Design and Analysis of a Hybrid Intelligent Controller for Longitudinal Dynamics in Autonomous Unmanned Aircraft Systems

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Abstract:

Given the increasing request for advanced levels of autonomy in Unmanned Aircraft Systems (UAS), the autonomous control of these systems (AUAS) has gained substantial importance and attention between the researchers. The controllers for these systems can be either traditional or intelligent. This research paper highlights on exploring the integration of a smart controller with a proportional integral derivative controller to handle the speed and altitude of an aircraft. This permits the autonomous longitudinal control for unmanned aircraft that includes the takeoff and altitude management. A hybrid control method, which combines numerous control systems, is proposed in this paper. Mainly, it comprises the model predictive control (MPC), neural network control (NNC) and the PID control. The recommended longitudinal controller includes three autopilots: the pitch orientation autopilot which employs the PID control for low angles of attack, the speed control autopilot which designed using PID methods, and MPC for high angles of attack, and the altitude control autopilot. The intelligent hybrid longitudinal controller was effectively simulated and examined. The PID controller showed a strong ability to correct errors associated to control surface actuators, whereas the NNC showed to be robust in handling the overall system response. The actual takeoff trajectory of the aircraft strictly corresponded to the required trajectory, with an extra ability to abort the takeoff if conditions were considered inacceptable.

Keywords: Unmanned Aircraft Systems, Autopilot, Proportional Integral Derivative, Model Predictive Control, Neural Network Control

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1. Introduction

An Unmanned Aircraft System (UAS) is a very complex system which consists of important mechanisms. In addition to the unmanned aircraft, UAS includes a ground control station responsible for monitoring, planning and controlling the flight and a data link that transmits real-time data and thereby eases the communication between the aircraft and the control station in continuous fashion [1]. UAS can function both autonomously and through remote control, enabling fully self-directed operation without requiring a pilot's presence on board. UAS are equipped with numerous electronic devices and systems which includes smart cameras, radar, and sensors, making them extremely adaptable [2]. As UAS technology spreads, upcoming developments are expected to comprise improved automation, greater capabilities enabled by sophisticated sensors, and well integration with electronic systems such as satellite communications. These developments will additionally increase the overall performance, reliability, and operational reach of UAS, making them more effective and resourceful in a variety of applications, from complicated defense missions to commercial operations. Regardless of their potential to transform industries, UAS encounter challenges associated to regulatory structures, safety in shared airspace, and cybersecurity suspicions [1-3]. UAS are extensively used military applications such as surveillance, reconnaissance, and combat missions. Furthermore, UAS are also implemented in civilian sectors such as environmental monitoring and research, disaster response and relief, agriculture schemes, and package delivery and logistic, etc. [4]

2. Aircraft Motion Mathematical Modeling

The mathematical modeling of aircraft fundamentally relies on the equations of motion, which encapsulate the longitudinal and lateral dynamics of the aircraft. These equations are formulated by applying Newton's laws of motion, which connect the summation of external forces and moments to the aircraft's linear and angular accelerations. Specifically, Newton's first law addresses the inertia of the aircraft, the second law relates force to the acceleration it produces, and the third law considers the interactions of forces [5]. Although these equations of motion are well-established and standard in the field, they are critical as they form the basis for deriving the transfer functions needed for control system design. The transfer functions will be derived from these standard equations to facilitate the analysis and synthesis of the aircraft's control systems, ensuring accurate prediction and management of its behavior during flight [6].

2.1 Longitudinal Equation of Motion

The equations governing the longitudinal motion of aircraft are presented below. These equations are based on the short period approximation mode, wherein the input force coefficients $C_{z_a} = C_{x_a}$ are assumed to be zero [7].

The Equations of the longitudinal motion of aircraft are represented below, these three equations are based on the short period approximation mode that where the input force coefficient: $C_{m_a} = C_{z_a} = C_{x_a}$ are equal to zero [7, 8].

$$\left(\frac{mU}{Sq}s - C_{x_u}\right)\acute{u}(s) - C_{x_\alpha}\acute{\alpha}(s) - C_w\theta(s) = 0 \quad (1)$$

$$C_{z_u}\acute{u}(s) + \left(\frac{mU}{Sq}s - C_{z_\alpha}\right)\acute{\alpha}(s) + \left(-\frac{mU}{Sq} - \frac{c}{2U}C_{z_q}\right)S\theta(s) = C_{Z_{\delta_e}}\delta_e(s) \quad (2)$$

$$-C_{m_\alpha}\acute{\alpha}(s) + \left(\frac{I_y}{Sq}S^2 - \frac{c}{2U}C_{m_\alpha}s\right)\theta(s) = C_{m_{\delta_e}}\delta_e(s) \quad (3)$$

These equations are essential for understanding the behavior of the aircraft's longitudinal motion and will be used to derive the transfer functions necessary for control system design.

In these equations:

- u(s) represents the forward speed perturbation.
- α(s) represents the angle of attack perturbation.
- θ(s) denotes the pitch angle.
- δ_e(s) denotes the elevator deflection.
- m represents the mass of the aircraft.
- U represents the reference velocity.
- S denotes the reference area.
- q represents the dynamic pressure.
- c denotes the mean aerodynamic chord.
- I_y represents the moment of inertia about the y-axis.

These equations are essential for understanding the behavior of the aircraft's longitudinal motion and will be used to derive the transfer functions necessary for control system design.

2.2 Steady Climb Conditions

A straightforward method to maintain a steady climb is to set a fixed throttle to achieve the favorite airspeed. Any deviation from the target speed can be corrected by adjusting the angle of attack. The reduction in the angle speed and the enhancement of climb rate are attained as a result of increasing the angle of attack. In contrast, reducing the angle of attack reimburses for a drop in airspeed, confirming that the required airspeed is conserved, however this results in the reduction of climb rate [8-9].

The following equations are used to analyze this process

$$T - D - W\ sin\gamma = 0 \qquad (4)$$

$$L - W\ cos\gamma = 0 \qquad (5)$$

By substituting W from Equation (5) into Equation (4), we get

$$T - D - \frac{L}{sin\,\gamma}\ cos\gamma = 0 \qquad (5)$$

Therefore

$$\tan\gamma = \frac{T-D}{L} \qquad (6)$$

For a negative climb rate (γ), where T equals to zero, and a small change in γ approximates $tan\,\gamma\ \approx \gamma\ \approx sin\gamma$. Consequently:

$$\frac{R}{C} = V\ sin\,\gamma\ \approx\ V_\gamma \approx \frac{(T-D)V}{L} \qquad (7)$$

3. The Takeoff Controller

In recent aircraft attaining a smooth takeoff needs smart complex control system, especially when a constant velocity, acceleration, and climb rate are required to be maintained. This approach needs the implementation of three different automated systems working together to manage several aspects of takeoff performance. The three control autopilot systems are:

- Speed Control
- Proportional-Derivative Velocity Control
- Proportional-Integral Velocity Control

✓ **Speed Control Autopilot**

The Speed Control Autopilot (SCA) is considered to be fundamental in managing the forward motion of the aircraft by regulating the thrust produced by the engines. The main objective of SCA is to keep a specific target flight speed, which is attained by automatic modification in the setting of the engine throttle. Where the system continually tracks the speed of the aircraft and responds to any deviations in the desired velocity by either increasing or decreasing the thrust [10-11]. Figure 1 shows the block diagram of SCA control system. The main parts of system include:

- **Compensator:** The main function of this part is to make the essential changes to the control inputs in order to keep the accuracy and stability in the speed management.
- **Engine Throttle:** This part models the aircraft's throttle system behavior, assesses how changes in the throttle setting impact engine output, which in turn influences the overall speed of the aircraft
- **Aircraft Dynamics:** This part of the system simulates the dynamics of the aircraft, accounting for external forces such as drag, lift, and engine thrust, which all influence the aircraft's motion.
- **Velocity/Acceleration Feedback Loop:** Lastly, this part continuously monitors the actual velocity and acceleration of the aircraft, and makes comparison with respect to the set points. Any discrepancies trigger corrective actions through the compensator and engine throttle model. Any detected inconsistencies automatically trigger corrective actions via the compensator and the engine throttle model, confirming the ideal performance and stability of the system

The aircraft forward speed is adjusted by regulating the thrust of the engine, which is controlled by the SCA. The system continually adjusts the engine throttle to preserve a consistent, predetermined flight speed, it automatically responds to changes in the conditions of flight which include the changes in the ascent rate and the wind. By leveraging a feedback loop that monitors velocity and acceleration in real time, the SCA makes necessary changes to ensuring smooth and reliable speed during takeoff. This technology is vital for improving the reliability and safety of aircraft throughout flight serious stages [10-12].

