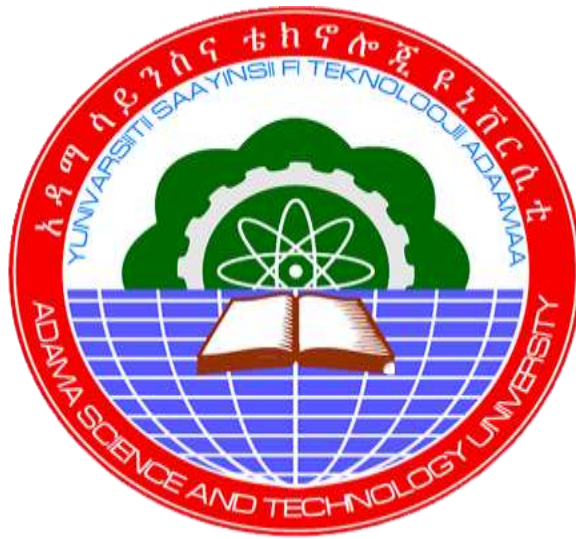


Attitude Stabilization of a Magnetic Torquer and Gravity Gradient-based
CubeSat Using ANFIS



Bekuretsion Tsegaye

A Thesis Submitted to the Department of Electrical Power and Control
Engineering, School of Electrical Engineering and Computing

Presented in Partial Fulfillment of the Requirement for the Degree of Master's
of Science in Electrical Power and Control Engineering (Control Engineering)

Office of Graduate Studies

Adama Science and Technology University

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DECLARATION

I hereby declare that this Master Thesis entitled “**Attitude Stabilization of a Magnetic Torquer and Gravity Gradient-based CubeSat Using ANFIS**” is my original work. That is, it has not been submitted for the award of any academic degree, diploma or certificate in any other university. All sources of materials that are used for this thesis have been duly acknowledged through citation.

Bekuretsion Tsegaye



01/03/24

Name of student

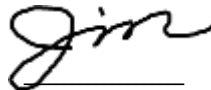
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RECOMMENDATION

I, the advisor of this thesis, hereby certify that I have read the revised version of the thesis entitled “**Attitude Stabilization of a Magnetic Torquer and Gravity Gradient-based CubeSat Using ANFIS**” prepared under my guidance by **Bekuretsion Tsegaye** submitted in partial fulfillment of the requirements for the degree of Master’s of Science in Electrical Power and Control Engineering (Control Engineering). Therefore, I recommend the submission of revised version of the thesis to the department following the applicable procedures.

Prof. Gang Gyoo Jin



01/03/24

Major Advisor

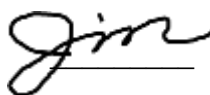
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APPROVAL SHEET

I, the advisor of the thesis entitled “**Attitude Stabilization of a Magnetic Torquer and Gravity Gradient-based CubeSat Using ANFIS**” and developed by **Bekuretsion Tsegaye**, hereby certify that the recommendation and suggestions made by the board of examiners are appropriately incorporated into the final version of the thesis.

Prof. Gang Gyoo Jin



02/04/24

Major Advisor

Signature

Date

We, the undersigned, members of the Board of Examiners of the thesis by **Bekuretsion Tsegaye** have read and evaluated the thesis entitled “**Attitude Stabilization of a Magnetic Torquer and Gravity Gradient-based CubeSat Using ANFIS**” and examined the candidate during open defense. This is, therefore, to certify that the thesis is accepted for partial fulfillment of the requirement of the degree of Master’s of Science in Electrical Power and Control Engineering (Control Engineering).

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Final approval and acceptance of the thesis is contingent upon submission of its final copy to the Office of Postgraduate Studies (OPGS) through the Department Graduate Council (DGC) and School Graduate Committee (SGC).

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School Dean

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Office of Postgraduate Studies, Dean

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I want to start by thanking God and Saint Mary for their constant blessings and help. I want to express my sincere thanks to Professor Gang Gyoo Jin, who guided me as my advisor throughout this entire process.

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LIST OF ACRONYMS

ACS	Attitude Control System
ADS	Attitude Determination System
ADCS	Attitude Determination and Control System
ANFIS	Adaptive Neuro-fuzzy Inference System
FLC	Fuzzy Logic Controller
LEO	Lower Earth Orbit
FSF	Full State Feedback

ABSTRACT

Tiny box-shaped satellites called CubeSat's are typically sent into low Earth orbit to survey the planet, try out cutting-edge communications systems, or run miniature experiments. This study's objective is to develop and improve an effective Attitude Control System (ACS) for the CubeSat. Magnetic coils are introduced to improve the three axis stabilization and the pointing capabilities of a gravity gradient stabilized satellite because these attributes are limited. A steady current switched in two directions, is applied to the magnetic coils that surrounding the satellite's X, Y, and Z axes. This produces a magnetic dipole moment that interacts with the geomagnetic field, generating a torque used to control the rotation of the CubeSat. A problem is that as the geomagnetic field changes in both strength and direction, magnetic control becomes non-linear and time-dependent. The ANFIS controller was used as the approach for controlling magnetic coils. Full State Feedback Controller provides the training data for Adaptive Neuro-Fuzzy Inference System(ANFIS). The Ackermann Formula is employed to calculate the state feedback gain matrix (K), which requires pre-defined poles. The Bessel polynomial method is utilized to provide these pre-defined poles. By simulating a mathematical model of a CubeSat with consideration for gravity gradient stabilization and magnetorquer using MATLAB, the performance of the controller was evaluated. Though both ANFIS and FSF controllers provided good results in the analysis, ANFIS controlled Cubesats had slightly higher peak values for roll (10°), pitch (30°), and yaw (20.5291°), which indicated an enhancement of the satellite's ability to rapidly adjust itself. On the other hand, Full State Feedback (FSF) was highly effective at stabilizing and keeping the satellite on course with minimum error rate. The choice between the two depends on mission requirements and computational considerations.

Keywords: Attitude control system, Full State Feedback Controller, ANFIS, Magenotorquer, Ackermann, Bessel polynomial

CHAPTER ONE

1 INTRODUCTION

1.1 CubeSat

A satellite, often known as an artificial satellite, is a spacecraft that has been put into orbit on purpose. A method of producing electricity for the technology they carry, like solar panels or radioisotope thermoelectric generators, is included on the majority of spacecraft, except passive satellites. Transponders are a kind of ground station communication technology that is included in most satellites. Small CubeSats, the most popular kind of satellite, employ a standardized bus to work and save expenses. (*What Is a Satellite?* | *Space*, n.d.)

Scientists and researchers employ CubeSats, which are nanosatellites, as research spacecraft. Units refer to CubeSat's common dimensions (U). Each unit has 10x10x10 cm in measurements. The CubeSat is available in sizes of 1U, 2U, 3U, 6U, and 12U, and each 1U typically weighs less than 1.33 kg.

Costs are decreased due to the extremely detailed CubeSat specifications. Companies can mass-produce parts and provide off-the-shelf components according to the standardized features of CubeSat's. Because of this, CubeSat engineering and development are less expensive than highly specialized tiny satellites. The fixed size and shape lowers the expense of shipping them to orbit and setting them up there.(NASA, 2017)

Tasks required for CubeSat's systems to operate properly are carried out by their numerous systems. The systems below make up a typical nanosatellite.

- ✓ System of Electrical Power
- ✓ System of determining and controlling attitude
- ✓ Communications System
- ✓ Structure and Mechanisms System
- ✓ System of Thermal Control

1.2 Attitude Determination and Control System

The Attitude Control System (ACS) and Attitude Determination System (ADS) are two distinct systems that make up the ADCS. The satellite's current attitude is sent using the

ADS. The ACS that rotates the satellite into the required attitude uses ADS information as input.

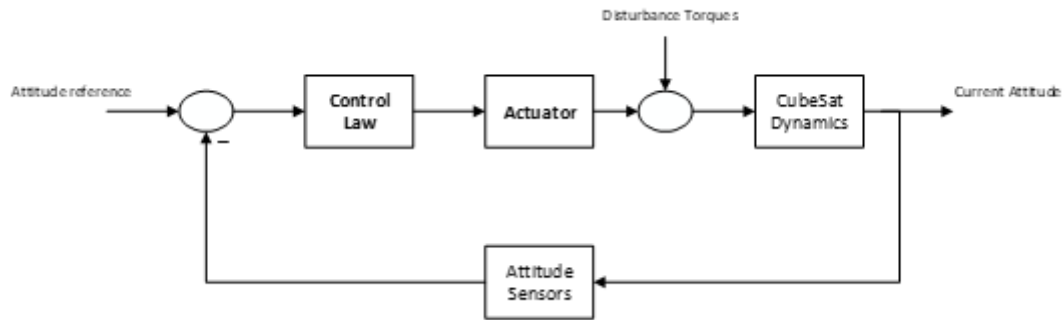


Figure 1.1 Block Diagram Of ADCS (Bin & Basri, 2021)

1.2.1 Attitude Determination System

Attitude determination is the process of determining the spacecraft's orientation with respect to an inertial reference or to an object of interest, like the Earth. Using a combination of sensors and mathematical models, attitude determination collects vector components in the body and inertial reference frames. These vector components are typically represented as quaternions, Euler angles, or rotation matrices. The sensors and algorithms that make up the Attitude Determination System are used to determine attitude.

1.2.2 Attitude Control System

Attitude control is the process of precisely orienting the spacecraft in the necessary attitude in the space environment. Attitude stabilization and attitude maneuver control are its two components. The process of stabilizing an attitude is preserving it with respect to some external relative frame. Attitude maneuver control is the process of shifting the spacecraft's orientation from one attitude to another. (Tikka, 2012) The actuator and controller are the two main parts of the attitude control system. The necessary torque to alter the attitude is provided by the actuator, which can be either active or passive.

The attitude control system has the following elements:

Actuators: The actuator adjusts the attitude by applying the desired torque. Actuators come in two varieties: active and passive.

Control Law: The controller computes the desired torque for the actuators and transforms this torque to the desired electrical commands to be sent to the actuators. Based on the estimated attitude and rate, the desired attitude and rate.

The spacecraft dynamics: in fact, this is not a factor in attitude control, it is focused on the dynamics and kinematics of the satellite orientation with respect to the center of mass when both internal and external torques are present.

Disturbance Torque: Torque disturbances fall into one of two categories: internal and external. First impacts of moving parts, reaction wheels, and fuel splash. The second category is environmental torques, which are caused by the aerodynamic effect, solar pressure, earth's magnetic field, and gravity gradient. As a result, the attitude must occasionally be adjusted with respect to the inertial frame.(Sidi, 2017)

1.3 Statement of the Problem

The CubeSat will be exposed to release mechanism forces when it separates from the launch vehicle and might tumble. To slow down the action, a detumbling mode is turned on. When the satellite's movement is sufficiently minimal, the gravitational boom will be released. This research will focus on attitude control following the successful completion of the detumbling mode and full deployment of the boom.

A gravitational gradient stabilized CubeSat has limited stability and pointing capabilities. Magnetic coils are used to enhance the three-axis stabilization and the pointing properties of CubeSat, which has limited stability and pointing capabilities. Magnetic coils surrounding the X, Y, and Z axes of the satellite can be fed with a constant current switched in two directions to form a magnetic dipole moment that will interact with the geomagnetic field to produce a satellite torque.

A problem is that as the geomagnetic field varies in both strength and direction, magnetic control becomes non-linear and time-dependent. The CubeSat magnetic torques must be controlled to keep the desired attitude.

Full-state feedback controllers have the advantage of utilizing the full state of the system to determine the control input, resulting in a more comprehensive understanding of the CubeSat's behavior. This approach can provide better control performance, making it a desirable option for a single controller solution for CubeSat's.

The usage of fuzzy logic controllers (FLC) in CubeSat attitude control is rising as a result of their adaptability and simplicity. However, the membership functions and regulations of FLCs determine their effectiveness; they are determined by a process of trial and error. To get over this issue, an Adaptive Neuro-fuzzy Inference System (ANFIS) with learning-based

fuzzy tuning will be employed to maintain the intended attitude. The training data for ANFIS was supplied through the full state feedback controller. The current performance of ANFIS, besides the issues with FLCs it tackles also boosts CubeSats' maneuverability by adjusting control parameters dynamically based on real-time data and learning from performance of full state feedback controller.

1.4 Objective

1.4.1 General Objective

The main objective is to stabilize the attitude of a CubeSat using an adaptive neuro-fuzzy controller.

1.4.2 Specific Objective

- ✓ Obtain a nonlinear mathematical model of CubeSat under the assumption that it is a rigid body, and then linearize the model.
- ✓ Design a full-state feedback controller using the Bessel polynomial.
- ✓ Obtain the training data from the full-state feedback controller.
- ✓ Train the adaptive neuro-fuzzy inference system (ANFIS) using a set of training data to generate fuzzy rule and membership functions.
- ✓ Simulate an ANFIS based control system based on the CubeSat attitude model.

1.5 Scope of the thesis

The scope of this thesis will focus on using magnetic torque and gravity gradient actuators to control CubeSat attitude stabilization. ANFIS and a full-state feedback controller are the recommended control techniques. ANFIS uses the training data from the full-state feedback controller to simulate the suggested system in MATLAB.

1.6 Limitation of the thesis

The thesis will only use a MATLAB model to demonstrate how the proposed controller stabilize the CubeSat.

1.7 Significance of the Study

The production and deployment of satellites requires complex technology, significant funding, and highly skilled labor. By resizing the satellite, low-cost satellites can be

produced. The development of small, inexpensive, effective satellites is crucial for developing nations, academic institutions, and amateur technologists.

For country whose space technology has not yet advanced, CubeSat technology may be a starting alternative. The complexity of a full-state feedback controller is one of its major drawbacks when implemented on a CubeSat. Due to the limited space and resources available, it can be challenging to maintain an accurate model of the spacecraft's dynamics. Moreover, the controller may not be capable of accounting for external disturbances or uncertainties. In this study, ANFIS based controller will overcome the drawback. FLC is an alternative for attitude control, but its efficacy depends on the design of rules and membership functions, which are chosen through a tedious process of logical reasoning and expert knowledge. ANFIS learning-based fuzzy tuning will be used to address this issue.

CHAPTER TWO

2 LITERATURE REVIEW

2.1 Attitude Stabilization of CubeSat

The process of preserving an existing orientation in relation to an external frame is known as attitude stabilization. Attitude stabilization can be active attitude stabilization or passive attitude stabilization.

A system's behavior in reaction to internal and external perturbations of equilibrium states is referred to as stability. For a small satellite, stability is a challenging issue. Due to the restrictions of size and weight, the design and development of any stabilization mechanism is very challenging and creates significant challenges for a CubeSat.

2.1.1 Passive Attitude Stabilization

Interacting with the torques of the environment to adjust the orientation results in passive stabilization. The usage of the Earth's magnetic field and gravitational field are the two primary methods for implementing passive stabilization. Utilizing parts and techniques that do not need moving parts, passive attitude stabilization creates a stable attitude. Additionally, passive attitude stabilization doesn't require electricity, making it appropriate for usage in nanosatellites due to their limited power capacity. (Fischell, 1964) Gravity gradients, dampers, hysteresis rods, and others are techniques and parts used in passive attitude stabilization. Such attitude stabilization is highly reliable. There are no moving parts, thus there are very few risks of splitting and breaking. The gravity gradient approach, which uses the change in gravity with altitude to produce a torque when the principal axes are not aligned with the orbit reference frame, is the only completely passive attitude control technique that has been utilized successfully.

2.1.1.1 Gravity Gradient Stabilization

On a large scale, the Earth's gravitational potential is largely symmetrical, but on smaller scales, it is extremely heterogeneous. This is because the planet is not spherical, there are notable variations in mass distribution (mountain peaks versus ocean dips), density (rocks, water, and air), and mass displacement within the system (in the Earth's core, in geophysical processes that lead to plate tectonics, or in atmospheric and oceanic currents). (Fischell, 1964)

For a circular orbit, the gravitational force is almost perpendicular to the velocity vector, while the drag that brings the satellite back down acts in the other direction.

The mass distribution of the spacecraft is intended to maintain one end closer to the Earth, which corresponds to the desired orientation of the spacecraft. To generate the torque, long booms are frequently stretched. Only early low Earth orbit satellites of this type have been employed to keep antennae or other sensors pointed toward the planet. (Sidi, 2017) This approach has the benefits of simplicity, reliability, affordability, and lifespan.

