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Pitch Control of an Aircraft Using Artificial Intelligence

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Authors' contributions

This work was carried out in collaboration between all authors. Author ABK designed the study, performed the numerical simulations & analysis and wrote the first draft of the manuscript. Authors FAA and CAO managed the analysis of the study and public release of information. Author MALA engineered hardware implementation. Author AAF verified HIL simulation and literature searches. All authors read and approved the final manuscript.

Research Article

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ABSTRACT

This paper presents the investigation into the design, simulation and analysis of two autopilots: a fuzzy Proportional-Integral-Derivative (PID) controller and, its hybrid with a PID controller for the control of pitch plane dynamics of an aircraft. The *Mamdani*-type *fuzzy inference system* is employed for the Fuzzy Inference System (FIS) in the fuzzy logic controller design. The dynamic modeling of system begins with a derivation of suitable mathematical model to describe the longitudinal motion of an aircraft. This research set the platform for thorough investigation into the various structures available for PID-FLC and its hybrids. Considering hardware implementation challenges and limitations, not all PID-FLC and its hybrid structures are viable. The PID-FLC is constructed as a parallel structure of a PD-FLC and a PI-FLC, with the output signal of the control loop, *y* serving as the input for the derivative parameter of the PD-FLC. The output of the PID-FLC is formed by algebraically adding the outputs of the two fuzzy control blocks as suggested in Guanrong et al., 2000. Also, the proposed hybrid fuzzy PID autopilot consists of the PID-FLC with a traditional PID controller structured by algebraically adding the outputs of the two control blocks. Result of simulation in MATLAB®/Simulink® shows that the proposed PID-FLC autopilot gave an unacceptable

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trend when subjected to a *step* response and *Dirac's delta* impulse response investigation. While the *intelligent* hybrid autopilot; PID-FLC with PID controller gave an acceptable time response characteristics.

Keywords: Aircraft; fuzzy logic control; pitch dynamics; autopilot; Matlab®/Simulink®.

1. INTRODUCTION

The rapid advancement of aircraft design from the very limited capabilities of the Wright brothers first successfully airplane to today's high performance military, commercial and general aviation aircraft require the development of many technologies, these are aerodynamics, structures, materials, propulsion and flight control.

The development of automatic control system has played an important role in the growth of civil and military aviation. Modern aircraft include a variety of automatic control system that aids the flight crew in navigation, flight management and augmenting the stability characteristics of the airplane. For this situation an autopilot is designed that control the pitch of aircraft that can be used by the flight crew to lessen their workload during cruising and help them land the aircraft during adverse weather condition. The autopilot is an element within the flight control system. It is a pilot relief mechanism that assists in maintaining an attitude, heading, altitude or flying to navigation or landing references. Designing an autopilot requires control system theory background and knowledge of stability derivatives at different altitudes and Mach numbers for a given airplane [1, 2].

One of the major problems of flight control system is due to the combination of nonlinear dynamics, modeling uncertainties and parameter variation in characterizing an aircraft and its operating environment. The aircraft motion in free flight is extremely complicated. Generally, aircraft fly in three-axis plane by controlling *aileron*, *rudder* and *elevator*. Flight Dynamics, as it is called now has its roots way back to the work of W.J. Duncan, which is perhaps not surprising since Duncan was the first Professor of Aerodynamics at Cranfield some 50 years ago. The classical linearized theory of stability and control of aircraft is timeless, it is brilliant in its relative simplicity and it is very securely anchored in the domain of the aerodynamicist [3].

The study of airplane stability and control is primarily focused on moments about the airplane center of gravity. A balanced (i.e., trimmed) airplane will have zero moment about its center of gravity. There are numerous places where moments can be generated in an airplane such as moments contributed by the wing, the fuselage, the engine propulsion, the controls (e.g., elevator, aileron, rudder, canard, etc.) and the vertical and horizontal tail surfaces. Note that the gravity force does not contribute any moment to the airplane since it is, by definition, applied at the center of gravity.

They are designed to change and control the moments about the roll, pitch and yaw axes. The control system of the aircraft is divided into two portions, longitudinal and lateral control. The key motion variables in the lateral axis correspond to sideslip (with sideslip angle β, or side velocity v), roll (with roll rate p) and yaw (with yaw rate r). Primary controls are rudder δ_r and ailerons δ_a. The lateral motion of an airplane is described in terms of two tightly coupled motions: yaw about the z-body axis (i.e. directional) and roll about the x-body axis (i.e. lateral). There are numerous components that contribute to the yawing moment in the airplane when perturbed in the lateral motion variables. Yawing moment generated at the wing is developed mainly from perturbed motions in sideslip β and roll rate p in the lateral axis. Due to sideslip, there is an increase in drag on one side of the wing that is more perpendicular to the flow and thereby would produce a yawing moment. If the wing is swept aft, then this yawing moment is stabilizing (i.e. producing a positive yawing moment to a positive sideslip). Other parts of the aircraft that contribute to the yawing moment are fuselage, vertical tail, propulsion, rudder, aileron and spoiler. The rolling motion is generally affected by the motion variables in yaw rate r, sideslip β and roll p. The components that contribute mostly to the rolling moment are the wing, the vertical tail, the ailerons (located on the wing and the rudder [4].

