Development of an Improved Controller for Enhancing the Performance of Unmanned Aerial Vehicle

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Abstract- In this work, an improvement was made tothe altitude control of a quadcopter by effectively turning the PID controller of a nonlinear model of a quadcopter. The result of the characterization of a nonlinear controller gave a peak overshoot that rapidly settled into a stable state. Although this outcome was better in performance than those of linear controllers. An effort was further made to considerably reduce the overshoot observed by the controller by using a linear modelled controller to tune the parameters of the PID controller for altitude control in the nonlinear model and adjusting the model airframe mass by multiplying it through the controller take-off gain. In the experiment done in this work, the maximum height reached by the drone was 3.29m. The median height was 1.5m. The overshoot was taken from the median and it was 1.79m. After enhancing the thrust control of the quadcopter through linearization, the overshoot obtained was 0.0016m.

Indexed Terms- Enhanced, Performance, Overshoot, Unmanned-aerial-vehicle, Non-linear, Controller

I. INTRODUCTION

Drones are drones that can fly independently, remotely, or in conjunction with a global positioning system (GPS). The US Air Force was using about 7500 UAVs as of 2012. In almost every industrialized nation as of 2017, the UAV production industry is expanding. (Zohdi, 2020)

The main objective of the UAV is the real-time surveying of broad areas, including those affected by a disaster like an earthquake, fire, or tsunami. Although crop dusting and crop health monitoring are two apparent uses for UAVs in agriculture, they also have a wide range of other applications. (Zohdi, 2020).

There has been a lot of interest in using aerial infrastructure to assist terrestrial communication systems. Drone small cells (DSCs) are airborne cellular base stations that can be placed on flying objects like unmanned aerial vehicles. DSCs can function as airborne base stations to assist communication systems in high demand and congestion. (Mozaffari et al., 2015). UAVs are a perfect solution for many AEC applications since they can visit areas that are dangerous, challenging to access, or inaccessible to personnel. They can also do some AEC-related tasks more quickly and inexpensively. (Albeaino et al., 2019). UAVs present a variety of technological issues for control engineers, including those related to instantaneous sensing, processing, and telecommunications needs, operational and environmental unpredictability, and the growing demand for more UAVs and larger UAV team autonomy and dependability (Vachtsevanos et al., 2007).Recent years have seen imaginative coordination of planning and research in control systems technologies like distributed artificial intelligence and intelligent systems to address these challenges (Vachtsevanos et al., 2007). Stabilization of an unmanned aerial vehicle system is a collection of components and algorithms deployed in inbuilt computers to ensure the centre of mass of the UAV moves steadily. Due to the complexity of the stabilization system's synthesis, a sufficient mathematical model is needed to describe it. (Kramar et al., 2021)

A multidimensional system with numerous controllable parameters and input activities is necessary to achieve a stable UAV stability system. It consists of interconnected state elements that account for many external disturbances on to control object, such as wind. The UAV stabilization systems are

dynamic, complicated systems with vector nature control actions (Kramar and others, 2021). Using a linear model controller to setup a non-linear model controller is one technique to improve stability in UAVs. Srinivasnagar (2018) presented a comparative study on linear and nonlinear control techniques for the near-hover attitude stabilization of a quadcopter.
Korea (2021) demonstrated a much more precise method of constructing an under-actuated quadcopter model using the Lagrange-Euler and Newton-Euler equations and creating flight controllers to guarantee the stability of both its linear and angular motion during hover conditions. For the available regular form, a reliable entire flight trajectory tracking control law based on a robust global fast terminal attractor has been constructed by Ullah et al. (2021) and is operated under matched uncertainty. To enhance the performance of the controller in full flight, the nonlinear drift factors, which undoubtedly change in full flight, are approximated in the proposed architecture using functional link neural networks. (Nemati & Kumar, 2014) devised a dynamic model of a quadcopter with tilting rotors, also known as a quadcopter with rotors that can tilt along one of its axes.

