Abstract

- This research is to create a control system for Flapping Wing Micro Aerial Vehicles (FWMAVs), which mimicks the flapping of birds. FWMAVs uses flapping of the wings to produce lift and thrust which cannot be done by fixed wing planes, which gives them great maneuverability in small spaces. This makes them ideal robot for doing indoor inspections, military missions, and surveillance in tight and confined spots.
- This paper analysis the complex movement of the FWMAV's . To develop the control system is it viable to understand the forces and how it is slightly less predictable for flapping wings cause of wing motion and angle changes. To tackle the problem of complexity in motion this paper utilizes the one of the most prominent control strategy using Model Predictive Control (MPC), to handle the complicated flight dynamics of FWMAVs.
- Creation of a dynamic model that accurately reflects the flight behavior/motion of FWMAVs, creating a feedback control system to manage roll, pitch, and yaw, and fine-tuning control parameters for the best performance and efficiency. This approach includes detailed mathematical modeling, time domain analysis (converting the equations motion into time domain for sampling), and using simulation tools like MATLAB/Simulink to test the control algorithms in different scenarios.
- In the end, this research has the aim of improving the stability, agility, and overall performance of FWMAVs, making them a great technology for surveillance purpose. By combining innovative control methods and enhancing the modeling process, This study contributes to the aerial robotic industry and its benefits for the future.

Contents

1. Overview of the System

1.1 Introduction of the system

A flapping wing aerial vehicle is a cool machine that copies how birds and insects fly. These small, lightweight flying robots are called Flapping Wing Micro Aerial Vehicles, or FWMAVs for short. Unlike regular airplanes that use fixed wings or rotors to fly, FWMAVs flap their wings in a special way to create both lift and thrust at the same time, which helps them stay balanced. This design makes them super good at moving around in tight spaces and turning easily. Because of these benefits, FWMAVs are perfect for jobs like checking indoor areas, military tasks, and keeping an eye on things in small places.

However, the control of FWMAVs presents a unique set of challenges due to their inherently complex and nonlinear dynamics. The wings are highly sensitive and its pretty unsteady and time-varying with respect to wing motion and orientation, this creates difficulty for stabilizing and controlling the system. General Control methods often have less success rate when applied to a non-linear 6DOF system, insisting for a development of an advance control strategy to understand these dynamic conditions

To address these challenges, this research aims to design and implement a control system for a FWMAV modeling and testing tools. Employment of a platform to develop and test control algorithms, including PID and adaptive control methods, tailored to manage the complex flight dynamics of the FWMAV. By integrating these tools, we aim to create a realistic and effective control framework that can be refined for future physical testing.

This introduction outlines the motivation and scope of the research, emphasizing the need for innovative control solutions in the context of bio-inspired FWMAVs. The following sections will detail the dynamics of the system, control system development, and future work need to be done to validate the approach and highlight the potential of FWMAVs in practical applications.

Flapping wing micro aerial vehicles presents great opportunity and increasing demand and challenges on small unmanned aerial vehicles, the research began with the idea of how birds, known scientifically as ornithopters, fly very efficiently. It looked at how their wing structure helps them stay aerodynamically superior and gain control in the air [1]. This bionic technology has made great progress. Around the world, various tech companies and universities have done extensive studies on flapping-wing aircraft, creating physical models that closely resemble birds. It's an aerodynamic system that has 6 D.O.F. Many roboticists are focusing on flapping flight to enhance drone agility and versatility. Birds, being the largest and possibly the most efficient flying animals, serve as a fascinating source of inspiration for drone design [2].

1.2 Project Aim:

The objective of this project is to develop and implement a feedback control system for a Flapping Wing Micro Aerial Vehicle (FWMAV) that guarantees stable, agile, and precise flight capabilities. This control system will manage the flapping motion to produce thrust while also regulating roll, pitch, and yaw to uphold the intended flight trajectory and orientation. The focus will be on employing a Controller to a system's plant model which will be able to control different variables attached to the system.

Specific Objectives: 1. Create a lively model of the FWMAV that shows its key flying features, including how it moves forward and spins around. 2. Build a feedback control system using Model Predictive Control (MPC) to adjust the flapping speed and height, which will help control the vehicle's tilt (roll, pitch, and yaw) and where it goes. 3. Fine-tune the controller settings to make sure it works really well, with quick reactions, little wobbling, and accurate control over how it flies. 4. Run tests of the control system using software like MATLAB/Simulink. If this control system works well, it will improve the FWMAV's flying accuracy, steadiness, and flexibility, making it perfect for tough real-life tasks like watching over areas, checking the environment, and helping in search-and-rescue operations in tight or dangerous places.