2.1.2 Active Attitude Stabilization

Active stabilization is stabilization that involves the satellite actively adjusting its own orientation. This is accomplished by analyzing data from sensors and orienting the satellite using specific torquer types. Spin stabilization and three-axis stabilization are the two subcategories of active stabilizing techniques.

Spin Stabilization: A body that is rotating about either its major or minor axis will maintain its spinning axis' direction in relation to the inertial space.

According to Euler's moment equations of angular motion, external moments applied about the object's center of mass and perpendicular to the spin axis are the only way to cause this direction to change. (Sidi, 2017)

Three axis stabilization: Some spacecraft need to be able to manipulate all three axes on their own while they are in orbit. Complete control of the spacecraft's orientation along all three axes is known as three-axis stabilization. The support provided to the satellite's sensors and actuators makes maneuvering relatively simple, more accurate, and more steady. (Young, 2006) Good pointing accuracy and non-inertial pointing accuracy are two benefits of these systems. However, the hardware is often complicated and expensive, which increases weight and power consumption.

2.2 Attitude Actuators

To change the attitude, the actuator applies the required torque. Actuators come in two varieties passive and active.

2.2.1 Active actuators

2.2.1.1 Reaction wheels

A reaction wheel is an accelerated, high-inertia rotor that is propelled by an electric motor. The reaction wheel will experience a torque as a result of this acceleration. The satellite will

experience a torque of the opposite sign to that of the wheel's, which can be used to adjust the satellite's angular velocity.

The main benefit of these devices is their very high accuracy, while the main drawback is their heavy mass and high power consumption. These machines come in three different varieties: flywheels, reaction wheels, and momentum wheels. (Markley & Crassidis, 2014)

2.2.1.2 Magnetic torquers

An actuator used to regulate satellite attitude is a magnetic torque. To apply a mechanical force on the satellite, it is intended to provide a regulated magnetic moment that interacts with the earth's magnetic field. It should be noted that only torques perpendicular to the magnetic field vector can be created, and therefore the employment of such a device is limited to low Earth orbits where the Earth's magnetic field strength has usable values. (Francois-Lavet, 2010)

2.2.2 Passive actuators

2.2.2.1 Gravity gradient

This approach is based on the idea that gravity weakens with square of the distance. The satellite's components are subject to more force the closer they are to the earth's center, depending on how it is constructed. As a result, this effect may be used to generate torques that move the satellite to a specific position. (Pelton & Madry, n.d.)

2.2.2.2 Magnetic dipole

The feasibility of this strategy is limited to low Earth orbits where the magnetic field strength is high enough, as it is mostly dependent on the magnetic field intensity at a given point in the spacecraft's orbit. A strong continuous magnetic dipole or permanent magnet mounted on the satellite will interact with the Earth's magnetic field vector to adjust the two axes. This is the basis of the technology. (Pelton & Madry, n.d.)

2.3 Disturbance Torques

2.3.1 Aerodynamic Torque

The spacecraft is experiencing torque as a result of atmospheric drag, which is influenced by both the form factor of the object entering the atmosphere and the density of the surrounding air. The spacecraft's center of mass is where the aerodynamic torque acts.

Because neutral gas molecules are present in the Earth's upper atmosphere, aerodynamic torque modifies the orbit shape, which in turn impacts the spacecraft's velocity. The torque

becomes essentially insignificant at higher altitudes due to the decrease in aerodynamic disturbances with altitude. Aerodynamic torque is difficult to compute due to fast changes in cross sectional area over time and variations in atmospheric density with solar activity.

2.3.2 Solar Radiation

Photons colliding with the spacecraft's surface produce the solar radiation force. On the spacecraft surface, incident photons have four possible outcomes: they can be absorbed to produce the least amount of force, they can be reflected in a diffuse manner to provide the second-greatest force, or they can pass through the surface and produce the largest force. In low Earth orbit, the torque arising from solar pressure is considered to be negligible enough to be ignored, and it is the primary disturbance torque for geosynchronous spacecraft.

2.4 Controller

2.4.1 Full-state feedback controller

The full-state feedback controller, which is used in control systems to determine the proper control input, is dependent on state variables, such as orientation and angular velocity in CubeSat attitude control. The state feedback matrix supporting this controller places a high priority on the stability of the system, assuring top performance in the system's current state. (Fadali & Visioli, 2020) When engineers and scientists employ a full-state feedback controller, system control can be improved. They can make sure the system operates as intended and complies with regulations.

2.4.2 Adaptive neuro fuzzy inference system

The Adaptive Neuro-fuzzy inference system (ANFIS) is based on the Takagi-Sugeno fuzzy inference system. Because it combines these two concepts, it can combine the advantages of neural networks and fuzzy logic into one framework. (Liu, 2017) Its inference mechanism is similar to a fuzzy collection of IF-THEN rules in that it can learn and approximate nonlinear functions. As a result, ANFIS is regarded as a global estimator.

The premise and consequence sections of the network structure can be divided into two separate sections. To be more precise, there are five layers in the architecture. The membership functions that match the input values are chosen by the first layer. One commonly used term for it is the "fuzzification layer." The membership degrees of each function are computed using the underlying parameter set $\{a, b, c, \}$. The second layer generates the firing strengths for the rules. Because of the way it operates, the second layer is referred to as the "rule layer". To normalize the computed firing strengths, the third

layer divides each result by the total firing strength. The normalized data and the resultant parameter set $\{p,q,r\}$ are passed into the fourth layer.(Guanrong Chen and Trung Tat Pham, 2001) The defuzzified values that are returned by this layer are fed to the final layer, which generates the output.

2.5 Review of Previous Works

Over the past several years, a variety of potential methods for controlling attitude dynamics have been discovered. One of the most successful and dependable of these is the employment of electromagnetic actuators, which turns out to be particularly practical for low Earth orbit (LEO) satellites.

In (Lovera & Astolfi, 2014) study, magnetic actuators are used to regulate the attitude of a spaceship. The authors strive to determine whether magnetic actuators for an ACS of a CubeSat in a low-earth circular orbit are effective. A proposed control law modeled after the well-known PD controller is used to carry out the experiment. Two scenarios that represented the attitude move were taken into consideration using the SCILAB application program to validate their utilization. The limitations of PD controller is observed.

In (Lu et al., 2021) authors of this study describe how they overcame the thrust misalignment during the CubeSat's orbit maneuver stage. By using moving masses, this solution tried to modify the thrust moment. Using a model with eight degrees of freedom, a CubeSat body with propellant and two orthogonal actuator masses was simulated. To reduce the disruptions and the intensity of the systematic coupling, a double-symmetry actuator system was suggested. On this foundation, the controller design combines the backstepping and sliding-mode control approaches. Moving mass actuators are particularly vulnerable to disturbance, and the possibility of actuator saturation exists.

In (Li et al., 2013) this study, an attitude control system with three reaction wheels or one wheel with three magnetorquers is proposed. Actuator hardware designs and embedded attitude control systems are also described for the purpose of developing prototypes. The efficiency of the suggested attitude control system for detumbling and attitude pointing objectives is demonstrated by numerical simulation results for five different scenarios for a 1U CubeSat-class nanosatellite. The lifespan of the satellite is shortened as the number of reaction wheels increases due to higher power consumption.

In (Mamarasulov et al., 2021) this paper suggests an MPC strategy for attitude control of a 1U CubeSat nanosatellite, using linear time-variant model. The MPC controller is based on

an LQR formulation and should track a given observation path. A complex simulation environment, which includes spacecraft dynamics and environmental models is used to implement a control algorithm. State estimation errors are handled through sensor fusion using an extended Kalman filter. The paper distinguishes the control performance of MPC and traditional LQR in terms of achieving better control outcomes as well as handling input constraints imposed by hardware. The study also highlights the increasing role of nanosatellites, including CubeSat's in space exploration due to their cost-efficiency and flexibility. However, the paper presents obstacles like nonlinear aspect of rotational dynamics and proposes further research in designing a NMPC algorithm to increase control competencies.

In (Michalczuk et al., 2023) this paper presents a fresh method of setting the current controller in a three-phase three-wire grid-connected converter. The aim was to make it produce high-quality sinusoidal currents in the presence of distorted voltage conditions. The paper proposes an approach that uses internal disturbance models for improved robustness in complex grid situations. It also suggests that, multiloop disk margin analysis be combined with global optimization as a means to address these tuning problems, and hence experimental evaluation of the controller gains is recommended. This inquiry shows how Particle Swarm Optimization can be employed for user-friendly tuning and creating multi-frequency current control system for grid-tied converters. Nevertheless, real-time identification of new harmonics remains prohibitively costly because of the limitation of the controller to predefined harmonics. However, this paper discloses about the success of full-state feedback controllers for high-performance current control using PSO algorithm for industrial applications due to their performance optimization. In summary, an innovative tuning method is introduced but it acknowledges that real-time harmonic identification has certain limitations therefore indicating possible areas where further research could be done into adaptive controller reconfiguration in dynamic grid environment.

In (Shehzad et al., 2023) this study, the problems of attitude stabilization in Nano CubeSat are discussed, which indicate that classical PID control techniques are not effective in LEO environment subjected to disturbances. In comparison to PID, ANN, RNN, the proposed ANFIS-PD control scheme stands out in terms of three-axis attitude controllability and rapid stability during 20-second simulations. However, the reliance on simulation is a major drawback because it limits its real-world applicability or adaptability since there was no experimental validation on any Nano CubeSat. The effectiveness of ANFIS-PD showcased

here is constrained to some specific disturbances only; hence its generality with respect to a wider range of perturbations needs further investigation. Consequently, future work should consider practical experimentation for understanding how adaptable it can be to various challenges and try different control methods such as G-FIS, GNN and ISMC as alternatives for robustness and versatility of ANFIS-PD orientation control algorithms in real-life operations using CubeSat's.

In (Nieto-peroy, 2019) this paper focuses on the progress of satellite attitude determination and control systems especially for microsats in the last two decades. It covers advancements in attitude determination methods which include algorithms and sensors, and control methods that use actuators such as reaction wheels and control moment gyroscopes (CMGs). Notably, the survey emphasizes the maturity of miniaturized star sensors and commercial-off-the-shelf (COTS) actuators that have made a significant contribution to high-precision attitude determination and control. However, persisting challenges also comprise complex nonlinear alignment errors, dynamics, and control issues of flexible satellites as well as low redundancy. Despite pointing out deep neural network (DNN)- based techniques as potential solutions to these problems, the study has identified a considerable gap relating specifically to limitations and applications of DNN in handling flexible satellite dynamics and control. Lastly, it is concluded that developments in attitude determination and control systems have had a positive effect on the rapid transformation of microsats, but more research is called for regarding the use of DNN to solve particular challenges faced by microsatellite systems.

In (Helmy et al., 2022) this paper there are issues regarding CubeSat mobility that can be addressed through the application of PID and modified PI-D controllers in enhancing CubeSat Attitude Control System (ACS). A genetic algorithm optimization is used to optimize controller gains, for better performance of CubeSat under external disturbance or white noise. Results from simulation point out efficacy of these controllers in solving movement problems.

While this paper contributes significantly to CubeSat attitude control, contextualization within existing literature is crucial. The problem of CubeSat mobility has been long-lasting with various control strategies proposed. There is an innovation in the use of GAO for gain tuning for optimization of controller performance. However, there could be an elaborate discussion on the variations in mass as well as dynamic factors of a CubeSat. The study does not present a comparison with other control techniques which are considered most advanced

thereby minimizing insight into the best approach used herein. It needs to be validated practically and also generalized to different situations under which CubeSat's are found which have not been explored yet promising future research work.

The collectively examined papers describe various aspects of satellite and CubeSat attitude control systems. Different types of electromagnetic actuators have been thoroughly researched, including magnetic actuators and reaction wheels for the maneuverability of CubeSat's. They refer to such questions as disturbances, white noise, and use PID, modified PI-D and genetic algorithm optimization to make life more convenient. The efficiency of these methods is validated using simulation results, although there is a lack of practical validations and comparison with other approaches. This is followed by discussions on possible CubeSat distinctions, applicability in practice and broader control techniques that should be considered in future researches. The papers also highlight the challenges related to maneuverability, indicating the necessity for more comprehensive approaches to handle dynamic disturbances and optimize control strategies effectively.

CHAPTER THREE

3 METHODOLOGY

3.1 Materials

Software like MATLAB, Microsoft Office, Microsoft Visio, and MathType equation were used in this research study. The software program, MATLAB, include various tools and capability. The thesis materials were edited using Microsoft Office. To create block diagrams and workflows, Microsoft Visio was used. Use MathType to produce mathematical formulas and equations in Microsoft Office Word and PowerPoint presentation tools.

3.2 Methodology

Figure 3.1 illustrated the approach that was taken in this research study to complete the necessary assignment. Data is gathered when reviewing the papers and literature that are closely linked. System modeling is developed by mathematically and graphically analyzing the collected data. The CubeSat dynamic model will be examined. Get the full-state feedback controller's training data ready for ANFIS, then construct an ANFIS-based controller. Use MATLAB/Simulink to run the simulation, then discuss and evaluate the results.

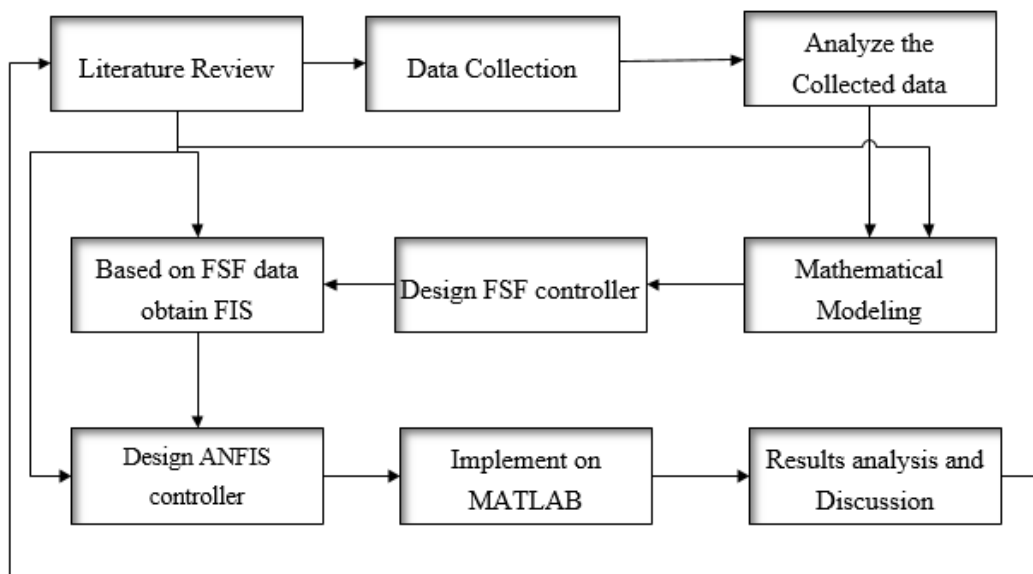


Figure 3.1 Block diagram of the research methodology

3.3 Mathematical Modeling of the CubeSat Attitude System

Modeling and simulation software is crucial for CubeSat system design. Modeling and simulation are essential components of the system design because they help assess the operational and spacecraft design parameters, which are difficult to confirm through ground-based testing. The design of a more dependable and capable CubeSat will benefit from the creation of a simulation tool that produces more accurate results. Since a CubeSat can be thought of as the perfect rigid body, the section provides crucial mathematical background information for understanding the kinematics of the attitude of a rigid body in general in space. The kinematic equations of motion and a Newton-Euler formulation are used to derive the CubeSat's dynamic model. A precise explanation of the reference frames being utilized as a foundation for the rotations is necessary for attitude dynamics, which define how a body is oriented in space. Consequently, this section covers descriptions of the many practical coordinate systems.

3.3.1 Reference Frames

A coordinate system used to represent an object's position and orientation is called a reference frame. The orientation of the CubeSat and its components in relation to some external reference point is defined using reference frames in the context of CubeSat attitude control. This can be used to determine the thruster, sensor, and other equipment direction as well as the forces and moments acting on the spaceship. Reference frames can be anchored to the spacecraft or they can be positioned in relation to an outside reference point like the Sun or the Earth. The precise needs of the attitude control system and the mission objectives will determine the sort of reference frame that is deployed.

