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Integrated Control System for Active Fin-controlled Rocket Stabilization and Guidance

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A PROJECT PROPOSAL TO THE DEPARTMENT OF MECHANICAL AND AEROSPACE ENGINEERING IN PARTIAL FULFILLMENT OF THE REQUIREMENT FOR THE BACHELOR'S DEGREE IN AEROSPACE ENGINEERING

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ABSTRACT

Active-fin control has become a special part of space launch vehicles and military applications. This contributes to improving the accuracy and reliability of modern rockets. The main objective of this project is to develop and demonstrate the active-fins control mechanism that enhances the rocket's stability and trajectory control. In this project, real-time sensor data such as IMU and GPS will be handled using sophisticated control algorithms to dynamically modify fin positions and guarantee desired flight routes. The project aims to enhance flight stability and trajectory accuracy. The project's main findings are expected to demonstrate improved stability and trajectory precision.

Keywords: Active-fins control, Control algorithm, Rockets, Stability, Trajectory

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LIST OF ABBREVIATIONS

CAAN	Civil Aviation Authority of Nepal
CD	Convergent-Divergent
CFD	Computational Fluid Dynamics
CG	Centre of Gravity
CP	Centre of Pressure
DoF	Degree Of Freedom
EKF	Extended Kalman Filter
FSI	Fluid Structure Interaction
GPS	Global Positioning System
HCL	Hydrochloric acid
IMU	Inertial Measurement unit
KF	Kalman Filter
KNSU	Potassium Nitrate Sucrose
LAR	Low Aspect Ratio
LQR	Linear Quadratic Regulator
MAR	Medium Aspect Ratio
MPC	Model Predictive Control
MOHA	Ministry of Home Affairs
O/F	Oxygen Fuel
PCB	Printed Circuit Board
PID	Proportional Integral Derivative
MAR	Moderate Aspect Ratio
ULAR	Ultra Low Aspect Ratio

1. INTRODUCTION

1.1. Background

The history of rocketry dates back to ancient times, with the earliest recorded use of rockets in China during the Song dynasty (960–1279 AD) for military purposes. These early rockets were simple, unguided, and often unstable in flight. During World War II, the German V-2 rocket became the first long-range guided ballistic missile, incorporating rudimentary stabilization and guidance systems using gyroscopes and movable fins. In the present time, active fin-controlled systems have varying applications which include modern military applications like guided missiles and artillery rockets for enhanced accuracy and effectiveness. Active fin-controlled rocket stabilization and guidance is an integrated control system used to improve the flight stability and accuracy of the rocket's trajectory by dynamically adjusting the orientation of fins based on real-time flight data. This makes it useful for launching and guiding rockets to a precise trajectory that enhances the mission success rate.

1.2. Problem Statement

A rocket without an active guidance system has limited applications in real-world scenarios due to its restricted maneuverability and stringent launch conditions. However, with the integration of active control systems in the rocket like stability and trajectory control in our case, its potential expands significantly. The success of a rocket's mission is heavily dependent on the trajectory it follows providing a narrow error margin. As rocket missions require extensive funding and precision, even a small error means a huge loss in mission objectives and finances. In extreme cases, even human life could be in danger due to inaccuracies. Hence, it is extremely crucial to have active stability, guidance, or both in a rocket system.

1.3. Objectives

Main Objective

- To actively control the rocket as desired during its flight using active fins.

Specific Objectives

- To develop a control system for the stability and guidance of a rocket.
- To ensure optimum control authority of control surfaces for rectifying lag responses.
- To optimize the fin configuration for optimum aerodynamic performance.

1.4. Application/Features

- Guidance: The active control system can be used to guide a rocket to follow a certain trajectory.
- Satellite deployment: Guided rockets are essential for placing satellites into precise orbits around Earth, ensuring they achieve the correct altitude and orientation for their missions.
- Research: Guided suborbital rockets are used for experiments that require brief exposure to space conditions or microgravity, such as biological studies or physics experiments.
- Defense system: The active fins can be used in making missiles for defense purposes.
- Recovery: In multi-stage rockets, the first part to separate is usually the booster which can be recovered with an additional contribution of active control fins.

1.5. Feasibility Analysis

1.5.1. Economic Feasibility

Integrating active guidance systems into rockets requires a substantial initial investment, but the benefits outweigh the costs. Reduced mission failure rates, the potential for re-usability, and available funding from government and private sectors provide strong financial incentives. Expenses can also be managed by making efficient material choices, streamlining design processes, and utilizing available resources. While upfront costs are high, long-term savings and increased mission success rates make this investment economically viable.

1.5.2. Technical Feasibility

The technical foundation for developing an active fins rocket is well-established. Key technologies, such as control mechanisms using servo motors and sensors like gyroscopes and accelerometers, are readily available. Consistent power supply is achievable with power management systems. Reliable real-time telemetry communication systems and simulation tools for performance optimization are also accessible. This demonstrates the strong technical feasibility of this project besides the wind tunnel which is only suitable for validation in low-velocity regions.

1.5.3. Operational Feasibility

CAAN is responsible for the safe and efficient execution of rocket activities in Nepal. It is essential to obtain regulations and permissions from CAAN for rocket operations, including a Rocket Launch Permit, which specifies launch details and ensures safety compliance. CAAN performs a thorough safety assessment, evaluating launch trajectory and potential impacts on surrounding areas to identify and mitigate risks, prioritizing the safety of airspace users and the public.

MOHA's responsibilities in Nepal include public safety, security, and emergency management. Depending on the project, specific regulations and permissions from MOHA may be required, such as security clearances for project personnel to ensure reliability and protect sensitive information. Coordination with law enforcement may be necessary to address security issues and establish appropriate measures. Compliance with MOHA's safety regulations, including protocols for handling hazardous materials and emergency response plans, is essential for maintaining a safe operational environment and demonstrating a commitment to public safety and security.

1.6. System Requirements

1.6.1. Hardware Requirements

Hardware	Applications
STM32, ESP32, Arduino	Micro-controllers
BNO 055, MPU6050, MPU9250	IMU sensing
Servo Motors(SG90, MG996R)	Actuation of Fins
Li-ion/Li-Po Batteries	Power Supply
SD Card Module, SD card, Flash Chip	Data storage
LED, Buzzers	Indication system
BMP180, BMP280	Altitude Sensing
GPS Module	Navigation
LoRa Module	Communication
3D printer	Components Fabrication
Laser cutter	Cutting
Lathe Machine, CNC Machining	Nozzle Machining

Table 1.1: Hardware Requirements

1.6.2. Software Requirements

Software	Applications
MATLAB	Calculation, graphs
Simulink	Control System Design, Simulation and Analysis
Arduino IDE and VS code	Programming
CATIA V5 and SOLIDWORKS	CAD Design
Open Rocket	Rocket Design and Simulation
Ansys	Aerodynamics Simulation
RDWorks	CNC Laser Cutter
UPstudio	3D Printing

Table 1.2: Software Requirements

1.6.3. Material Requirements

Materials	Applications
Conc. HCL, Hydrogen Peroxide	PCB Fabrication
KNO_3, Sucrose, Dextrose	Propellant
Epoxy, Hardener, Glass fiber, Carbon fiber	Composite Body Fabrication
Mild Steel, Graphite, Cement	Nozzle Fabrication

Table 1.3: Materials Requirements

2. LITERATURE REVIEW

The active control of the rocket can be achieved with the application of control surfaces and thrust vectoring. The usual control surfaces of a rocket are canard and fins. Any of them can be made mobile to actively guide a rocket. The major problem with canard control design is roll reversal. The vortical flows arising from the canard changes the pressure distribution on stabilizer surface and can cause a large rolling moment in the reverse direction. When the roll reversal phenomenon occurs the vehicle rotates in the reverse direction of the roll command. In this situation, the control system will be improper unless this phenomenon can be predicted and accounted for in advance which requires extensive simulation. The amount of this induced rolling moment on stabilizers depends on some parameters such as: aerodynamics geometry, control surface deflection angle, vehicle angle of attack and flight velocity [1].