1.3 Literature Review:

In earlier research, various techniques have been employed to develop effective control systems for flapping wing aerial vehicles. One notable approach is the system identification method, which leverages test data from the system to forecast its dynamic behavior. Another intriguing technique discussed in this report is mathematical modeling, which plays a crucial role in gaining a thorough understanding of the system's dynamics. helps to understand the true nature of the system and how it works, This method is totally based on implementation of core physics and aerodynamics of the system. By developing accurate mathematical models, researchers can understand the intricacies of the system, hence making the creation of more effective control algorithms that improve performance and stability in practical scenario. The proper construction of mathematical model is done by understanding the kinematics and aerodynamics of the system., treating the vehicle as a rigid body with six degrees of freedom [3]. This dual-model approach allows for a thorough analysis of the complex interactions between the aerodynamic forces generated by the flapping wings and the resulting motion of the vehicle.

After Deriving the Dynamics of the System it is then converted into a state space model as done in [4]. Thereafter, to analyse the system and give command and feedback it is essential to represent the previous form in time domain for analyzing time samples for each wing beat. Numerous sophisticated control methodologies, including model predictive control (MPC), neural networks, neuro-fuzzy logic, fuzzy logic, sliding mode control, and adaptive control, have emerged within the domain of process control [5]. The variety of system models and types is significant, as the Model Predictive Control (MPC) paradigm is applicable to both linear and nonlinear models. Consequently, MPC can effectively address complex nonlinearities and interactions, such as the dynamics of six-degree-of-freedom aircraft, control structure interactions, slosh modes in rockets, and mission-specific dynamics in spacecraft, including high-resolution space telescopes. These features are essential characteristics of dynamics within aerospace systems [6] For FWMAV it is feasible to implement MPC to successfully predict the system’s future almost random behaviour.

1.4 Proposal or Methodology:

Proposal:-

The objective of this project is to develop a resilient control system for a Flapping Wing Micro Aerial

Vehicle (FWMAV) that guarantees stable and agile flight through the application of sophisticated feedback control methodologies. This research will specifically concentrate on creating a mathematical model that combines aerodynamic and kinematic dynamics, facilitating a thorough understanding of the vehicle's operational characteristics. The initiative aims to deploy a MPC controller with feedback linearization, which will be meticulously calibrated to improve performance and stability during a range of flight maneuvers.

Methodology:-

To fulfill the project's aims, the following methodology will be adopted:-

Mathematical Modeling:- Construct a comprehensive mathematical model of the FWMAV by merging aerodynamic force models with kinematic models, considering the vehicle as a rigid body with six degrees of freedom. This process will entail deriving equations that characterize the vehicle's motion in response to the aerodynamic forces produced by its flapping wings.

Time Domain Analysis:- Transform the mathematical model into the time domain to evaluate the system's temporal response. This phase will involve analysing the sampling rate of each wing beat and how it affects the inner and outer loops consecutively in the control architecture, enabling a detailed analysis of the FWMAV's dynamics and their progression throughout flight.

Control System Design:- Establish a MPC controller as the main feedback control mechanism. The parameters of the controller will be systematically adjusted to enhance the FWMAV's performance, with an emphasis on reducing oscillations and ensuring rapid response times to variations in flight conditions.

Simulation and Validation:- Employ simulation software such as MATLAB/Simulink and CoppeliaSim to model the dynamics and control system of the FWMAV. Simulations will serve as a testing ground for various scenarios and will validate the efficacy of the control algorithms under diverse operational circumstances.

Experimental Implementation:- Following the attainment of satisfactory results from the simulations, the control system will be executed on a physical prototype of the FWMAV.

Simulation/Validation & Experimental Implementation will be done at the other half of the project life cycle.

