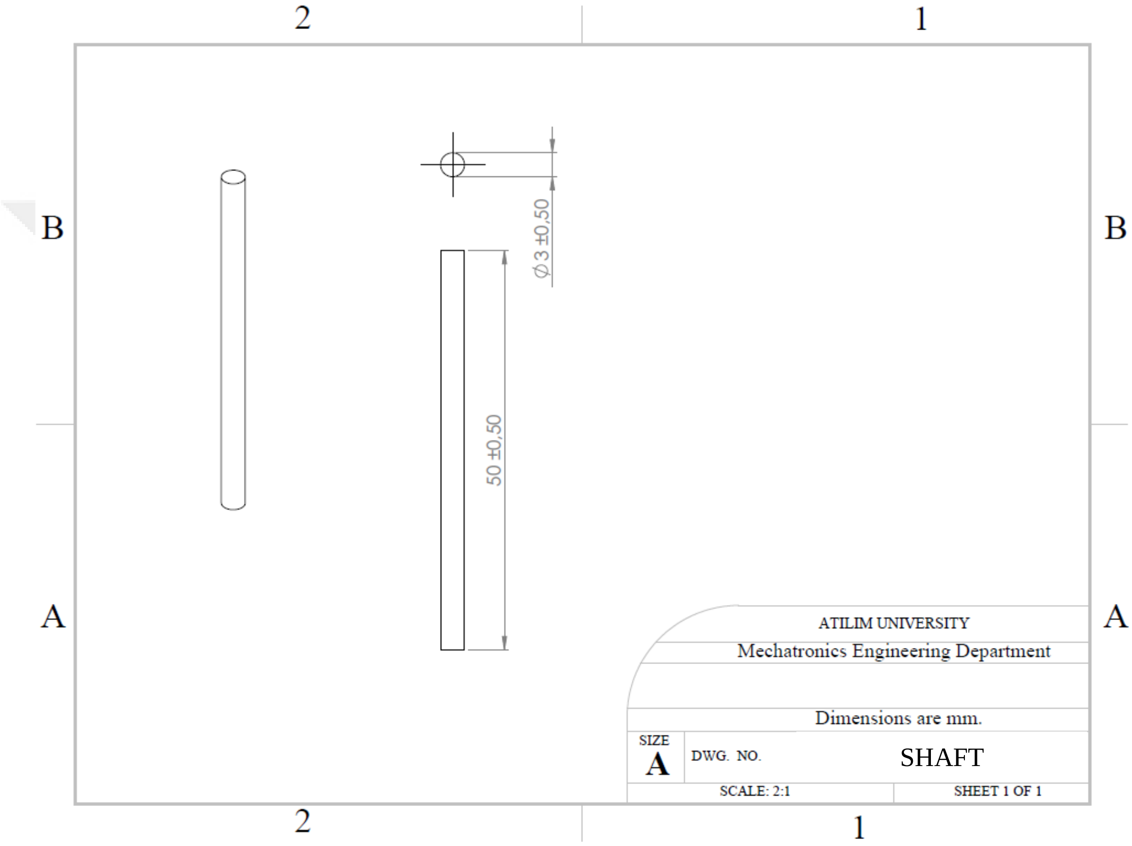


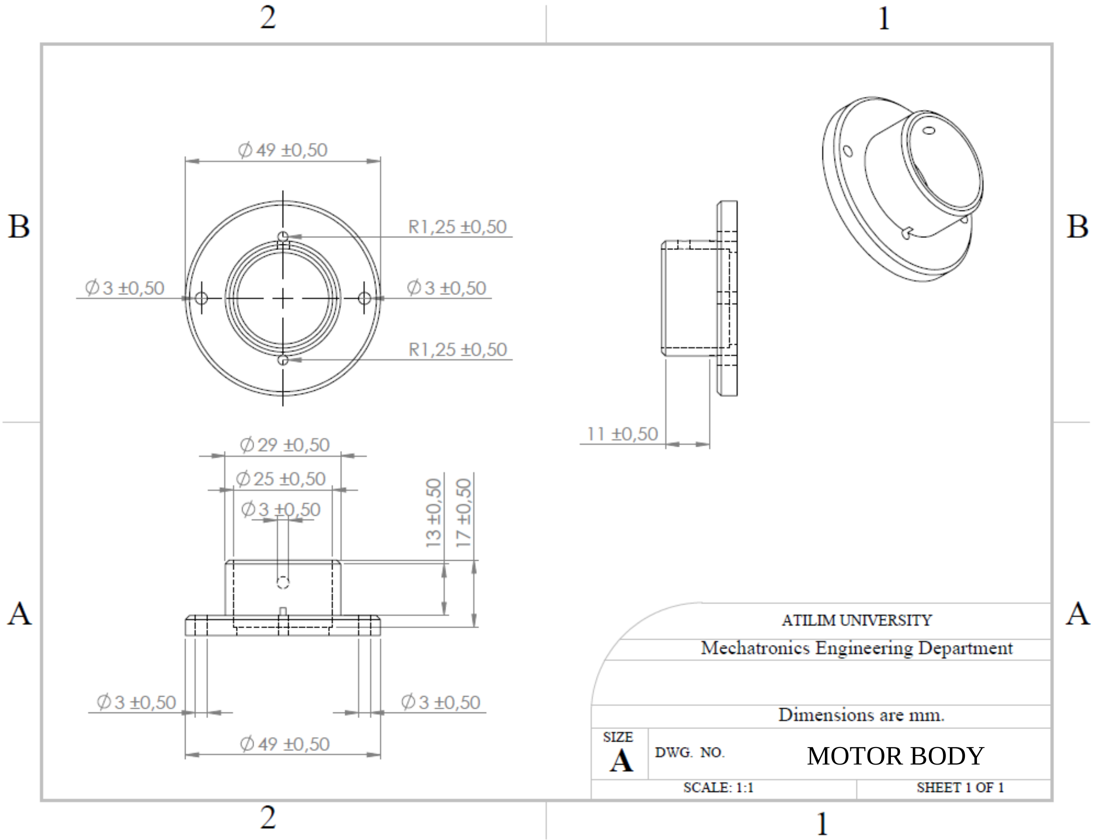


ITEM NO	PART NUMBER	QUANTITY
1	Bed	1
2	Upper Bed	1
3	Potentiometer	1
4	Coupling	1
5	Shaft	1
6	Axis of Declination	1
7	RW panel	1
8	Motor body	1
9	Motor	1
10	RW	1



2
1
B
A