3.3.1.1 Body-Fixed Body Frame

A reference frame that is attached to and moves with a spacecraft is called a body-fixed body frame. The x, y, and z axes are all parallel to the spacecraft's longitudinal, transverse, and vertical axes, respectively. It is frequently used to describe the orientation of the spacecraft and its components. This enables the spacecraft's orientation to be described in terms of pitch, roll, and yaw angles, which can be used to control the positioning of sensors, thrusters, and other equipment. (Thesis & Engineering, 2019) The benefit of using a body-fixed body frame is that it offers a constant reference point, but using this frame can make it difficult to communicate with the spacecraft or other systems because the orientation of the spacecraft with respect to external reference points may change over time.

3.3.1.2 Earth-Centered Inertial Frame

A coordinate system fixed to the Earth, with its origin at its center and its x, y, and z axes aligned with its rotational axes, is known as an Earth-Centered Inertial (ECI) reference frame. In this frame of reference, the Earth appears to be stationary while spacecraft (like a CubeSat) appear to be in motion. The fact that this reference frame accounts for both the Earth's rotation and the gravitational forces pulling on the objects makes it useful for analyzing how they move through space. CubeSat are typically a few centimeters to a few meters in size and are frequently launched into low Earth orbit (LEO). (Rawashdeh, 2013) They are frequently employed for a variety of space missions, such as communication, Earth observation, and scholarly investigation. The ECI reference frame is widely used to analyze the motion of CubeSat and other objects in Low-Earth orbit (LEO) because it makes it feasible to estimate the position and velocity of the satellite with respect to the Earth.

3.3.1.3 Spacecraft Orbit Frame

The spacecraft orbit frame (SOF) is a frame of reference that is fixed with respect to the satellite as it orbits the Earth. Three axes define it: the x-axis points in the direction of the satellite's velocity vector, the y-axis lies in the orbital plane and is perpendicular to the x-axis, and the z-axis is perpendicular to the x-y plane and points in the direction of the earth's north pole. (Doruk, 2008) The SOF serves as a crucial frame of reference for satellite navigation and control by describing the satellite's position and orientation in relation to its orbit. The satellite's various sensors and instruments, including magnetometers, inertial measurement units, and sun sensors, can be used to determine it (IMUs).

3.4 Attitude Kinematics and Dynamics of CubeSat

A CubeSat's movement and orientation in space are determined by forces like gravity, friction, and thrust, and are referred to as attitude kinematics. Studying these forces and how they impact the satellite's orientation and movement is known as attitude dynamics. Differential equations and simulations can be used to model and understand these phenomena. While simulations allow for the testing of various scenarios to see how the satellite will respond, differential equations account for various forces acting on the satellite and its mass, size, and shape. For predicting a CubeSat's behavior in space and ensuring proper operation, it is essential to understand the attitude kinematics and dynamics of the CubeSat.

3.4.1 Attitude Dynamics of CubeSat

A triple of differential equations that express the relationships between a rotating rigid body's force moments, angular velocities, and angular accelerations. These equations are based on Newton's Second Law. (Hanspeter Schaub and John L. Junkins, 2009) (Mahdi et al., 2014)

$$\sum F = \frac{d(m.v)}{dt} = m \cdot \frac{dv}{dt} = m.a \quad (3.1)$$

$$r \times \sum F = r \times ma = r \times \frac{dv}{dt}$$

$$\frac{d(r \times mv)}{dt} = \left(\frac{dr}{dt} \times mv \right) + \left(r \times m \frac{dv}{dt} \right)$$

$$\frac{d(r \times mv)}{dt} = (v \times mv) + \left(r \times m \frac{dv}{dt} \right)$$

$$\frac{d(r \times mv)}{dt} = r \times m \frac{dv}{dt}$$

$$r \times \sum F = \frac{dH}{dt}$$

$$\sum M = \frac{dH}{dt} \quad (3.2)$$

Where m is mass, v is velocity, a is the vector acceleration of (m) relative to an inertial frame, $(m.v)$ is the linear momentum, r is the distance vector from the point of rotation to the object, M is the external moments applied about the rigid body's center of mass and H is the rigid body's total angular momentum about its center of mass. H is given by

$$H = I.\omega^{b/i} \quad (3.3)$$

where ω is the angular velocity of the body frame with respect to an inertial frame and I is the CubeSat's moment of inertia.

In a recent study, the satellite's moment of inertia has the form:

$$I = \begin{bmatrix} I_x & 0 & 0 \\ 0 & I_y & 0 \\ 0 & 0 & I_z \end{bmatrix} \quad (3.4)$$

A rigid body's reference frame rotates about the inertial frame but remains fixed within the body. Consequently, equation (3.2) yields.

$$\left[\frac{dH}{dt} \right]_{Inertia} = \left[\frac{dH}{dt} \right]_{Body} + \omega^{b/i} \times H = M \quad (3.5)$$

The rigid body's rotational equation of motion about its center of mass can be written as follows:

$$M = \frac{d(I\omega)}{dt} + \omega \times (I\omega) \quad (3.6)$$

where $\omega = \omega^{b/i}$

$$\begin{aligned} \begin{bmatrix} M_x \\ M_y \\ M_z \end{bmatrix} &= \begin{bmatrix} I_x & 0 & 0 \\ 0 & I_y & 0 \\ 0 & 0 & I_z \end{bmatrix} \begin{bmatrix} \dot{\omega}_x \\ \dot{\omega}_y \\ \dot{\omega}_z \end{bmatrix} + \begin{bmatrix} \omega_x \\ \omega_y \\ \omega_z \end{bmatrix} \times \begin{bmatrix} I_x & 0 & 0 \\ 0 & I_y & 0 \\ 0 & 0 & I_z \end{bmatrix} \begin{bmatrix} \omega_x \\ \omega_y \\ \omega_z \end{bmatrix} \\ \begin{bmatrix} M_x \\ M_y \\ M_z \end{bmatrix} &= \begin{bmatrix} \dot{\omega}_x I_x \\ \dot{\omega}_y I_y \\ \dot{\omega}_z I_z \end{bmatrix} + \begin{bmatrix} \omega_y \omega_z I_z - \omega_y \omega_z I_y \\ \omega_x \omega_z I_x - \omega_x \omega_z I_z \\ \omega_x \omega_y I_y - \omega_x \omega_y I_x \end{bmatrix} \end{aligned} \quad (3.7)$$

Euler's equations of motion for a rigid body for the roll, pitch, and yaw axes are the following three dynamic equations.

$$\begin{aligned} M_x &= \dot{\omega}_x I_x + (I_z - I_y) \omega_{yz} \\ M_y &= \dot{\omega}_y I_y + (I_x - I_z) \omega_{zx} \\ M_z &= \dot{\omega}_z I_z + (I_y - I_x) \omega_{xy} \end{aligned} \quad (3.8)$$

3.4.2 Attitude Kinematics of CubeSat

3.4.2.1 Euler Angles

A rigid body's orientation in three dimensions is described by a set of three angles called the Euler Angles. They are frequently employed in aerospace engineering, particularly in the design and operation of CubeSat. Suppose initially that when the relationship between these two frames is realized, the orbital frame (x_o, y_o, z_o) and the body frame (x_b, y_b, z_b) both coincide.

The three Euler Angles are often identified by roll, pitch, and yaw. Roll is used to indicate rotation about the x-axis, pitch is used to represent rotation about the y-axis, and yaw is used

to represent rotation about the z-axis. Any vector can be converted from orbit frame to body frame using the direction cosine matrix that is created by combining the outputs of these rotations.(Anton H.J. de Ruiter & FoRbes, 1997)(Sidi, 2017) Hence from direction cosine,

$$F^b = C_1(\varphi)C_2(\theta)C_3(\psi)F^o \quad (3.9)$$

where F^b is the body frame and F^o is the orbit frame

$$\begin{bmatrix} x_b \\ y_b \\ z_b \end{bmatrix} = \begin{bmatrix} c\theta.c\psi & c\theta.s\psi & -s\theta \\ s\phi.s\theta.c\psi - c\phi.s\psi & s\phi.s\theta.s\psi + c\phi.s\psi & s\phi.c\theta \\ c\phi.s\theta.c\psi - s\phi.s\psi & c\phi.s\theta.s\psi - s\phi.c\psi & c\phi.c\theta \end{bmatrix} \cdot \begin{bmatrix} x_o \\ y_o \\ z_o \end{bmatrix} \quad (3.10)$$

The orbit frame angular velocity with respect to the Earth equals:

$$\omega^{o/i} = -\omega_o Y_o \quad (3.11)$$

$$\omega_o = \sqrt{\frac{\mu}{R_o^3}}$$

Where $\mathbf{R}_o$ radius vector from the center of the Earth to the center of the CubeSat and ω_o is equal to 1.107×10^{-3} rad/s for a 500km orbit altitude.

As a result, given equation (3.9), $\omega^{o/i}$ provides

$$\omega^{o/i} = -\omega_o \begin{bmatrix} s\psi.c\theta \\ s\phi.s\theta.s\psi + c\psi.c\phi \\ c\phi.s\theta.s\psi - s\phi.c\psi \end{bmatrix} \quad (3.12)$$

Given basis vectors (X_b, Y_b, Z_b) , the angular velocity of the body-fixed reference frame F_b is given by:

$$\omega = \omega^{b/i} = \omega^{b/o} + \omega^{o/i} \quad (3.13)$$

Furthermore, $\omega^{b/o}$ can be used to represent the angular velocity of the body frame in relation to the orbital frame for the sequence $C_1(\varphi) \leftarrow C_2(\theta) \leftarrow C_3(\psi)$.

$$\begin{bmatrix} \omega'_x \\ \omega'_y \\ \omega'_z \end{bmatrix} = \begin{bmatrix} 1 & 0 & -s\theta \\ 0 & c\phi & s\phi c\theta \\ 0 & -s\phi & c\phi c\theta \end{bmatrix} \cdot \begin{bmatrix} \dot{\phi} \\ \dot{\theta} \\ \dot{\psi} \end{bmatrix} \quad (3.14)$$

Subsequently, by rearranging equations (3.12) and (3.13) in (3.14), this results in

$$\begin{bmatrix} \omega_x \\ \omega_y \\ \omega_z \end{bmatrix} = \begin{bmatrix} 1 & 0 & -s\theta \\ 0 & c\phi & s\phi c\theta \\ 0 & -s\phi & c\phi c\theta \end{bmatrix} \cdot \begin{bmatrix} \dot{\phi} \\ \dot{\theta} \\ \dot{\phi} \end{bmatrix} - \omega^o \begin{bmatrix} s\psi.c\theta \\ s\phi.s\theta.s\psi + c\psi.c\phi \\ c\phi.s\theta.s\psi - s\phi.c\psi \end{bmatrix} \quad (3.15)$$

A rigid body in orbit has the following kinematic differential equations:

$$\begin{bmatrix} \dot{\phi} \\ \dot{\theta} \\ \dot{\phi} \end{bmatrix} = \begin{bmatrix} 1 \\ c\theta \end{bmatrix} \begin{bmatrix} c\theta & s\phi s\theta & c\phi s\theta \\ 0 & c\phi c\theta & -s\phi c\theta \\ 0 & c\phi & c\phi \end{bmatrix} \cdot \begin{bmatrix} \omega_x \\ \omega_y \\ \omega_z \end{bmatrix} + \begin{bmatrix} \omega_o \\ c\theta \end{bmatrix} \begin{bmatrix} s\psi \\ c\psi c\theta \\ s\psi s\theta \end{bmatrix} \quad (3.16)$$

3.5 CubeSat Linearized Dynamic Model

A CubeSat's motion in terms of its orientation in space is described by a linearized dynamic model using Euler angles. To describe the motion of the satellite in a clearer and more controllable manner, this model uses linearized equations of motion for a CubeSat that are expressed in terms of Euler angle rates and accelerations. In order to increase computational efficiency, it also eliminates trigonometric terms. It is helpful for predicting, controlling, and designing control systems for the satellite. (Sidi, 2017)

Operating points for linearization in the context of small angle approximation for a CubeSat's motion describe specific states where the system is considered to be in equilibrium (0°,0°,0°) or nominal conditions. These operating points are carefully chosen to ensure that the deviations from these states are small enough to justify the linearization process effectively. The method of linearization involves approximating trigonometric terms, such as sine and cosine, using their linear counter parts. This simplification eliminates nonlinear terms from the equations of motion, making them easier to analyze and compute.

In this instance, linearization for small angles requires substituting:

$\sin \sigma \approx \tan \sigma \approx \sigma$ and $\cos \sigma \approx 1$ then Equation (3.11) becomes

$$\begin{bmatrix} \omega_x \\ \omega_y \\ \omega_z \end{bmatrix} = \begin{bmatrix} \dot{\phi} + \omega_o \\ \dot{\theta} - \omega_o \\ \dot{\phi} - \omega_o \phi \end{bmatrix} \quad (3.17)$$

The following linearized dynamic equations are developed by inserting this equation into Equations (3.14):

$$\begin{aligned}
I_x \ddot{\phi} - \omega_o^2 (I_z - I_y) \phi - \omega_o (I_x + I_z - I_y) \dot{\psi} &= M_x \\
I_y \ddot{\theta} &= M_y \\
I_z \ddot{\psi} + \omega_o^2 (I_y - I_x) \psi + \omega_o (I_z - I_y + I_x) \dot{\phi} &= M_z
\end{aligned} \tag{3.18}$$

Equations (3-14) demonstrate that while motion in pitch is independent, motion in roll and yaw are coupled through the orbit rate. Consequently, the motion in the pitch axis is considered as a Single Input Single Output (SISO) system, whereas the motion in the roll and yaw axes is regarded as a Multi Input Multi Output (MIMO) system. Equations (3–14) may be rewritten as follows:

$$\begin{aligned}
\ddot{\phi} &= \frac{1}{I_x} (\omega_o^2 (I_z - I_y) \phi + \omega_o (I_x + I_z - I_y) \dot{\psi} + M_x) \\
\ddot{\theta} &= \frac{M_y}{I_y} \\
\ddot{\psi} &= \frac{1}{I_z} (-\omega_o^2 (I_y - I_x) \psi - \omega_o (I_z - I_y + I_x) \dot{\phi} + M_z)
\end{aligned} \tag{3.19}$$

3.6 Disturbance Torques

A CubeSat can rotate or change its orientation as a result of external forces, which are referred to as disturbance torques. These can be caused by a variety of factors, including atmospheric drag, magnetic fields, and solar radiation pressure. These torques must be taken into account when designing and operating a CubeSat since they can affect its stability and control. To reduce the impacts of disturbance torques, CubeSats often use control devices, like magnetic torquers or reaction wheels, to maintain their target orientation. To further reduce the impact of disturbance torques, CubeSat designs frequently incorporate symmetrical shapes, low drag coefficients, and low magnetic susceptibility materials.

3.6.1 Gravity Gradient Torque

Gravity gradient torque is the force that a CubeSat encounters as a result of the varying gravitational pulls on various regions of the satellite. During an Earth orbit, a CubeSat experiences a torque or twisting force because the gravitational pressure on the top of the satellite is larger than the pull on the bottom. This torque may force the satellite to rotate or alter its orientation, which may have an impact on the satellite's functionality and communication capacities. CubeSat's frequently use magnetic torquers or reaction wheels to counteract this torque and keep their orientation consistent. (Curtis, 2021) (Anton H.J. de Ruiter & Forbes, 1997) (Mahdi et al., 2014)

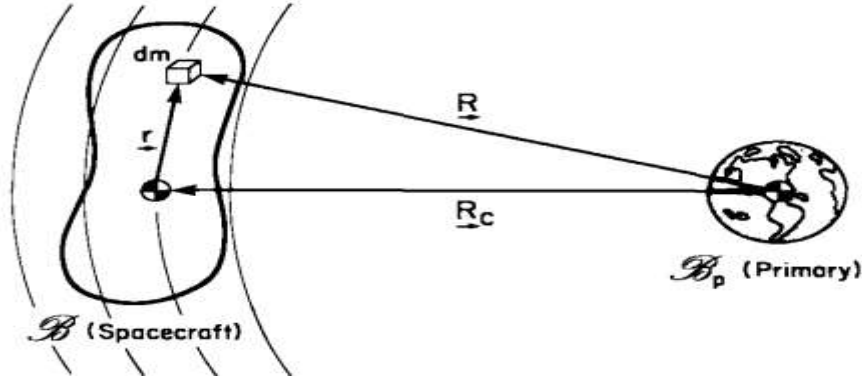


Figure 3.2 CubeSat in the gravitational field (Bin & Basri, 2021)

Assume that the gravity gradient vector is:

$$G = \begin{bmatrix} G_x \\ G_y \\ G_z \end{bmatrix} \quad (3.20)$$

The gravitational force that a mass element experiences is

$$dF = - \left[\frac{\mu dm}{|r|^3} \right] r \quad (3.21)$$

Where R is the location of the CubeSat's center of mass in orbit, ρ is the separation between any mass element dm in the body and the body's center of mass, μ is universal gravitational constant and $r = R + \rho$ is the separation between the mass dm and the Earth's center of mass.