In longitudinal control, the elevator controls pitch or the longitudinal motion of aircraft system. The elevator is situated at the rear of the airplane running parallel to the wing that houses the ailerons. Pitch control is a longitudinal problem and this work presents a design of an autopilot that controls the pitch of an aircraft. Pitch is controlled by the rear part of the tail plane's horizontal stabilizer being hinged to create an elevator. By moving the elevator control backwards the pilot moves the elevator up (a position of negative camber) and the downwards force on the horizontal tail is increased. The angle of attack on the wings increased so the nose is pitched up and lift is generally increased. In micro-lights and hang gliders the pitch action is reversed and the pitch control system is much simpler, so when the pilot moves the elevator control backwards it produces a nose-down pitch and the angle of attack on the wing is reduced. The pitch angle of an aircraft is controlled by adjusting the angle and therefore the lift force of the rear elevator [5]. Lot of works has been done in the past to control the pitch of an aircraft for the purpose of flight stability and yet this research still remains an open issue in the present and future works.

Following the introduction is Section 2 where the mathematical derivation for an aircraft pitch plane model in transfer function is put forward. Section 3 gives mathematical description of a simple actuator with its basic characteristics that drives the plant. In section 4, Fuzzy Logic is introduced from the standpoint of control. This section also includes a brief description of how a Fuzzy Inference System (FIS) is built from a MATLAB®/Simulink® GUI interface. Under this same section we delved into the theory and design consideration for a typical Fuzzy PID autopilot and hence its hybrid. The autopilots simulations results are also presented here in graphical form. In section 5, the results of simulation are discussed. This is immediately followed by a conclusion in section 6. Finally, the areas for future improvements are put forward in a section 7.

2. MATHEMATICAL MODEL FOR PITCH CONTROL

In order to reduce the complexity of analysis, under certain assumptions, the equation governing motion of an aircraft can be separated into two groups, namely the longitudinal and lateral equations. This section provides a brief description on the modeling of pitch control longitudinal equation of aircraft, as a basis of a simulation environment for development and performance evaluation of the proposed controller techniques. The system of longitudinal dynamics is considered in this investigation and derived in the transfer function.

The pitch control system considered in this work is shown in Fig. 1 where X_b, Y_b and Z_b represent the aerodynamics force components. θ, Φ and δ_e represent the orientation of aircraft (pitch angle) in the earth-axis system and elevator deflection angle.

The forces, moments and velocity components in the body fixed coordinate of aircraft system can be described as showed in Fig. 2. The aerodynamics moment components for roll, pitch and yaw axis are represent as *L*, *M* and *N*. The term *p*, *q*, *r* represent the angular rates about roll, pitch and yaw axis while term *u*, *v*, *w* represent the velocity components of roll, pitch and yaw axis. α and β represents the angle of attack and sideslip respectively.

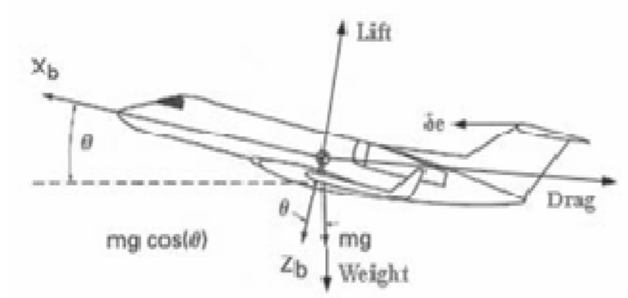

Fig. 1. Longitudinal dynamics description of an aircraft

The parameters considered for the aircraft modeling and analysis include the dimensional derivatives $Q=36.8Ib/ft^2$, $QS=6771Ib$, $QS\hat{c}=3859ft.lb$ and $\hat{c}/2u_0=0.016$. Note, that dimensional derivative and stability derivative parameters used for modeling the aircraft in this research are in the their original units because in dealing with aerospace systems it is saver to do so, conversion to SI unit might be challenging and introduce errors [6]. The longitudinal dynamics also control the forward speed and altitude of the aircraft.

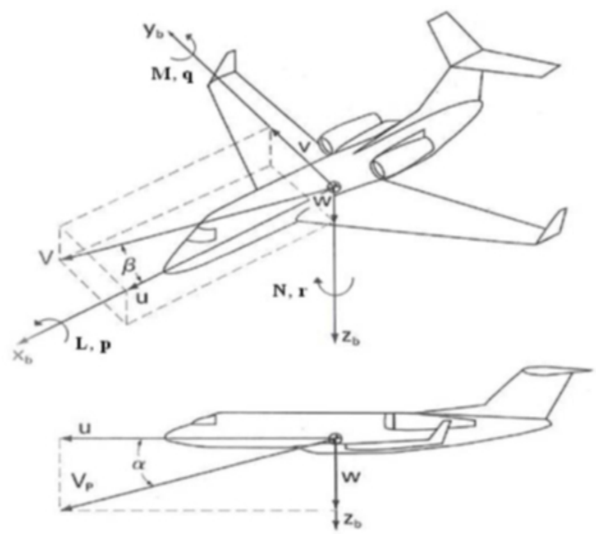

Fig. 2. Forces and moment acting on an aircraft

A few assumption need to be considered before continuing with the modeling process. First, the aircraft is at a steady state cruising at constant altitude and velocity, thus the thrust and drag are cancel out and the lift and weight balance out each other. Second, the change in pitch angle does not change the speed of an aircraft under any circumstance. Also, the atmosphere in which the plane flies is assumed undisturbed, thus forces and moment due atmospheric disturbance are considered *zero*. Hence, considering Fig. 1 and Fig. 2, the following dynamic equations describe the longitudinal dynamics of a typical aircraft;

Force equations:

$$X - mgS_{-} = m(\dot{u} + qv - rv). \tag{1}$$

$$Z + mgC_{-}C_{¤} = m(\dot{w} + pv - qu). \tag{2}$$

Momentum equation:

$$M = I_y \dot{q} + rq(I_x - I_z) + I_{xz}(P^2 - r^2). \tag{3}$$

The longitudinal stability derivatives parameter used are denoted in Table 1.