Control System Flow Chart

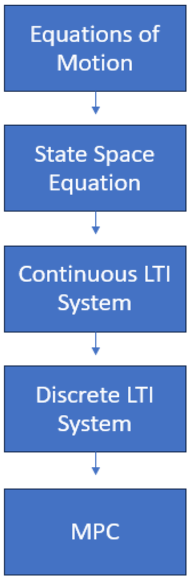


Fig.1

The shown in figure 1 it shows the control system flow chart, The control system flow begins with the **equations of motion**, which describe the dynamics of a system, such as a drone or FWMAV, in terms of its velocities, angular rates, forces, and torques. These nonlinear equations are then transformed into a **state-space representation**, which organizes the system's dynamics in terms of state variables, control inputs, and outputs. This step helps to describe the system in a more manageable form, capturing the relationship between states (e.g., position, velocity) and inputs (e.g., forces, torques) through matrices. Next, this **state-space model** is linearized around an operating point to obtain the **continuous linear time-invariant (LTI) system**, which assumes the dynamics do not change with time. To implement this system on a digital computer or controller, it must be discretized using sampling techniques, resulting in a **discrete LTI model**, which can now operate in discrete time steps. The **Model Predictive Controller (MPC)** is then designed based on this discrete LTI model. The MPC predicts future states, optimizes control actions over a time horizon, and provides feedback to the system to achieve desired performance while considering constraints. This entire flow ensures robust control and efficient handling of complex dynamic systems. The Starting Three Stages will be discussed in this report, the remaining one will be implemented in the future.

2. Designing The Control System

2.1 Aerodynamic & Kinematics of the system

An initial comprehension of the existing systems and their methodologies was developed, including Kubeetle, the Festo-smartbird produced by Festo’s Bionic Learning Network, the AeroVironment Nano Hummingbird, DelFly MAV, and the Beetle Mimicking Flapping MAV, along with an analysis of their motor rotations to achieve six degrees of freedom (6DOF).

Subsequently began investigation into the aerodynamics of the system, focusing on the external reactions of aerodynamic forces that facilitate lift for the FWMAV to estimate the most optimized wingbeat frequency and power consumption.

$$F_l$$
$$F_t$$
$$F_d$$
$$F_g$$

For Flapping Wing Micro Air Vehicles (FWMAVs), the wings produce lift F_l and drag F_d as they traverse through the air and the thurst force F_t for the forward motion The characteristics of this force, including its direction and magnitude, are influenced by the combined effects of the wing's flapping velocity and the surrounding airflow. This net force plays a crucial role in facilitating the vehicle's forward propulsion and overall stability. In addition to the aerodynamic forces of lift and drag, gravitational forces exert a vertical influence on the FWMAV. During consistent vertical flight, the lift produced by the flapping wings counterbalances the force of gravity, thereby sustaining a stable flight condition. Nevertheless, due to the continuous motion of the wings, the surrounding flow conditions remain in a state of flux. The forces acting upon the wings are subject to constant variation as they flap, resulting in a complex and non-linear dynamic environment that necessitates meticulous control to ensure stable flight.

Orientation while the system is placed and how its positioned in space is crucial and it depends upon how the system coordinates with its body frame to earth inertial frame, Euler angles and angular movements of FWAMV plays an important role and how the actuators works together to provide the pitching, rolling ang yawing for the system, commonly described Euler angles are as follows:-

- **Roll angle (Φ)**: How much the FWMAV tilts to the side (bank angle).
- **Pitch angle (Θ)**: How much the head of the system (direction towards the angle of attack) points up or down.
- **Yaw angle (Ψ)**: The direction the FWMAV is heading (turning left or right).

The angular movements with respect to s body from axis are as follows:-

- p: Rotation around x axis
- q: Rotation around y axis
- r: Rotation around z axis

As the System is distributed in 3 axis x,y,z it has rotational inertia along these axes which are as follows:-

- J_x: Rotational Inertia along the x-axis
- J_y: Rotational inertia along the y-axis
- J_z: Rotational inertia along the z-axis

Lastly, Aerodynamics Moments along the body frame axis for the system are as follows:-

- M_x: Mass Moment along the x-axis
- M_y: Mass Moment along the y-axis
- M_z: Mass Moment along the z-axis

Combining all these equations and deriving the free body diagram we can get the dynamic and kinematic equations for the rotational motion of the aerodynamic system, in order to conduct
The translational movement within three-dimensional space is determined by the forces interacting with the vehicle's structure, articulated within a reference frame fixed to the body. The equation is as follows,

$$\overrightarrow{F}^b = m\left(\overrightarrow{\dot{V}}^b + \overrightarrow{w}^b * \overrightarrow{\dot{V}}^b\right)$$

$$\overrightarrow{F}_{net} = m\left(\dot{u}\hat{i} + \dot{v}\hat{j} + \dot{w}\hat{k} + u\hat{i} + v\hat{j} + w\hat{k}\right)$$