The assumption is $\rho \ll R$ following which the moment about the body's center of mass becomes

$$dG = \rho \times dF = - \left[\frac{\mu dm}{|r|^3} \right] \rho \times r \quad (3.22)$$

In the case of $\rho \ll R$, $\frac{1}{r^3}$ can approximately be expressed as:

$$\frac{1}{r^3} \approx \frac{1}{R^3} \left[1 - \frac{3R \cdot \rho}{R^2} \right] \quad (3.23)$$

Integration of Equations 3.19 and 3.22 over the entire body mass, then

$$G = \frac{3\mu}{R^5} \int_M [R, \rho][\rho \times R] dm \quad (3.24)$$

After computing the scalar and vector products, then

$$\begin{aligned} T_{Gx} &= \frac{3\mu}{2R^3} (I_z - I_y) \sin(2\phi) \cos^2(\theta) \\ T_{Gy} &= \frac{3\mu}{2R^3} (I_z - I_x) \sin(2\theta) \cos(\phi) \\ T_{Gz} &= \frac{3\mu}{2R^3} (I_x - I_y) \sin(2\theta) \sin(\phi) \end{aligned} \quad (3.25)$$

By linearizing equations (3-24) for a body in a circular orbit and using small-angle

approximations for (ϕ) and (θ) , then substitute ω_o with $\sqrt{\frac{\mu}{R_o^3}}$. The gravity gradient torque's linearized form is

$$\begin{aligned} T_{Gx} &= 3\omega_o^2 (I_z - I_y) \psi \\ T_{Gy} &= 3\omega_o^2 (I_z - I_x) \theta \\ T_{Gz} &= 0 \end{aligned} \quad (3.26)$$

where T_{Gx} , T_{Gy} , and T_{Gz} , respectively, represent the gravity gradient torque about the Roll, Pitch, and Yaw axes. Equation (3-26) is then obtained by substituting equation (3-25) to equation (3-18). Equation (3.26) depicts satellite linearized equations with torque generated by gravity gradient

$$\begin{aligned} \ddot{\phi} &= -\frac{4}{I_x} \omega_o^2 (I_y - I_z) \phi + \omega_o (I_x - I_y - I_z) \dot{\psi} \\ \ddot{\theta} &= -\frac{3}{I_y} \omega_o^2 (I_x - I_z) \theta \\ \ddot{\psi} &= -\frac{1}{I_z} \omega_o^2 (I_y - I_x) \psi - \omega_o (I_x - I_y + I_z) \dot{\phi} \end{aligned} \quad (3.27)$$

3.6.2 Magnetic Field Torque

The force that a magnetic field applies to an object is referred to as magnetic field torque. This force can be used to regulate the attitude, or orientation, of a CubeSat in space. This is accomplished by using devices known as magnetorquers, which generate magnetic fields by running an electric current through one or more coils of wire. The magnetic field that is formed by the coils' current flowing through them induces a torque, or rotational force, on

the CubeSat. The magnetic field's strength and the torque it exerts on the CubeSat are determined by the quantity of current passing through the coils. The magnetic field will be stronger and the torque that can be applied to the CubeSat will be greater as current flows. Therefore, the CubeSat's attitude can be changed by adjusting the current passing through the magnetorquer coils. The amount of torque that can be produced depends on the number of coils as well. The magnetic field's strength will increase as there are more coils. A CubeSat with multiple magnetorquer coils will therefore be able to produce more torque and exert more control over its attitude. It's important to note that increasing the current flow and coil number will also increase the torque that can be applied to the CubeSat, improving the ability to control its attitude. The magnetic coils' torque can be modelled as follows: (Mahdi et al., 2014) (Curtis, 2021)

$$T_m^b = m^b \times B^b \quad (3.28)$$

Where m^b magnetic moment produced by the body and $B^b = [B_x^b \ B_y^b \ B_z^b]^T$ is the vector of the local geomagnetic field.

$$m^b = \begin{bmatrix} m_x^b \\ m_y^b \\ m_z^b \end{bmatrix} = m_x^b + m_y^b + m_z^b = \begin{bmatrix} N_x i_x A_x \\ N_y i_y A_y \\ N_z i_z A_z \end{bmatrix} \quad (3.29)$$

Where N_k is the number of windings in the magnetic coil, i_k is the coil current and A_k is the coil's span area.

The magnetic torque can be easily represented as follows:

$$\begin{bmatrix} T_{mx} \\ T_{my} \\ T_{mz} \end{bmatrix} = \begin{bmatrix} m_y B_\psi - m_z B_\theta \\ m_z B_\phi - m_x B_\psi \\ m_x B_\theta - m_y B_\phi \end{bmatrix} \quad (3.30)$$

Where:- The magnetic torques about the Roll, Pitch, and Yaw axes are T_{mx} , T_{my} , and T_{mz} , respectively, the magnetic moments are denoted by m_x , m_y , and m_z , respectively, and the effects of the Earth's magnetic field on the roll, pitch, and yaw axes are represented by B_ϕ , B_θ , and B_ψ .

3.7 The CubeSat Overall Linearization Mathematical Model

Equation (3-30) is added to equation (3-27) to get the final version of the linearized attitude dynamic model of the CubeSat, which includes torque from the magnetic coil and gravity gradient represented in body frame components.

$$\begin{aligned}\ddot{\phi} &= -\frac{4}{I_x} \omega_o^2 (I_y - I_z) \phi + \frac{\omega_o (I_x - I_y - I_z)}{I_x} \dot{\psi} + \frac{m_y B_\psi - m_z B_\theta}{I_x} \\ \ddot{\theta} &= -\frac{3}{I_y} \omega_o^2 (I_x - I_z) \theta + \frac{m_z B_\phi - m_x B_\psi}{I_y} \\ \ddot{\psi} &= -\frac{1}{I_z} \omega_o^2 (I_y - I_x) \psi - \frac{\omega_o (I_x - I_y + I_z)}{I_z} \dot{\phi} + \frac{m_x B_\theta - m_y B_\phi}{I_z}\end{aligned}\quad (3.31)$$

3.8 State Space Equation for CubeSat Dynamics

It is possible to develop a state space model based on an understanding of the physical laws governing the system or on the input-output interactions. For modeling to work, state variables must be specified, and present uncertainty must be understood statistically.

Defining the state variables as $x_1 = \phi$, $x_2 = \theta$, $x_3 = \psi$, $x_4 = \dot{\phi}$, $x_5 = \dot{\theta}$, $x_6 = \dot{\psi}$ gives the state space model that describes the satellite's dynamic behavior.

$$\dot{\mathbf{x}}(t) = \mathbf{A}\mathbf{x}(t) + \mathbf{B}\mathbf{u}(t) \quad (3.32a)$$

$$\mathbf{y}(t) = \mathbf{C}\mathbf{x}(t) \quad (3.32b)$$

where $\mathbf{x} = [\phi, \theta, \psi, \dot{\phi}, \dot{\theta}, \dot{\psi}]^T$ is the state vector, $\mathbf{u} = [m_x, m_y, m_z]^T$ is the input magnetic moment vector, $\mathbf{y}$ is the output vector, and $\mathbf{A}$, $\mathbf{B}$ and $\mathbf{C}$ are the matrices given by

$$\mathbf{A} = \begin{bmatrix} 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 \\ -\frac{4}{I_x} \omega_o^2 (I_y - I_z) & 0 & 0 & 0 & 0 & \frac{\omega_o (I_x - I_y - I_z)}{I_x} \\ 0 & -\frac{3}{I_y} \omega_o^2 (I_x - I_z) & 0 & 0 & 0 & 0 \\ 0 & 0 & -\frac{1}{I_z} \omega_o^2 (I_y - I_x) & -\frac{\omega_o (I_x - I_y + I_z)}{I_z} & 0 & 0 \end{bmatrix}$$

$$\mathbf{B} = \begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & \frac{B_\psi}{I_x} & \frac{-B_\theta}{I_x} \\ \frac{-B_\psi}{I_y} & 0 & \frac{B_\phi}{I_y} \\ \frac{B_\theta}{I_z} & \frac{-B_\phi}{I_z} & 0 \end{bmatrix} \text{ and } \mathbf{C} = \begin{bmatrix} -16 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1.02 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 \end{bmatrix} \quad (3.32c)$$

It can be easily verified that the pair of $(\mathbf{A}, \mathbf{B})$ in Equation (3.32c) is controllable with the parameters in Tables 5.1- 5.4

CHAPTER FOUR

4 CONTROLLER DESIGN

4.1 Full State Feedback Controller

Full-state feedback control is a technique that's commonly utilized to keep CubeSat's oriented properly. Essentially, a state vector is used to measure the roll, pitch, and yaw angles of the CubeSat's orientation. With this data, the attitude control system can determine the necessary control action required to bring the satellite's attitude to the desired orientation. The appropriate control signal is calculated using state vector feedback by the controller which can either minimize the difference between the actual and desired attitude or reach a certain level of precision. There's also compensation for disturbances or uncertainties embedded in the control signal.(Setiawan & Pratama, 2021)

Basically, the control input u is given by:

$$u = -Kx \quad (4.1)$$

where K is the state feedback gain matrix. There are several methods for calculating the feedback matrix K , including optimal control theory and the pole placement method. In this thesis, the pole placement method is employed in this thesis.

The control action was accomplished under the state feedback control (Figure 4-1) by adding the feedback matrices K to generate the control input u .

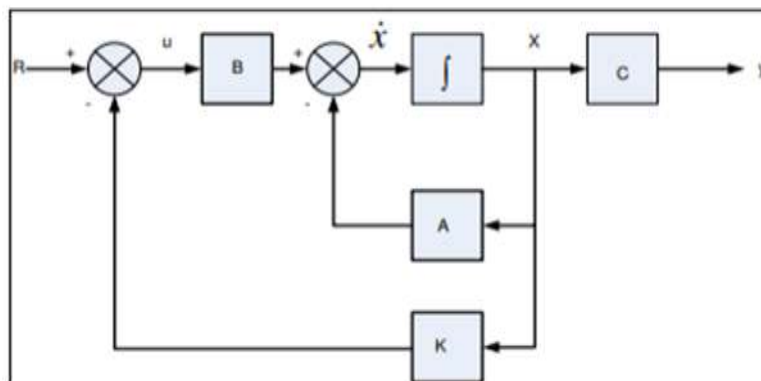


Figure 4.1 Full State Feedback Control Block Diagram (Radzak & Arshad, 2005)

4.1.1 Controllability

If a controlled input can transfer (change) the control system's initial states to some other desired states in a finite amount of time, the control system is said to be controllable.

Using controlled inputs within a finite duration of time, the ability of an attitude control system to change the initial orientation of a CubeSat to a desired orientation is known as controllability in the context of CubeSat attitude control. An attitude control system is considered controllable when it is capable of effectively and efficiently adjusting the attitude of the CubeSat to match mission requirements and objectives.

4.1.2 Pole placement method

There are different pole assignment methods, including the brute force method, similarity transformation method and Ackermann formula. Each has its own advantages and disadvantages.(BOGLOU, 1988) One of the most commonly used methods is the Ackermann formula. The Ackermann formula calculates the feedback gain matrix K in four steps as

Step 1: Obtain the polynomial $\Delta(\lambda)$ from the given poles of n .

$$\Delta(\lambda) = (\lambda - \bar{\lambda}_1)(\lambda - \bar{\lambda}_2) \cdots (\lambda - \bar{\lambda}_n) = \lambda^n + \bar{a}_1\lambda^{n-1} + \cdots + \bar{a}_n \quad (4.2)$$

Step 2: In $\Delta(\lambda)$, obtain $\phi(A)$ by substituting A for λ .

$$\phi(A) = A^n + \bar{a}_1A^{n-1} + \cdots + \bar{a}_{n-1}A + \bar{a}_nI \quad (4.3)$$

Step 3: Obtain the controllability matrix U .

$$U = [B \ AB \ \cdots \ A^{n-1}B] \quad (4.4)$$

Step 4: Find K with the following formula

$$K = [0 \ \cdots \ 0 \ 1]U^{-1}\phi(A) \quad (4.5)$$

This method needs the pre-defined poles to calculate K . The Bessel polynomial method is a technique for designing feedback controllers for linear time-invariant (LTI) systems. The fundamental idea behind the Bessel polynomial method is to specify the desired poles of the closed-loop system using the coefficients of a Bessel polynomial. This is accomplished by first figuring out the open-loop system's characteristic polynomial, and then utilizing the Bessel polynomial coefficients to eliminate the system's unwanted poles. The resulting

polynomial is then used to design the feedback controller.(Srivastava, 2023) Table 4.1 shows the pole locations applicable to linear systems of order 10 and below.

Table 4.1 Poles of Bessel polynomials adjusted to one second of settling time.(Rodríguez et al., 2013)

n	Pole locations of $B_n(s)$
1	-4.6200
2	-4.0530±j2.3400
3	-5.0093, -3.9668±j3.7845
4	-4.0156 ± j5.0723, -5.5281± j1.6553
5	-6.4480, -4.1104 ± j6.3142, -5.9268 ± j3.0813
6	-4.2169 ± j7.5300, -6.2613 ± j4.4018, -7.1205 ± j1.4540
7	-8.0271,-4.3361 ± 0.7519,-6.5714 ± j5.6786, -7.6824 ± j2.8081
8	-4.4554± j9.9715, -6.8554± j6.9278, -8.1682 ± j4.1057, -8.7693 ± j1.3616
9	-9.6585, -4.5696 ± j11.1838, -7.1145 ± j8.1557, -8.5962 ± j5.3655, -9.4013 ± j2.6655
10	-4.6835±j12.4022, -7.3609±j9.3777, -8.9898±j6.6057, -8.9657±j3.9342,-10.4278±j1.3071

For CubeSat attitude control, the control law's objective is to designate pole locations that will achieve adequate dynamic responses according to transient response specifications. To begin pole-placement, the closed-loop system's pole locations must first be chosen. Remember that the feedback's impact on the open-loop poles determines the required control effort. Near a pole, the system may become nearly uncontrollable if there happens to be a zero, which necessitates significant control gains and effort to move such poles. (*Pole Placement*, 2001) In the harshness of space, quick-response controllers are vital for maintaining a CubeSat's stability. Engineers can use pole positioning to craft controllers that stabilize the CubeSat's orientation and maintain it in a designated range.

For CubeSat attitude control to succeed in achieving mission goals, precise stabilization and pointing are key. One powerful tool for designing CubeSat control systems is the Bessel polynomial method featuring pole placement. By designing a controller that strategically places the closed-loop poles of the system, system stability can be guaranteed, facilitating an appropriate response to disturbances and increased precision and accuracy in mission

objectives attainment. For CubeSat attitude control applications, it is significant to ensure that the frequency response of the system is maximally flat, which can be achieved through the utilization of Bessel polynomials.

Using the feedback gains, K , from equation (4-1), the feedback system becomes

$$\begin{aligned}\dot{x} &= (A - BK)x \\ y &= Cx\end{aligned}\tag{4.6}$$

4.2 Intelligent Control

Full-state feedback controllers for CubeSat control need an exact model of the CubeSat's dynamics and precise model parameters, which can be difficult to obtain. The sensitivity of fixed gain controllers to disturbances is also high. In contrast, intelligent controllers with less strict mathematical design criteria, such as fuzzy logic, neural networks, and neuro-fuzzy controllers, are recognized for their ease of use, ability to tolerate uncertainty, and simplicity. A precise mathematical description of the CubeSat's dynamics is not required by these controls.