Ø 10 ±0,50
Ø 3 ±0,50
Ø 3 ±0,50
Ø 3 ±0,50
14 ±0,50
Ø 3,50 ±0,50
ATILIM UNIVERSITY
Mechatronics Engineering Department
Dimensions are mm.
SIZE
A
DWG. NO.
COUPLING
SCALE: 2:1
SHEET 1 OF 1


2
1
B
A
∅3 ±0,50
50 ±0,50
ATILIM UNIVERSITY
Mechatronics Engineering Department
Dimensions are mm.
SIZE
A
DWG. NO.
SHAFT
SCALE: 2:1
SHEET 1 OF 1



2
1
B
A
Ø 49 ±0,50
R1,25 ±0,50
Ø 3 ±0,50
Ø 3 ±0,50
R1,25 ±0,50
11 ±0,50
Ø 29 ±0,50
Ø 25 ±0,50
Ø 3 ±0,50
13 ±0,50
17 ±0,50
Ø 3 ±0,50
Ø 3 ±0,50
Ø 49 ±0,50
ATILIM UNIVERSITY
Mechatronics Engineering Department
Dimensions are mm.
SIZE
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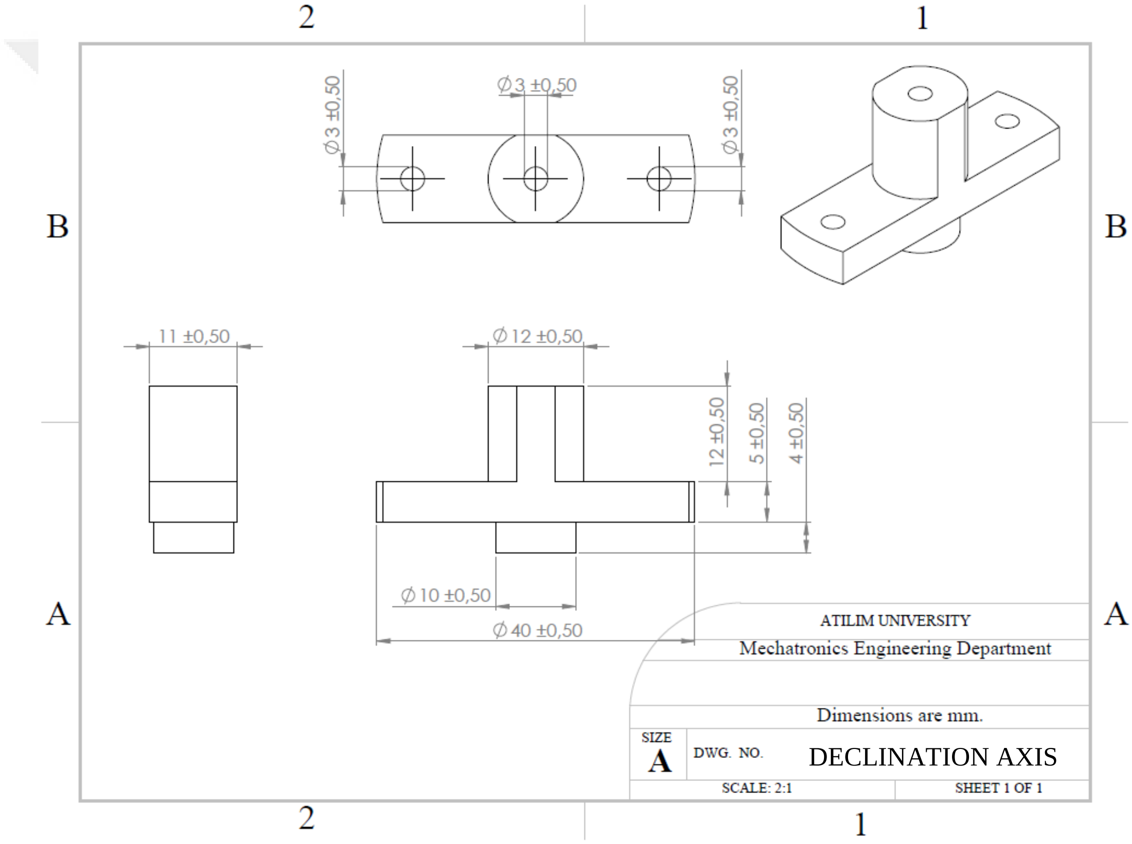
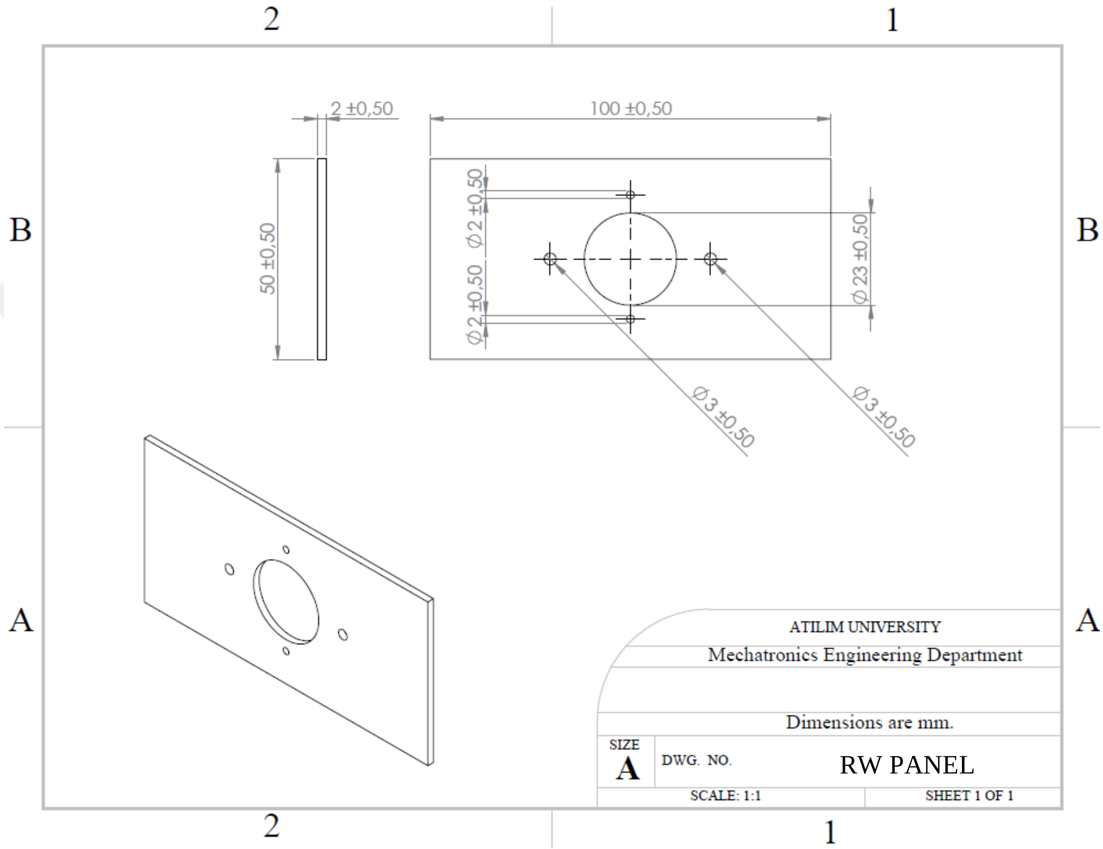
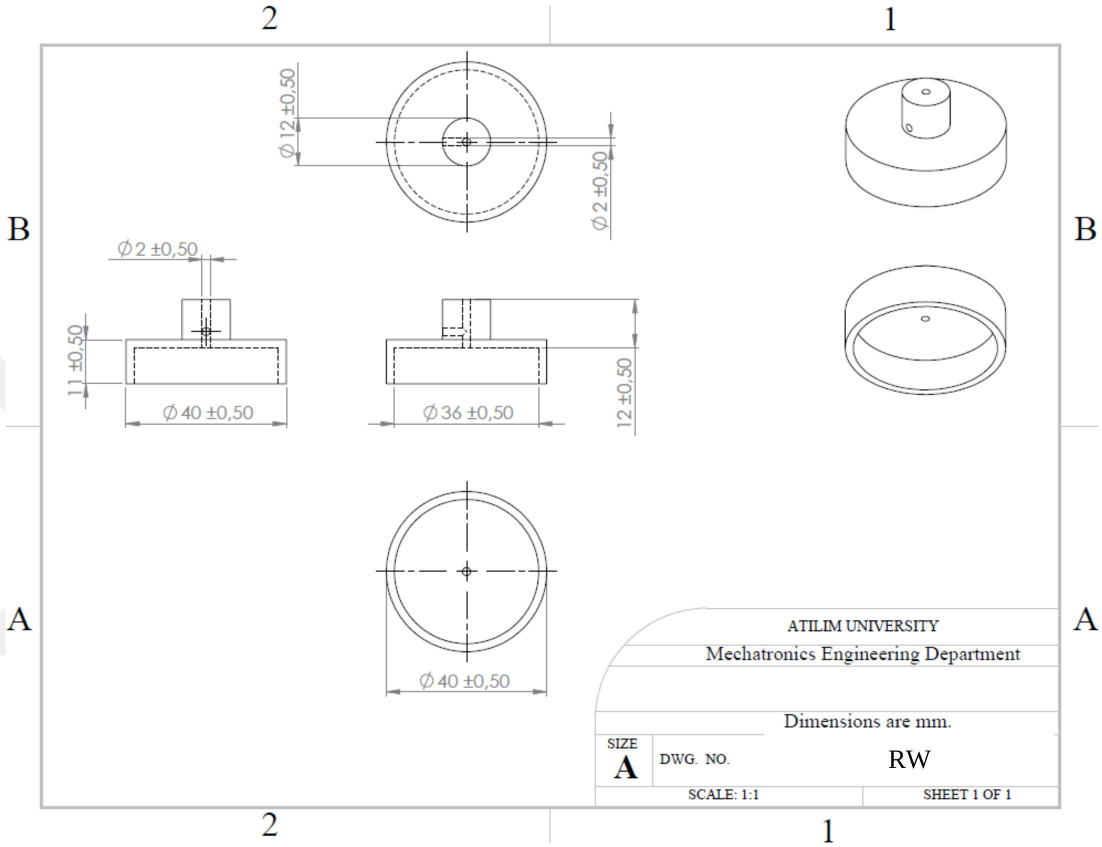
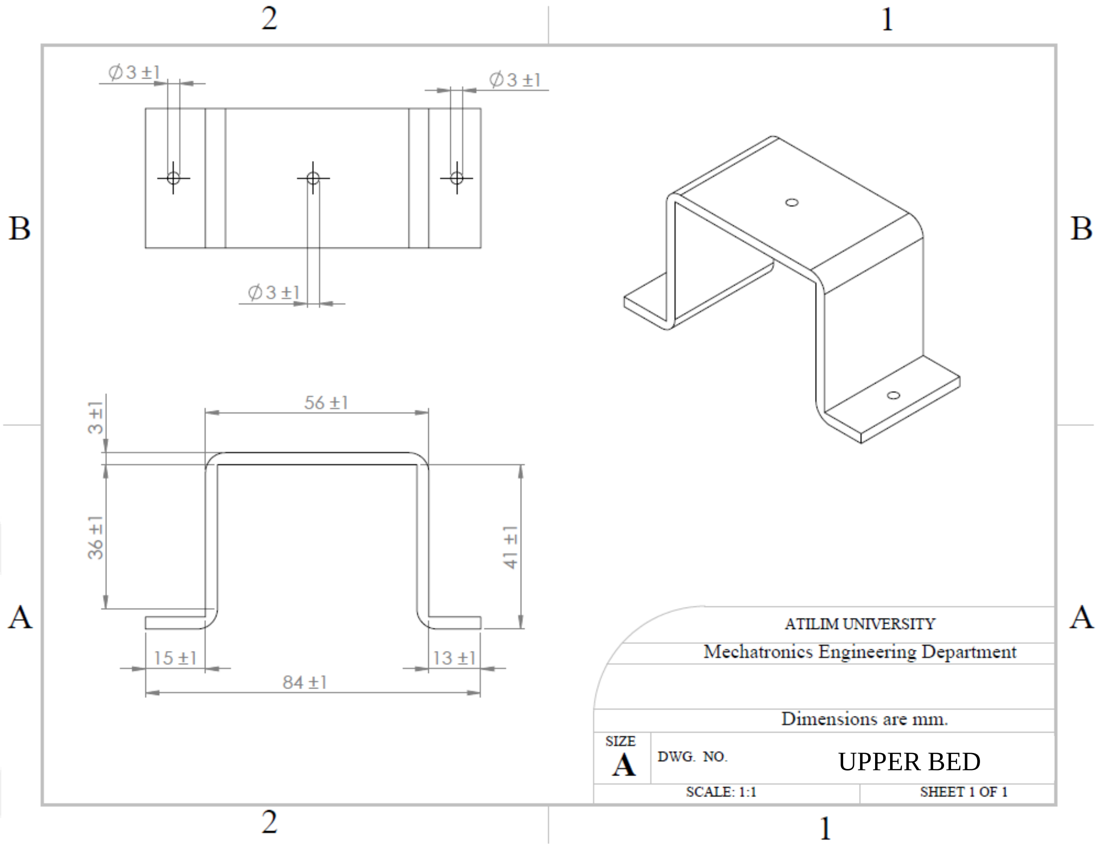
DWG. NO.