As the angular velocity with respect to body frame in 3 dimensional axis can be related the net forces w.r.t to angular velocities in x-y-z plane as shown below,

$$\begin{bmatrix} F_x \\ F_y \\ F_z \end{bmatrix} = m\left(\begin{bmatrix} \dot{u} \\ \dot{v} \\ \dot{w} \end{bmatrix} + \begin{bmatrix} p \\ q \\ r \end{bmatrix} * \begin{bmatrix} u \\ v \\ w \end{bmatrix}\right)$$

Rotational motion in three-dimensional space pertains to the behavior of a rigid body as it rotates around a specified axis, characterized by components of angular velocity typically represented as p, q, and r, corresponding to rotations about the x, y, and z axes, respectively. The dynamics governing this motion are articulated through Euler's equations, which establish a relationship between the angular velocities of the body and the torques and inertial forces exerted on it, thereby incorporating the influences of angular acceleration and the moment of inertia of the body.

$$\overrightarrow{M}^b = \left(I^b * \overrightarrow{\dot{w}}^b + \overrightarrow{w}^b * \left(I^b \overrightarrow{w}^b\right)\right)$$

The rotation matrix serves as a tool for converting vectors between the inertial frame and the body frame through a series of rotations that correspond to the yaw, pitch, and roll angles. Commonly represented as R, this matrix enables the transformation of forces and velocities from the inertial frame, which is fixed to the Earth, to the body frame, which is fixed to the vehicle, and the reverse. This capability is essential for ensuring precise navigation and control within a three-dimensional environment which is as follows,

$$\begin{bmatrix} 0 & I_{zz}r & -I_{yy}q \\ -I_{xx}r & 0 & I_{xx}p \\ I_{yy}q & -I_{xx}p & 0 \end{bmatrix} \begin{bmatrix} p \\ q \\ r \end{bmatrix}$$

The equation of motion for our FWMAV can be derived by constructing a Free Body Diagram and by taking normal and tangential forces for each vector and consulting the guidance provided in [8] These below equations will require testing to ensure that variations in parameters are appropriately accounted for.

$$u = u\square r - wq + g\sin(\vartheta)$$
$$v = wp - ur - g\cos(\vartheta)\sin(\phi)$$
$$w = uq - up - g\cos(\phi)\, cos(\vartheta) + U_1/m$$

$$p = \frac{(I_{yy} - I_{zz})}{I_{xx}} qr + J_x q\Omega$$

$$q = \frac{(I_{zz} - I_{xx})}{I_{yy}} pr + J_y p\Omega + U_2/m$$

$$r = \frac{(I_{xx} - I_{yy})}{I_{zz}} pq + J_z r\Omega + U_3/m$$

Where, U_1, U_2, U_3 are thrust, roll and yaw inputs respectively.

For designing a controller, it is essential to develop a motor mixing algorithm, to relate all the motors to each other in the system, which are subsequently control inputs for the system,

$$U_1 = c_t\,(\Omega_2^2 - \Omega_1^2 - \Omega_3^2)$$
$$U_2 = c_q(\Omega_2^2 + \Omega_1^2 - \Omega_3^2)$$
$$U_3 = c_q(\Omega_3^2 + \Omega_1^2 - \Omega_2^2)$$

in a Flapping Wing Aerial Vehicle (FWMAV), the control inputs U_1, U_2 and U_3 are essential for achieving stable flight and effective maneuverability. Input U_1 is responsible for the flapping motion, which produces the thrust necessary for both forward movement and vertical positioning along the z-axis, thereby enabling the vehicle to either hover or advance. The input U_2 governs the roll motion which is done by the hinge, facilitating the banking or tilting of the FWMAV to enhance lateral stability and facilitate turns. Meanwhile, U_3 regulates the yaw motion, allowing for adjustments in the vehicle's heading and orientation to alter its direction. These control inputs function synergistically to maintain the FWMAV's equilibrium and execute intricate aerial maneuvers, while also responding to the dynamic aerodynamic forces generated by the flapping wings. For the Pitch Moment our aim is to provide the system C.O.M at the head region of the bird with the help of flapping modification which may facilitate a certain degree of pitch adjustment. However, further assessment will be required in subsequent phases of the study.