However, a straightforward FLC might have a constrained operating range and need substantial manual adjustment through trial and error to achieve high performance. In contrast, gathering a set of training data for an ANN can be very difficult. Despite these obstacles, intelligent techniques like FL, ANN, and ANFIS have been developed to help full-state feedback controllers for CubeSat's perform better by overcoming the challenges that arise in CubeSat control, such as complex computations, model nonlinearity, and uncertainties in model parameters.(de Silva, 2018)

4.2.1 Fuzzy Logic Controller

Fuzzy logic is one kind of artificial intelligence that builds human-like reasoning into a control system. Designing a fuzzy system can be compared to human thought processes, which involve deriving conclusions from prior knowledge.

A rule-based controller is the fuzzy logic controller (FLC). The FLC's structure is similar to that of a knowledge-based controller, but it applies fuzzy set theory concepts to both its logic and data representation.(Chen, 2010) As shown in Figure 4-2 below, the FLC's basic configuration is simply represented in four parts.

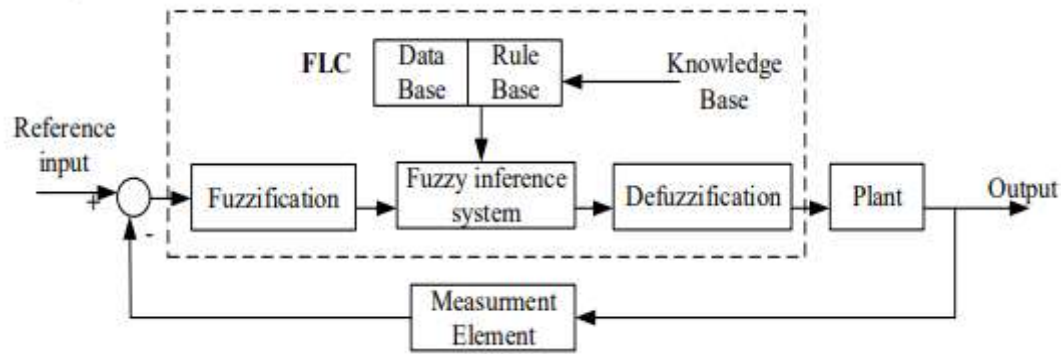


Figure 4.2 Fuzzy logic control system (Khedr, 2013)

4.2.1.1 Fuzzifier

A fuzzifier performs a variety of tasks, including measuring the input parameter values, scale mapping the input parameters into the corresponding domain of discourse, and the fuzzification process, which transforms input parameters from crisp to fuzzy values.

4.2.1.2 Knowledge base

Both a linguistic rule base and a database are present here. The database offers the definitions required to define the control rules and perform fuzzy manipulation, and the linguistic control rules keep track of the domain experts' control goals and control policies.

4.2.1.3 Decision making logic

One of a fuzzy logic controller's (FLC) key functions is the logic that underlies its capacity to decide and take output actions utilizing fuzzy concepts and rules. The FLC uses the idea of fuzzy logic to handle imprecise and uncertain information, and it has proven to be especially useful in situations where precise mathematical models are hard to come by or nonlinear behavior is present. The FLC can be used to regulate a system in many situations, outperforming traditional control approaches. To do this, language words for the rule base that make use of fuzzy sets and membership functions are created by combining expert knowledge and experience. (Chen, 2010) To provide a clear outcome, fuzzy inference techniques are used with these rules.

4.2.1.4 Defuzzifier

A mapping style that transforms fuzzily defined variables into precise values. It converts a control action that has been fuzzified into a non-fuzzy action. However, the primary disadvantage of the fuzzy logic controller is its restricted speed of operation, necessitating a greater amount of manual adjustment through trial and error in cases where high performance is necessary. The fact that system response time slows down as the number of

rules rises is another drawback of fuzzy logic. To obtain effective results, the rules are reset once more if the system doesn't operate satisfactorily. It cannot be modified in response to changing data. The system's accuracy is reliant on the skills and wisdom of human experts. The weighting factors in the fuzzy sets should be improved over time, and the rules should be updated accordingly. (Guanrong Chen and Trung Tat Pham, 2001) Techniques for swarm optimization, genetic algorithms, neural networks, etc. Fuzzy logic control systems can be optimized with this method. Consequently, an innovative technique called Adaptive Neuro-Fuzzy Inference System (ANFIS) has been developed, which combines the advantages of fuzzy logic and artificial neural networks.

4.2.2 Artificial Neural Network control

Compared to fuzzy logic, a neural network is the most general type of artificial intelligence (AI) for simulating human thought. The neural network is renowned for its capacity for learning as well as its ability to approximate any continuous function arbitrarily.

An artificial neural network is composed of a number of low-cost processors. A huge network of processors can do numerous tasks that are beyond the capacity of a single processor. (Liu, 2017) All processors are limited to a relatively basic mathematical task. The main concept is shown as shown in Figure 4-3.

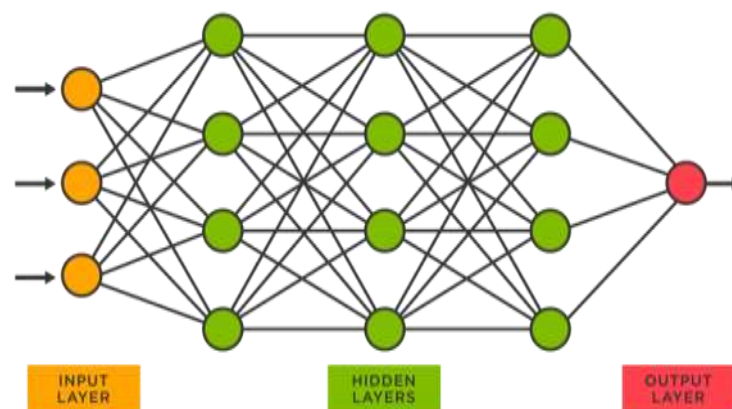


Figure 4.3 Many tiny processing units are connected to form a neural network. (What Is a Neural Network? | TIBCO Software, n.d.)

Artificial neural networks (ANN) have many advantages for intelligent control applications. These networks have a distinct advantage over conventional control techniques in that they don't require programming; instead, they learn from experience and modify their parameters. When dealing with nonlinear systems or situations where there are no precise mathematical models available, ANNs particularly shine. This crucial capacity to learn from sparse

training data and generalize to unobserved control can be a game-changer in a variety of circumstances. Due to their speed and ability to implement algorithms in real time, ANNs are excellent for a variety of applications. Another benefit of ANNs is their capacity for graceful failure, which prevents catastrophic failure that might jeopardize critical applications' system performance and safety.(Liu, 2017) ANNs have the potential to improve the efficiency of control systems, ensuring efficient control of complicated and nonlinear processes.

A weighted summer and an activation make up the basic model of a single artificial neuron, as seen in figure 4-4.

The neuron, represented by the letter i in Equation 4.7, receives its inputs from the external world or other linked neurons through their dendrites. All of these inputs with their respective weights add up to the neuron's activation, or activity, which is symbolized by the letter S . Each input has a weight based on a factor (w) that represents the strength of the dendritic synaptic connection. In terms of expression in mathematics:

$$S = i_1 w_1 + i_2 w_2 + i_3 w_3 + i_4 w_4 + i_5 w_5 \dots \quad (4.7)$$

Consequently, the neuron receives inputs and weights them based on the strength of the connection. Then, just like a biological neuron, it "fires" when the total of the weighted inputs exceeds a preset threshold. These neurons learn by changing their weights. Early artificial neural networks did this by using simple binary outputs.(de Silva, 2018) However, it was found that a continuous output function was more versatile, such as the Sigmoid function, for instance.

$$O = \frac{1}{1 + e^{-s}} \quad (4.8)$$

This function simply replaces the threshold function and always outputs an integer between zero and one, which is why it is commonly referred to as an activation or squashing function. In addition to the Sigmoid Function, the Linear, Logarithmic, and Tangential Functions are also sometimes employed as activation functions.

For a neuron with n inputs, the previously stated statement could be formalized.

$$S = i_1 w_1 + i_2 w_2 + i_3 w_3 + i_4 w_4 + \dots + i_n w_n \quad (4.9)$$

$$S = \sum_{x=1}^{x=n} w_x i_x \quad (4.10)$$

$$S = \bar{I} \cdot \bar{W} \quad (4.11)$$

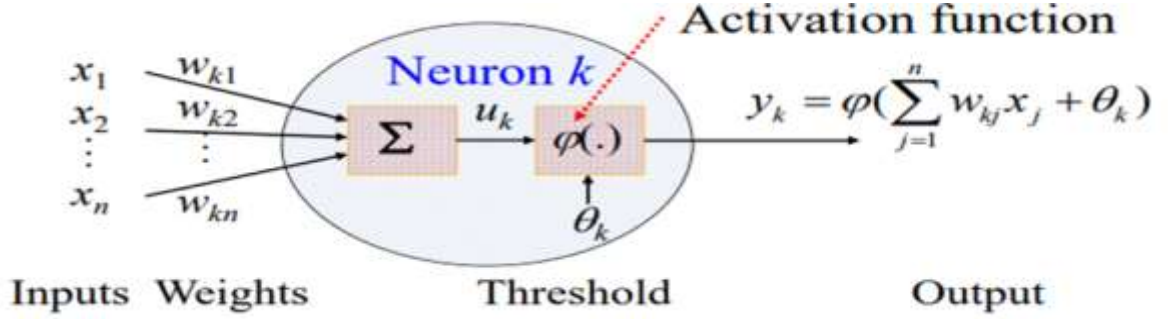


Figure 4.4 Artificial Neuron (Zhong et al., 2015)

4.2.2.1 Feedforward networks

An ANN is a network made up of separate neurons joined by synapses. Figure 4.5 shows a feedforward neural network with three layers. Figure 4.5 shows the feedforward network composed of three neurons for the input layer, one for the output layer, and two for the hidden layer.

Each layer of neurons is completely interconnected with every layer below it. A fully linked multilayer network, as it is commonly called, has no restrictions on the number of neurons in each layer or the number of hidden layers.

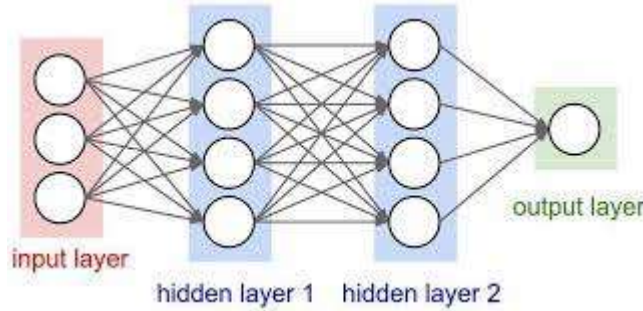


Figure 4.5 Three-layer feedforward neural network(Araya-Polo et al., 2017)

4.2.2.2 Recurrent Networks

The outputs of this type of artificial neural network are fed back into the inputs, adding feedback connections to the network. The capacity to store memories is one of the most intriguing actions that these connections are capable of exhibiting.

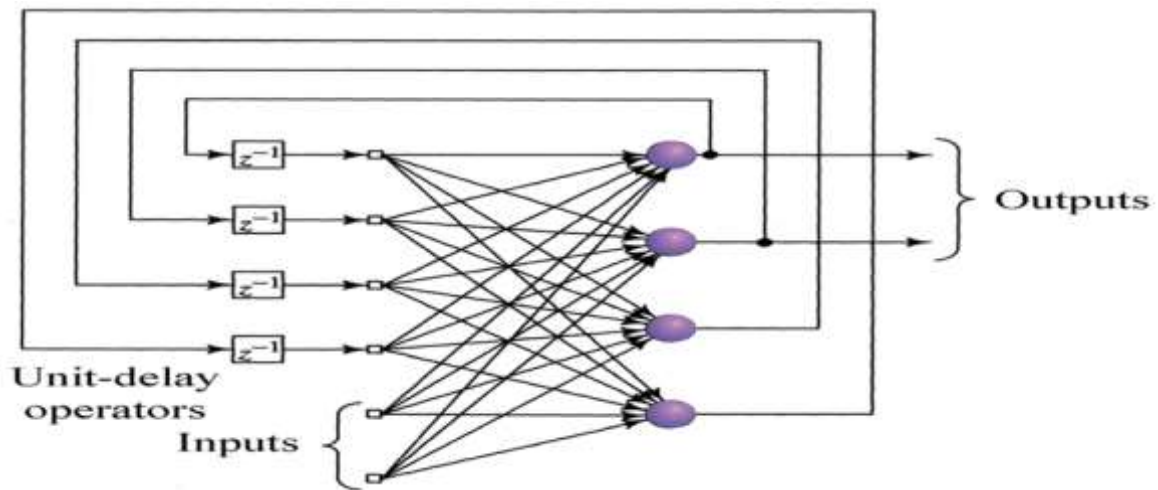


Figure 4.6 Recurrent (Feedback) networks (*A Recurrent Network | Scientific Diagram*, n.d.)

The process of changing the weights and biases in a neural network to get the intended response or output for a given input is known as learning.

Supervised Learning: Training data is fed into the network, showing the range of possible inputs and the matching intended outputs. Until the gap between the intended and actual outputs is smaller than a predefined minimal value, the weights are adjusted. Due to the availability of full-state feedback controller input and output data, supervised learning is used in this thesis.

Unsupervised Learning: Because the method does not modify the network's parameters using feedback information, it is also known as open loop adaptation. Image compression and speech recognition are two uses for unsupervised learning.

Backpropagation and hybrid learning algorithms are used in learning.

Backpropagation: To train a multi-layer perceptron network, you need to use forward and backward propagation in succession. Forward propagation starts by putting a sample from the training set into the network inputs and going layer-by-layer until the expected outputs are produced. It just takes the existing network parameters and node biases into account, and these don't change during this step. Subsequently, an error signal is generated by comparing the outputs of the network output nodes with the respective desired values. This signal is then backpropagated layer-by-layer until the parameters and bias changes occur in the final layer. Backpropagation, unlike the feedforward method, adjusts all the network nodes' parameters and biases. (Wu et al., 2011) This process of going forward and backward allows

the network parameters and node biases to be adjusted, which leads to a decrease in the errors in the responses to the desired outputs.

Hybrid learning Algorithm: This thesis makes use of a hybrid learning algorithm that combines the least squares estimator and the backpropagation algorithm. Backpropagation or steepest descent can be used to find the parameters in an adaptive network, however, these techniques frequently take a very long time to converge. However, it has been noted that an adaptive network's output is linear about a few of its parameters. These may be found using the linear least squares method, which speeds up the procedure.

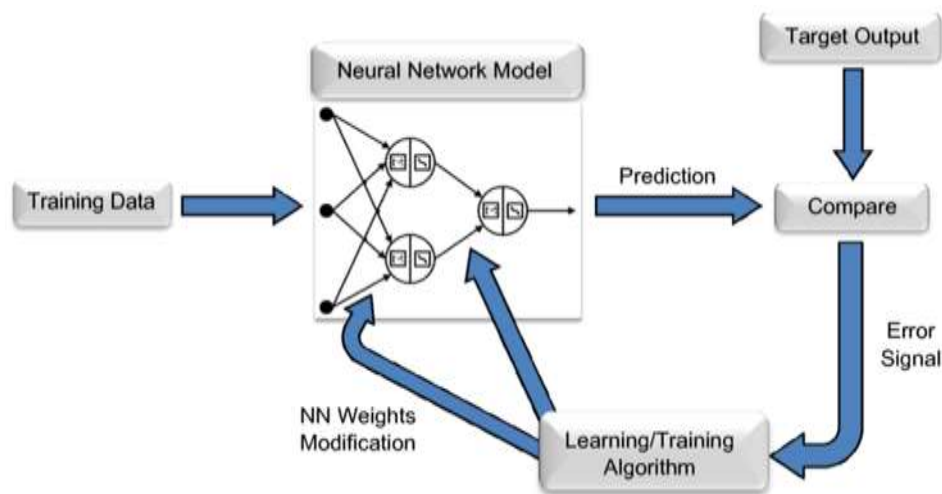


Figure 4.7 Training process of neural network (*The Representation of Neural Network Training Process.* | *Download Scientific Diagram*, n.d.)

Neural network training hinges on several factors that are necessary to consider. Such factors entail the performance index, training time frame, and the maximum iteration count. The accuracy or error rate is what the performance index corresponds to, and when training achieves a satisfactory level, it comes to a halt. A few repetitions of training on the same data is the definition of the maximum iteration count, which, upon surpassing, results in terminating training generally.(de Silva, 2018) Even if the desired performance has not been achieved, the completion of training can be influenced by the time given for it.