There are standard fin configurations as trapezoidal,elliptical,clipped delta, rectangular and grid. Theoretically, elliptical fins are ideal as they provide the best lifting force; however, they also produce enough induced drag to also provide drag stability to the rocket. Clipped Delta fins are primarily used on high performance rockets to yield a low drag force. The elliptical and clipped delta configurations provided more positive figures of merit compared to the other types of fins [2]. But there are many rockets that don't follow the fixed geometrical shape because of some limitations and through computational analysis they created their own configuration as Samurai Sounder [3] and Shark caved [2]. Based on the aspect ratio of the fins, three types of fins are defined; MAR, LAR and ULAR. The behaviour of MAR and LAR is similar since both types of fins generate lift mainly through circulation. On the other hand, ULAR fins generate lift due to the pressure distribution created by the wing tip or leading edge vortices, for rectangular or delta platforms respectively.[4]

The fundamental problem in model rockets is the cost of in-plant tuning, since each iteration, or flight, needs of a new motor, in addition to the risk of destroying the model in the process[4]. Until now, PID controllers are the most popular controller used in rocket control systems due to their simplicity and satisfactory performances. This is because the implementation of PID controller is fairly easy to understand, build and tune. But a common problem occurred in PID control is noise produced by any real sensor[5].

The inevitable part of any control problem is modeling the process or plant. With the advent of fast processors and numerical software like MATLAB®, Maple®, Python®, etc., it is now possible to take a complex non-linear 6-DoF equation like that of a rocket and run a program that can trim and linearize it with ease[6]. The aerodynamics of the rocket body are computed with the Extended Modified Barrowman Equations developed by Barrowman, Galejs and modified by the author. The actuator dynamics also have a detrimental effect in the stability of the rocket, in consequence, the actuator must also be modeled.[4]

The data received through sensors often contains significant noise, necessitating real-time filtering. This is achieved through various algorithms. The ultimate goal of algorithms research is to find an optimal solution for a given problem. Although it is rare to find a completely optimal algorithm for most problem domains, one exception is Bayesian state estimation. Here, the Kalman Filter, an algorithm that propagates a system's varying quantities over time, can be shown to be the best algorithm possible for its domain. At its core, it propagates a state characterized by a Gaussian distribution using linear transition functions in an optimal way. Since it is optimal, it has remained relatively unchanged since it was first introduced, but has received many extensions to apply it to more than just linear Gaussian systems. The EKF exemplifies this by linearizing nonlinear transition and observation functions using a Taylor Series expansion. [7]

For the analysis of the rocket a commercially available software for students ANSYS was preferred. While doing the fluid analysis around a body we are concerned with the silhouette of the body in the fluid domain. The geometrical model doesn't need to be an exact replica. To study the fluid flow for our case we used the k-epsilon model as it has been tested most widely and has been shown to predict, with the same empirical input, many different flows, including separating and complex three dimensional flows, with an accuracy sufficient for practical purposes. The desired output from the CFD analysis are fins that provide high lifting force with low drag[8].

3. THEORETICAL BACKGROUND

3.1. Rocket Theory

The theory of rockets revolves around Newton's third law of motion, stating that for every action, there's an equal and opposite reaction. Rockets propel themselves by expelling high-speed exhaust gases, generated through controlled combustion of propellants. Key components include the propellant, rocket engine, nozzle, and payload. Flight dynamics involve ensuring stability, controlling trajectory, and understanding orbital mechanics during the flight. A typical flight of a model rocket can be characterized by the four phases[9]:

1. Launch: The model rocket is launched from a vertical launch guide.
2. Powered flight: The motor accelerates the rocket during the powered flight period.
3. Coasting flight: The rocket coasts freely until approximately at its apogee.
4. Recovery: The recovery device opens and the rocket descends slowly to the ground.

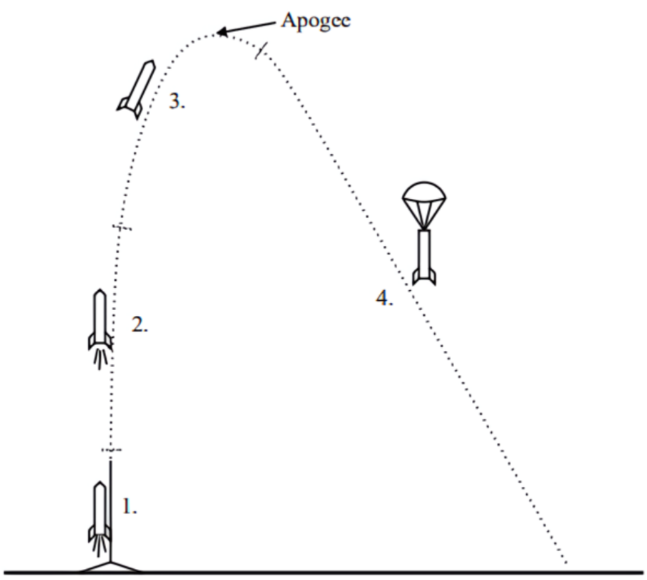

Figure 3.1: Flight Profile

3.1.1. Forces on Rocket

A model rocket encounters three basic forces during its flight: thrust from the motors, gravity, and aerodynamic forces.

Thrust is generated by the motors by exhausting high-velocity gases in the opposite direction. Normally the thrust of a rocket motor is aligned on the center axis of the rocket, so that it produces no angular moment to the rocket.

When the forces and moments generated are summed up, the gravitational force can be seen as a single force originating from the CG. A homogeneous gravitational field does not generate any angular moment on a body relative to the CG.

Aerodynamic forces, on the other hand, produce both net forces and angular moments. To determine the effect of the aerodynamic forces on the rocket, the total force and moment must be calculated relative to some reference point[9].

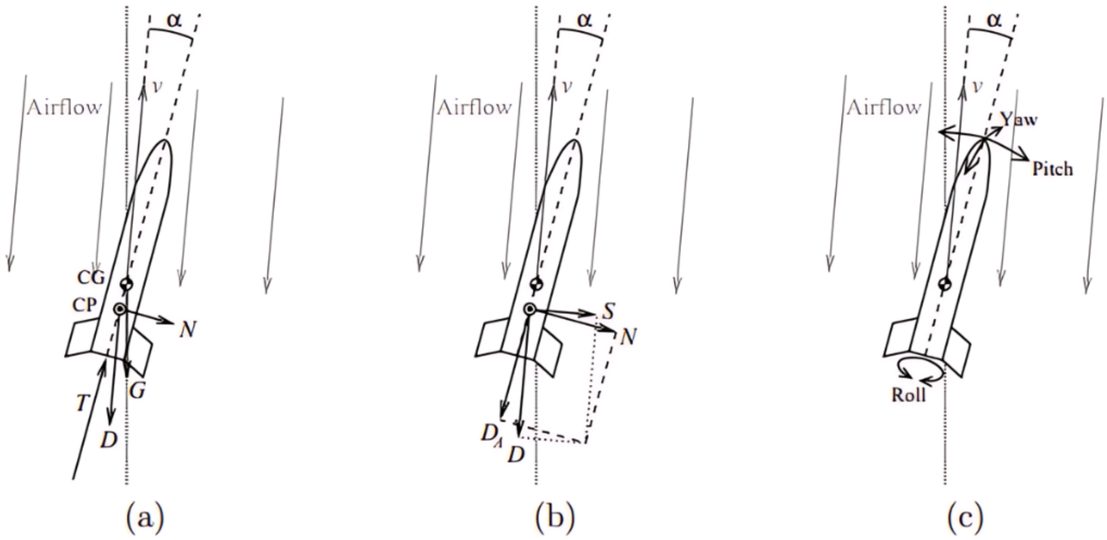

Figure 3.2: Forces acting on Rocket in Free Flight

3.1.2. Stability

Rocket stability refers to the ability of a rocket to maintain orientation and trajectory during flight. Achieving and maintaining stability is crucial for the success of a rocket mission, as unstable flight can lead to unpredictable behavior, loss of control, and potential mission failure.