2.2 State Space & Controller Implementation

General State Form can be written as,

$$\dot{x} = \mathrm{Ax} + \mathrm{Bu}$$
$$y = Cx + Du$$

Where, u is the inputs, x is the state variables matrix and y is the output matrix for our system

$$U = \begin{bmatrix} U_1 \\ U_2 \\ U_3 \end{bmatrix}$$

$$y = \begin{bmatrix} x \\ y \\ z \\ \theta \\ \phi \\ \psi \\ u \\ v \\ w \\ p \\ q \\ r \end{bmatrix}$$

$$
\mathrm{x} = \begin{bmatrix} x \\ y \\ z \\ \theta \\ \phi \\ \psi \end{bmatrix}
$$

For the state space modelling, the equations of motion can be written in a state space format as shown below (needs further adjustments),

$$
\begin{bmatrix} \dot{u} \\ \dot{v} \\ \dot{w} \\ \dot{p} \\ \dot{q} \\ \dot{r} \end{bmatrix}
= \begin{bmatrix}
1/m & 0 & 0 & 0 & 0 & 0 \\
0 & 1/m & 0 & 0 & 0 & 0 \\
0 & 0 & 1/m & 0 & 0 & 0 \\
0 & 0 & 0 & 1/I_{xx} & 0 & 0 \\
0 & 0 & 0 & 0 & 1/I_{yy} & 0 \\
0 & 0 & 0 & 0 & 0 & 1/I_{zz}
\end{bmatrix}
\begin{bmatrix}
mvr & -mwq & mgsin(\vartheta) & 0 & 0 \\
-mur & mwp & -mgcos(\vartheta)sin(\phi) & 0 & 0 \\
muq & -mvp & -mgcos(\phi)cos(\vartheta) & 0 & U_1 \\
I_{yy}rq & -I_{zz}rq & 0 & J_x q\Omega & 0 \\
I_{zz}rp & -I_{xx}pr & 0 & J_y p\Omega & U_2 \\
-I_{yy}qp & I_{xx}pq & 0 & J_z r\Omega & U_3
\end{bmatrix}
$$

$$
\dot{\mathrm{v}} = {M_B}^{-1}[-C_B\mathrm{v} + g_B(\eta) + o_B(\mathrm{v})\omega + E_B]
$$

Above Equation referred from [ref9], provides Newton-Euler formulation in a state space Form, Where Matrix 2 is $\boldsymbol{M_B}^{-1}$, while matrix 3 relates to the rest of the variables. Note every variable is in body frame reference. This Equation will greatly help to relate all th e force and momentum motion together.