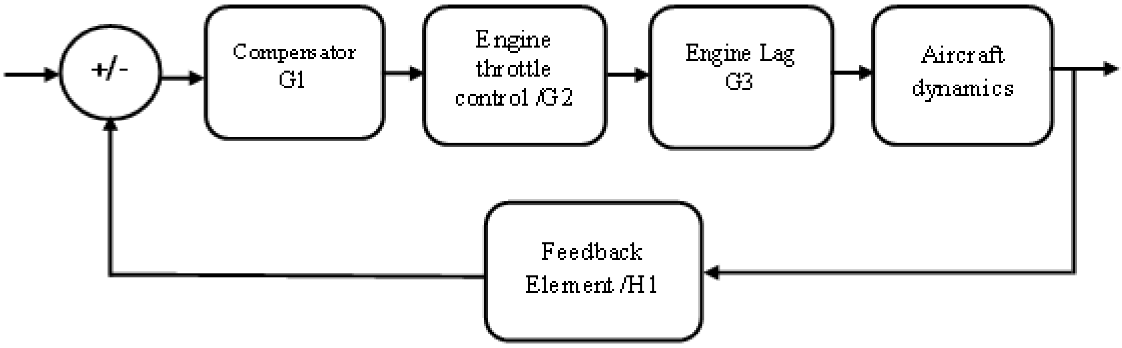

Figure 1: Speed Control Autopilot Block Diagram

The design process begins by developing stable transfer functions that characterize both the controller and the aircraft's dynamic behavior. The transfer functions are described as follows [10-12]:

$$G_1 = \frac{K_a\,(s + 0.1)}{s} \qquad (a)$$

Equation (a) denotes is the system response model, where K_a is the controller gain and (s+0.1) is the first order dynamic component

$$G_2 = \frac{10}{s + 10} \qquad (b)$$

Equation (b) denotes the low pass filter which suppresses the signals with high frequencies in order to improve the response

$$G_3 = \frac{1}{s + 0.1} \qquad (c)$$

The First order transfer function shown in Equation (c) additional stabilizing the dynamics by gradually slows the system response

$$H_1 = 10S + 1 \qquad (d)$$

The transfer function shown in Equation (d) impacts the way the system responds to variations in the velocity and acceleration by feedback.

By combining these transfer functions, the open-loop transfer function of the system shown in Equation 8 is derived. This represents the complete dynamic behavior of the autopilot, mainly with respect to the velocity and acceleration feedback. After introducing the feedback path gain, the closed-loop transfer function is expressed as:

$$\frac{\Delta_u}{\Delta_{\delta_T}} = \frac{0.038S+0.38}{S^3+10S^2+0.592S+0.53} \quad (8)$$

Such that, the controller proportional response to the system input was denoted by the numerator, whereas the overall dynamic behavior of the closed-loop system, comprising the third-order dynamics which account for stability, damping, and inertia was described by the denominator.

- **Proportional-Derivative Velocity Control**

Proportional-Derivative Velocity Control is one of the classical control systems that widely used in control engineering applications for velocity regulation. The control systems of this type consists two parts, the proportional and the derivative. The main task of proportional (P) component is to decrease the error between the actual and the required velocities. Nevertheless, this action can cause some fluctuations. Therefore, the derivative (D) part is used to provide an effective steady response in order to reach the desired velocity. In this study, a PD controller with open-loop gain k is proposed, as presented in Figure2. The controller has been automatically adjusted to find the best values of $k_p$and $k_{d,}$ confirming maximum stability of the system [13].

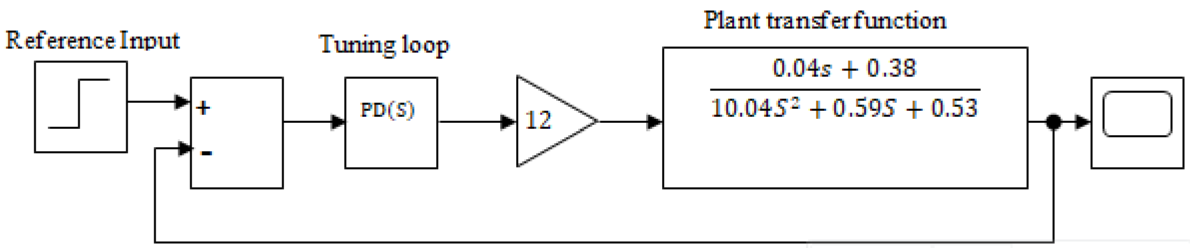

Figure 2: The PD Speed Control Autopilot

Table 1 presents the parameters of the speed control system response to a unit step and root locus plot for different values of k_p, k_d and the amplifier gain, $\boldsymbol{k_{amp}}$. It can be observed that the system exhibits a very fast settling time with presence of some steady-state error. Although increasing the gain helps to reduce this steady-state error, it also leads to a greater overshoot, as higher gains resemble a lower damping ratio. The forward amplifier gain has been slightly adjusted to improve the controller's performance.

Table 1: Tuned Proportional-Derivatives Speed Controller Parameters

Parameter	Value
Rise time (sec)	0.107
Settling time (sec)	0.802
Overshoot	9.76%
Closed-loop stability	Stable
k_p	125.5
k_d	20.9
k_{amp}	12

- **Proportional Integral Velocity Control Autopilot**

A Proportional Integral controller with dual feedback loops is proposed to remove the overshoot problem encountered in the proportional derivative controller. While the outer loop stabilizes the overall closed-loop response of the system, the inner loop is responsible to stabilizes the response of the forward gain element. Figure 3 demonstrates the proportional integral speed control autopilot block diagram [13-14].

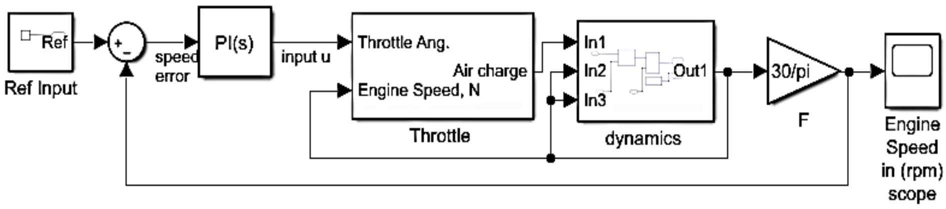

Figure 3: The Proportional Integral Speed Control Autopilot

Table2 demonstrates the parameters of the tuned proportional integral speed controller. Although the Proportional Integral presents slower settling time compared to the PD controller, the step response of the tuned controller shows remarkable enhancement, particularly in reducing the overshoot to about 5%, which is very less as compared to that of the Proportional Derivative controller. Moreover, the Proportional Integral controller presents a faster rise time, which indicates response improvement. Even though the Proportional Integral controller effectively reduces the overshoot, its robustness against real-world disturbances remains a concern that needs additional consideration.