4.2.3 Adaptive Neuro Fuzzy inference system

Fuzzy logic and artificial neural networks together yield a neuro-fuzzy controller that can potentially outperform fuzzy logic or regular ANN controllers. This type of controller makes use of a Tagaki Sugno Kang (TSK) fuzzy inference system and is referred to as an adaptive

network-based fuzzy inference system (ANFIS). Its ability to self-modify its membership function to get a desired performance is its primary advantage.

The ANFIS architecture is shown in the figure in Figure 4-8. The circular nodes in the structure reflect constant operations, like product or max/min calculations, whereas the square nodes represent the parameter sets of the TSK fuzzy system. To speed up the process of fine-tuning parameters, a hybrid learning rule is employed. (Liu, 2017) This rule employs the sequential least squares approach in the forward pass to determine the consequence parameters and the backward pass to determine the premise parameters.

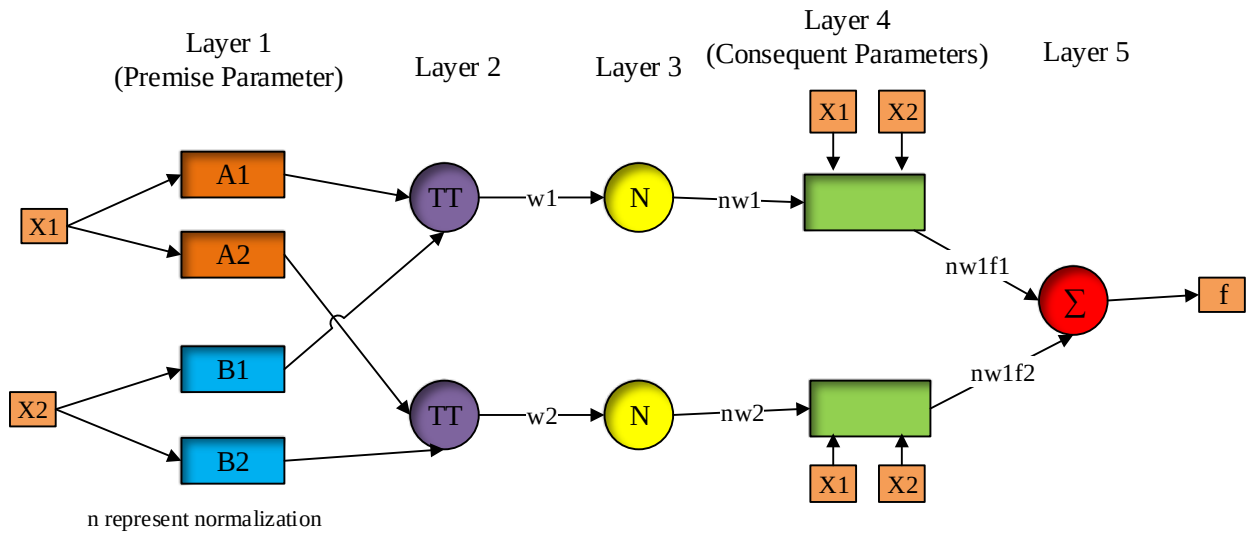


Figure 4.8 ANFIS architecture

A fuzzy inference system with two inputs (x_1 and x_2), an output (f), and the first order Takagi-Sugeno-Kang (TSK) rule base applied to it is shown in figure 4-8.

Rule 1: if x_1 is A_1 and x_2 is B_1 then $f_1 = p_1x_1 + q_1x_2 + r_1$

Rule 2: if x_1 is A_2 and x_2 is B_2 then $f_2 = p_2x_1 + q_2x_2 + r_2$

⋮

Rule n : if x_1 is A_n and x_2 is B_n then $f_n = p_nx_1 + q_nx_2 + r_n$

where the consequent functions of A_1 to A_n , B_1 to B_n , p_1 to p_n , q_1 to q_n and r_1 to r_n are all constants. The type of membership function used can be selected from those featured in a fuzzy logic toolbox.

In this thesis, a generalized bell-shaped membership function is used, and it can be described as follows:

$$\mu_A(x) = \frac{1}{1 + \left| \frac{x-c}{a} \right|^{2b}} \quad (4.12)$$

The parameter sets a, b, and c are optimized during the training process, and they are referred to as premise parameters.

ANFIS has **five layers**, each of which has its own specific purpose.

Layer 1: - Due to their adaptability, the nodes need a suitable premise membership function. The membership degree of the associated linguistic words for each node is given by the equations, where i is the number of nodes and A and B are the linguistic terms.

$$y_{1,i} = \mu_{A_i}(x_i) \quad (4.13)$$

$$y_{1,i} = \mu_{B_i}(x_i) \quad (4.14)$$

Layer 2: - Undertakes a T norm operation

In this layer, each node is a fixed node with the label TT. Each node in the output indicates the rule's firing strength and the output is the result of multiplying all of the incoming signals.

$$y_{2,i} = w_i = \mu_{A_i}(x_1) \mu_{B_i}(x_2) \dots \mu_{P_i}(x_n) \quad i = 1, 2, \dots, n \quad (4.15)$$

Layer 3: - Determines the ratio of the rule's firing strength

Every node in this layer has the label N and is a fixed node. The **i** node determines the ratio of the i rule's firing strength to the firing strength of all rules combined.

$$y_{3,i} = \frac{w_i}{\sum_{i=1}^n w_i} \quad (4.16)$$

Layer 4: - Generates the linear consequent functions.

Each node **i** in this layer has a node function and is an adaptable node.

$$f_n = p_n x_1 + q_n x_2 + r_n \quad (4.17)$$

Layer 5: - Sums all incoming signals.

This layer's single node, a fixed node with a label, adds up all incoming signals to generate the following overall output:

$$y_{5,i} = f = \sum_{i=1}^n \bar{w}_i f_i = \frac{\sum_{i=1}^n \bar{w}_i f_i}{\sum_{i=1}^n w_i} \quad (4.18)$$

The Takagi Sugeno fuzzy inference system is comparable to ANFIS. Gradient descent and least squares techniques along with backpropagation can be used to modify the membership functions and other parameters on training data pairs. As a result, the ANFIS modelling procedure is better structured and depends less on experience. Since every node in the first and fourth layers is adaptable, you can modify any of their settings to get the desired outcome. Although the nodes in layers two and three are fixed and lack parameters, the gradient-based learning process and the training data are used to change these parameters.

To establish the most precise mathematical link between inputs and outputs, the first layer (premise parameters) and fourth layer (consequent parameters) of the ANFIS must have their parameters changed during the learning process. The learning cycle consists of two passes: the backward pass updates the premise parameters using gradient descent, and the forward pass determines the consequent parameters using the least squares method. This hybrid approach makes use of the original fuzzy inference system and refines it over time by combining backpropagation and least square optimization. (Rodríguez et al., 2013) The same stopping criteria that are used for neural networks are implemented, and the error is measured at each epoch.

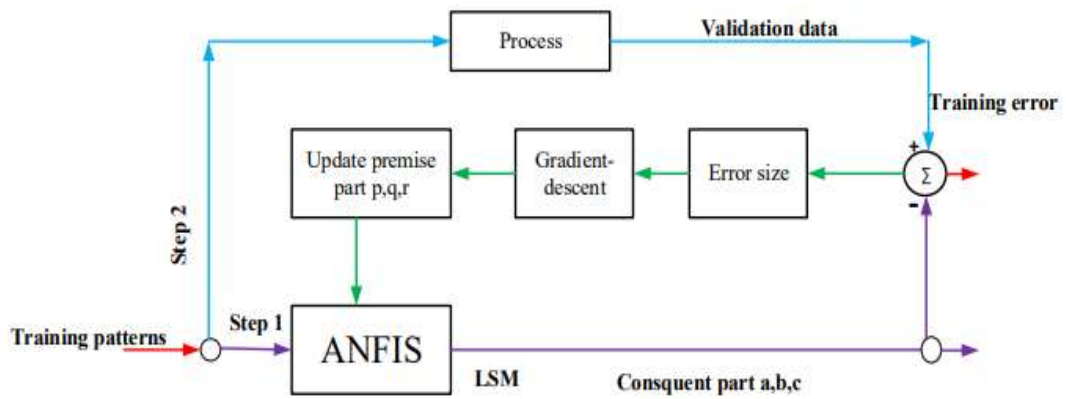


Figure 4.9 ANFIS learning process using hybrid algorithm (Araya-Polo et al., 2017)

CHAPTER FIVE

5 SIMULATION RESULT

5.1 Introduction

The proposed Attitude Control System (ACS) methods as outlined in the previous chapter undergo comprehensive simulation to evaluate their performance on the mathematical model of the CubeSat, which aims at evaluating how effective these control strategies are towards achieving three-axis stabilization and enhancing pointing capabilities of the CubeSat taking into account that magnetic control is non-linear and time-dependent due to changes in the geomagnetic field.

It uses Matlab as a simulation tool. The magnetic coils surrounding the X, Y, and Z axes of the CubeSat have an Adaptive Neuro-Fuzzy Inference System (ANFIS)-based fuzzy logic controller designed for them. It is worth mentioning that ANFIS has crucial support data from full state feedback controller.

To gain an understanding, conduct an investigation, into the connection between the input variables (X) and the corresponding output variable (Y). This exploration aims to enhance knowledge of the Attitude Control System (ACS) proposed for CubeSat's. Through histograms, visually depict the distribution of input variables across axes such as Roll, Pitch and Yaw. This provides insights into the variability present in the training data and helps evaluate the range and distribution of input parameters. Furthermore, utilize distributions to represent the relationships and dependencies between input and output variables for each axis. By doing, gain an understanding of how changes in input variables relate to variations in the output variable. Overall, this comprehensive analysis allows to holistically evaluate the training set used for the ANFIS based logic controller while providing insights, into the dynamics of CubeSat's attitude control system.

The graphical outcomes of the simulation along with the representations of data will play a role in assessing the suggested ACS methods and understanding their effects, on CubeSat attitude control when dealing with changing geomagnetic conditions.

5.2 Simulation Parameters

In the simulation model for the CubeSat, a comprehensive set of parameters has been defined to characterize its physical properties, initial conditions, and magnetic coil specifications.

The satellite parameters include fundamental attributes such as mass, dimensions, Earth radius, and altitude, influencing its dynamics in space. Initial conditions, encompassing roll, pitch, and yaw angles along with their respective rates, establish the starting configuration for the CubeSat's attitude. Additionally, the model incorporates detailed coil parameters, specifying the number of windings and the coil areas along the three axes. These parameters are crucial in understanding the magnetic control system's behavior. The ensuing tables categorize these parameters systematically, providing a clear overview of the input values utilized in the simulation, contributing to a comprehensive understanding of the CubeSat's behavior in a controlled environment.

Table 5.1 Satellite Parameters (Mahdi Et Al., 2014)

Parameter	Value	Unit
Mass (kg)	1	kg
X-axes Length (m)	0.1	m
Y-axes Length (m)	0.1	m
Z-axes Length (m)	0.1	m
Earth Radius (m)	6371.2×10^3	m
Satellite Altitude (m)	600×10^3	m
Distance from Earth Center to Satellite (m)	6971.2×10^3	m
Angular velocity of the CubeSat (rad/sec)	1.083×10^{-2}	rad/sec
Moment of Inertia about X (I_x)	0.1043	$\text{kg} \cdot \text{m}^2$
Moment of Inertia about Y (I_y)	0.1020	$\text{kg} \cdot \text{m}^2$
Moment of Inertia about Z (I_z)	0.0031	$\text{kg} \cdot \text{m}^2$

Table 5.2 Geomagnetic Field Parameters (Mahdi et al., 2014)

Parameter	Value	Unit
Geomagnetic Field (B_{ϕ})	25.01×10^{-6}	T
Geomagnetic Field (B_{θ})	11.14×10^{-6}	T
Geomagnetic Field (B_{ψ})	-16.59×10^{-6}	T

Table 5.3 Coil Parameters (Mahdi Et Al., 2014)

Parameter	Value	Unit
Number of Coil Windings (N_x)	305	-
Number of Coil Windings (N_y)	305	-
Number of Coil Windings (N_z)	305	-
Coil Area X (A_x)	0.006375	m ²
Coil Area Y (A_y)	0.006375	m ²
Coil Area Z (A_z)	0.006375	m ²
Maximum Magnetic Moment ($m_{\max}$)	0.1	Am ²

Calculating **A** and **B** with the parameters in Tables 5.1-5.3 and choosing the pre-defined poles of 6 so that the settling time of the feedback system has the settling time= 0.1724[orbit time]

$$p_1 \text{ and } p_2: (-4.2169 \pm j7.5300)/0.1724$$

$$p_3 \text{ and } p_4: (-6.2613 \pm j4.4018)/0.1724$$

$$p_5 \text{ and } p_6: (-7.1205 \pm j1.4540)/0.1724$$

the feedback gain matrix **K** can be calculated by the Ackermann formula as

$$K = \begin{bmatrix} -1.822 & -0.674 & 0.442 & 206.770 & 104.700 & -38.308 \\ 0.453 & 0.255 & -0.098 & 336.697 & 151.193 & -77.148 \\ -2.442 & -0.847 & 0.601 & 537.801 & 259.364 & -109.554 \end{bmatrix}$$

5.3 Full State Feedback Control

This thesis details the main contribution of a Full State Feedback Controller to the CubeSat's attitude control system. This controller has been designed to operate through magnetic coils that are responsible for controlling the CubeSat's angular orientation about its roll, pitch and yaw axes. Therefore, the gains of the controller have been adjusted accordingly. The purpose of this process is to shape desired performance indicators characterizing how the CubeSat reacts to external disturbances as well as perturbations.

As the initial conditions,

$\phi(0) = -10[\text{deg}]$, $\theta(0) = 30[\text{deg}]$, $\psi(0) = 10[\text{deg}]$, $\dot{\phi}(0) = 0[\text{deg/s}]$, $\dot{\theta}(0) = 0[\text{deg/s}]$, $\dot{\psi}(0) = 0[\text{deg/s}]$, was used.

Thus, based on the state-space representation of dynamics of CubeSat, the controller has been implemented. State equations include angular rates around all three axis (roll, pitch and yaw). These equations get integrated with a Runge-Kutta scheme. It is important to note that stability and required settling times are achieved only when controller gains are carefully tuned which depend on system characteristics and orbital considerations.

Figures that have been plotted displaying the simulation results, offer a visual representation of CubeSat's response due to Full State Feedback Controller. The first plot shows how x_1 , x_2 and x_3 change with time and this gives the measurement of how well satellite angle is controlled. The second plot has dx_1 , dx_2 , dx_3 as the corresponding angular rates while the third one has u_1 , u_2 and u_3 for control inputs.

In addition, these simulation results have two purposes in this thesis. This validates how effective the Full State Feedback Controller is at stabilizing the orientation of the CubeSat. The data was also gathered for use in training the Adaptive Neuro Fuzzy Inference System (ANFIS) based fuzzy logic controller that is to be used. It guarantees correct orientation of a CubeSat under the Full State Feedback Controller and uses data collected to make its ANFIS-based controller perform better.