Table 1. Longitudinal derivative stability parameters

Longitudinal derivatives	X-Force(s^{-1})	Z-Force(F^{-1})	Pitching moment(FT^{-1})
Rolling velocities	X_u=-0.0045	Z_u=-0.369	M_u=0
Yawing velocities	X_w=0.036	Z_w=-2.02	M_w= -0.051
	$X_{\dot{w}}$=0	$Z_{\dot{w}}$=0	$M_{\dot{w}}$=0
Angle of attack	X_α=0	Z_α=-335.42	M_α=-8.8
	$X_{\dot{\alpha}}$=0	$Z_{\dot{\alpha}}$=0	$M_{\dot{\alpha}}$=-0.8976
Pitching rate	X_q=0	Z_q=0	M_q=-2.05
Elevator deflection	$X_{\delta e}$=0	$Z_{\delta e}$=-28.15	$M_{\delta e}$=-11.874

It is required to completely solve the aircraft problem with the following assumption:

Rolling rate, is given as

$$p = \dot{\Phi} - \dot{\cdot}\, S_{-}, \tag{4}$$

Yawing rate, as

$$q = \dot{-}\, C_{¤} + \dot{\cdot}\, C_{-} S_{¤}, \tag{5}$$

Pitching rate

$$r = \dot{\cdot}\, C_{-} C_{¤} - \dot{-}\, S_{¤}, \tag{6}$$

Pitch angle

$$\dot{-} = qC_{¤} - rS_{¤}, \tag{7}$$

Roll angle

$$\dot{\Phi} = p + qS_{¤}T_{-} + rC_{¤}T_{-}, \tag{8}$$

Yaw angle

$$\dot{\cdot} = (qS_{¤} + rC_{¤})\sec{-}. \tag{9}$$

Equation (1), equation (2) and equation (3) should be linearized using small disturbance theory. The equations are replaced by a reference value plus a perturbation or disturbance, as shown in (10).

$$
\begin{aligned}
&u = u_0 + \Delta u,\ v = v_0 + \Delta v,\ w = w_0 + \Delta w. \\
&\qquad p = p_0 + \Delta p,\ q = q_0 + \Delta q,\ r = r_0 + \Delta r. \\
&X = X_0 + \Delta X,\ M = M_0 + \Delta M,\ Z = Z_0 + \Delta Z. \\
&\text{¢} = \text{¢}_0 + \Delta \text{¢}.
\end{aligned}
\tag{10}
$$

For convenience, the reference flight condition is assumed to be symmetric and the propulsive forces are assumed to remain constant. This implies that,

$$v_0 = p_0 = q_0 = r_0 = \Phi_0 = \cdot_{\ 0} = w_0 = 0. \tag{11}$$

After linearization the following equations were obtained for the longitudinal dynamics, of the aircraft keeping in mind that (12), (13) are the force equations and (14) momentum equation.

$$\left\{\frac{d}{dx} - X_u\right\}\Delta u - X_w \Delta w + (g\cos\text{¯}_0)\Delta\text{¯} = X\text{¢}_e \Delta\text{¢}_e, \tag{12}$$

$$-Z_u \Delta u + \left\{(1 - Z_w)\frac{d}{dt} - Z_w\right\}\Delta w - \left\{(u_0 + Z_q)\frac{d}{dt} - g\sin\text{¯}_0\right\}\Delta\text{¯} = Z_{\text{¢}e}\Delta\text{¢}_e, \tag{13}$$

$$-M_u \Delta u - \left\{M_w \frac{d}{dt} + M_w\right\}\Delta w + \left\{\frac{d^2}{dt^2} - M_q \frac{d}{dt}\right\}\Delta\text{¯} = M_{\text{¢}e}\Delta\text{¢}_e. \tag{14}$$

By manipulating (12), (13) and (14) and substituting the parameters values of the longitudinal stability derivatives in Table 1, the following transfer function for the change in the pitch rate to the change in elevator deflection angle is given as:

$$\frac{\Delta q(s)}{\Delta\text{¢}_e(s)} = \frac{-(M_{\text{¢}e} + M_{\dot{\sim}} Z_{\text{¢}e}/u_0)s - (M_{\sim} Z_{\text{¢}e}/u_0 - M_{\text{¢}e} Z_{\sim}/u_0)}{s^2 - (M_q + M_{\dot{\sim}} + Z_{\sim}/u_0)s + (Z_{\sim} M_q/u_0 - M_{\sim})}, \tag{15}$$

The transfer function of the change in pitch angle to the change in elevator angle can be obtained from the change in pitch rates to the change in elevator angle in the following way;

$$\Delta q = \Delta\dot{\text{¯}}, \tag{16}$$

$$\Delta q(s) = s\Delta\text{¯}(s), \tag{17}$$

$$\frac{\Delta\text{¯}(s)}{\Delta\text{¢}_e(s)} = \frac{1}{s}.\frac{\Delta q(s)}{\Delta\text{¯}(s)}. \tag{18}$$