Future state prediction of each state can be done using these equations,

$$
u_{k+1} = u_k + \dot{u}_k . T_s/N
$$

$$
v_{k+1} = v_k + v_k \frac{T_s}{N}
$$

$$
w_{k+1} = w_k + w_k \frac{T_s}{N}
$$

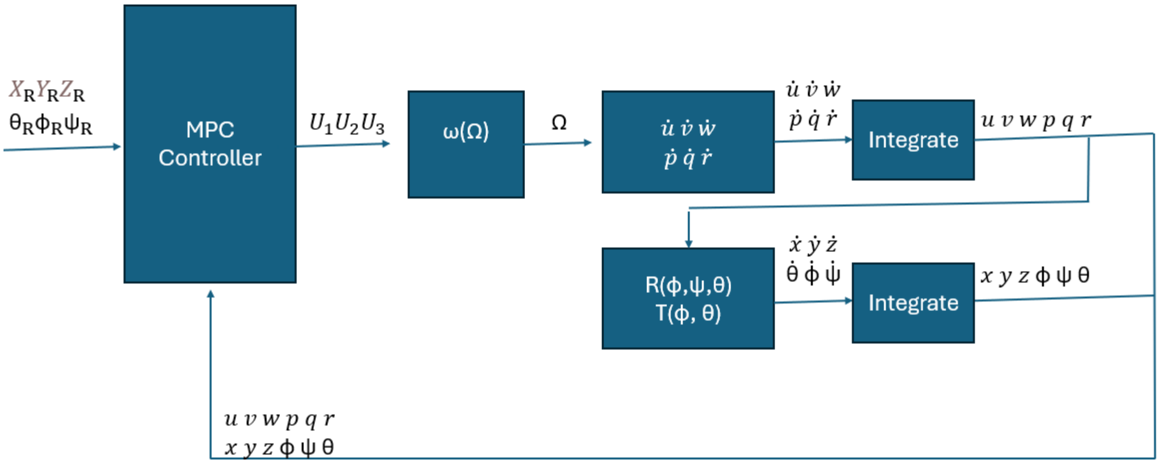
$$
p_{k+1} = p_k + p_k \frac{T_s}{N}
$$

$$
q_{k+1} = q_k + q_k \frac{T_s}{N}
$$

$$
r_{k+1} = r_k + r_k \frac{T_s}{N}
$$

Designing the control architecture for the FWMAV:-

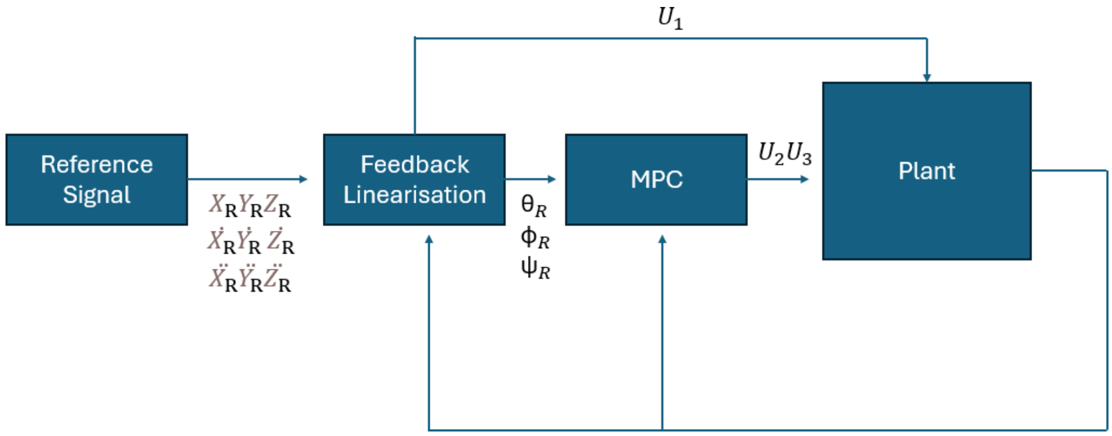
FWMAV Plant Model:-



The plant model for fwmav functions by utilizing the outputs generated from the Model Predictive Control (MPC) system, specifically the thrust and torque commands denoted as U1,U2,U3. These commands serve as control signals for the individual motors. The model translates these inputs into angular frequencies for each motor, which subsequently affect the velocities of the system, By integrating these velocities, the state variable s are updated to accurately reflect the current motion of the system. The computed velocities and angular rates are then processed through a rotational and transformation matrix, facilitating the conversion of body-frame with inertial-frame. This results in outputs in linear velocities and angular velocities, which indicate the system's spatial position and its orientation in terms of roll, pitch, and yaw. This data is subsequently integrated over time to yield updated state variables such as the linear positions and angular positions, reflecting the system's new position and orientation. Ultimately, this detailed feedback is relayed back to the MPC controller, allowing it to make informed predictions and adjustments based on the system's current state, thereby ensuring enhanced control and stability throughout the flight.

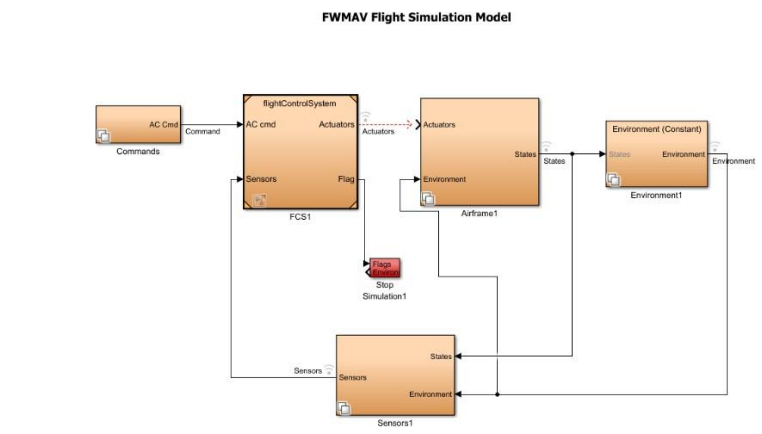
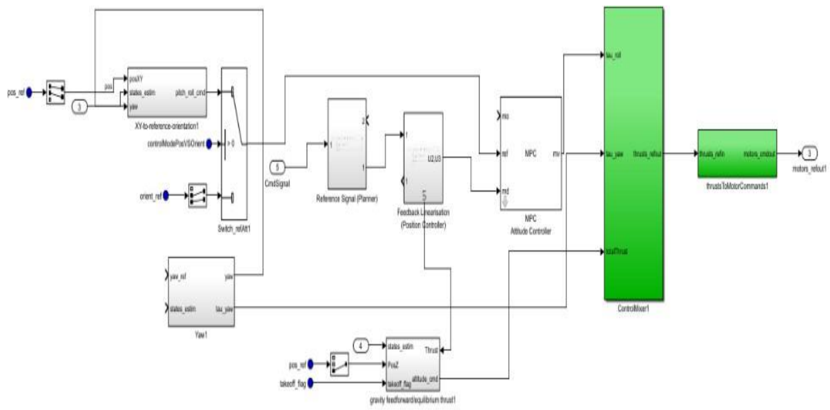
One alternative approach for managing nonlinear systems in Model Predictive Control (MPC) without tackling the complex nonconvex optimization problem directly is to initially establish a linear relationship between the system's input and output. This can be achieved through a method known as inner loop feedback linearization [8].