Table 2: The Parameters of the tuned PI speed controller

Parameter	Value
Rise time	1.37 sec

Settling	1.9 sec
Overshoot	5.15%
Closed-loop stability	Stable
k_p	0.0057
k_i	0.008

- **Proportional Integral Derivative Velocity Control Autopilot**

By considering the disturbances in the systems, the proportional integral performance may degrade and the therefore the proportional integral derivative controller shown in Figure4 will be the best choice for the velocity controller autopilot. The updated design is obtained by including an input filter to the original design. The step response for the tuned Proportional Integral Derivative controller showed exceptional performance, with insignificant overshoot, close to zero, alongside faster rise and settling times. This controller demonstrated optimum behavior and achieved highly acceptable levels in terms of controller parameters. This proposes an effective balance between stability and responsiveness in the performance of the system.

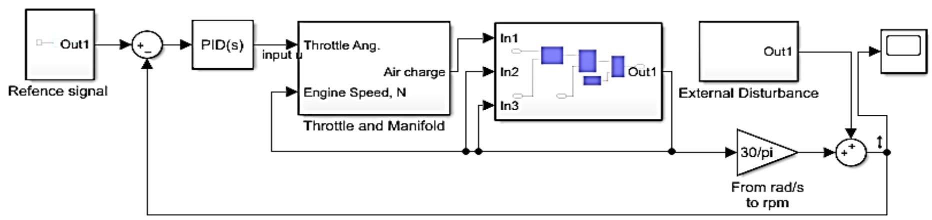

Figure 4: PID Speed Control Autopilot

This proposed autopilot will be integrated to the altitude control system for the purpose of simulating the takeoff, landing and navigation phases. Table 3 presents the parameters chosen of the tuned Proportional, Integral Derivatives speed controller.

Table 3: Parameters of the tuned PID speed controller

Parameter	Value
Rise time	0.107 sec
Settling	1.802 sec
Overshoot	0.48%
Closed-loop stability	Stable
k_p	0.024
k_i	0.027

k_d	0.00559

- **Pitch Orientation Autopilot** (POA)

POA is known as an automatic flight control system designed to cope and stabilize the pitch of the aircraft. POA controls the pitch rate of the aircraft by regulating the elevators of aircraft to keep a desired pitch angle during the phases of flight which includes the climb, level flight, or descent, without requiring continuous input from the pilot [13-15]. It is a critical component in the aircraft regarding the control of the overall stability. POA supports keep altitude, vertical speed controls, and confirms the remaining of correct flight path of the aircraft. The pitch rate of the aircraft can change due to several factors. For instance, when the horizontal tail of the aircraft is moved downward, an induced lift force will be generated. If the acceleration of the aircraft is amply high, this force results in a pitch-up movement. Furthermore, random pitch-up events can also be caused by a shift in the center of pressure on the wings, this changes the aerodynamic forces that acts on the aircraft [13-15].

The block diagram of the proposed pitch orientation control system for the aircraft is demonstrated in Figure 5, such that the input represents the desired pitch rate. The pitch rate controller design for low angles of attack is based on the relationship between the elevator deflection (δe) and angle of the pitch (θ). This relationship is represented by the transfer function given in Equation 9 and the block diagram shown in Figure 5. The transfer function permits for the change of the elevator deflection with respect to the changes in pitch angle, which is critical for effectively handling the pitch rate. This design ensures that the pitch angle directly effects the deflection in the elevator, allowing the controller to stabilize the performance of the aircraft at the instances of low angle of attack. Consequently, the control system will be adaptable at can maintain stable aircraft performance [10-17].

$$\frac{\dot{\theta}}{\delta_e} = \frac{-15(s+0.4)}{s^2+0.9+8} \qquad (9)$$

Where: $S_{rg} = 0.527 G_{servo} = \frac{10}{s+10} S_{ig} = 0.78$

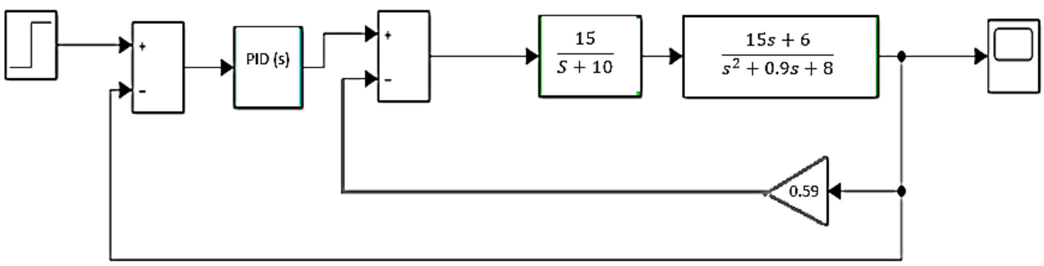

Figure 5: PID Pitch Rate Controller for Low Angle of Attack Block Diagram

The results of the tuned Proportional, Integral Derivatives controller showed that the integrator gyro gain used in the conventional pitch rate controller beside the compensator gain, cannot be totally replaced with entire PID controller. The response of the system tends to respond to the K_i input, otherwise a significant overshoot is induced. Table4 shows the details of the parameters of the tuned PID controller, which aim to reduce these problems.

Table 4: The Characteristic of PID Pitch Rate Controller

Parameter	Value
Rise time	0.0075 sec
Settling	0.9 sec
Overshoot	69%
Closed-loop stability	Stable
k_p	2
k_i	0.573
k_d	0.9

It has been observed that in case of high angles of attack, the aircraft tends to show instability which results from nonlinear behavior of the system. In such situations, the conventional feedback design techniques, including the PID method, do not function properly. This causes a real problem since the majority of aircraft are designed to fly stable at high angles of attack. This paper introduces a new technique aiming to solve this problem [10-17].

- **Explicit Model Predictive Controller for Pitch Rate**

An explicit model predictive controller (MPC) is a technique particularly implemented in situations where the traditional PID controller induces instability due to the nonlinear dynamics produced at high angles of attack. By using prognostic models to solve real time optimization problems, the Explicit MPC confirms that the pitch rate remains controlled, and the aircraft flies stable at high angles of attack. The MPC considers the restrictions, system dynamics, and optimal control trajectories, make them robust for nonlinear and multifaceted aircraft protocols. In MPC method, the dynamic behavior of the system is exemplified in state-space form considering the aircraft as a multivariable system. This allows the controller to predict the future conditions of the aircraft and make the corrections accordingly to maintain the aircraft stability during high angles of attack [10-18]. Equations 10 and 11 represent the state-space form.

$$\dot{x} = Ax + Bu \qquad (10)$$
$$y = Cx + Du \qquad (11)$$

The linear open-loop dynamic model of the aircraft is represented by the following state-space matrices.

$$A = \begin{bmatrix} -0.016 & -61.56 & 0 & -33.17 \\ -0.002 & -1.35 & 1 & 0.0001 \\ 0.00018 & 43.25 & -0.869 & 0 \\ 0 & 0 & 1 & 0 \end{bmatrix}, \qquad B = \begin{bmatrix} -2.71 & -13 \\ -0.17 & -0.26 \\ -17.35 & -1.58 \\ 0 & 0 \end{bmatrix}$$
$$C = \begin{bmatrix} 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}, \qquad D = \begin{bmatrix} 0 & 0 \\ 0 & 0 \end{bmatrix}$$

Since the controlled variable in this setup is the pitch rate, then the manipulated variables will comprise of the elevator and flaps angles. The main objective is to adjust the attack angle and the pitch angle to keep the system with the required pitch rate and therefore stabilizing the aircraft orientation during flight. The block diagram of the proposed method is shown in Figure 6 [19].