Hence, the transfer function for the pitch system dynamics of an aircraft can be described by (19). For the typical values of stability derivatives given in Table 1, (20) will serve as the mathematical model depicting the longitudinal dynamics of the aircraft that will be used for the controller design, simulation and analysis [7].

$$\frac{\Delta q(s)}{\Delta\text{¢}_e(s)} = \frac{1}{s}.\frac{-(M_{\text{¢}e} + M_{\dot{\sim}} Z_{\text{¢}e}/u_0)s - (M_{\sim} Z_{\text{¢}e}/u_0 - M_{\text{¢}e} Z_{\sim}/u_0)}{s^2 - (M_q + M_{\dot{\sim}} + Z_{\sim}/u_0)s + (Z_{\sim} M_q/u_0 - M_{\sim})}, \tag{19}$$

$$\frac{\Delta\text{¯}(s)}{\Delta\text{¢}_e(s)} = \frac{11.7304s + 22.578}{s^3 + 4.9676s^2 + 12.941s}. \qquad (20)$$

3. ACTUATOR DYNAMICS

For simplicity, a first order model of an actuator is employed with the transfer function as given in (21). The actuator device time constant *τ = 0.0167sec.*, is employed:

$$H(s) = \frac{1}{{}^{2}s+1}. \qquad (21)$$

4. FUZZY LOGIC CONTROL (FLC)

Here, is a superficial introduction to fuzzy logic and it basic constituents as regards control of dynamic systems. Also, we considered how to build such controllers in Simulink® environment of MATLAB®. Simulations of the built controllers and their results are also presented.

Fuzzy logic controllers fall into the class of *Intelligent Control Systems.* An intelligent control system combines the techniques from the fields of Artificial Intelligence (AI) with those of control engineering to design autonomous systems that can sense, reason, and plan, learn and act in an intelligent manner. Intelligent behavior is therefore the ability to reason, plan and learn, which in turn requires access to knowledge. Artificial Intelligence is a by-product of the Information Technology (IT) revolution, and is an attempt to replace human intelligence with machine intelligence. An intelligent control system combines the techniques from the fields of AI with those of control engineering to design autonomous systems that can sense, reason, plan, learn and act in an intelligent manner. Such a system should be able to achieve sustained desired behavior under conditions of uncertainty, which includes.

- Uncertainty in the plant mode.
- Unpredictable environmental changes.
- Incomplete, inconsistent or unreliable sensor information.
- Actuator malfunction.

Fuzzy logic tool was introduced in 1965, by Lofti Zadeh, and is a mathematical tool for dealing with uncertainty. It offers to a soft computing partnership the important concept of computing with words. It provides a technique to deal with imprecision and information granularity. The fuzzy theory provides a mechanism for representing linguistic constructs such as ‘many’, ’low’, ‘medium’, ‘often’, ’few’. In general the fuzzy logic provides an inference structure that enables appropriate human reasoning capabilities [8].

Fuzzy Logic Control (FLC) system is one of the main developments and successes of fuzzy sets and fuzzy logic. A FLC is characterized by four modules: *fuzzifier*; *defuzzifier*; *inference* engine and *rule* base.

In terms of inference process there are two main types of Fuzzy Inference Systems (FIS): the *Mamdani*-type and the *Takagi Sugeno Kang* (TSK)-type. In terms of use, the *Mamdani* FIS is more widely used, mostly because it provides reasonable results with a relatively simple structure, and also due to the intuitive and interpretable nature of the rule base. The fuzzy rule-base consists of a set of antecedent consequent linguistic rules of the form:

$$\text{IF} \quad L \quad \text{THEN} \quad M. \tag{22}$$

This style of fuzzy conditional statement is often called a 'Mamdani'- type rule, after Mamdani (1976) who first used it in a fuzzy rule-base to control steam plant. The rule-base is constructed using *a prior* knowledge from either one or all of the following sources:

- Physical laws that govern the plant dynamics.
- Data from existing controllers.
- Imprecise heuristic knowledge obtained from experience expert.

If the third item above is used, then knowledge of the plant mathematical model is not required. Once the inputs are fuzzified, the corresponding input fuzzy sets are passed to the inference engine that processes current inputs using the rules retrieved from the rule base [8].

4.1 The Rule Base

In our proposed FLC, there are two inputs to the *fuzzy inference system.* One is the control error $e(k)$, which is the difference between the reference signal $r(k)$ and the output signal $y(k)$, the other one is the change in this error $\Delta e(k)$. These two inputs, defined as in (24) and (25), are first fuzzified and converted to fuzzy membership values that are used in the rule base in order to execute the related rules so that an output can be generated.

$$e(k) = r(k) - y(k), \tag{23}$$

$$\Delta e(k) = e(k) - e(k-1). \tag{24}$$

The fuzzy rule base, which may also be called the fuzzy decision table, is the unit mapping two crisp inputs, $e(k)$ and $\Delta e(k)$ to the fuzzy output space defined on the universe of $\Delta u(k)$.There are nine rules that have been utilized in designing the controller and the rules are defined in Table 2. The knowledge required to generate the fuzzy rules can be derived from an offline simulation. However, it has been noticed that, for monotonic systems, a symmetrical rule table is very appropriate, although sometimes it may need slight adjustments based on the behavior of the specific system. If the system dynamics are not known or are highly nonlinear, trial-and-error procedures and experience play an important role in defining the rules. Each fuzzy set consists of three types of membership function, which are negative (N), zero (Z) and positive (P).