MOTOR BODY
SCALE: 1:1
SHEET 1 OF 1

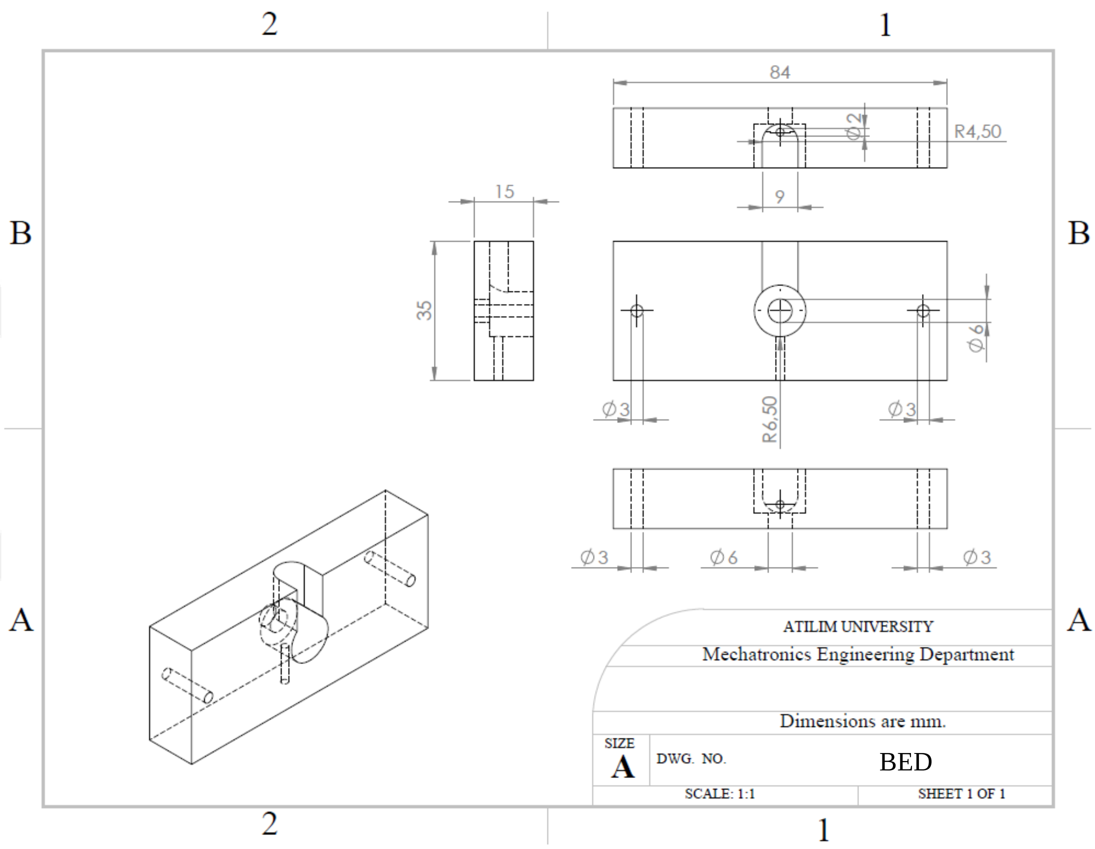

2
1
B
A
Ø3 ±0,50
Ø3 ±0,50
Ø3 ±0,50
11 ±0,50
Ø12 ±0,50
12 ±0,50
5 ±0,50
4 ±0,50
Ø10 ±0,50
Ø40 ±0,50
ATILIM UNIVERSITY
Mechatronics Engineering Department
Dimensions are mm.
SIZE
A
DWG. NO.
DECLINATION AXIS
SCALE: 2:1
SHEET 1 OF 1


2
1
B
A
2 ±0,50
100 ±0,50
50 ±0,50
Ø 2 ±0,50
Ø 2 ±0,50
Ø 23 ±0,50
Ø 3 ±0,50
Ø 3 ±0,50
ATILIM UNIVERSITY
Mechatronics Engineering Department
Dimensions are mm.
SIZE
A
DWG. NO.
RW PANEL
SCALE: 1:1
SHEET 1 OF 1


Ø12 ±0,50
Ø2 ±0,50
Ø2 ±0,50
11 ±0,50
Ø40 ±0,50
Ø36 ±0,50
12 ±0,50
Ø40 ±0,50
ATILIM UNIVERSITY
Mechatronics Engineering Department
Dimensions are mm.
SIZE
A
DWG. NO.
RW
SCALE: 1:1
SHEET 1 OF 1



2
1
B
A
∅3 ±1
∅3 ±1
∅3 ±1
56 ±1
3 ±1
36 ±1
41 ±1
15 ±1
13 ±1
84 ±1
ATILIM UNIVERSITY
Mechatronics Engineering Department
Dimensions are mm.
SIZE
A
DWG. NO.
UPPER BED
SCALE: 1:1
SHEET 1 OF 1


2
1
B
A
84
R4,50
⌀2
9
15
35
⌀6
⌀3
R6,50
⌀3
⌀3
⌀6
⌀3
ATILIM UNIVERSITY
Mechatronics Engineering Department
Dimensions are mm.
SIZE
A
DWG. NO.