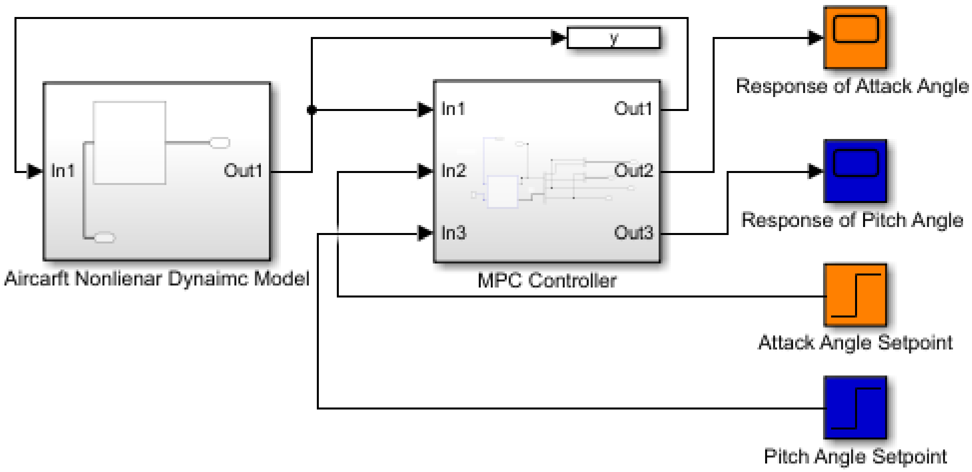

Figure 6: MP Pitch Controller for High Angle of attack

The main functions of MPC controller is to eliminate the offset for the reference model (zero gain offset), which is forced to prevent the instability produced by input saturation. The manipulated variables (MV) and output variables have already been scaled within the MPC controller, confirming the stability. The dimensionless MPC weights are then applied to the scaled MV and OV values to adjust the response of system [19].

- **The Altitude Control Autopilot**

The altitude of an aircraft can be maintained at a specific height by an altitude hold autopilot. A typical altitude hold autopilot is shown in Figure 7. Essentially this autopilot is designed to minimize deviations between the actual altitude and the desired altitude during cruise flight. Moreover, it aids maintaining the cruise altitude after the takeoff phase.

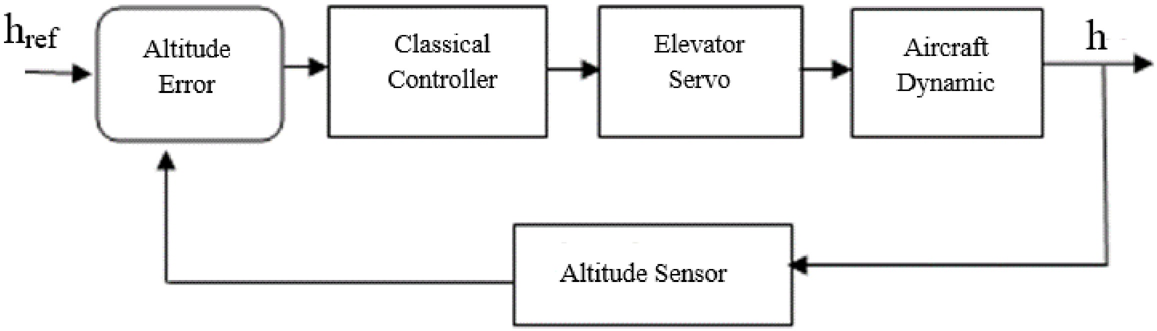

Figure 7: Altitude Control Autopilot

To design such an autopilot, an ideal case is first considered. In this case the velocity of the aircraft is assumed to be controlled separately, and the lateral dynamic effects are neglected. These two assumptions constrain the motion to the vertical plane [6, 10-19].

The transfer functions needed for this design include the elevator servo mechanism and aircraft dynamics. The elevator transfer function of first-order lag is exemplified by Equation 12:

$$\frac{\delta_e}{e} = \frac{k_a}{s+10} \qquad (12)$$

The aircraft longitudinal dynamics are derived from the standard equations of the longitudinal motion. To find the best performance indices for the proposed altitude hold control system, the transfer function of altitude variation $\boldsymbol{h}$ to the deflection of elevator δ_e must be derived first .This can be obtained by applying the aircraft performance coefficient in the longitudinal equations which shows the mathematical relationship between the aircraft's rate of climb (q), pitch angle ($\boldsymbol{\theta}$), and the angle of attack (α). These include the lift equation and the equations governing pitch and climb rate [6, 10-19].

The rate of climb is the vertical component of the velocity which influenced by the aircraft's pitch angle (θ) and angle of attack (α). This relationship is presented as:

$$q = \dot{h} = u_0 sin(\theta - \alpha) \qquad (13)$$

where:

q represents the rate of climb, $h^{\cdot}$ represents the time derivative of the altitude, u_0 denotes aircraft velocity, θ represents the pitch angle and α is the angle of attack.

The pitch angle (θ) is influenced by the aircraft's aerodynamic properties and control inputs such as elevator deflection (δe). By using the short-period approximation for longitudinal motion, θ can be correlated δe as follows [10-19].:

$$\frac{\delta e}{\theta} = \frac{k_e}{s + w_n^2} \qquad (14)$$

where: k_e represents the control efficacy and w_n is the system natural frequency.

The angle of attack (defines the orientation of the aircraft with respect to rate of climb due to air influence) is defined as the difference between the pitch angle and the flight path angle (γ), i.e.:

$$\alpha = \theta - \gamma \qquad (15)$$

from Equation13

$$\Delta\dot{h} = u_0 \sin(\Delta\theta - \Delta\alpha) \qquad (16)$$

Substituting for the flight path angle γ

$$(\Delta\theta - \Delta\alpha) = \gamma \qquad (17)$$

For small angles Equation 16 can be reduced to

$$\Delta\dot{h} = u_0(\Delta\theta - \Delta\alpha) \qquad (18)$$

Where

$$(\Delta\alpha = w)$$

The rate of change in the altitude h can be written as the flight path angle times the velocity and therefore:

$$\dot{h} \approx U_0 sin\gamma = U_0(\theta - \alpha) = U_0\theta - U_0\left(\frac{w}{U_0}\right) = U_0\theta - w$$

Now the change of altitude with the elevator deflection for the desired aircraft will be

$$\frac{\boldsymbol{h}}{\boldsymbol{\delta_e}} = \frac{\boldsymbol{K(s+w)(s-3.6)}}{\boldsymbol{s(s+0.25)(s^2+3.6s+9)}} \qquad (19)$$

After tuning the closed loop for the best values of the gain k it has been found that the compensation for the k only will not keep stability, since increasing k will lead the low frequency poles to the RHP, therefore a lead compensator has been added with internal closed loop [10-19]..

The lead compensator transfer function (T.F) is given by:

$$T.F = \frac{s+a}{s+b} \quad a < b \qquad (20)$$

- **Neural Network controller**

The classical controller designed for controlling longitudinal motion (speed and altitude) of the aircraft has shown a significant response (results are shown in section 4), the longitudinal controller is the main control element during the takeoff and landing, uncertainties can reduce the performance of the system.

A **Neural Network Controller** for controlling the longitudinal motion (speed and altitude) of an aircraft is a complicated type of artificial intelligence based control techniques that utilized to adjust sophisticated dynamics of the flight [20]. It regulates the throttle settings to keep the desired speed. By examining the real-time input data and forestalling the future conditions, the controller predicts the necessary throttle adjustments. Also by controlling the elevators, the neural network can modify and adjust the pitch of the aircraft which facilitates varying or maintaining the required altitude, which in turn keeps the desired or planned flight path and therefore avoid any deviation that may affect the aircraft safety [20].