In this research, the triangular membership functions are chosen for each fuzzy set. The universe of discourse is set between -0.4 to 0.4 that implies the range of pitch angle (±0.4 radian).The appropriate membership function to represent each fuzzy set need to be defined and each fuzzy set must have the appropriate universe of discourse. In addition, the membership functions are evenly distributed so that the tuning process of the controller can be easily done [9].

4.2 Building the Fuzzy Inference System (FIS)

Using the *FIS* editor of MATLAB, the two inputs to the fuzzy controller are the error (e) which measures the system performance and the rate at which the error changes (Δe), whereas the output of the control signal (Δu). A *Mamdani* type FLC is used with triangular membership functions for the inputs and output. The FLC uses *MIN* for *t*-norm operation, *MAX* for *s*-norm operation, *MAX* for *aggregation*, *MIN* for *implication*, and *CENTROID* for defuzzification. The membership function maps the crisp values into fuzzy variables. The choice of membership function has an important bearing on the performance of the fuzzy logic controller. The triangular membership was chosen for the two inputs and the output of the synthesized fuzzy logic controller. This was simply selected from the *FIS* editor interface [10].

The Rule editor is used to input the 9 rules given in Table 2. It contains a large editable text field for displaying and editing rules. The Boolean operator '*min'* is used for the verbal connector *'and'* to simulate the input space of the rules. In Fig.3, the two yellow columns are for the two inputs and the blue column for the control output. Finally, a three dimensional mapping of the two inputs and the control is depicted in a three dimensional plot as shown in Fig.4.

Table 2.Fuzzy logic rules for the aircraft controller design

Number	Rules
1.	If (e is N) and (Δe is N) then (Δu *is* N)
2.	If (e is N) and (Δe is Z) then (Δu is N)
3.	If (e is N) and (Δe is P) then (Δu is N)
4.	If (e is Z) and (Δe is N) then (Δu is N)
5.	If (e is Z) and (Δe is Z) then (Δu is Z)
6.	If (e is Z) and (Δe is P) then (Δu is P)
7.	If (e is P) and (Δe is N) then (Δu is P)
8.	If (e is P) and (Δe is Z) then (Δu is P)
9.	If (e is P) and (Δe is P) then (Δu is P)