Static Stability

The static stability of a rocket can be defined as the tendency for a rocket to return to its original position. The behavior of the rocket and how it rotates in response to the wind is best described by the rocket's static stability margin[10].
There are basically three stability conditions for any body, including rockets. They are: positive stability, neutral stability and negative stability. In positive stability, the CG is ahead of the CP; in neutral stability, the CG and CP coincides, whereas in negative stability, the CG is behind the CP. Positive stability is crucial for a rocket to ensure a controlled and successful flight, whereas neutral or negative stability can lead to unpredictable behavior or flight failure. Positioning the CG ahead of the CP and using properly sized and placed fins improves the stability ensuring a steady flight path. A commonly used criterion to quantify rocket stability is the static margin (or stability margin). [11]

$$Static\,Margin = \frac{X_{CP} - X_{CG}}{d} \tag{3.1}$$

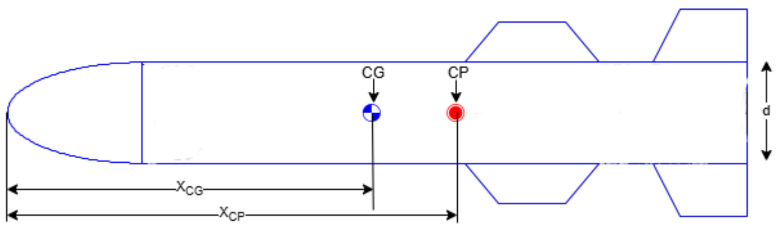

Figure 3.3: Location of CG and CP

Dynamic Stability

A rocket that is statically stable may still be poor at returning the rocket to the original orientation quickly enough. Model rockets may encounter several types of dynamic instability depending on their shape, size and mass.[11]. Dynamic stability refers to the rocket's behavior over time after it has been disturbed. While static stability ensures the rocket has the initial tendency to return to its original position, dynamic stability determines whether it will actually return to that position over time and in what manner. The dynamic response of a system can be used to analyze how a system behaves under a particular dynamic force. For any rocket, determining its dynamic stability is crucial for better understanding of how the rocket behaves after experiencing an external disturbances during flight.

3.1.3. Propellant Theory

Composition

The composition of the propellant is selected on the basis of availability of the constituents, cost, safety, cast-ability, consistency of performance, and adequate performance. The propellant is composed of Sucrose as fuel and Potassium Nitrate as the oxidizer. The standard ratio of constituents for KNSU is 65 percent Potassium Nitrate and 35 percent Sucrose, by mass. This ratio has proven to give the best overall performance combined with acceptable casting qualities. The combustion temperature rises sharply with an increased O/F ratio. At the 65/35 ratio, steel nozzles suffer little or no erosion, as there is an adequate margin between the theoretical flame temperature (1450C) and the melting point of steel (approx. 1500C). At higher O/F ratios, this margin is reduced such that a small error in weighing during preparation could result in a heat-damaged nozzle. The standard O/F ratio of 65/35 is not pour-able and must be scooped into the casting mold. which gives them a practical advantage of prime importance[12].

Combustion

A rocket motor operates on the basic principle of converting heat energy, from chemical reactions to kinetic energy. In other words, the heat liberated by the combustion of propellant supplies the heat energy; the high-velocity exhaust products exiting the motor have gained kinetic energy. This is why the exhaust experiences a significant drop in temperature as it flows through the nozzle, a requirement of the thermodynamics law of ”conservation of energy”

$$
\begin{multline}
C_{12}H_{22}O_{11} + 6.29KNO_3 \rightarrow 3.80CO_2 + 5.21CO + 7.79H_2O + 3.07H_2 + 3.14N_2 + \\
3.00K_2CO_3 + 0.27KOH
\end{multline}
$$

Burn rate

Another important parameter of the propellant is the generalization of properties relating the burn rate at the given chamber pressure which is given by:

$$r = \alpha.P^n \tag{3.2}$$

where a is the pressure coefficient and n is the pressure exponent which determine the overall variation of one property with respect to the change in another. P represents the combustion chamber pressure and r represents the burn rate of the fuel. To determine the values, initially the burn rate of the propellant is determined at different chamber pressure and plotted in a graph. With the curve traced with the data points, the values of a and n can be determined.

Grain Configuration

A cylindrical grain refers to a type of propellant grain where the internal cross-section remains constant along its axis, regardless of the shape of perforations. Perforations are the central cavities or flow passages within a propellant grain, which can have different shapes such as cylindrical, tubular, rod, or star-shaped. The most commonly used grain type is end-burning, where the propellant burns from one end. During motor burn time, neutral burning occurs when the thrust, pressure, and burning surface area remain relatively constant. Progressive burning refers to a burn time where the thrust, pressure, and burning surface area increase, while regressive burning describes a burn time where these parameters decrease. A stoichiometric mixture is one with the correct proportions of fuel and oxidizer for complete combustion, and the balance of oxygen determines whether the propellant is under-oxidized or over-oxidized. At the end of burning, any unburned propellant remaining or expelled through the nozzle is referred to as a sliver[13].

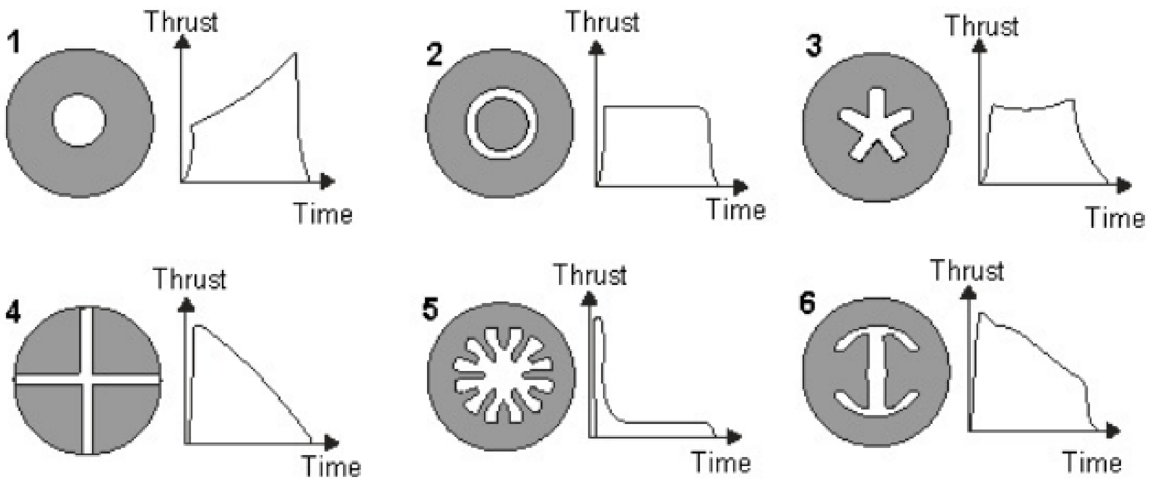

Figure 3.4: Thrust Profile for different grain profiles

3.1.4. Nozzle Theory

Rocket nozzles are crucial components in rocket propulsion systems, designed to accelerate exhaust gases to produce thrust. They efficiently convert the thermal energy of combustion gases into kinetic energy, driving the rocket forward. A well-designed nozzle maximizes the thrust and overall efficiency of the rocket. Rocket engines usually have a fixed geometry CD nozzle with a much larger divergent section.