BED
SCALE: 1:1
SHEET 1 OF 1

APPENDIX C

ARDUINO CODES

```
//FUZZY MOTOR SPEED CONTROL
//error=command-feedback (+ = too slow
//                    (- = too fast)
//P=Too Slow, Z=Just right, N=Too Fast
//errorDot=(d/dt)error   (+ =getting faster
//                    (- = getting slower)
//Output: FAST or NoChange or SLOW
//Output: F=Call for speeding, Z=Do not change anything, N=Call for slowing
//Command input  :A0
//Feedback input :A1
//CW output      :D2
//CCW output     :D3
//int analogPin1=A0; //the pin that the potentiometer for Command input
//int analogPin2=A1; //the pin that the feedback generator sensor
const int CW=13; //the pin that the CW rotation output as PWM
const int CCW = 12; //the pin that the CCW rotation output as PWM
float errorCurrent=0.0;
float errorPrevious=0.0;
float errorDot;
//Input Membership Functions:
```

```
float Dome;

float Domed;

float DomeN, DomeZ, DomeP;

float DomedN, DomedZ, DomedP;

float Ri;

float R1;

float R2;

float R3;

float R4;

float R5;

float R6;

float R7;

float R8;

float R9;

float neg_strength;

float zero_strength;

float pos_strength;

//the Rule Matrix:

//              error

//         N       Z      P

//  errorDot R1=S     R2=F    R3=F

//         R4=S     R5=NC   R6=F

//         R7=S     R8=S    R9=F
```

```
//Output Membership Function:
float percent_output;
float neg_center=-100.0;
float zero_center=1.0;
float pos_center=100.0;
//Fuzzy Motor Speed Control:
void setup(){
  //Initialize serial communication at 9600 bps:
  Serial.begin(9600);
  //Declare Pin D2 and D3 to be OUTPUT:
  pinMode(CW, OUTPUT);
  pinMode(CCW, OUTPUT);
}
void loop(){
 //Determine CW or CCW rotation:
  errorPrevious=errorCurrent;
  //Read Command Value as a voltage
  //from the adjustment potentiometer
  //connected to A0:
  float commandVoltage=analogRead(A0);
  //Read the feedback speed as a voltage
  //from the sensor generator
  //connected to A1:
```

```
float speedVoltage=analogRead(A1);
errorCurrent=commandVoltage-speedVoltage;
errorDot=errorCurrent-errorPrevious;
//RULES:
//Rule 1:
if((errorCurrent < 0.0)&&(errorDot < 0.0)){
 if(errorCurrent < 2.0){//(-4 <= e < -2):
 DomeN=1.0;
 //a:
 if(errorDot < -5.0) {//(-10 <= edot < -5):
 DomedN=1.0;
 }else{//(-5 <= edot <-2.5):
 if(errorDot < -2.5){
   DomedN=(-1/5)*errorDot;
 }else{//(-2.5 <= edot < 0);
 DomedN=(1/5)*errorDot+1;
 }
 }//else. (End of a.)
 }else{//e < 0:
 DomeN=(-1/2)*errorCurrent;
 //a:
 if(errorDot < -5.0 ){//(-10 <= edot < -5):
 DomedN=1.0;
```

```
    }else{//(-5 <= edot <-2.5):
    if(errorDot < -2.5){
      DomedN=(-1/5)*errorDot;
    }else{//(-2.5 <= edot < 0);
    DomedN=(1/5)*errorDot+1;
    }
    }//else. (End of a.)
    }
    Dome=DomeN;
    Domed=DomedN;
    //b for Ri:
    if(Dome <= Domed){Ri=Dome;
    }else{
      Ri=Domed;
    }
    //End of b.
    R1=Ri;
  }else{
    R1=0.0;
  }
//Rule 2:
  if(((errorCurrent >= -1.0)&&(errorCurrent<1.0))&&(errorDot < 0.0)){
    if(errorCurrent < 0.0){//(-1 <= e <0):
```

```
DomeZ=(1/2)*errorCurrent+1.0;
//a:
if(errorDot < -5.0) {//(-10 <= edot < -5):
DomedN=1.0;
}else{//(-5 <= edot <-2.5):
if(errorDot < -2.5){
  DomedN=(-1/5)*errorDot;
}else{//(-2.5 <= edot < 0);
DomedN=(1/5)*errorDot+1;
}
}//else. (End of a.)
}else{//0<=e < 1:
if (errorCurrent < 1.0){
DomeZ=(-1/2)*errorCurrent+1.0;
//a:
if(errorDot < -5.0 ){//(-10 <= edot < -5):
DomedN=1.0;
}else{//(-5 <= edot <-2.5):
if(errorDot < -2.5){
  DomedN=(-1/5)*errorDot;
}else{//(-2.5 <= edot < 0);
DomedN=(1/5)*errorDot+1;
}
```

```
    }//else. (End of a.)
    }
    }
    Dome=DomeZ;
    Domed=DomedN;
    //b for Ri:
    if(Dome <= Domed){Ri=Dome;
    }else{
      Ri=Domed;
    }
    //End of b.