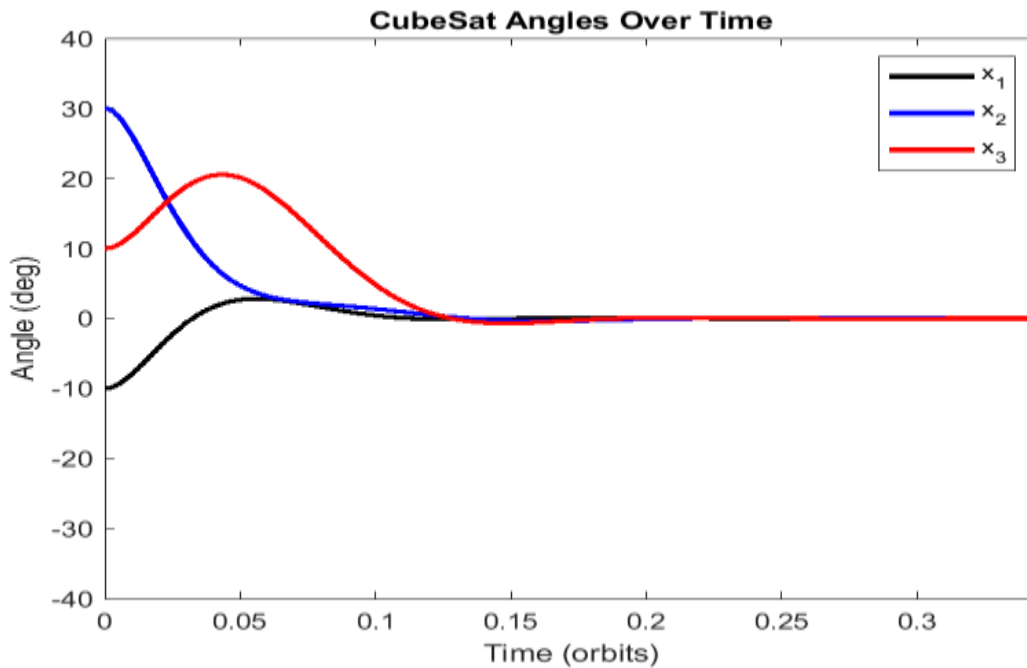


Figure 5.1 CubeSat angle over time

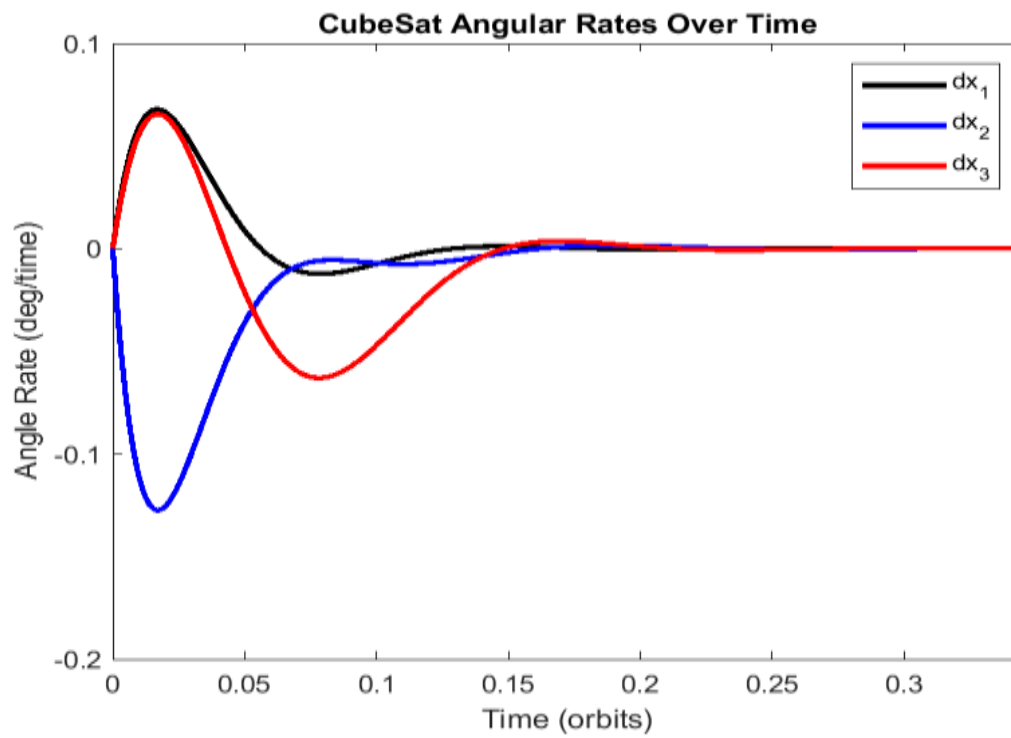


Figure 5.2 CubeSat rate over time

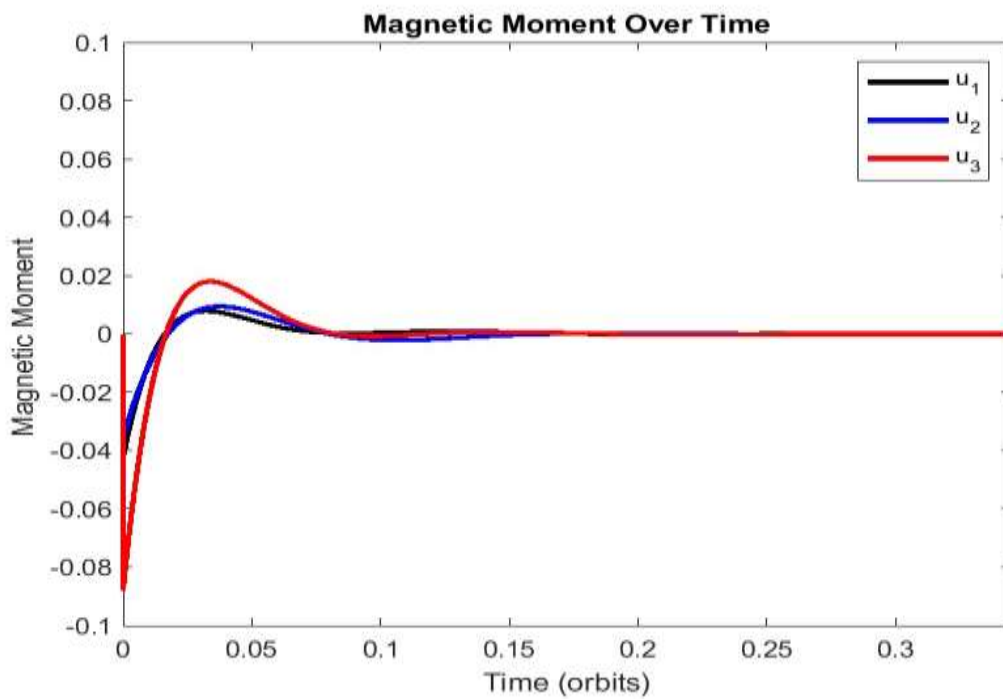


Figure 5.3 Magnetic Moment rate over time

5.4 Exploratory Data Analysis of Attitude Control Variables

Below, the plots that show the relationship between input/output and roll, pitch as well as yaw variables in a CubeSat system. Histograms and joint distribution plots can be used to determine distribution and dependency of training data. Histograms also reveal the probability density function (PDF) for each of our input axes, giving insights into how diverse and large our training sets can be. In addition, these joint distribution plots depict intricate relationships that exist between X (input) and Y (output) for every axis through complicated dynamics displayed in graphical forms.

Showing histograms for both position and velocity variables, the distribution of roll axis presents a more detailed picture about their individual features. These joint plots also give more information on how changes in input variables lead to fluctuations in the output variable, explaining system's behavior. Figures for pitch and yaw axes are provided in appendix 1.

In addition to being viewed through the graphical displays, the data is also helpful in finding out how the dataset is changing. To evaluate and assess the recommended Adaptive Neuro-Fuzzy Inference System (ANFIS) based fuzzy logic controller, this study has to be conducted.

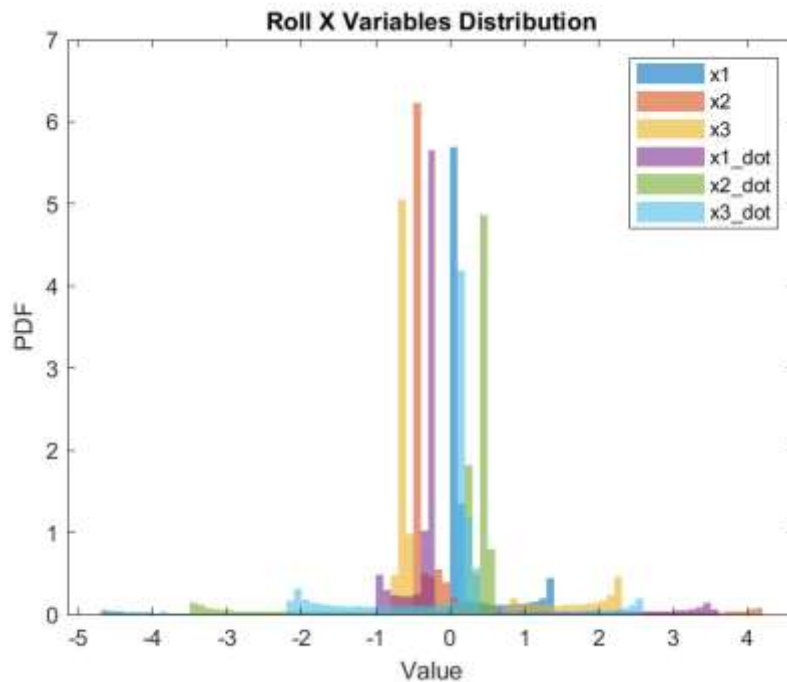


Figure 5.4 Roll Variables Distribution

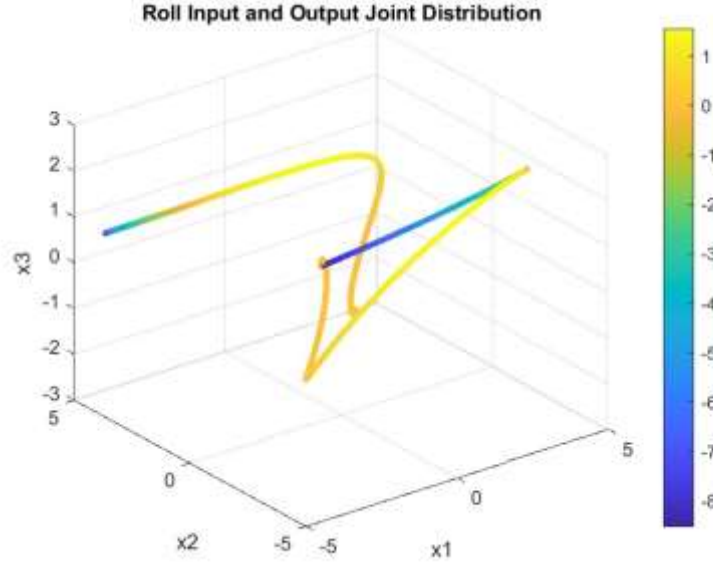


Figure 5.5 Roll input and Output joint distribution

5.5 ANFIS Controller

A CubeSat attitude control system was implemented using Adaptive Neuro-Fuzzy Inference System (ANFIS) based on training data obtained from Full State Feedback (FSF) controller as shown in the above figure. CubeSat has three controllers that operate on roll, pitch and yaw axis with each controller using trained ANFIS to generate control inputs. The simulation results are depicted in three subplots. The first plot illustrates the variation of roll (x_1), pitch (x_2), and yaw (x_3) angles over time (in terms of orbits). The second plot displays the corresponding angular rates (dx_1 , dx_2 , dx_3), while the third plot shows the control inputs (u_1 , u_2 , u_3) applied to the CubeSat.

With the help of the FSF controller, training data obtained from it is used to modify the ANFIS controllers so that they can adjust their inputs in response to the current state of CubeSat. This method uses knowledge embedded in FSF training data to improve the performance of ANFIS based controllers. For instance, during the training phase, histograms and joint distribution plots were generated. They provide more understanding about how input variables relate to output variables and thus capture system dynamics.

The effectivity of ANFIS-based approach in CubeSat is shown by this simulation. There is improvement in the performance as well as robustness of FSF training data by changing control inputs according to various dynamics.

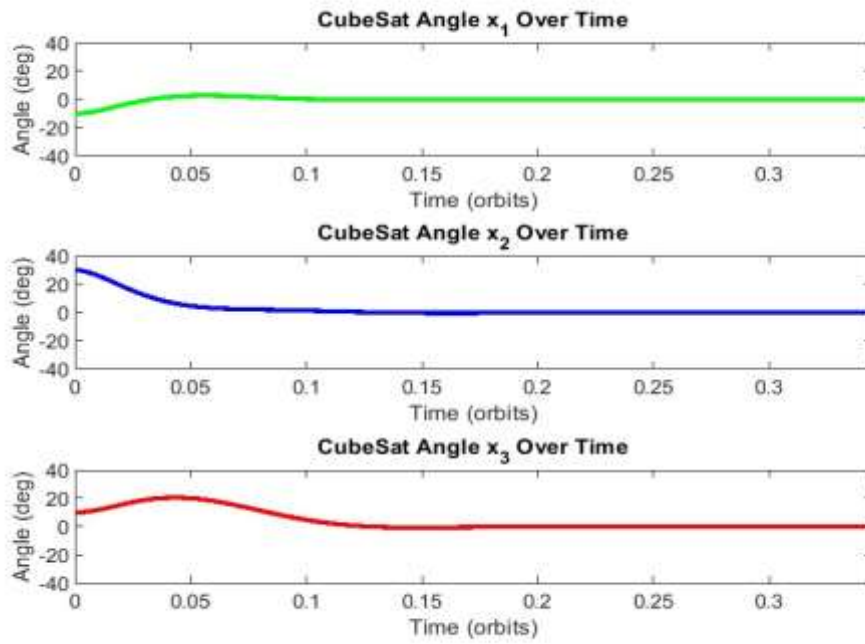


Figure 5.6 CubeSat angle over time

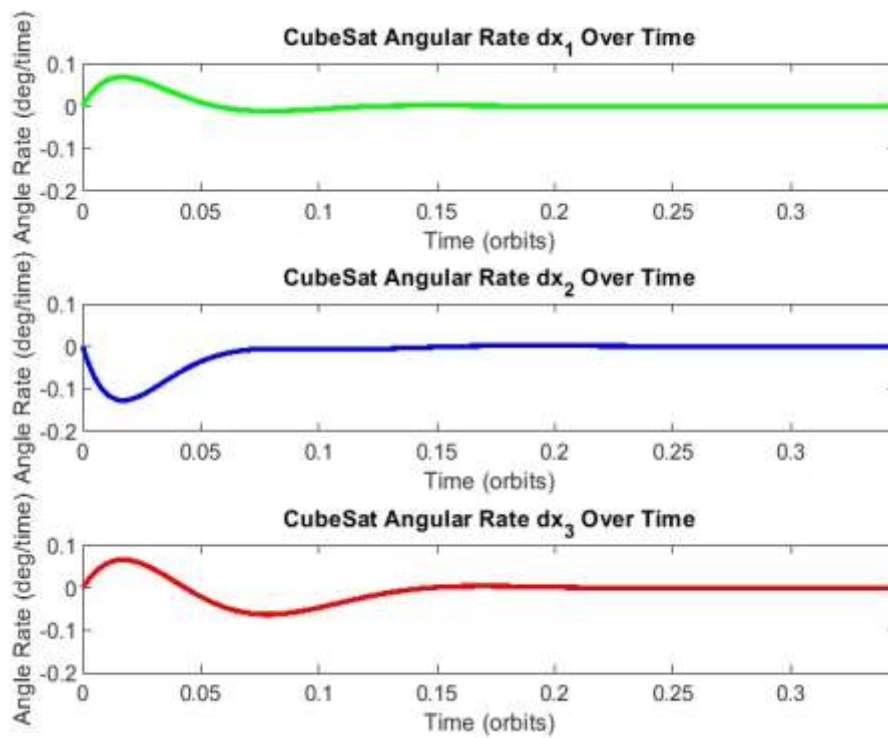


Figure 5.7 CubeSat angle over time

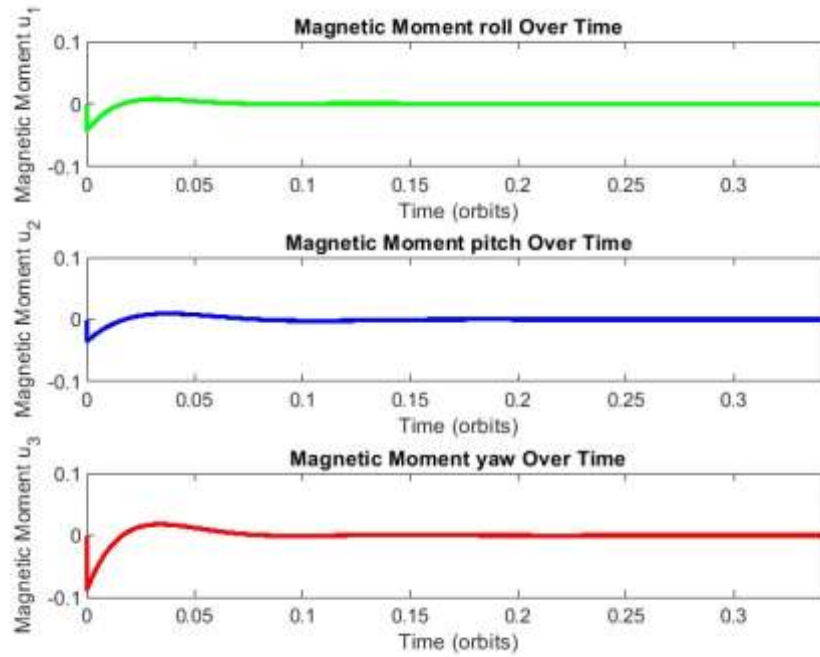


Figure 5.8 Magnetic Moment over time

5.6 Comparison between Full State Feedback Controller and ANFIS

Table 5.4 System analysis (ANFIS and FSF)

Controller	Angles	Peak Time	Settling Time	Peak Value	Steady State Error
Full State Feedback controller	Roll	0	0.1058	0.1745	0
	Pitch	0	0.1177	0.5236	0
	Yaw	0.0433	0.1677	0.3582	0
	Roll Rate	0.0168	0.1212	0.0012	0
	Pitch Rate	0.0171	0.1466	0.0022	0
	Yaw Rate	0.0170	0.1979	0.0011	0
ANFIS controllers	Roll	0	0.1058	10	0
	Pitch	0	0.1176	30	0
	Yaw	0.0433	0.1677	20.5291	0
	Roll Rate	0.0168	0.1212	0.0679	0
	Pitch Rate	0.0171	0.1465	0.1274	0
	Yaw Rate	0.0170	0.1979	0.0656	0

The FSF controller has peak times for roll, pitch, and yaw angles that are quite low; this shows fast response to changes in CubeSat's orientation. Correspondingly, the peak values of roll, pitch and yaw angles remain well with set standards emphasizing on the stability of FSF controller. Furthermore, low settling times as well as steady state errors across all controlled parameters highlight how strong FSF control is in keeping desired CubeSat attitude.