The amount of thrust produced by the rocket is given as:

$$F = \dot{m}.v_e + A_e.(p_e - p_a) \tag{3.3}$$

The exhaust velocity v_e can be derived from the energy equation for compressible flow in the nozzle, assuming isentropic expansion:

$$v_e = \sqrt{\frac{\gamma - 1}{2\gamma R T_c}\left[1 - \left(\frac{P_c}{P_e}\right)^{\frac{\gamma}{\gamma-1}}\right]} \tag{3.4}$$

The area ratio $\frac{A_e}{A_t}$ (exit area to throat area) is critical for achieving desired exhaust velocities:

$$\frac{A_e}{A_t} = \left(\frac{1}{M_e}\right)\left[\frac{2}{\gamma+1}\left(1 + \frac{\gamma-1}{2}M_e^2\right)\right]^{\frac{\gamma+1}{2(\gamma-1)}} \tag{3.5}$$

The throat is the point where the flow transitions from subsonic to sonic, governed by:

$$\frac{A_t}{A^*} = \frac{1}{M}\left(\frac{\gamma+1}{2}\left[1+\frac{\gamma-1}{2}M^2\right]\right)^{\frac{\gamma+1}{2(\gamma-1)}} \tag{3.6}$$

where A^* represents the reference area, often equal to the throat area A_t, and M is the Mach number at any point in the nozzle.

Specific impulse measures the efficiency of the rocket engine, representing thrust per unit mass flow rate of propellant:

$$I_{sp} = \frac{V_e}{g_0} \tag{3.7}$$

3.2. Control System

To implement precision stability and especially guidance, static stability is not enough. It needs a control system that controls the vehicle's fins in real time based on the position and orientation of the vehicle. A control system is a set of devices or mechanisms that manages, commands, directs, or regulates the behavior of other devices or systems with a feedback mechanism.

Key Components of a Control System include:

1. Controller: The brain of the control system, it processes inputs and determines the necessary actions to achieve the desired output.
2. Sensors: Devices that measure variables (e.g., temperature, pressure, speed, orientation) and provide feedback to the controller.
3. Actuators: Devices that execute the controller's commands to influence the system (e.g., motors, valves).
4. Set-point: The desired value or state that the control system aims to maintain.
5. Feedback Loop: The process of continuously measuring the output, comparing it to the set-point, and adjusting inputs accordingly.
6. Control Algorithm: Mathematical and logical rules that the controller uses to determine the appropriate control action. There are different control methods like PID control, LQR, MPC adaptive control, or state-space control.

3.3. PID

PID control is one of the most widely used control algorithms in industrial and automation systems due to its simplicity and effectiveness. It combines three types of control actions—proportional, integral, and derivative—to provide a control signal that corrects errors between a desired set-point and the actual process variable.

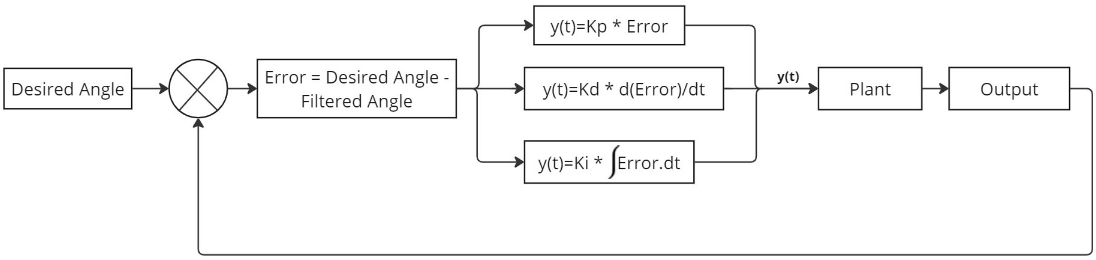

Figure 3.5: PID controller with feedback loop

- **Control Error ($e(t)$)**: The difference between the desired set-point $r(t)$ and the measured process variable $y(t)$:

$$e(t) = r(t) - y(t) \tag{3.8}$$

- **Control Output ($u(t)$)**: The signal sent to the actuator to correct the error. In PID control, $u(t)$ is computed as the sum of three terms: proportional, integral, and derivative.

1. Proportional Control (P): The proportional term produces an output that is proportional to the current error value. It is the simplest form of control, where the control action is directly proportional to the error.

$$u_P(t) = K_P e(t) \tag{3.9}$$

   Where K_P is the proportional gain, which determines the reaction to the current error.

2. Integral Control (I): The integral term is concerned with the accumulation of past errors. If the error has been present for a while, the integral term increases the control output, which helps eliminate residual steady-state errors.

$$u_I(t) = K_I \int_0^t e(\tau) d\tau \tag{3.10}$$

   Where K_I is the integral gain, which determines the reaction to the sum of past errors.

3. Derivative Control (D): The derivative term predicts future error based on its rate of change. It provides a control output that is proportional to the rate of change of the error, helping to reduce overshoot and improve stability.

$$u_D(t) = K_D \frac{de(t)}{dt} \tag{3.11}$$

Where K_D is the derivative gain, which determines the reaction to the rate of change of the error.

PID Control Equation

The PID control law is the sum of the proportional, integral, and derivative terms:

$$u(t) = K_P e(t) + K_I \int_0^t e(\tau) d\tau + K_D \frac{de(t)}{dt} \tag{3.12}$$

Alternatively, it can be written as:

$$u(t) = K_P \left[e(t) + \frac{1}{T_I} \int_0^t e(\tau) d\tau + T_D \frac{de(t)}{dt} \right] \tag{3.13}$$

where $T_I = \frac{1}{K_I}$ is the integral time and $T_D = K_D$ is the derivative time.

3.4. Kalman Filter

The Kalman Filter is a powerful mathematical tool used in control systems, signal processing, and navigation for estimating the state of a dynamic system from a series of noisy measurements. Named after Rudolf E. Kalman, who developed the filter in the 1960s, it provides optimal estimates by minimizing the mean square error. Its applications range from aerospace and robotics to finance and economics, making it a foundation in modern control theory.

In rocket trajectory estimation, the Kalman Filter can be used to combine measurements from sensors (such as gyroscopes, accelerometers, and GPS) to accurately estimate the rocket's position, velocity, and orientation. The state vector might include position coordinates, velocity components, and attitude angles. The filter recursively updates these estimates based on sensor data, accounting for noise and disturbances, ensuring accurate tracking of the rocket's trajectory throughout its flight.

KF algorithm differs from the conventional method of timing prediction. It can estimate the system's state via a set of incomplete observations (i.e. missing time points in time-series data) or noisy observations (measurement error). The KF is a fast recursive filter model. It takes up small memory and only needs to retain data for system's state at a time, rather than a long period of time. The actual measured data are used to correct the estimated results[14].

It operates in two main steps: prediction and update. In the prediction step, the algorithm estimates the current state The Kalman Filter operates in two main steps: prediction and update. In the prediction step, it estimates the current state $\hat{x}_{k|k-1}$ and error covariance $P_{k|k-1}$ based on the previous state estimate, control inputs, and the state transition matrix F_k. This step projects forward the state estimate given the dynamics of the system and any control inputs.

$$\hat{x}_{k|k-1} = F_k \hat{x}_{k-1|k-1} + B_k u_k \tag{3.14}$$

$$P_{k|k-1} = F_k P_{k-1|k-1} F_k^T + Q_k \tag{3.15}$$

where $\hat{x}_{k-1|k-1}$ is the previous state estimate at time $k-1$, B_k is the control input matrix, u_k is the control input at time k, $P_{k-1|k-1}$ is the error covariance matrix of the state estimate at time $k-1$, F_k^T is the transpose of F_k, and Q_k is the process noise covariance matrix.

In the update step, the Kalman Filter incorporates the latest measurement (z_k) to refine the state estimate and its associated uncertainty. The Kalman Gain (K_k) determines how much weight to give to the measurement relative to the predicted state estimate, adjusting the state estimate ($\hat{x}_{k|k}$) and error covariance ($P_{k|k}$) accordingly. [15].

$$K_k = P_{k|k-1} H_k^T (H_k P_{k|k-1} H_k^T + R_k)^{-1} \tag{3.16}$$

$$\hat{x}_{k|k} = \hat{x}_{k|k-1} + K_k (z_k - H_k \hat{x}_{k|k-1}) \tag{3.17}$$

$$P_{k|k} = (I - K_k H_k) P_{k|k-1} \tag{3.18}$$

where H_k is the measurement matrix which maps the state space into the measurement space, H_k^T is the transpose of H_k, R_k is the measurement noise covariance matrix, z_k is the measurement at time k, and I is the identity matrix.