Since the longitudinal controller is considered as the primary control element during serious stages in the aircraft which includes the takeoff and landing, the presence of uncertainties can considerably reduce the overall performance of the system. To consider this, a neural network controller was proposed to adjust the dynamics of the aircraft during both the takeoff phase and altitude control. The proposed controller was designed to learn by imitation to get advantage of the designed classical control methods. Specifically, the proposed neural network is trained using the traditional controller as a reference and then obtaining the input data from the classical system where altitude and velocity of the aircraft are considered as the desired outputs. To ease this process, the controlled parameters are sent to the workspace file in MATLAB, enabling the neural network to learn and predict the suitable system response to keep controlling the dynamic behavior of the aircraft. This technique confirms that the neural network can efficiently repeat and enhance the control actions taken during takeoff and altitude control. Figure 8 demonstrates the architecture of the proposed neural network controller [20-23].

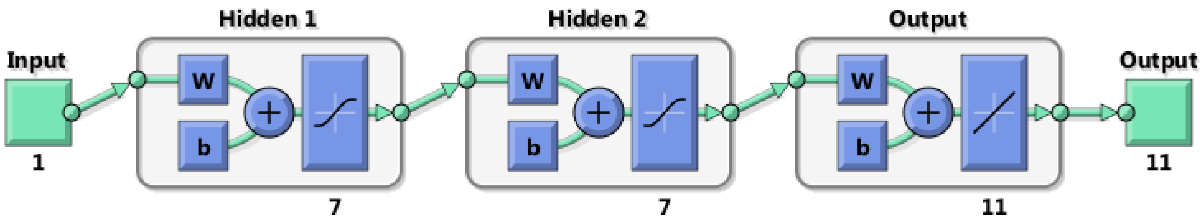

Figure 8: The Proposed Neural Network Controller Architecture

The proposed neural network has been built according to the characteristic listed in Table 5. Where the number of neuron in the hidden layer affect the desired output target performance

Table 5: Neural Network Controller Characteristics

	Type of network	Feed-forward
1	Data division	Randomly divided (Dividerand)
2	Training algorithm	Levenberg-Marquardt (Trainlm)
3	Performance evaluation method	Mean Square Error
4	Epoch	1000 iteration
5	Number of hidden layers	2
6	Number of neuron per each layer (can be adjusted for training purpose)	7
7	Number of trained networks	11

The proposed neural network was trained successfully in order to achieve the ideal performance after many iterations. Once the desired response was obtained, the network training was stopped, and a Neural Network Controller block was generated. This block was then integrated with the proposed proportional integral differential controller to obtain best system performance. Figure 9 shows the output response of trained network, the network has 11 outputs, each with different attitude to the desired target, the network will be integrated to the controller model, for the purpose of simulation [20-23].

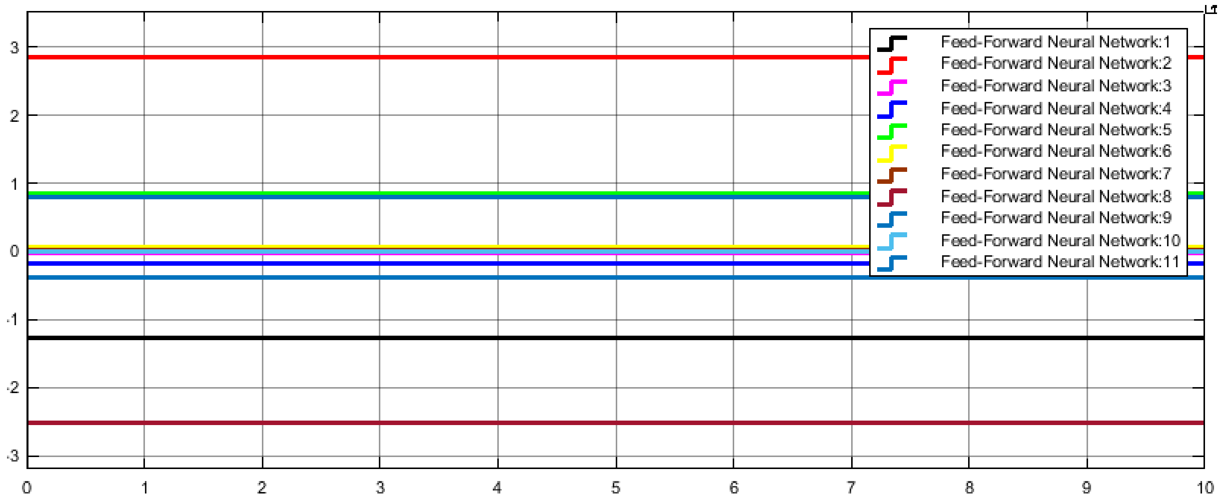

Figure 9: The response of the Trained Network for the Longitudinal Controller

✓ The proposed Aircraft Longitudinal Autopilot

The longitudinal autopilot is set to control the aircraft in both during the takeoff and landing. In this paper the takeoff part will be covered. The takeoff operation requires a tight coordination between the speed of the aircraft and its altitude. Therefore, the speed autopilot and the altitude autopilots have been integrated as shown in Figure 10 [20-23].

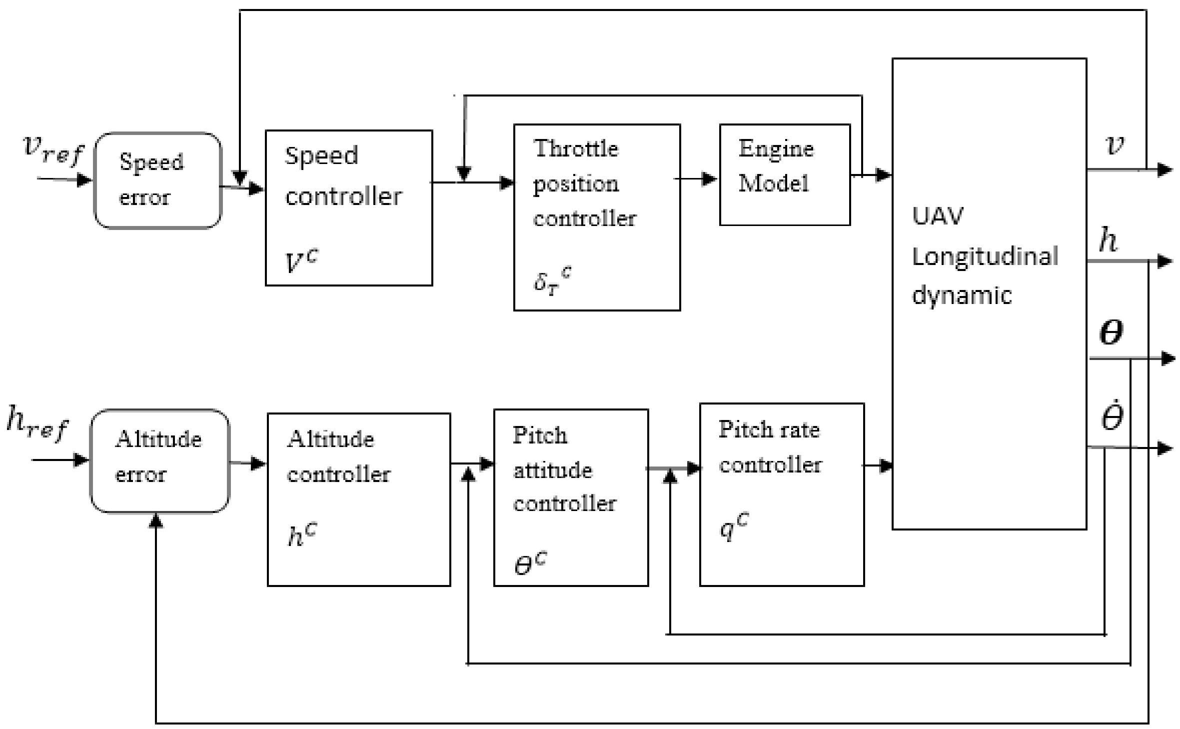

Figure 10: Aircraft Longitudinal Autopilot

The longitudinal autopilot is designed to control the aircraft control during the takeoff and landing phases. This paper focuses on the takeoff phase. The takeoff operation needs specific coordination between both altitude and speed of the aircraft. To attain this, the speed and altitude autopilots are integrated into a combined system, as shown in Figure 11.