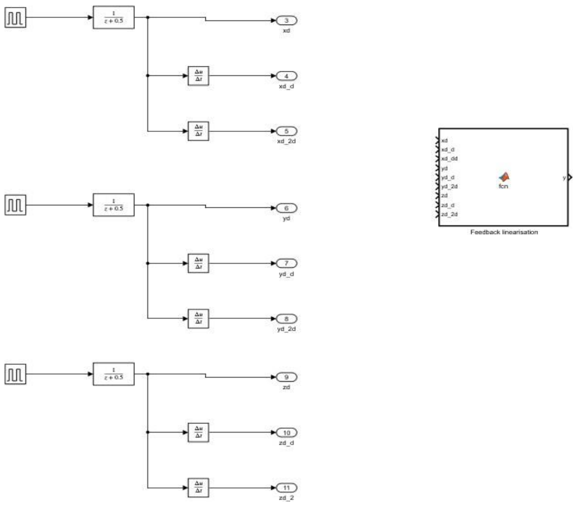
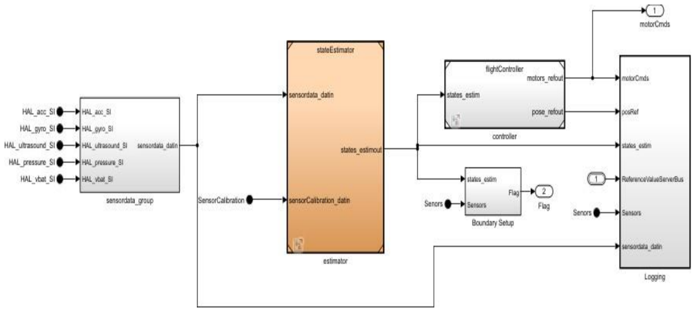
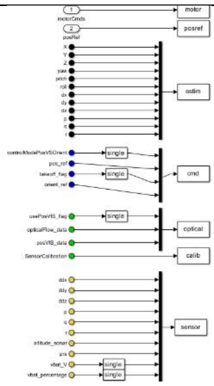
FWMAV Control Architecture:-



The control framework for the system comprises multiple layers designed to ensure stable flight and accurate maneuverability. At the highest level, the reference planner formulates the desired trajectory by specifying the target coordinates (x, y, z), along with the corresponding velocities (ẋ, ẏ, ż) and accelerations (ẍ, ÿ, z̈). This data is subsequently processed by the feedback linearization controller, which functions as a position controller to determine the requisite pitch, roll, and yaw angles necessary for the system to adhere to the intended trajectory. Following this, the Model Predictive Control (MPC) operates as the attitude controller, translating the angular references into motor commands U2 and U3 for roll and yaw, while optimizing control inputs through the prediction of future states and the minimization of a cost function. The plant embodies the actual dynamics of the system, executing these control commands, while a feedback loop persistently monitors the system's state and modifies the control inputs as required, thereby improving stability and responsiveness during flight.

Simulink Model Creations:-

	The Commands Subsystem is responsible for reference trajectory and control commands to the FSC Subsystem which is the most important subset connecting control algorithms together for getting desired stable system. Airframe subsystem is the outer part of the FWMAV which relates the aerodynamics with the physical structure and sends/receive data from the environment subsystem block. Lastly, the feedback and real-time status is given back to the system by the sensors subsystem.
	The Flight Controller Subsystem in the FCS is Made up of Position Controller (Feedback Linearization) (in progress) and attitude controller which is handled by the MPC. Reference Signal which is also called as planner Block provides trajectory equations to the position controller to handle the x-y-z positions of FWMAV w.r.t body frame. Counteracting gravity force is included that will affect the overall forward/vertical thrust motion of the vehicle.