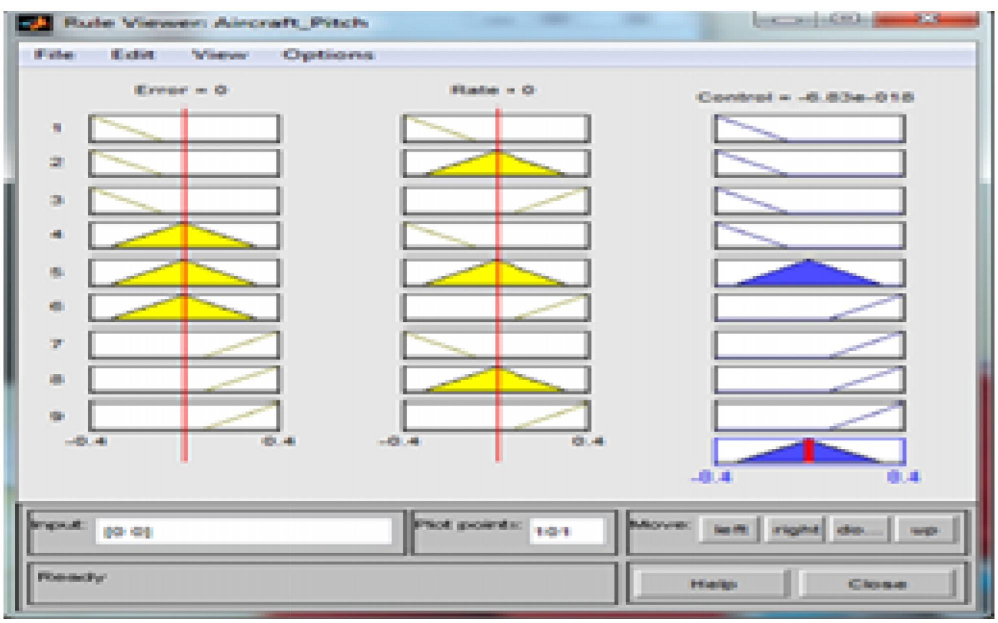

Fig. 3. The fuzzy inference in the rule viewer GUI

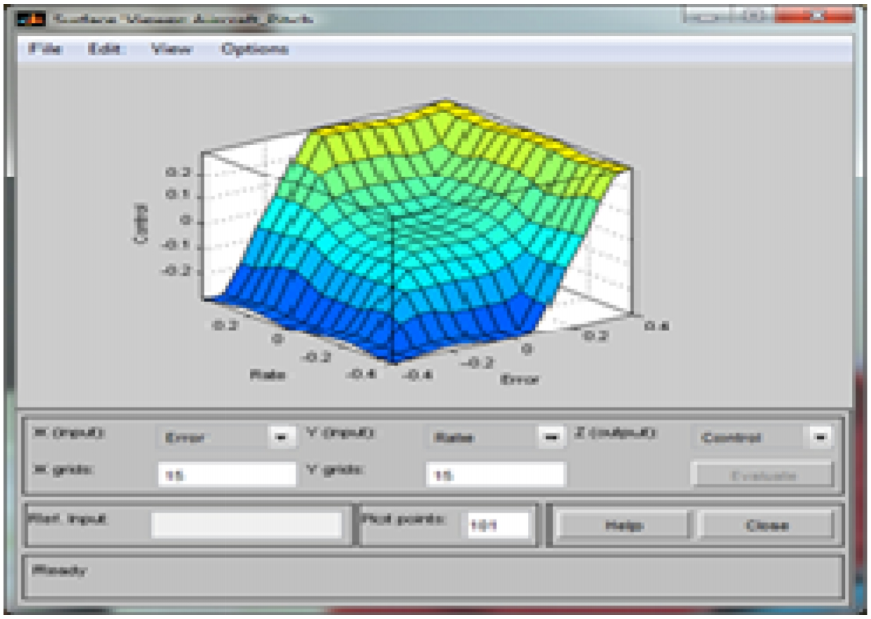

Fig. 4. Three-dimensional plot of the output surface

4.3 Fuzzy PID Autopilot

A PID fuzzy controller is a controller that takes error, summation of error and rate of change of error (rate for short) as inputs. Fuzzy controller with three inputs is difficult and not easy to implement, because it needs a large number of rules and memory (Leonid, 1997).Generally, to represent PID-FLC, it is required to design a fuzzy inference system with three inputs that represent the proportional, derivative, and integral components, and each one of them can have up to 8 fuzzy sets. Therefore, the maximum number of required fuzzy rules in any situation is 8x8x8 =512 rules. But for this research only 3 fuzzy sets were used for the rule base, thus the maximum rules it would yield would be 3x3x3=27 if three inputs were to be implemented.

The PID-FLC can be constructed as a parallel structure of a PD-FLC and a PI-FLC, such that the input signal for the derivative gain to the PD-FLC is the control loop output signal, *y* [11]. The output of the PID-FLC is formed by algebraically adding the outputs of the two fuzzy control blocks, suggested by Leonid. This will reduce the number of maximum rules possible to 8x8 +8x8= 128 rules. Thus, for this research we will end up with 3x3+3x3=18 rules, considering the three fuzzy sets given in Table 2.

It is interesting to note that the PID-FLC structure proposed in (Guanrong et al., 2000) which is the crux of this research proposes that the gain K_{p2} in Fig. 5to have a numerical value of -1. This turns-out to distort simulation result, but on adopting the value of 1, simulation result was appreciated. Hence, the parameter $K_{p2}=1$ was used throughout the simulation in this research. Though we strongly advice the trial of both $K_{p2}=-1$ first in any design, if simulation result is not appreciated only then will it be justified to use $K_{p2}=1$ as done in this research.

The Simulink model for the fuzzy PID logic control of the aircraft pitch dynamics was implemented by linking the FIS designed above with a Simulink model for the autopilot.

Manual tuning means via trial-and-error was used to obtain the proportional, derivative and output gains associated with the controller [12].

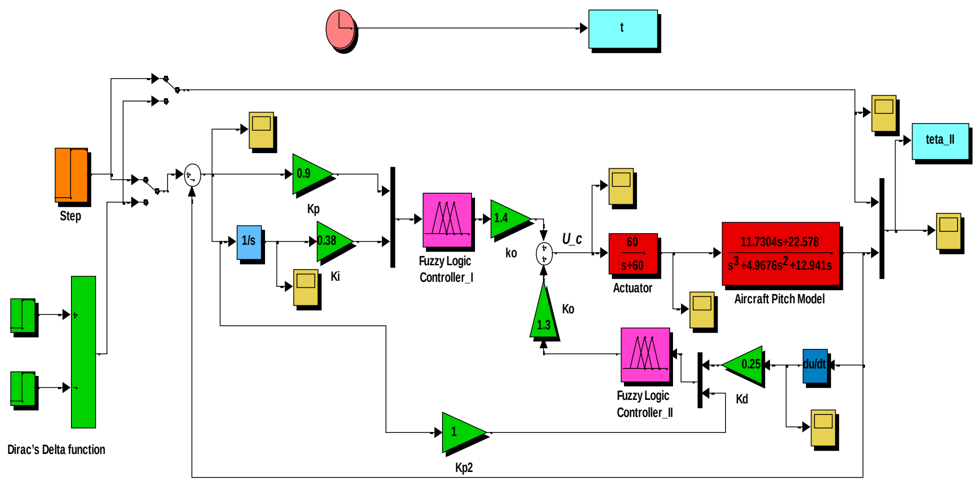

Fig.5.Simulink model of the fuzzy PID autopilot

From investigating the Eigen values of the pitch plane aircraft model we were able to deduce the most appropriate *solver(s)* for this simulation. The aircraft has the following Eigen values: $\lambda_1=0$, $\lambda_2=-2.4838+2.6021i$ and $\lambda_3=-2.4838-2.6021i$. Thus, the system is unstable, the Simulink solver *ode45* (Dorman Prince)-default and *ode113* (Adam's Method) are the two most likely solvers to be used for the simulation. After experimenting with both, *ode113* was found to be most suitable [13]. MATLAB/Simulink version 2010a was used for all simulation in this research.

From the trend observed in Fig. 6, the need to modify this autopilot is inevitable. Studies in applied research show that it is even more interesting to combine the use of fuzzy logic controllers with traditional controllers in order to make these controllers more robust.