A neural network-based sliding mode control (SMC) was proposed by Nguyen et al. (2021) for the attitude and altitude system of the quadcopter in the presence of external disturbances. Emran et al. (2015) postulated that payload add-or drop occurs commonly in various quadcopter applications. Cedro & Wieczorkowski (2019) worked on quadcopter dynamics modelled by tuning PID controller gains using Newton’s equation of motion.Zakriti (2019) presented a mathematical model of a quadcopter by taking into account the different mechanical actions and disturbances that act on the system, thus, simulating the behaviour of the drone under Simulink, this requires the use of a cascaded PID controller to govern the manipulation of the drone for trajectory tracking to make a smooth implementation.Jiang &Pourpanah (2019) worked on a quadcopter UAV system that is based on neural network-enhanced dynamic inversion control for multiple real-world application scenarios

II. METHOD

The proposed system was characterized by developing a mathematical model for a quadcopter and simulation of altitude manoeuvring of the quadcopter.

2.1 Mathematical model of a quadcopter.

I. The quad-copter has four rotors and is arranged in a way that the odd-number pairs rotate in the same direction while the even-number pairsrotates in opposite directions. A right-ended coordinate frame shown in Figure 1was used.

There are three variables needed for torque: yaw, roll, and pitch. Additionally, three variables are needed for translation: x, y, and z.

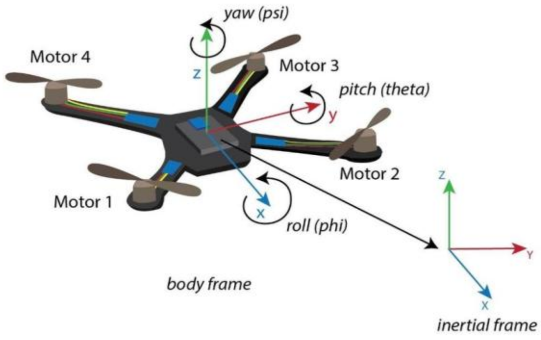

Figure 1: Quad-copter Configuration

i. When a quadcopter is rotated by an angle, the movement of the drone in the x or y-direction is taken as a component of the force in the z-direction. The spinning of the rotors produces four effects: thrust, roll, pitch and yaw. Force can only be induced directly in the z-axis, but not the x-axis or the y-axis directly.

ii. Thrust

Each motor produces an upward thrust. This is the upward lift force that is generated by the rotor. It is proportional to the angular speed of the rotor.

The thrust produced by theith rotor is given as

$$T_i = K_T w_i^2; i = 1, \dots, 4 \qquad (1)$$

T_z is the thrust produced by rotors that move the drone in the upward direction,

K_T is a constant known as the propeller lift coefficient and w_i^2 is the angular speed.

$T_z = k_T(\sum_{i=1}^{4} w_i^2)$ (2)

Since the angular speed of the rotor is proportional to the voltage it is assumed that

$$w_i^2 = C_m V_i^2 \quad (3)$$

C_m is a constant and V_i^2 is the applied voltage.

iii. Roll Torque (torque around the x-axis)

The rotational movement called the roll is obtained from the following equation.

$$\tau_\phi = \ell\,(T_1 - T_3) \quad (4)$$

iv. Pitch Torque (torque around the y-axis)

The pitch torque is derived as:

$$\tau_\theta = \ell\,(T_4 - T_2) \quad (5)$$

In both roll and pitch, ℓ is the distance between the rotor and the centre of mass of the quad-copter.

v. Yaw Torque (torque around the z-axis)

The angular speed and rotor acceleration create torque around the rotor axis given by:

$$\tau_i = K_\tau w_i^2 \quad (6)$$

K_τ is the propeller drag coefficient.