3.5. Computational Fluid Dynamics (CFD)

Computational Fluid Dynamics (CFD) is a tool built on the principle of fluid dynamics that utilizes discretization techniques and solve the problem accordingly in each discrete points. At the beginning of time, to see the behaviour of air flow around body wind tunnels were used but as the time progressed CFD gradually penetrated into the engineering process as a complement to various categories of testing. CFD from being a tool to add depth to information, became a primary source for engineering practice in case of vehicles with narrow flight envelope as missiles or model rockets [16].

The CFD can be used for the conceptual and preliminary design of the rocket. For the final design it is recommended to validate the results with wind tunnel.This strategy of integration is an emerging trend and must be strongly encouraged and developed for the maturation of the CFD approach [17]. The fins of rocket, whether active or passive, plays a massive role in maintaining stability. CFD can be used to explore various configuration of the fins and how they correlate with the interested parameter as the drag & lifting forces.

4. METHODOLOGY

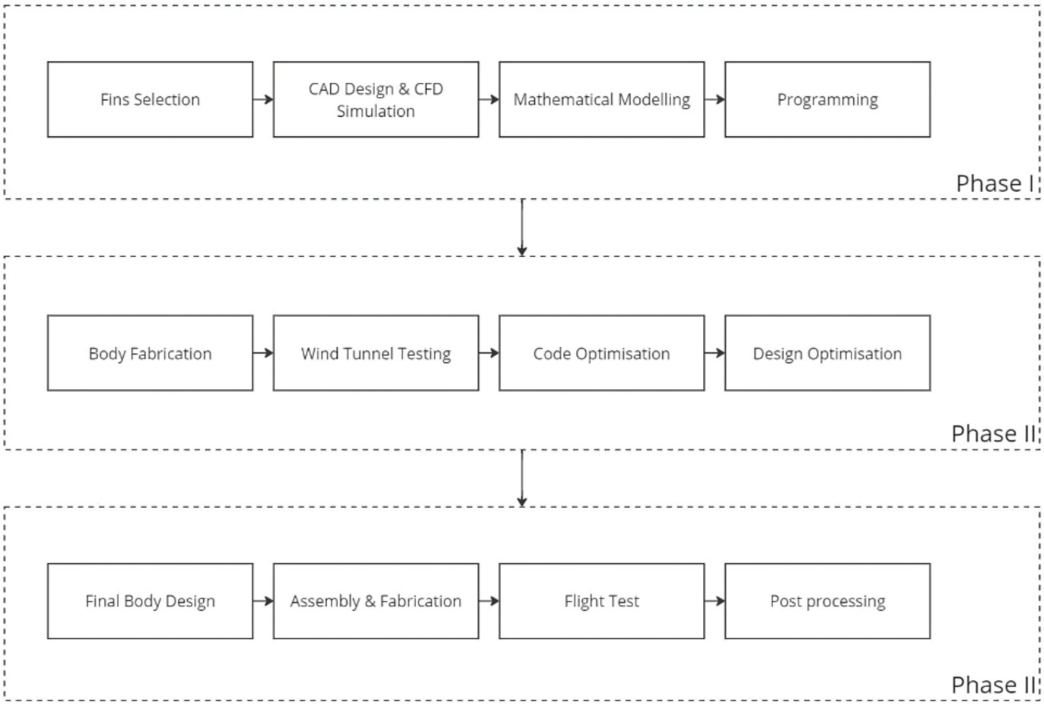

Figure 4.1: Methodology

4.1. Control system

Designing a control system involves several steps:

1. Modeling the System: Creating a mathematical representation of the system's dynamics.
2. Choosing Control Strategy: Selecting between different control methods like PID control, adaptive control, or state-space control.
3. Implementing Controllers: Designing and programming the controllers based on the chosen strategy.
4. Simulation and Testing: Using simulations to predict system behavior and conducting real-world tests to validate the design.
5. Optimization and Tuning: Adjusting parameters to improve performance and efficiency.

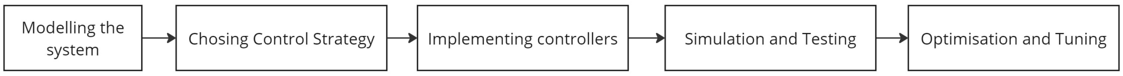

Figure 4.2: Control system

4.1.1. Mathematical Modeling

1. Defining the System and Requirements: The requirements for the rocket stability and guidance system will be defined. This include identifying the key components such as the rocket body, fins, actuators, sensors (gyroscopes, accelerometers), and the control system. The system's inputs (desired trajectory, disturbances) and outputs (rocket orientation, position) will be documented.

2. Developing the System Dynamics: The equations of motion for the rocket will be derived. This will involve modeling the rocket's translational and rotational dynamics using Newton's second law for translation and Euler's equations for rotation.

3. Creating a Simulink Model: MATLAB will be opened, and a new Simulink model will be created. Blocks will be used to represent the system components.

4. Implementing the System Dynamics in Simulink: The derived equations of motion will be implemented in the Simulink model. Blocks will be connected to represent the relationships between different components of the rocket dynamics. Blocks for forces (thrust, drag, gravity) and torques (aerodynamic torques from fins) will be included.

5. Defining the Control Objectives: The control objectives for the fins actuation system will be defined. This will include maintaining rocket stability (preventing excessive rotation) and ensuring guidance (following a desired trajectory).

6. Design the PID Controller: A PID controller will be designed to actuate the fins based on the control objectives. The controller will use feedback from sensors to adjust the fin angles and achieve the desired rocket orientation and trajectory.

7. Implementing the PID Controller in Simulink: A PID Controller block from the Simulink library will be added to the model. The controller will be connected to the system:

    - The input to the PID controller will be the error signal, which is the difference between the desired orientation (setpoint) and the measured orientation.
    - The output of the PID controller will be the control signal that adjusts the fin angles to reduce the error.

8. Tuning the PID Controller: The PID controller parameters (K_P, K_I, K_D) will be adjusted to achieve the desired performance. This can be done manually or using Simulink's automatic tuning tools:

   - The PID Tuner app in Simulink will be used for automatic tuning.
   - Alternatively, methods such as the Ziegler-Nichols method or trial and error will be used for manual tuning.

9. Simulating the Model: The simulation will be run to observe the rocket's response to the control inputs. Scope and display blocks will be used to visualize the performance of the fins actuation system and the PID controller. The results will be analyzed to ensure the system meets the desired performance specifications.

10. Validating and optimising the Model: The Simulink model will be validated by comparing the simulation results with theoretical predictions or experimental data. The model will be optimised to improve accuracy and performance.

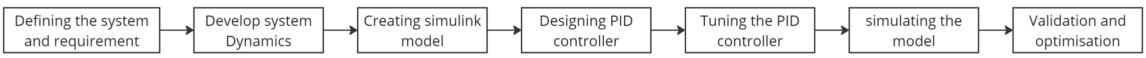

Figure 4.3: Mathematical Modelling

4.1.2. Control system Algorithm

The following block diagram represents the algorithm of our control system.