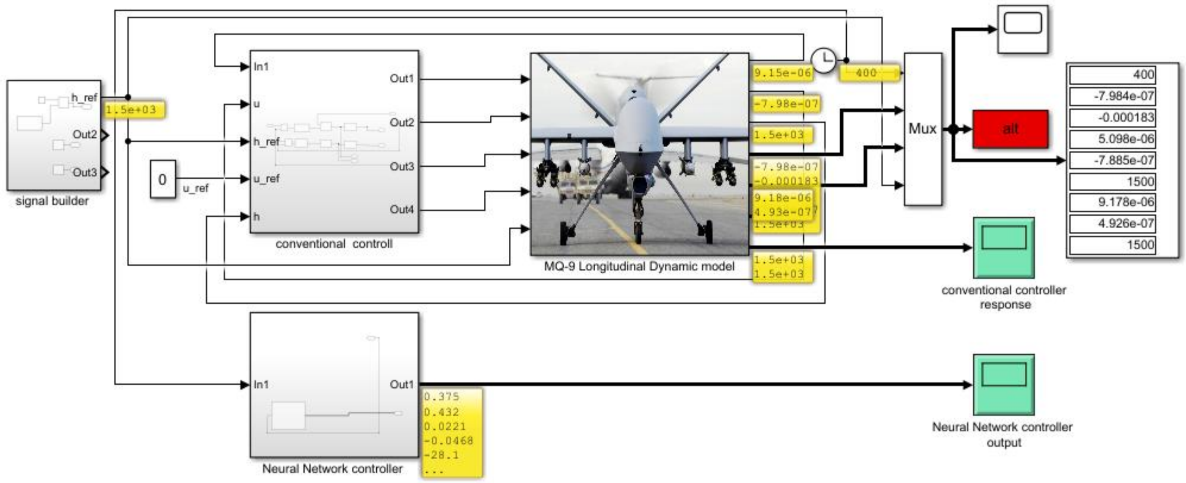

Figure 11: The Longitudinal Autopilot Design Using Simulink

MATLAB Simulink was utilized to simulate the takeoff and altitude control of the aircraft. The proposed system integration which includes the aircraft model, classical controller, and neural network controller and the signal builder is presented in Figure11. The signal builder is used as the reference input for the system. It guides the desired operational parameters for takeoff and altitude control.

4. Simulation Results

A. Speed Control Autopilot

As shown in Figure 12 and13, the response of the Proportional Integral speed controller was compared to that of the Proportional Integral Derivative controller. It could be observed that the Proportional Integral controller showed a good performance in reaching the desired speed with negligible steady-state error. Additionally, it effectively eliminated the overshoot issue that was observed with the Proportional Derivative controller, as listed in Table 1. This suggests that the Proportional Integral controller can provide favorable speed management specially, in the cases where minimum overshoot is required.

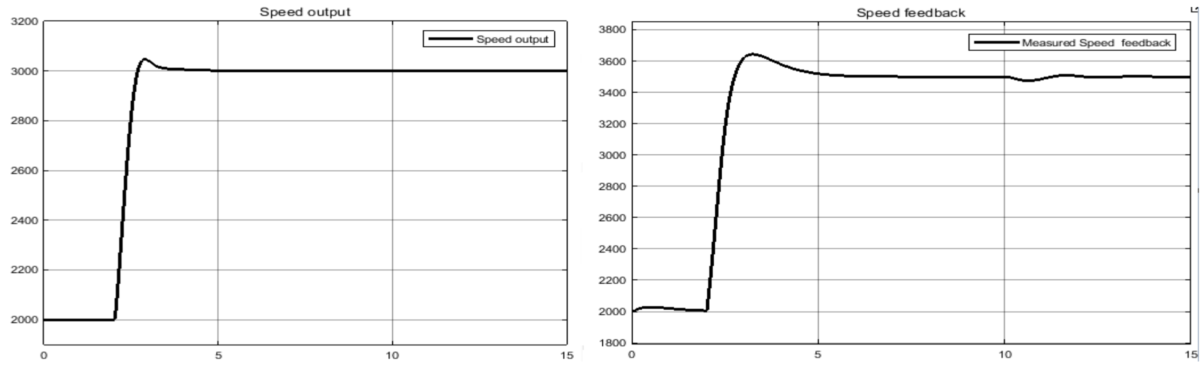

Figure 12: Comparison of Speed Control Performance between Proportional-Integral-Derivative (PID) Controller and Proportional-Derivative (PD) Controller

As shown in Figure 13, the engine speed is directly correlated to the throttle angle. This relationship is very important, as the altitude of the aircraft may sometimes be managed using the auto-throttle system. And therefore the desired engine speed precisely trails the throttle angle facilitates maintain linearity and precision in achieving the desired speed, which, in turn, supports maintaining the target altitude.

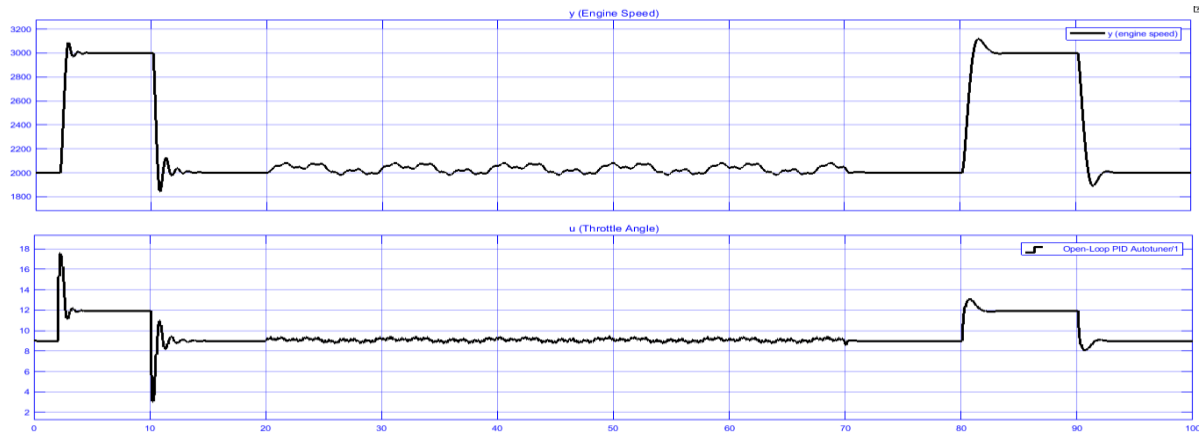

Figure 13: Engine speed versus throttle angle

The characteristics of the proposed speed controller are listed in Table 6 for the Proportional Derivative (PD), Proportional Integral (PI), and Proportional Integral Derivative (PID) designs. The PD controller showed good performance for the rise and settling times, however it revealed a relatively high overshoot of 9.76%. For the PI controller the overshoot was reduced to 5.1%, even though its rise and settling times were slower compared to those of the PD controller. While the PI controller meets the design needs under normal conditions without disturbances, the PID controller could be the optimal option that best fulfil comprehensively the overall design requirements.