The total torque around the Z_b axis is the yaw torque given by

$$\tau_\psi = K_\tau(w_1^2 + w_3^2 - w_2^2 - w_4^2) \quad (7)$$
$$= K_\tau C_m(V_1^2 + V_3^2 - V_2^2 - V_4^2) \quad (8)$$

In equation (3), the voltage level is proportional to the angular speed and, therefore, the torque as seen in equation (6).

i. Equations of motion of a quadcopter
ii. State

In the design of a quad-copter, there are six degrees of freedom of which three are translational and three are rotational. The translation variables are: $\begin{bmatrix} X \\ Y \\ Z \end{bmatrix}$ and it is taken from the position of the centre of mass, as seen in And the rotational variables are: $\begin{bmatrix} \phi\ (roll) \\ \theta\ (pitch) \\ \psi\ (yaw) \end{bmatrix}$ The linear velocity around the body frame is given as $\begin{bmatrix} V_{XB} \\ V_{YB} \\ V_{ZB} \end{bmatrix}$.

The body frame is given in Figure 1.

The angular velocity along the body frame is given as $\begin{bmatrix} w_{bX} \\ w_{bY} \\ w_{bz} \end{bmatrix}$.

iii. Positions

$\begin{bmatrix} \boldsymbol{x, y, z} \\ \boldsymbol{\phi}, \theta, \psi \end{bmatrix}$

Velocities

$\begin{bmatrix} \boldsymbol{x}', \boldsymbol{y}', \boldsymbol{z}' \\ \boldsymbol{\phi}', \boldsymbol{\theta}', \psi' \end{bmatrix}$ Angular speed $w_b = \begin{bmatrix} w_{bx} \\ w_{by} \\ w_{bz} \end{bmatrix}$

$$= \begin{bmatrix} 1 & 0 & -sin \\ 0 & cos\phi & cos\theta sin\phi \\ 0 & sin\phi & cos\phi sin\theta \\ & & \end{bmatrix} \begin{bmatrix} \phi' \\ \theta' \\ \psi' \end{bmatrix} \quad (9)$$

iv. Kinetic Energy

$K = \frac{1}{2}\, m(x'^2 + y'^2 + z'^2) + \frac{1}{2}\left(I_x w_{bx}^2 + I_y w_{by}^2 + I_z w_{bz}^2\right)$ (10)

Where $I_x, I_y,$ and I_z are inertial along these axes.

v. Potential Energy

$PE = mgz$ (11)

vi. Lagrangian: a function that describes the state of the dynamics of the drone system in terms of position coordinates and their time derivatives. It is equal to the difference between kinetic energy and potential energy.

L = K – PE (12)

Euler LaGrange equation is $\frac{d}{dt}\left(\frac{\delta l}{\delta q_j}\right) - \frac{\delta l}{\delta q_j} = \Gamma_j$ (13)

Γ represent external forces and torques,

$q = \{x, y, z, \phi, \theta, \psi\}$; the quadcopter has four rotors but six degrees of freedom represented by q. This is why one motion has to be decoupled from the other.

The torque $\tau_{ext} = \begin{bmatrix} \tau_\phi \\ \tau_\phi \\ \tau_\psi \end{bmatrix}$

$\tau_\phi = \ell\,(T_1 - T_3); \tau_\phi = \ell\,(T_1 - T_3)$, and $\tau_\psi = K_\tau(w_1^2 + w_3^2 - w_2^2 - w_4^2)$

The external forces are the forces acting on the x, y, and z-axis. When the drone is tilted along the x or y-axis, to a certain degree of angle, the thrust produced by the rotor will produce a component of force in that direction. The external force is given in equation (14) with the assumption that there is a drag force acting on the thrust, and R is the rotation matrix.

$$F_{ext} = R * Trust - Drag \qquad (14)$$

$$= R \begin{bmatrix} 0 \\ 0 \\ k_t(w_1^2 + w_2^2 + w_3^2 + w_4^2) \end{bmatrix} - \begin{bmatrix} A_x V_x \\ A_y V_y \\ A_z V_z \end{bmatrix}$$ where

$A_x, A_y, and\ A_z$ are damping constants in various directions,while $V_x, V_y, and\ V_z$ are velocities.

$$\Gamma_J = \begin{bmatrix} \tau_{ext} \\ F_{ext} \end{bmatrix}$$

R transforms the force in the z frame to other frames.