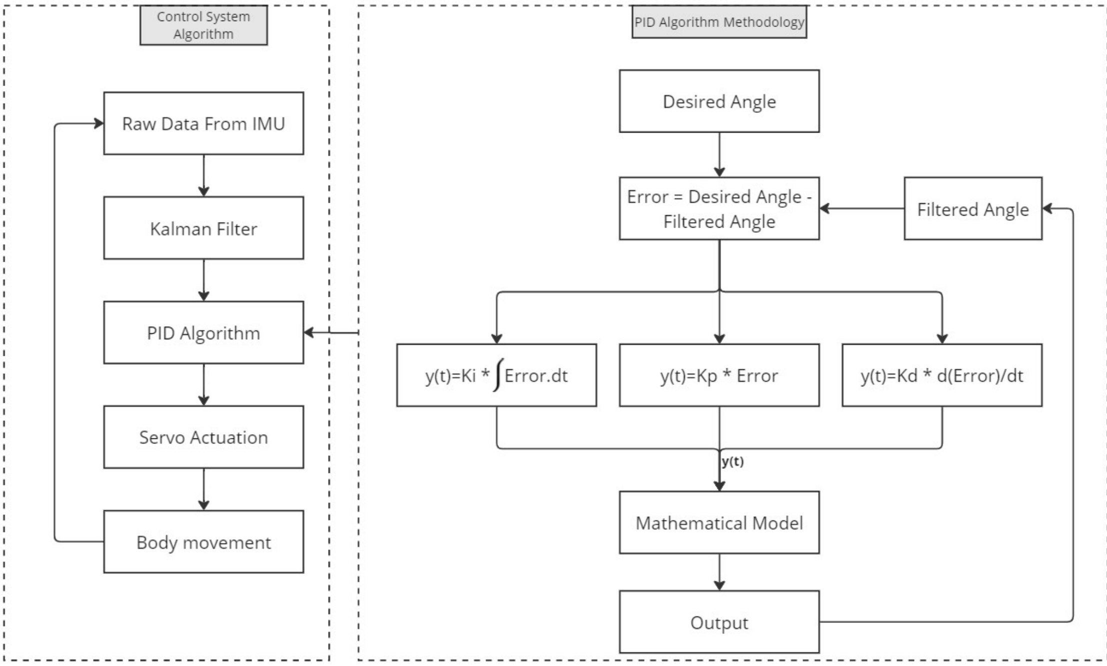

Figure 4.4: Control system Programming Algorithm

This diagram outlines the control system and PID algorithm methodology for a system using IMU data to achieve precise angle control. The control system algorithm starts with collecting raw data from the IMU, which is then filtered using a Kalman filter to reduce noise and provide more accurate data. The filtered data is fed into a PID algorithm, which determines the necessary corrections and sends signals to the servo actuators. These actuators adjust the body movement to match the desired angle.

The PID algorithm methodology begins with defining a desired angle. The system calculates the error as the difference between the desired angle and the filtered angle from the IMU data. The proportional component of the PID algorithm multiplies this error by a proportional gain. The integral component takes the integral of the error over time and multiplies it by an integral gain. The derivative component takes the derivative of the error over time and multiplies it by a derivative gain. These components are combined to produce the control output $y(t)$. This output is then used to adjust the system, ensuring it achieves the desired angle accurately. In summary, the system processes IMU data with a Kalman filter, computes adjustments with a PID algorithm, and uses servo actuation to correct the body movement, maintaining a specified angle accurately.

4.2. Flight Computer Development

4.2.1. Schematic Representation

The following block diagram represents the different flight computers to be developed in different phases of our project:

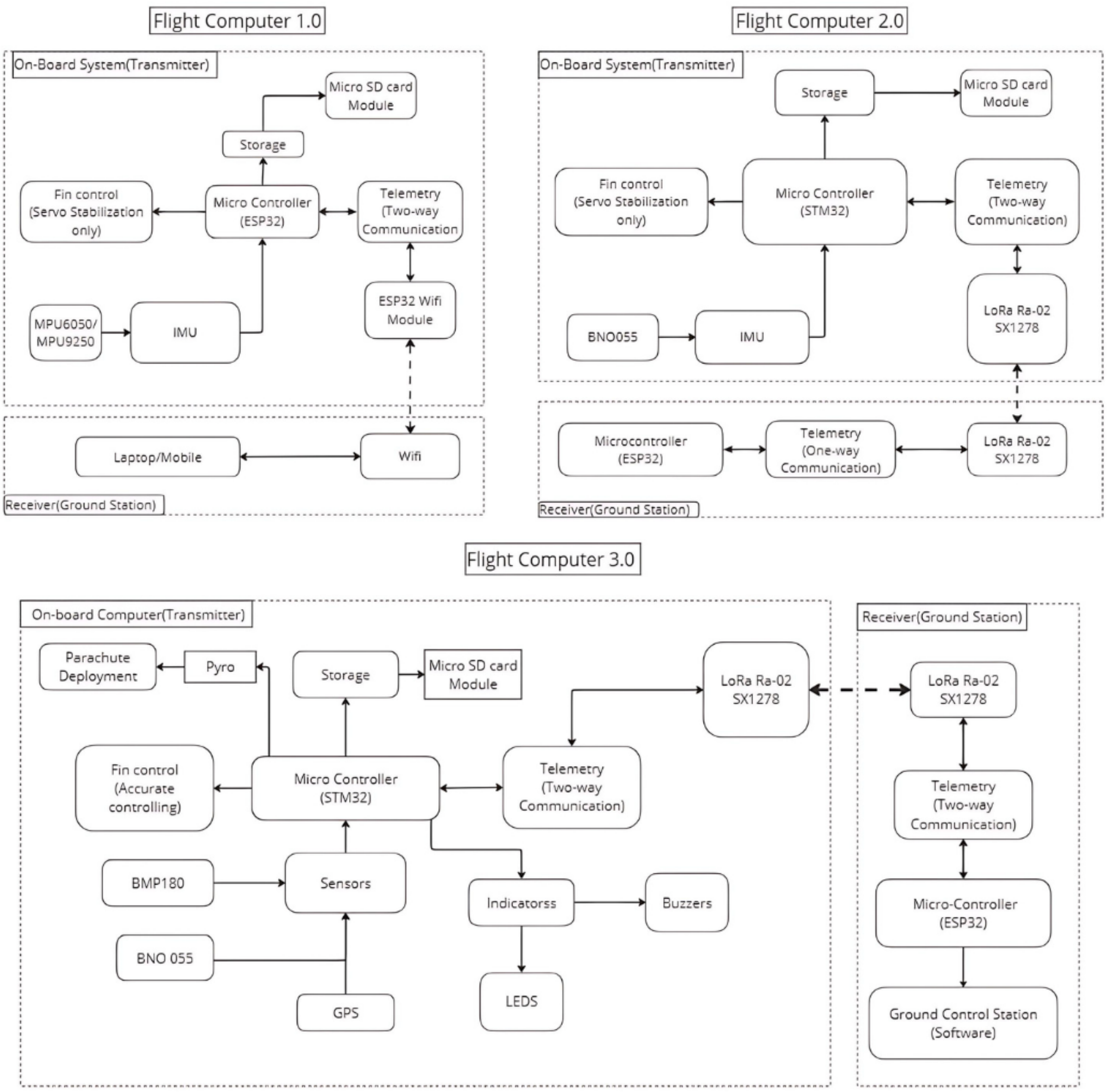

Figure 4.5: Flight Computer Schematic

4.2.2. Programming Algorithm

The following block diagram represents different flight computers programming algorithm to be developed in different phases of our project:

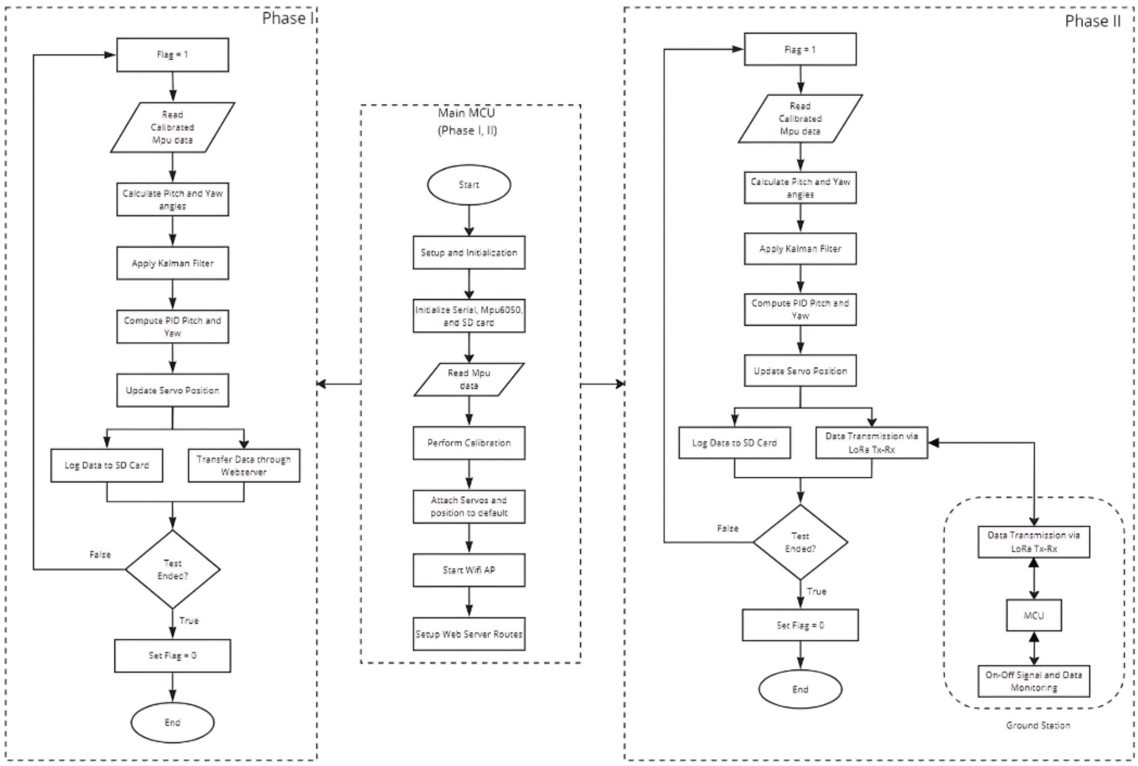

Figure 4.6: Main Programming Algorithm

4.2.3. PCB Designing and Fabrication

PCB is the most crucial part of our project as we will be developing multiple hardware components in our avionics system. Before designing PCB, the circuit will be checked and verified using breadboard and matrix board. Once it is verified, the PCB designing will be started. For schematic and PCB editing, KiCAd software will be used. The traces should be given suitable width based on their functionality. For fabrication, the PCB design will be printed in a glossy paper using printing ink. The ink then will be transferred on the cleaned copper board using acetone. After this etching process is carried out. The etching is done by putting the copper board on the solution of HCL and Hydrogen Peroxide in the ratio of 1:3. In 5 minutes, the PCB will be ready. Once the drilling and soldering are complete, our PCB will be fully operational.

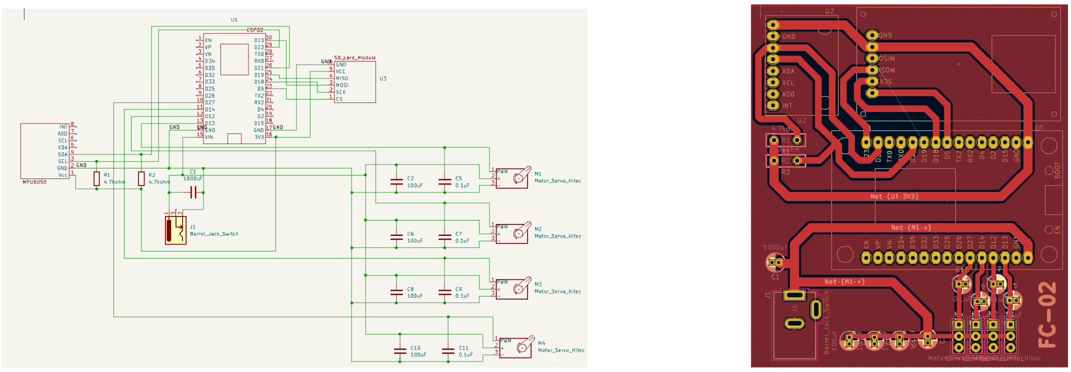

Figure 4.7: PCB Schematic and PCB Design

Figure 4.8: Avionics Bay

4.3. Vehicle Development

4.3.1. Body Fabrication

The fuselage will be made using glass fiber composite in composite lab. The nosecone will be either 3D printed or can be moulded using composite like glass fiber and fiber cloth. The fin will be made from lightweight material like plywood, acrylic or 3D printing for complex cross section. The mechanical linkage will be made from 3D printing.

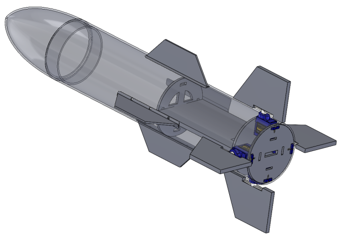

Figure 4.9: CAD Design

Figure 4.10: Disassembled Body

Figure 4.11: Assembled Body

4.3.2. Propulsion System

Propellant Preparation

Potassium nitrate KNO_3 will be used as the oxidizer, and Dextrose will be used as the fuel. Dextrose is chosen to increase the burn time, allowing for longer flight durations and enabling more flight data to be gathered and extended maneuvers to be performed.

The fuel will be prepared by heating a solution of KNO_3 and dextrose using an induction heater until the crystallization point is reached. An oxidizer-to-fuel ratio of 65:35 will be used.

In previous tests, sucrose was used as the fuel, resulting in a burn time of less than 2 seconds, which will be insufficient for effective testing of our control system. It is expected that using dextrose will significantly improve the burn time.

Along with Dextrose, other cool propellants like epoxy will also be tested to increase burn time without losing the thrust significantly.

Static Thrust Measurement

The static thrust will be measured in a Thrust Stand. Loadcell will be the sensor used to measure thrust in Newton. The signal from loadcell will be amplified using an amplifier HX711 and the data is processed through a Arduino Nano microcontroller. Using this thrust curve, we can analyse and obtain the required fuel composition to achieve desired burn time.

Ignition System

The rocket ignition systems uses nichrome wire and gunpowder to initiate the motor. A container of gunpowder is positioned above the motor and facing its grain structure. When an electric current passes through the nichrome wire, it heats up, igniting the gunpowder. This ignition triggers a pressure increase within the container, causing the diaphragm to release. This ignition technique ensures simultaneous contact between the ignited gunpowder and the entire length of the fuel grain, promoting a lateral burn and effectively increasing the booster's burn rate. As a result, the rocket experiences enhanced thrust performance during flight.

Motor Casing and Nozzle

The motor dimensions will be determined by using simulation software like Openmotor to obtain the desired output. The casing will be made from light weight and heat resistant material like carbon fiber, or glass fiber. For this, we will be working in the composite lab for motor case manufacturing. The nozzle needs to be lightweight too. For that, we will be using either graphite or cemented nozzle. The nozzle design will be done using Openmotor simulation.

4.4. Stability Analysis

The rocket's stability needs to be ensured before commencing any other phases of the project. We will be making a fin controlled rocket which will mainly handle the dynamic stability while obviously contributing to the static stability along with canard.