Table 6: Comparison of PD, PI, and PID Controller Parameter Values

Controller Type	Rise Time (sec)	Settling Time (sec)	Overshoot (%)	Closed-loop stability	k_p	k_i	k_d
PD	0.107	0.802	9.76	Stable	125.5	-	20.9
PI	1.37	1.9	5.1	Stable	0.00057	0.008	-
PID	0.107	1.802	5.56	Stable	0.024	0.027	0.00559

B. The Pitch Orientation Autopilot

The pitch-up problem is conventionally solved by limiting the aircraft attack angle below the critical angle of attack, this limitation will reduce the performance of the aircraft since lower angle of attack results in slower maneuvering capabilities to the aircraft. The aircrafts that subjected to pitch-up are typically flown at higher angle of attack, therefore the automatic pitch orientation control system has been used to ensure stable flight, even if the angle of attack exceeded the critical angle.

Figure 14 (a, b) shows the response of the MPC and PID controllers respectively. The PID controller was set to control the pitch rate of aircraft at low angle of attack, whereas the MPC was better suited to control the pitch rate at high angles of attack. Both controllers were responded to a commanded pitch angle of 10 degrees at relatively fast settling and rise times, zero overshoot and a smallest steady state error.

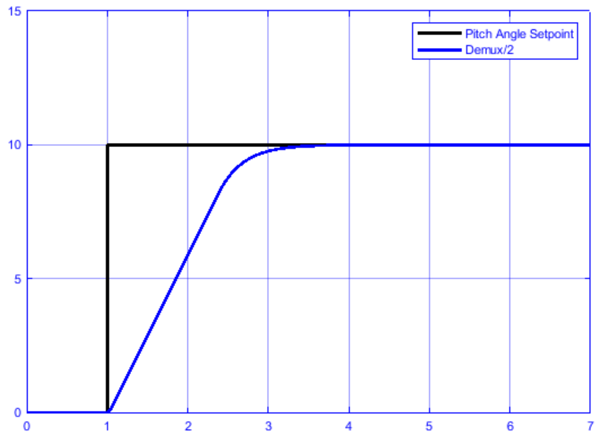

Figure 14: (a) MPC Controller response

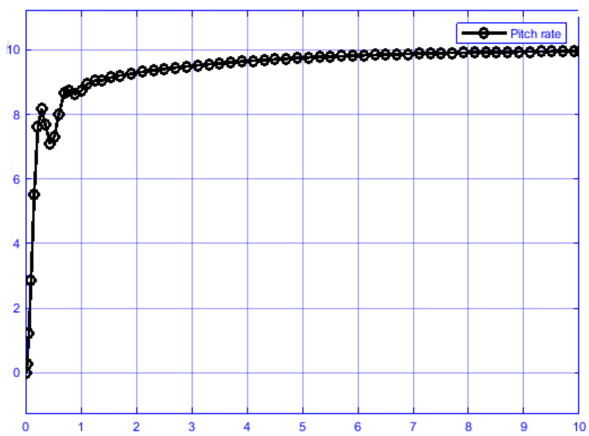

Figure 14: (b) PID Controller Response

C. The Altitude Controller

The elevator and the engine throttle can be used to control the altitude of the aircraft. Deflecting the elevator up or down generates forces that cause the aircraft to either lose or gain height. Similarly, adjusting the engine throttle also impacts the altitude, by indirectly affecting the velocity of the aircraft. Both approaches are possible for altitude control. Figure15 illustrates the response of the controller to both thrust inputs and elevator deflection. Meanwhile.

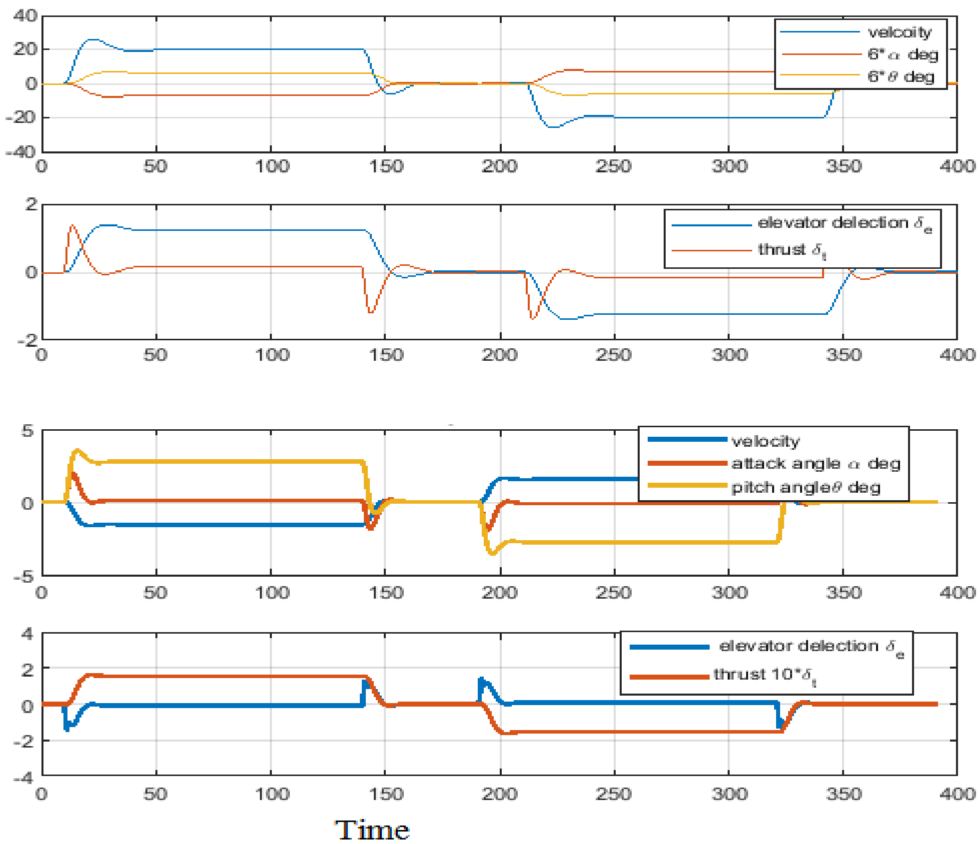

Figure 15: The Response of the Altitude Controller

Figure16 shows the response of the controller when the initial offset for the desired altitude is 80 meters and the controller tends to maintain zero offset.