    R2=Ri;
  }else{
    R2=0.0;
  }
  //Rule 3:
  if((errorCurrent > 0.0)&&(errorDot < 0.0)){
    if(errorCurrent < 1.0){
    DomeP=(1/2)*errorCurrent;//e<1 kuralı için 0<=e<1 bölgesinde 1/2e doğrusunun alt ucu
    }else{
      if(errorCurrent<2){//1<=e<2:
      DomeP=(1/2)*errorCurrent;
```

```
  }else{//2<=e<4:
  DomeP=1.0;
  }
}
//a:
if(errorDot < -5.0) {//(-10 <= edot < -5):
DomedN=1.0;
}else{//(-5 <= edot <-2.5):
if(errorDot < -2.5){
  DomedN=(-1/5)*errorDot;
}else{//(-2.5 <= edot < 0);
DomedN=(1/5)*errorDot+1;
}
}//else. (End of a.)
Dome=DomeP;
Domed=DomedN;
//b for Ri:
if(Dome <= Domed){Ri=Dome;
}else{
  Ri=Domed;
}
//End of b.
R3=Ri;
```

```
 }else{
   R3=0.0;
 }
//Rule 4:
if((errorCurrent<0.0)&&((errorDot>=-2.5)&&(errorDot<2.5))){//-4<=e<-2
if(errorCurrent<-2.0){//-4<=e<-2:
DomeN=1.0;
}else{
  DomeN=(-1/2)*errorCurrent;
}
//a1:
if(errorDot<0.0){//-2.5<=ed<0:
DomedZ=(1/5)*errorDot+1;
}else{//0<=ed<+2.5:
DomedZ=(-1/5)*errorDot+1;
}//end of a1.

Dome=DomeN;
Domed=DomedZ;

   //b for Ri:
   if(Dome <= Domed){Ri=Dome;
   }else{
```

```
    Ri=Domed;

   }

   //End of b.


   R4=Ri;

 }else{

   R4=0.0;

 }

//Rule 5:

if(((errorCurrent>=-1.0)&&(errorCurrent<1.0)&&((errorDot>=-
2.5)&&(errorDot<2.5)))){

if(errorCurrent<0.0){

DomeZ=(1/2)*errorCurrent+1.0;

}else{

  DomeZ=(-1/2)*errorCurrent+1.0;

}

//a1:

if(errorDot<0.0){//-2.5<=ed<0:

DomedZ=(1/5)*errorDot+1;

}else{//0<=ed<+2.5:

DomedZ=(-1/5)*errorDot+1;

}//end of a1.

Dome=DomeZ;
```

```
}
Domed=DomedZ;
  //b for Ri:
  if(Dome <= Domed){Ri=Dome;
  }else{
    Ri=Domed;
  }
  //End of b.
  R5=Ri;
 }else{
  R5=0.0;
 }
//Rule 6:
if((errorCurrent>0.0)&&((errorDot>=-2.5)&&(errorDot<2.5))){
if(errorCurrent<1.0){//0<=e<1:
DomeP=(1/2)*errorCurrent;
}else{//e<4
if (errorCurrent<2.0){//-1<=e<2:
  DomeP=(1/2)*errorCurrent;
}else{//2<=e<4:
DomeP=1.9;
}
}
//a1:
```

```
if(errorDot<0.0){//-2.5<=ed<0:
DomedZ=(1/5)*errorDot+1;
}else{//0<=ed<+2.5:
DomedZ=(-1/5)*errorDot+1;
}//end of a1.
Dome=DomeP;
Domed=DomedZ;
  //b for Ri:
  if(Dome <= Domed){Ri=Dome;
  }else{
    Ri=Domed;
  }
  //End of b.
  R6=Ri;
 }else{
  R6=0.0;
 }
//Rule 7:
if((errorCurrent<0.0)&&(errorDot>0.0)){//-4<=e<-2
if(errorCurrent<-2.0){//-4<=e<-2:
DomeN=1.0;
}else{//-2<=e<-1:
  DomeN=(-1/2)*errorCurrent;
```

```
}


//a2:
if(errorDot<5.0){//0<=ed<+5:
DomedP=(1/5)*errorDot;
}else{//+5<=ed<+10:
DomedP=1.0;
}//end of a1.
Dome=DomeN;
Domed=DomedP;
   //b for Ri:
   if(Dome <= Domed){Ri=Dome;
   }else{
     Ri=Domed;
   }
   //End of b.
   R7=Ri;
 }else{
   R7=0.0;
 }
//Rule 8:
if(((errorCurrent>=-1.0)&&(errorCurrent<1.0)&&(errorDot>0.0))){
if(errorCurrent<0.0){//-1<=e<0:
```

```
DomeZ=(1/2)*errorCurrent+1;
}else{
  DomeZ=(-1/2)*errorCurrent+1;
}
//a2:
if(errorDot<5.0){//0<=ed<+5:
DomedP=(1/5)*errorDot;
}else{//+5<=ed<+10:
DomedP=1.0;
}//end of a1.