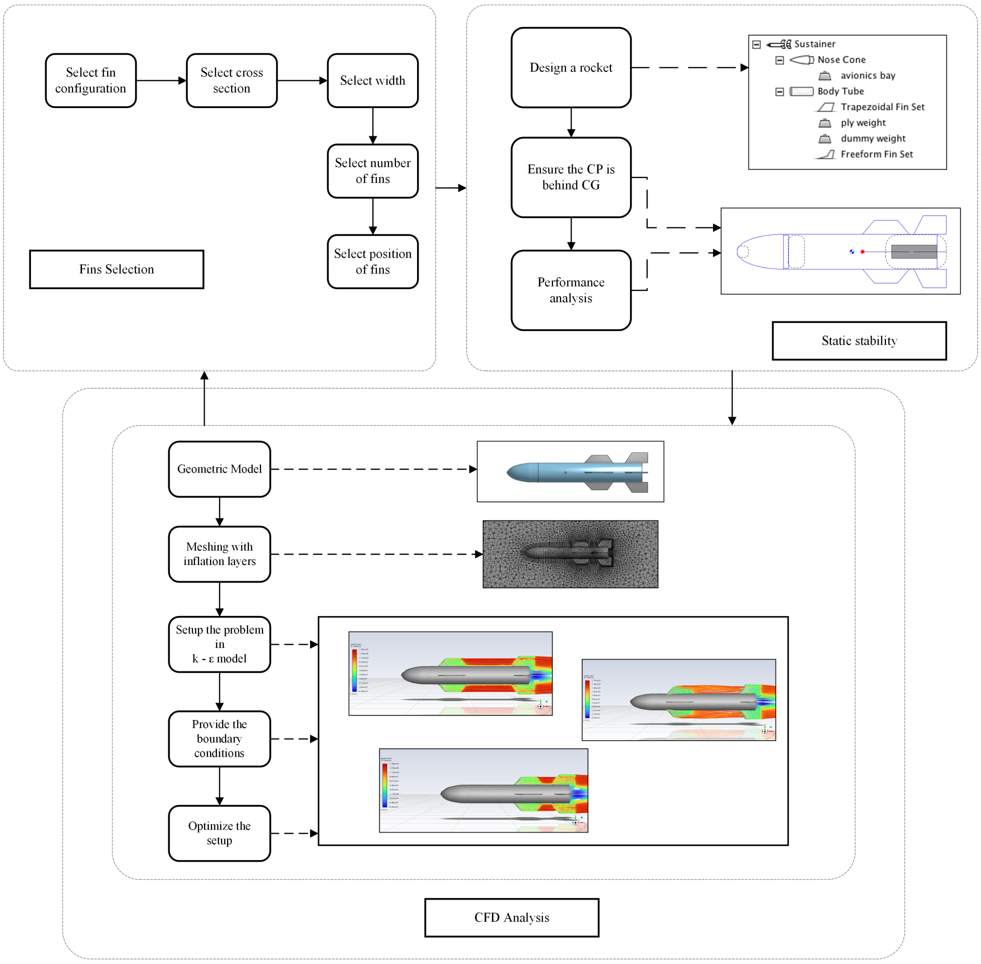

Figure 4.12: Stability Analysis

4.4.1. Selection of fins

The geometrical parameters that mainly define fins are its cross section, tip chord ratio, cant angle, sweep angle, effective aspect ratio and width. We will either be using standard configuration of the fins while changing the different geometrical properties or a freeform fin that adheres to the requirement of the design.

4.4.2. Static Stability Analysis

3 The static stability of the rocket will be calculated using OpenRocket. The software will be used to design the rocket ,determine the stability margin and its performance. The rocket design will be optimized within the software till it is made statically stable with suitable margin. A good rule of thumb is of 1-2 calibers.

4.4.3. CFD Analysis

For the CFD analysis, Ansys will be used. A steady state simulation will be done to measure the drag and lift forces from the fin. The Direct Optimization tool in Ansys will be used to validate the optimization of fins. A dynamic state simulation with two way FSI will also be done to check the dynamic stability of the model.

4.5. Wind Tunnel Testing

The wind tunnel will be used to validate the data from simulations. A setup will be made that allows the movement of the model in only one axis. Once the setup is done, the control system of the rocket will be activated. The data that is obtained will be further processed using MATLAB to analyze the behaviour of the model.

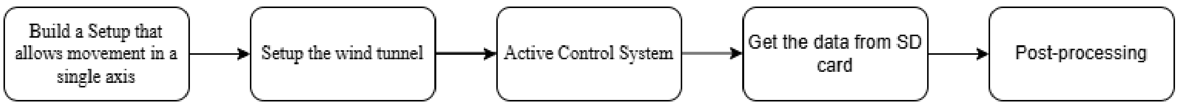

Figure 4.13: Wind Tunnel Flowchart

Figure 4.14: Wind Tunnel Testing

4.6. Servos Linkage

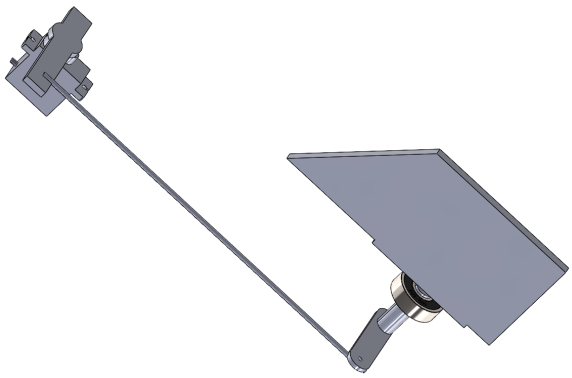

Figure 4.15: Servo Linkage

The servo linkage mechanism for the fins will be as shown in Fig [4.15]. The servo will be placed above the rocket's motor without touching it, to avoid the excessive heating. A small diameter rod will connect the servos' control horn and the attachment at fins. This mechanism will be attached to the body frame by using bearings.

5. EXPECTED OUTCOME

5.1. Implication and significance

The implementation of active fins technology for rockets carries significant implications globally. By augmenting traditional rocket components with active fins, the potential for enhanced control and stability during launches is considerable. This advancement improves safety measures by minimizing the risk of accidents and also boosts operational efficiency by ensuring precise trajectory adjustments. As humans seek to expand their capabilities in space, the integration of active fins technology represents a pivotal step toward achieving safer, more efficient, and more ambitious space missions.

5.2. Budget Analysis

S.N	**Name of Particulars**	**Cost (NRs.)**
1	Micro Controller	30,000
2	Sensors	10,000
3	PCB Fabrication	5,000
4	Power Management system	5,000
5	Communication	5,000
6	Body Fabrication	20,000
7	Propulsion	10,000
8	Recovery	5,000
9	Travel Expenses	30,000
10	Miscellaneous	10,000
Total		**1,30,000**

Table 5.1: Budget Analysis

5.3. Work schedule

The following Gantt Chart demonstrates our work schedule:

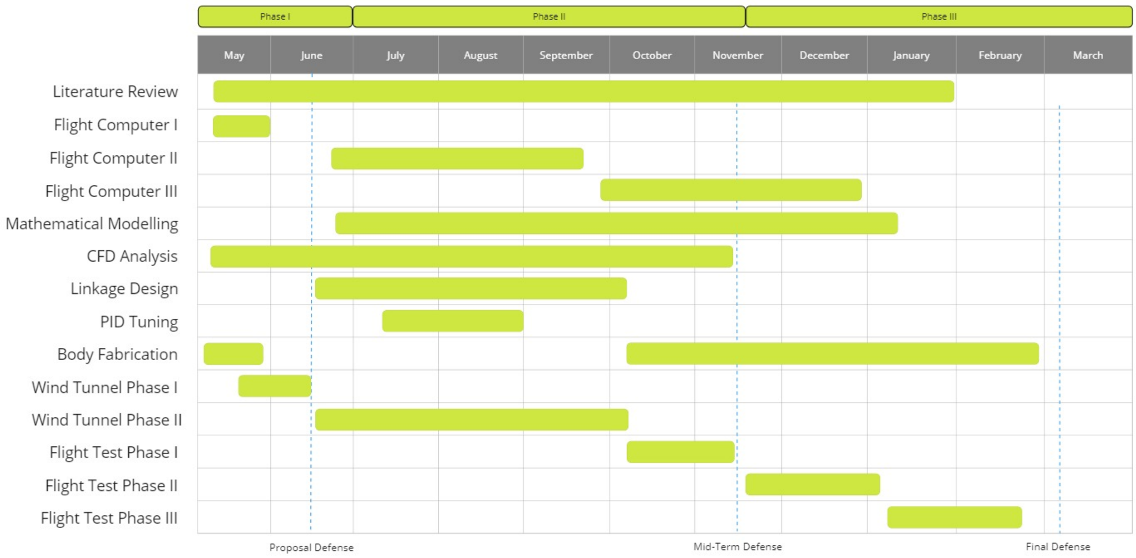

Figure 5.1: Gantt Chart

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