III. SIMULATION OF QUADCOPTER ALTITUDE CONTROL

3.1 Environment model of a quadcopter

Figure 2 is the environmental model of the quadcopter. The value of the air density used is 1.184.

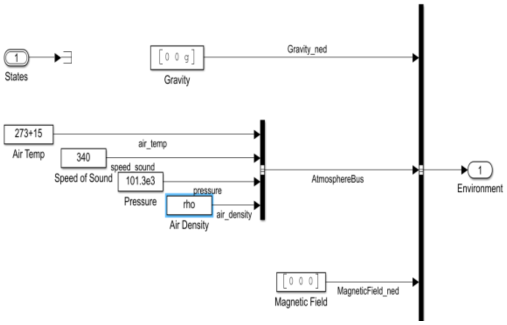

Figure 2: Environment model of the quadcopter.

The data from the environment model is fed into the blocks of the gravity force calculation, drag calculation, and motor force and torque of the nonlinear airframe model. Figure 3 is the Air Frame model of the quadcopter.

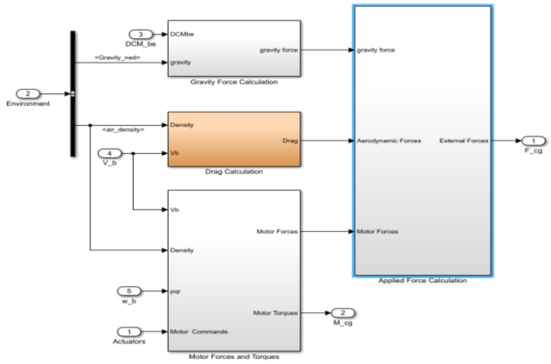

Figure 3: Airframe Model.

Figure 4 is the sensor data processing model. This model processes the data received from the sensors, the gyroscope sensor and the pressure sensor and the accelerator sensor and uses the process data to estimate the state of the quadcopter. The model in Figure 5 is used to estimate the altitude of the quadcopter. The complete block model of this is shown in Figure 6.

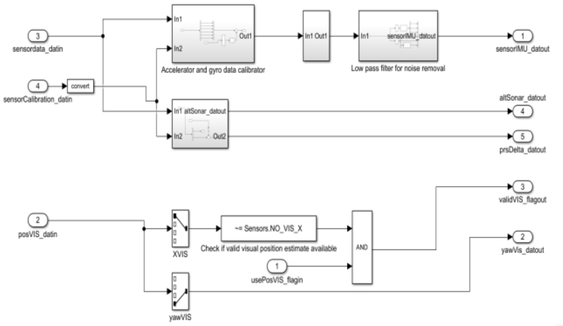

Figure 4: Sensor Data Processing Model

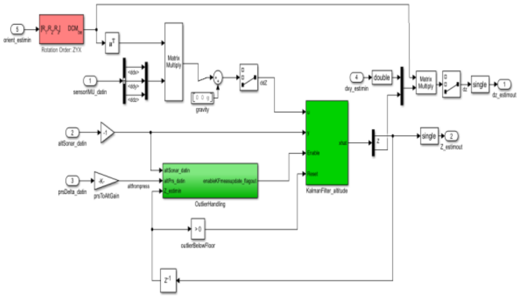

Figure 5: Altitude Estimation Model

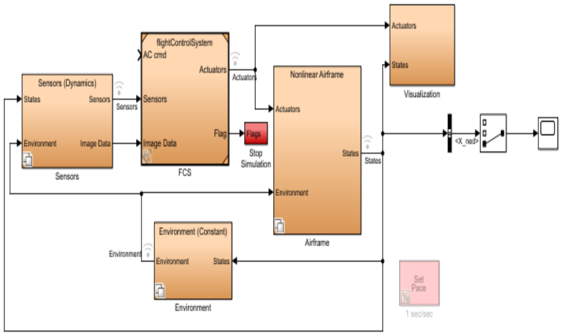

Figure 6: QuadcopterModel

The model in Figure 6 has a set reference point of (0 0 -1). That is, the x-and y-axis is zero and the altitude is -1. The flight control block is where the controllers are situated and it is designed for automatic code generation. The visualization block plots the signal while the simulation runs. The environment block is where gravity and air pressure are modelled. The sensor block simulates the sensors in the model. The Airframe block is where the motors' commands are modelled. The flag is used to stop the simulation in case a loss of stability is detected and the set pace is used to set the time the simulation will run.