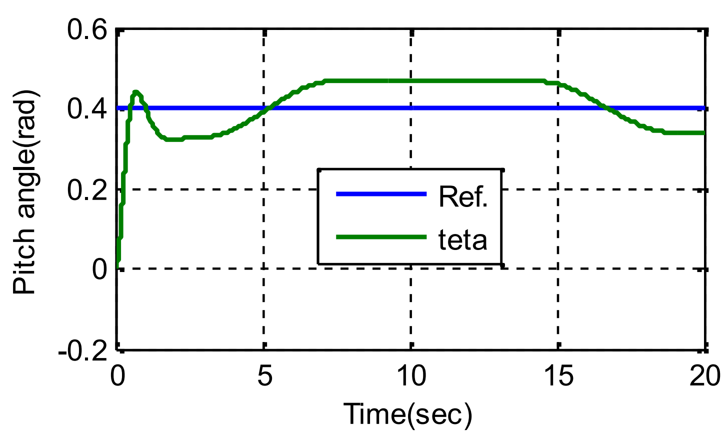

Fig. 6.Simulation result of fuzzy PID autopilot

4.4 Hybrid Fuzzy PID Autopilot

The traditional control, which includes the classical feedback control, modern control theory and large-scale control system theory, has encountered many difficulties in its applications. The design and analysis of traditional control systems are based on their precise mathematical models, which are usually very difficult to achieve, owing to the complexity, nonlinearity, time varying and incomplete characteristics of the existing practical systems. One of the most effective ways to solve the problem is to use the technique of hybrid methodology of the traditional and intelligent control techniques.

For the fuzzy PID controllers simulated in this work (Fig. 5), we chose to design a hybrid version of it by adding a PID controller to the existing designs. Our desire is to get rid of the mild oscillation in the result obtained in Fig. 6. For the hybrid fuzzy PID autopilot we propose the scheme as shown in Fig. 7. Note also that the solver *ode113* was used for the simulation here.

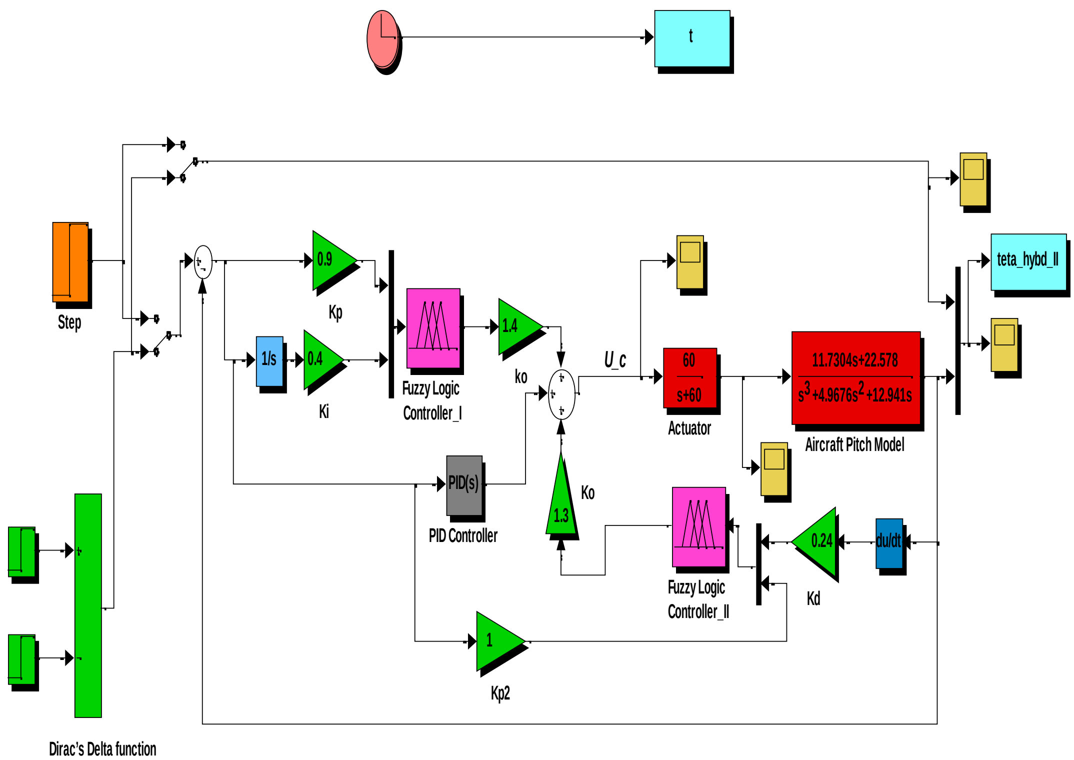

Fig. 7. Simulink model of the hybrid fuzzy PID autopilot

The proposed hybrid autopilot possesses two main parts: the classical PID and fuzzy PID controllers. Both control efforts are added algebraically to drive the plant via an actuator. Note, attempts were made to build the hybrid autopilot by including the PID controller at the output of the fuzzy logic controller signal but simulation proved abortive.

A standard PID controller is also known as the "three-term" controller, whose transfer function is generally written in the "ideal form" as

$$G_{PID}(s) = K_p + \frac{K_I}{T_I s} + K_D T_D s, \tag{25}$$

Where K_p is the proportional gain, K_I the integral gain, K_D the derivative gain, T_I the integral time constant and, T_D the derivative time constant. In this paper, the classical PID and fuzzy PID controller are combined by algebraically summing both controllers via a *summation block* in the Simulink modeling environment. The MATLAB/Simulink simulation model of the proposed intelligent hybrid controller with a step function and Dirac's Delta impulse is also necessary to ascertain the behavior of the hybrid controller. The simulation results are depicted in Fig. 8.