On the other hand, the ANFIS controllers show good performance as witnessed by the fact that it has peak times comparable to FSF control. Enhanced peak values in roll and pitch angles for CubeSat's controlled by ANFIS suggest the potential for achieving more dynamic and agile maneuvers. Notably, the yaw angle has a peak value of 20.5291 implying that there is a strong response to external inputs or changes in magnetic field of earth. The ANFIS controllers still manage to minimize steady-state errors despite these high peaks thereby showing their flexibility and efficiency towards maintaining desired attitude for CubeSat's.

CHAPTER SIX

6 CONCLUSION AND RECOMMENDATION

6.1 Conclusion

Distinct characteristics emerge in the comparative analysis of Full State Feedback (FSF) and Adaptive Neuro-Fuzzy Inference System (ANFIS) controllers for CubeSat attitude control. For roll, pitch and yaw angles, the FSF controller is characterized by accuracy, quick moves with peak times falling between 0.0170 to 0.0433 orbital time rates. Corresponding roll, pitch and yaw rates are effectively controlled with peak values of 0.1745, 0.5236 and 0.3582 orbit time respectively. Minimal steady-state errors characterize the FSF controller showing its high robustness in maintaining desire attitude for CubeSat attitude system

On the other hand, the ANFIS controllers perform well and stabilize the CubeSat on roll, pitch, and yaw angles with their settling times comparable to FSF control. Astonishingly, ANFIS-controlled CubeSat has slightly increased peak values of roll and pitch angles meaning improved maneuvering state. Steady-state errors for ANFIS control remain insignificant showing that neuro-fuzzy inference system (ANFIS) remains an efficient tool in keeping the intended attitude of CubeSat on course.

The present comparative analysis has pointed out that both controllers have performed well; one should choose FSF or ANFIS depending on the specific mission's needs and computational aspects. ANFIS-controlled CubeSat's, having a slightly increased peak values with roll, pitch, and yaw angles at 10,30, and 20.5291 respectively, may be successful in situation requiring rapid change of orientation or adjustment to varying external conditions. On the other hand, FSF is best when it comes to quick stabilization and low steady-state errors which makes sure that the direction of a satellite remains constant and stable.

Stability and maneuverability tradeoffs must be well thought out to avoid any negative impact on CubeSat activities. FSF controller is the right one for stabilization priority mission. ANFIS-based controlled CubeSat with their improved peak values are perfectly positioned to excel in cases needing agile moves. The developed Attitude Control System effectively solves post-detumbling challenges ensuring that the CubeSat remains stable and oriented after boom deployment.

6.2 Recommendation

After doing an in-depth analysis of Full State Feedback (FSF) and Adaptive Neuro-Fuzzy Inference System (ANFIS) controllers for CubeSat attitude control, there are several recommendations that may improve the effectiveness of these systems further. To begin with, a suggestion is made to investigate using a combination of both FSF and ANFIS controllers into a hybrid system. This should bring together the advantages of FSF that include robustness and ANFIS which comes with adaptability leading to improved performance across different missions.

Moreover, it is proposed that more tuning of ANFIS controller parameters should be done to make it adaptable. This includes improving the training procedure and using a bigger dataset which will enable better learning and response. Additionally, this paper suggests real-time implementation of these controllers in a CubeSat environment, to corroborate their performance practically, beyond simulation understanding.

The aim is to keep these suggestions together for the improvement of the CubeSat's control systems towards making them more robust and adaptable in future space solutions.

Research Fund Acknowledgement

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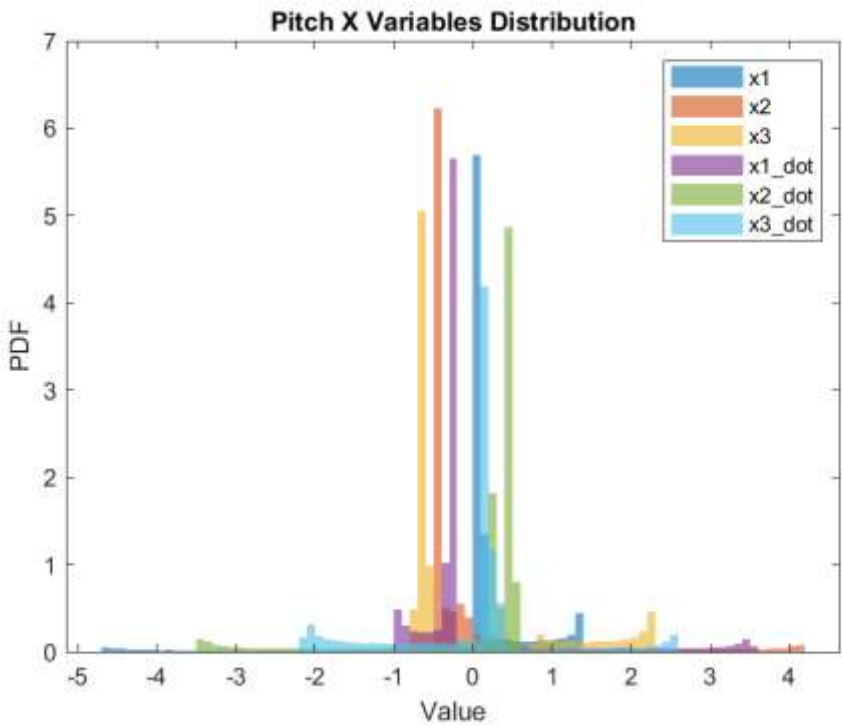
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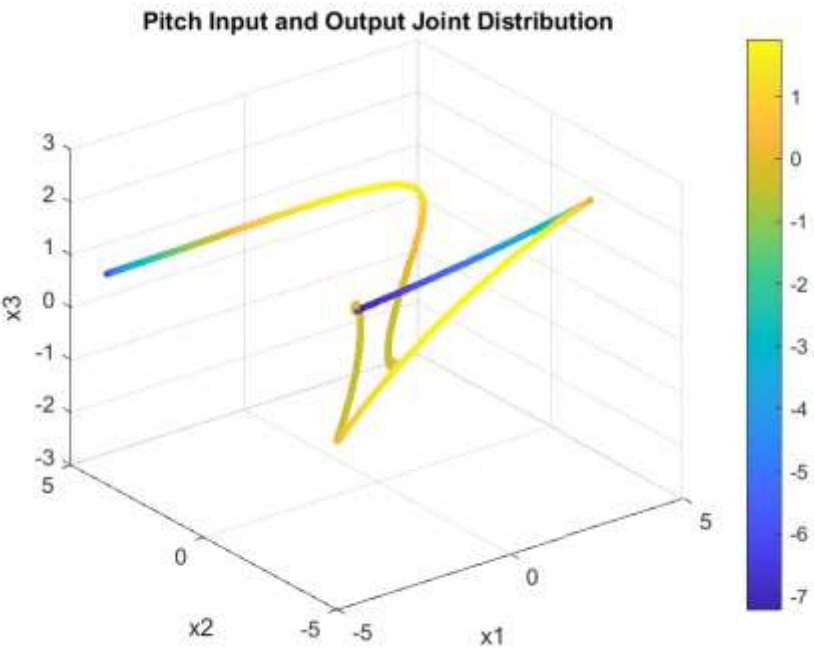
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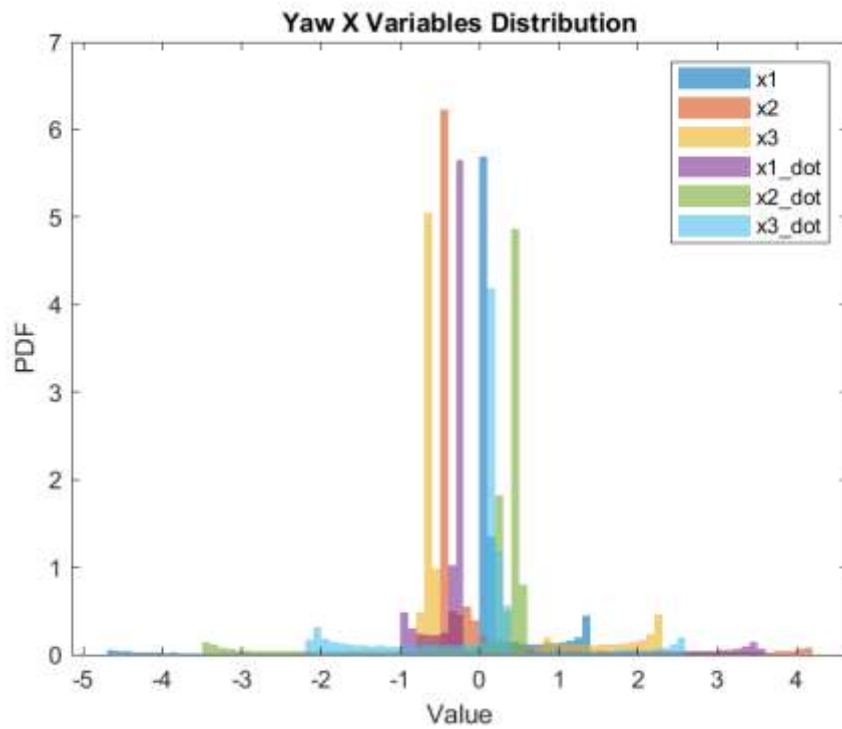
**APPENDIX 1: INPUT/OUTPUT TRAINING DATA
RELATION FOR YAW AND PITCH AXES.**



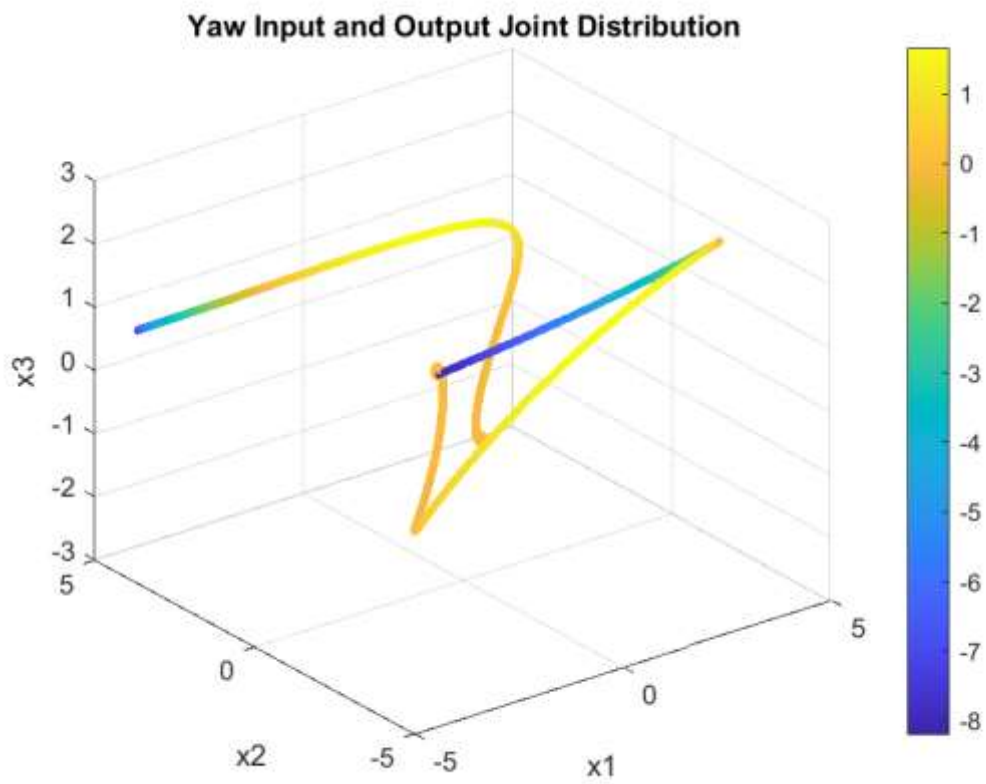
Roll Variables Distribution



Roll input and Output joint distribution



Yaw Variables Distribution



Yaw input and Output joint distribution

APPENDIX 2: SIMULATION OF FULL-STATE FEEDBACK CONTROLLER.

```
% simCubeSat_SC

global a41 a46 a52 a63 a64 b42 b43 b51 b53 b61 b62

Ix = 0.1043; Iy = 0.1020; Iz = 0.031; %%%%%%%%%%

B_phi = 25.01e-6;

B_theta = 11.14e-6; %%%%%%%%%%

B_psi = -16.59e-6;

% Number of coil windings

Nx = 305; Ny = 305; Nz = 305;

Ax = 0.006375; Ay = 0.006375; Az = 0.006375;

a41= -4*wo^2*(Iy-Iz)/Ix;

a46= wo*(Ix-Iy-Iz)/Ix;

a52= -3*wo^2*(Ix-Iz)/Iy;

a63= -wo^2*(Iy-Ix)/Iz;

a64= -wo*(Ix-Iy+Iz)/Iz;

A= [ 0 0 0 1 0 0; 0 0 0 0 1 0; 0 0 0 0 0 1;...

    a41 0 0 0 0 a46; 0 a52 0 0 0 0; 0 0 a63 a64 0 0];

b42 = Ny*Ay*B_psi/Ix;

b43 = -Nz*Az*B_theta/Ix;

b51 = -Nx*Ax*B_psi/Iy;

b53 = Nz*Az*B_phi/Iy;

b61 = Nx*Ax*B_theta/Iz;

b62= -Ny*Ay*B_phi/Iz;
```

```
B= [0 0 0; 0 0 0; 0 0 0; 0 b42 b43; b51 0 b53; b61 b62 0];
```

```
ts= 100;
```

```
p= [-4.217+7.530j, -4.217-7.530j, -6.261+4.402j, -6.261-4.402j,-7.121+1.454j, -7.121-1.454j];
```

```
p= p/ts;
```

```
K= place(A,B,p);
```

```
t= 0; h= 0.05; loop= 40000; %round(orbit_time/h);
```

```
% intiatization of integrators for ragulator problem
```

```
x10= deg2rad(-10);
```

```
x20= deg2rad(30);
```

```
x30= deg2rad(10);
```

```
x= [x10 x20 x30 0 0 0]';
```

```
buf = [t x' 0 0 0];
```

```
for i = 1:loop
```

```
    ixyz= -K*x;
```

```
    u= max(-0.1,min(ixyz,0.1));
```

```
    x = RK4(@Cubesat, t, x, u, h);
```

```
    t = t + h;
```

```
    buf = [buf; t x' u'];
```

```
end
```