IV. STABILITY PERFORMANCE IMPROVEMENT

4.1 Altitude Control Enhancement

A state estimator was used in the model to convert pressure readings to altitude. The firmware on the drone recorded data during flight and the data was logged into the model using Data Logging. An experiment done with this model is Hover Maneuvering. The model of the flight controller of the nonlinear model is shown in Figure 7, and its altitude controller used to set the parameters of the controller of the nonlinear model is shown in Figure 8.

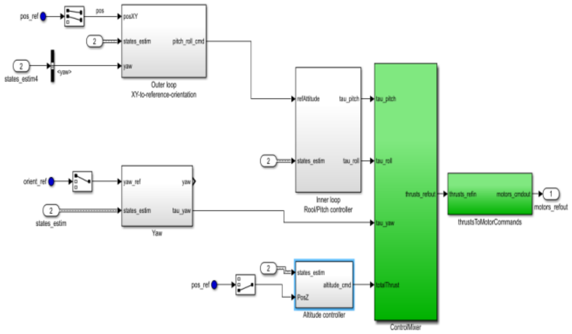

Figure 7: Flight controller of the nonlinear model.

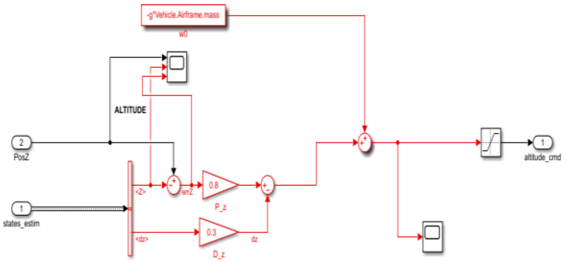

Figure 8: Altitude controller of the nonlinear model

To carry out a linear analysis of the design, a linear model is made, as shown in Figure 9,although less accurate, it can be used to obtain values that are used to tune the non-linear controller to obtain a better control for the controller when substituted into the non-linear model.

4.2 Enhancing thrust control of the quadcopter

Nonlinear models are very good in simulation, but they do not lend themselves well to linear analysis. For this purpose, a linear model is needed. A linear model can help turn the controller into the nonlinear model of the quadcopter.

The flight software is very difficult, if not impossible to linearize, therefore, a completely different model is designed for linearization with the following assumptions:

I. $\phi = \theta = \psi = 0; y = x = 0;$ his means that the airframe can only go up and down.
II. Sensor dynamics and noise are negligible. This way, the rate of change of altitude is estimated directly without taking the derivative of any noisy signals.
III. The true altitude of the drone is known. This introduces a feedback loop to limit the effect of overshoot.

At the hover point,the momentis equal to zero since the moment at that point is zero as the roll angle is zero. At the hover point, the properties of the drone become:

$\phi = \theta = \psi \ = 0; y = \ x = \ 0;$

The drone takes an incremental in the z-axis. On the graph, the value of Z is negative because the drone acts against gravity as it moves upward. The drone takes an incremental step untill the reference point is reached at which the drone becomes stable.

$$z = \ z_0 + \ \Delta z \qquad (15)$$

Figure 9 is a linear controller for altitude stability.