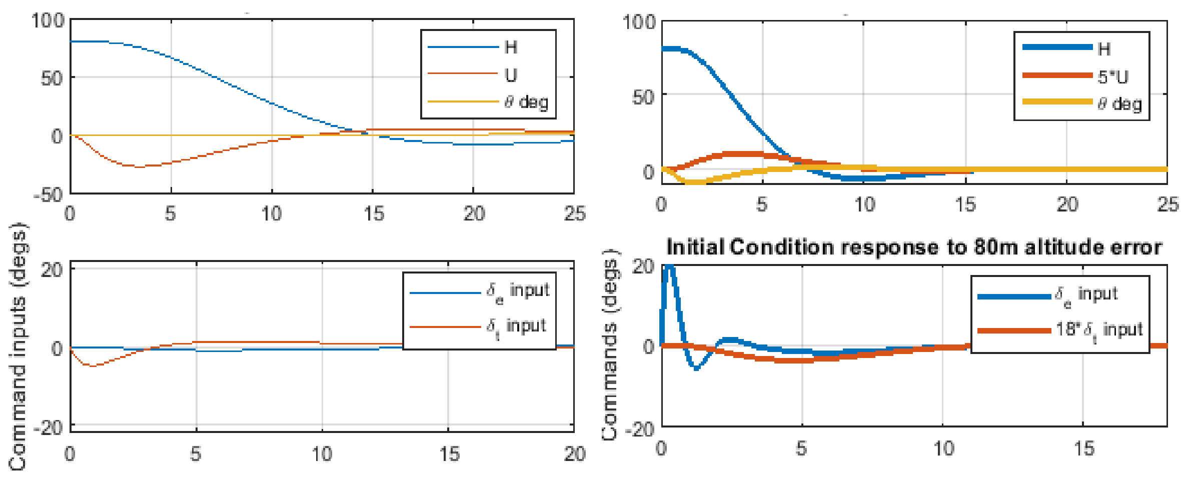

Figure 16: Altitude Error of 80 m for both Thrust and Elevator Controllers

In Figure 17 (a, b) the longitudinal controller follows an altitude command of 1500 meters, such that Figure17 (a) represents the response of the controller using the elevator control method, whereas Figure17 (b) represents the response of the controller using thrust control method. In both the thrust and elevator control methods, there is small offset from the desired altitude but with acceptable overall response. The main difference between these two approaches is not about choosing one over the other, but rather understanding the appropriate conditions for applying each method.

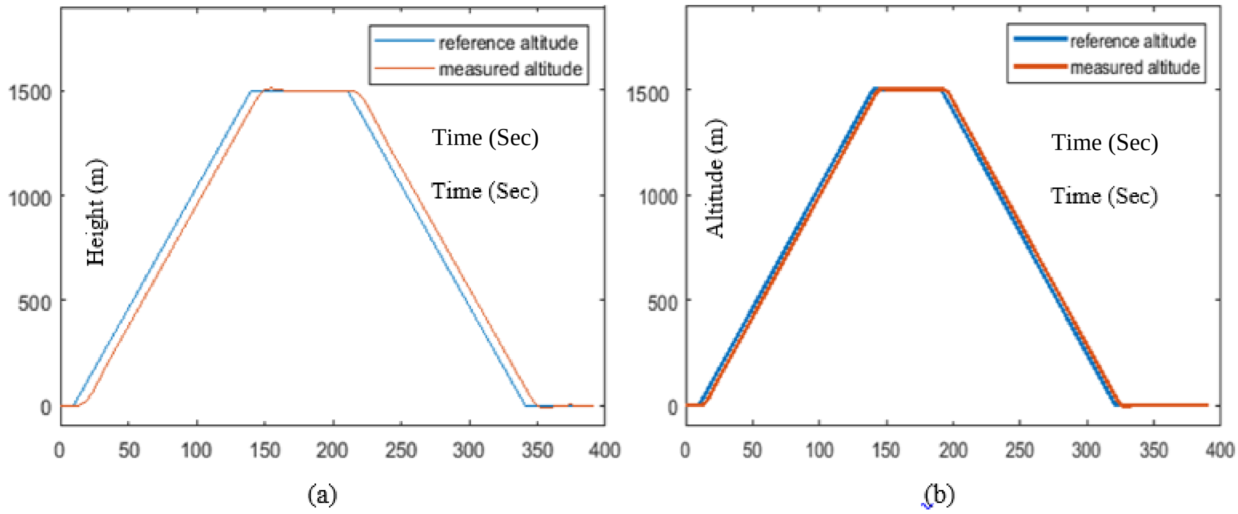

Figure 17: (a) Controller follows an Altitude Command of 1500 of 1500 meters for Thrust. (b) Longitudinal Controller follows an Altitude Command of 1500 meters for Elevator Inputs

D. Neural network controller

The proposed neural network controller has been trained for 1000 iterations, validated, and tested, as shown in Figure 18. The trained network was integrated with a classical lead-lag controller. Both controllers were designed to control the same aircraft dynamics model, ensuring that they work in parallel on similar system parameters [24-26]

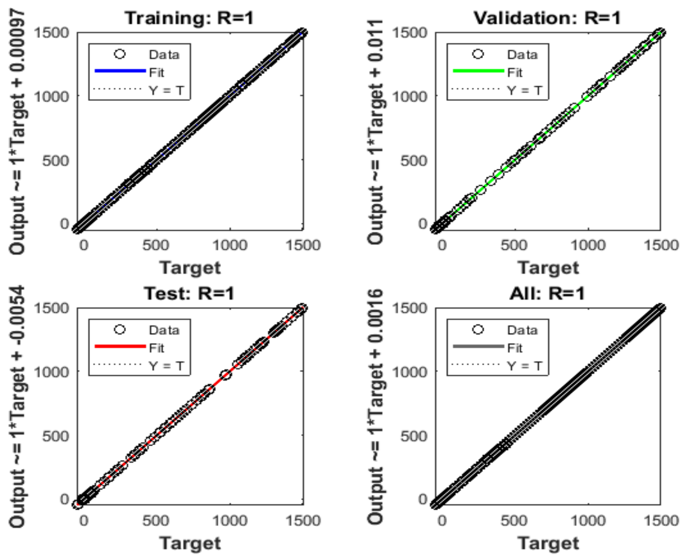

Figure 18: Neural Network Longitudinal Controller Training Response

As shown in Figure 19 the proposed neural network responded to the altitude command of 1500 meters. It is obvious that the actual altitude and the desired altitude are allied clearly with zero offset. By comparing these results to the lead-lag controller response, it could be clearly seen that the proposed neural network controller exhibits better performance. Nevertheless, the hybrid controller was recommended since it can control and manage the same plant using two different controllers at the same time and this advantage permits each controller to reimburse any limitation encountered on the other one.

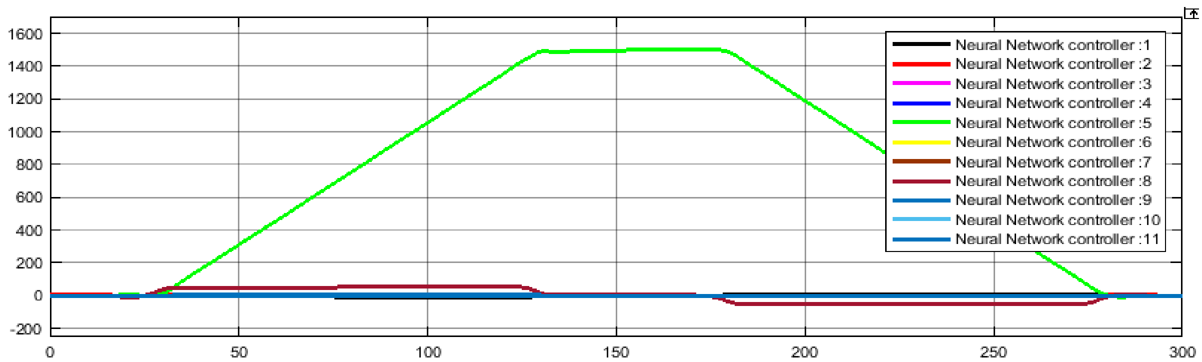

Figure 19: Longitudinal Neural Network following 1500 m Altitude Command

5. Conclusion

This paper proposed a new method to control the longitudinal motion of an autonomous aircraft. A longitudinal controller is assigned for the takeoff and the altitude control tasks. It is also used during landing in combination with lateral controller where a very prices control of the airspeed and the altitude are highly required during these two flight phases. The speed controller was designed using PD, PI and finally PID. The PID method was found to be the most appropriate. The pitch orientation controller was designed with two options. The PID for the low angle of attack and the MPC for the high angle of attack. The altitude was controlled by two different methods named thrust and elevator control surface methods. It has been observed that the elevator control method has the fastest effect of changing altitude while the thrust method has the contribution of changes the flight path angle and hence the altitude. The neural network controller improved the overall system response and robustness.

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