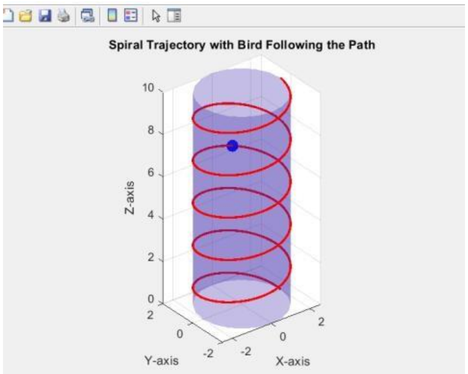
	Generalized form of feedback linearization for x-yz parameters going in the F.l and output (input states U2,U3) which will going into the MPC controller.
	Overview of the FCS System. Having Estimator (to estimate the states). Flght cont Ro.ller for MPC and control algorithm implementation. Boundary Controller which provides boundaries and to signal system failure. Logging is like a registry responsible for storing all the inputs together to maintain the record.
	Logging system consisting of all the different commands and variables coming all to together for record and prediction.

Path Trajectory,

$$x = r.cos(2 * pi * f * t)$$
$$y = r.sin(2 * pi * f * t)$$
$$z = h_i + (h_f - h_i)/2$$

Where t is sampling time and h is the height (initial and final)

Putting the path trajectory into the reference signal(planner) for testing,



Taking derivative and double derivative of above equations will provide velocity and acceleration in x-y-z plane.

2.3 Analysis & Future Work:

The current stage of the research presents a comprehensive framework for the control and dynamics of FWMAV. The analysis have provided the connection between aerodynamic forces, system orientation and control inputs required for stability. With this work we have established the foundation for understanding complex nonlinear dynamical systems. It was challenging to provide explanations and derivations for each formula due to the rigorous process of entering equations through keyboard in the Word file, but I made an effort to clarify them as much as possible. I'm not sharing the entire Simulink model because it isn't complete, and I'm unsure if it's entirely correct; I need to make some modifications first.

Goals Achieved:-
-The controller architecture consists of a position controller utilizing state feedback linearization as the outer loop, and an attitude controller based on Linear Parameter Varying Model Predictive Control (LPV-MPC) as the inner loop.
- We have established a sampling time TsTsTs and defined the number of controlled states and inner control loop iterations.
- Reference signals for the trajectory generation have been computed, including translational and angular position references over time.
- The initial state vector of the FWMAV has been defined, incorporating velocities and positions in all three dimensions, as well as initial angular orientations.
- Thrust and torque coefficients have been utilized to compute control inputs for thrust, roll, pitch, and yaw, based on the angular velocities of the vehicle's motors.

Future work will involve several key areas for enhancement and validation. First, the implementation of the proposed control architecture will require extensive simulation and testing under various operational conditions to evaluate its robustness and responsiveness. Furthermore, empirical testing will be vital to validate the mathematical models and simulations, allowing for adjustments based on observed flight behavior.

Additionally, a thorough exploration of the integration of machine learning techniques (if possible according to time constraints) could enhance the adaptability and efficiency of the control system. By employing adaptive algorithms, the FWMAV could learn from previous flight data and optimize its performance in real-time, improving manoeuvrability and stability during complex tasks. This could be particularly beneficial in environments where traditional control methods may struggle to maintain performance.

Future Work Objectives:

- Inertia and Center of Mass Calculation Develop detailed diagrams and determine the placement of components. Calculate inertia across the x, y, and z axes and identify the center of mass (C.O.M).
- Bond Model Optimization Refine the Bond model to improve the understanding of system dynamics and behavior.
- Controller Development Create a linearization feedback controller that operates as a position controller.
- Model Predictive Control (MPC) Design Develop a cost function for the MPC that includes

constraints, such as motor input limits.

- Discrete Linear Parameter-Varying (LPV) Matrices Generation Produce the discrete LPV matrices Ad, Bd, Cd, Dd in the code. Formulate the state equation $x(k+1) = A(p(k))x(k) + B(p(k))u(k)$ and the output equation $y(k) = C(p(k))x(k) + D(p(k))u(k)$.
- Simulation and Model Validation:- Create a thorough simulation of the system. Employ system identification methods to validate the mathematical model using data gathered from simulation tests.
- Hardware Implementation and Mechanical Design Install the required hardware components. Ensure the mechanical systems are designed and configured correctly.
- Real-time Feedback Integration:- Incorporate real-time information from onboard sensors (gyroscopes, accelerometers, vision systems). Continuously adjust the vehicle's control inputs to ensure stable flight under varying conditions.
- Code Finalization Complete the code by incorporating necessary constraints and ensuring compatibility with both LPV discrete and continuous models.

By adhering to this organized approach, you can effectively tackle each objective, ensuring clarity and advancement throughout your project.

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