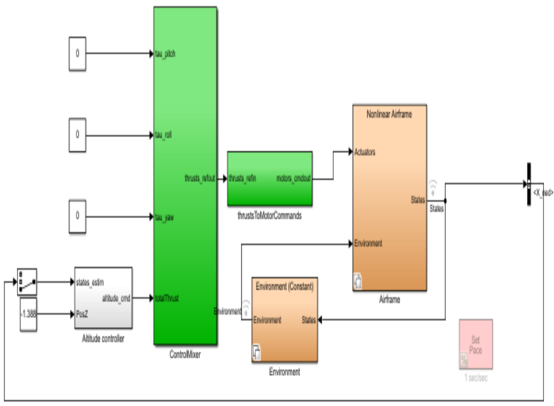

Figure 9:Linear Control Model

In the nonlinear model, all sensor blocks are removed so that there is no noisy signal and result in a clean altitude signal. This signal is fed into a controller that will fine-tune it and carry out filtration at the same time. When the tuning is complete, the controller is replaced with that of the linear model and result are compared.

V. RESULTS AND DISCUSSION

Figure 10 gives the altitude attained by the drone.

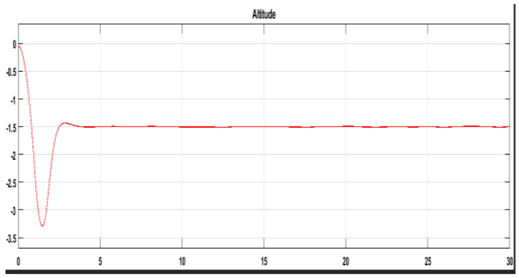

Figure 10: Results of characterization of a nonlinear model of a quadcopter.

The drone moves upward but it is represented on the negative axis of the scale because it is acting against gravity as it moves upwards.

The maximum height reached by the drone is 3.29m. The median height is 1.5m. The overshoot is taken from the median and it is $3.29 - 1.5 = 1.79m$

The value is taken as an error. The reference height in this flight is 1.5m.

The negative effect of such an error is that if there is a roof in the environment of flight, say, an indoor environment, the tendency of the drone to hit the roof before attaining stability is there, and this can cause damage to the propellers which will reduce the functionality of the drone. Futhermore, the power consumed during the overshoot adds to a waste of power that is not desired. The time to attain stability is also reduced.

Figure 11 is the result obtained after the controller of the nonlinear model was parameterized with the designed linear model. The model was again tested with a reference height of 1.386 meters. As seen on the graph, the drone rose to a steady state with negligible overshoot.

The minimum value on the graph is -1.402m, which is the maximum height of flight. The median is -1.386m. The overshoot from the median is $|-1.402|—|1.386| = 0.0016m$

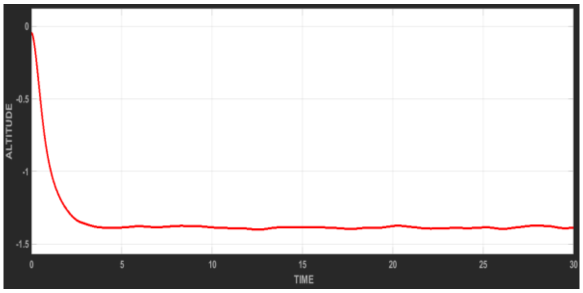

Figure 11. Graph of the improved nonlinear controller for the quadcopter

CONCLUSION

By improving the control system, an unmanned aerial vehicle's performance may be raised. The drone can be better controlled in this manner. Drone performance is improved by the nonlinear controller, but they are difficult to build. After their controllers are created, it might be challenging to determine the appropriate parameters due to their intricacy. Overshoots are a result of the nonlinear model's difficulty in adjusting the controller. Designing a linear model utilizing the control parameters of the nonlinear model on the linear model and then giving it auto-tuning is one method of fine-tuning the nonlinear model to reduce the influence of an overshoot. In the non-linear controller, the values acquired in this manner can be replaced. This method allows for the elimination of the overshoot issue. This may be done to improve each of the quadcopter's other parameters.

The findings of this study demonstrate that if a quadcopter's controller is properly calibrated, overshoot may be decreased. The study concludes that by fine-tuning an unmanned aerial vehicle's controller using a comparable linear model, the performance will be improved.

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