Dome=DomeZ;
Domed=DomedP;
   //b for Ri:
   if(Dome <= Domed){Ri=Dome;
   }else{
     Ri=Domed;
   }
   //End of b.
   R8=Ri;
 }else{
   R8=0.0;
 }
//Rule 9:
```

```
if((errorCurrent>0.0)&&(errorDot>0.0)){
if(errorCurrent<-2.0){
DomeP=(1/2)*errorCurrent;
}else{
  DomeP=1.0;
}
//a2:
if(errorDot<5.0){//0<=ed<+5:
DomedP=(1/5)*errorDot;
}else{//+5<=ed<+10:
DomedP=1.0;
}//end of a1.
Dome=DomeP;
Domed=DomedP;
   //b for Ri:
   if(Dome <= Domed){Ri=Dome;
   }else{
     Ri=Domed;
   }
   //End of b.
   R9=Ri;
 }else{
   R9=0.0;
```

```
  }
  neg_strength=(R1*R1+R4*R4+R7*R7+R8*R8);//SLOWING THE SPEED
  zero_strength=(R5*R5);//No Change
  pos_strength=(R2*R2+R3*R3+R6*R6+R9*R9);//INCREASING THE SPEED

percent_output=(neg_center*neg_strength+zero_center*zero_strength+pos_center*pos_strength)/(neg_strength+zero_strength+pos_strength);
 //Change the percent_output to Binary as PWM:
 int pwm_output=percent_output*255;
 analogWrite(CW, pwm_output);
}
//PID MOTOR SPEED CONTROL
//error=command-feedback (+ = too slow
//                       (- = too fast)
//P=Too Slow, Z=Just right, N=Too Fast
//errorDot=(d/dt)error   (+ =getting faster
//                       (- = getting slower)
//Output: FAST or NoChange or SLOW
//Output: F=Call for speeding, Z=Do not change anything, N=Call for slowing
//Command input  :A0
//Feedback input :A1
//CW output      :D9
//CCW output     :D3
//int analogPin1=A0; //the pin that the potentiometer for Command input
```

```
//int analogPin2=A1; //the pin that the feedback generator sensor

#include<stdio.h>

const int CW=9; //the pin that the CW rotation output as PWM

const int CCW = 12; //the pin that the CCW rotation output as PWM

float errorCurrent=0.0;

float errorPrevious=0.0;

float errorDot;

int Kg=20; //dc generator feedback gain for adjusting it to a level of potentiometer voltage

int Kp=10; //Proportional controller gain

int Kd=1; //Derivative controller gain

//Input Membership Functions:

float Dome;

float Domed;

float DomeN, DomeZ, DomeP;

float DomedN, DomedZ, DomedP;

float Ri;

float R1;

float R2;

float R3;

float R4;

float R5;

float R6;
```

```
float R7;
float R8;
float R9;
float neg_strength;
float zero_strength;
float pos_strength;
const int analogPin0=A0; //The pin that the potentiometer is attached to
const int analogPin1=A1; //The pin that the generator is attached to
//Fuzzy Motor Speed Control:
void setup(){
  //Initialize serial communication at 9600 bps:
  Serial.begin(9600);
  //Declare Pin D2 and D3 to be OUTPUT:
  pinMode(CW, OUTPUT);
  pinMode(CCW, OUTPUT);
}
void loop(){
    //Read the potentiometer voltage:
int sensorReading0=analogRead(analogPin0);
//Write the result to screen:
//Convert the analog reading from 0-1023 to a voltage (0-5V):
float voltage0=sensorReading0*(5.0/1023);
//Print out the value you read:
```

```
//Serial.println(voltage0);
  //Read feedback generator voltage:
int sensorReading1=analogRead(analogPin1);
//Write the result to screen:
//Convert the analog reading from 0-1023 to a voltage (0-5V):
float voltage1=sensorReading1*(5.0/1023);
//Print out the value you read:
//Serial.println(voltage1);
 //Determine CW or CCW rotation:
  errorPrevious=errorCurrent;
  //Read Command Value as a voltage
  //from the adjustment potentiometer
  //connected to A0:
 // float commandVoltage=analogRead(A0);
  //Read the feedback speed as a voltage
  //from the sensor generator
  //connected to A1:
 // float speedVoltage=analogRead(A1);
 float commandVoltage=voltage0;
 float speedVoltage=voltage1*Kg;
 errorCurrent=commandVoltage-speedVoltage;
 errorDot=errorCurrent-errorPrevious;
Serial.println("Command Input:");
```

```
Serial.println(commandVoltage);

Serial.println("Feedback Speed:");

Serial.println(speedVoltage);

 //Print out the errorCurrent value you read:

Serial.println("Error:");

Serial.println(errorCurrent);

Serial.println("Error_Dot:");

Serial.println(errorDot);

float percent_output=(Kp*errorCurrent+Kd*errorDot)/commandVoltage;

 //Change the percent_output to Binary as PWM:

 int pwm_output=percent_output*255;

 analogWrite(CW, pwm_output);//

delay(1000);

}
```