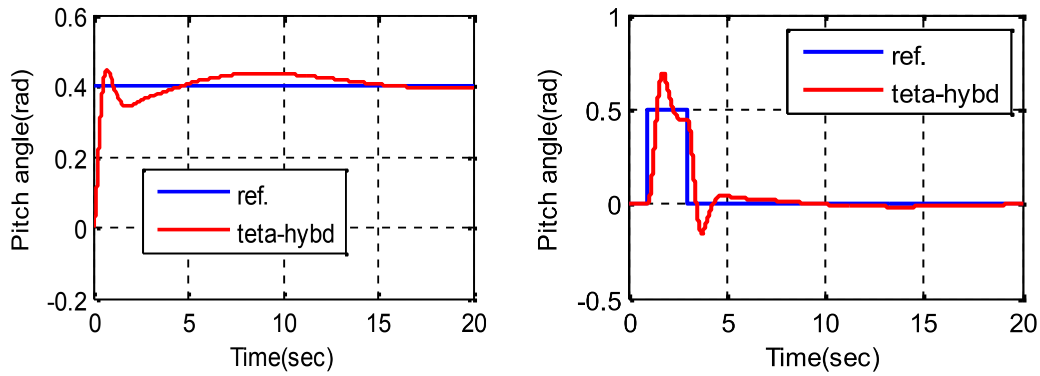

Fig. 8. Simulation result for the hybrid fuzzy PID autopilot-step and Dirac's response

5. RESULTS AND DISCUSSION

It is clearly seen from the simulation result in Fig. 6 that the aircraft fuzzy PID autopilot given in Fig. 5 is inadequate for set-point tracking of a reference pitch angle of about 23º (0.4 radians). The major drawback is observed at about *20 seconds* into the simulation time –the beginning of a mild oscillation. When the PID-FLC autopilot was subjected to a *Dirac's* impulse investigation, the same oscillatory trend was observed at the same time.

From simulation results in Fig. 8, it is evident that the hybrid autopilot is capable of robust performance. It can be seen that the undesired oscillatory trend that plagued the PID-FLC autopilot is absence here after the *step* response and Dirac's delta impulse response investigations. For this hybrid autopilot, the traditional PID controller design consist of the following parameters; K_p*=0.15,* K_I*=0.032,* K_D*=-0.33* and filter coefficient, *N=0.36.* It is also of importance here to note that the time response characteristics of this Intelligent hybrid autopilot are: *rise time*, t_r*=0.7s*, *percentage overshoot*, *PO=15%*, *settling time*, t_s*=15s* and a steady state error, *SSE=0.* Note that from Fig. 6, the percentage overshoot is acceptable, hence the integral and derivative gains of the traditional PID controller played a crucial rule in the result we obtained in Fig.7.

It is also of importance to note here that other possible hybrid PID structures where investigated (those with the output of the PID-FLC control signal serving as input to the traditional PID controller), simulation proved abortive. While that implemented in this work was successful, that is by adding the control signals from both the PID-FLC and the traditional PID controller algebraically. Hence the combined control signals driving the plant via an actuator.

Hardware implementation of fuzzy logic controllers has many requirements, one of which is limitations concerning the structure. Many of the hybrid fuzzy controllers simulated in literature have limitations and challenges with their structure when hardware implementation is require. It is desirable to simplify the structure of the hybrid fuzzy PID controller to offer higher flexibility versus low-chip resources, especially when considering Field Programmable Gate Array platform (FPGA) for hardware implementation. The algorithm was implemented using the Simulink® plug in, *System Generator*, which complements traditional Hardware Description Language (HDL) by providing a higher level graphical language for the development of FPGA designs. The design is then translated into the lower level required by the Xilinx's ISE program. By utilizing this graphical based higher level of abstraction at the design entry level, the requirement of a detailed knowledge of HDL languages is no longer required. Because of this new environment the time required to implement the previously developed control design on the FPGA is reduced.The final verification of the FPGA design was a hardware-in-the-loop simulation utilizing a Xilinx prototyping board directly with *Simulink* through a standard USB connection by synchronizing the FPGA clock to *Simulink* time [14, 15, and 16].

This autopilot is design for a general aviation amphibian aircraft prototype [17] which is currently under construction at *CSTP*, though full flight testing has not been carried out.

6. CONCLUSIONS

In this paper, we designed and simulated two autopilots; first a PID-FLC and second, a hybrid of PID-FLC with a traditional PID controller. The autopilot design began with a suitable derivation of pitch plane dynamics of the aircraft to be controlled. The fuzzy logic controller was design in MATLAB®/Simulink® Fuzzy Inference System (FIS). The structure of the hybrid autopilot was successfully simulated as an algebraic sum of two controllers; a convectional PID controller and a PID-fuzzy logic controller. The combined output of both control signals was used to drive the plant via an actuator. Dynamic investigations of the designed autopilots were carried out using *step* response and *Dirac's* response. It is evident from simulation result in Fig. 6 that when the PID-FLC autopilot was subjected to a *step* response investigation, it exhibited an unacceptable trend 20 seconds into the simulation. This anomaly was also evident when the autopilot was subjected to *Dirac's* impulse investigation.

This necessitated the synthesis of a hybrid of the PID-FLC with a traditional PID controller. Attempt to design the *intelligent* hybrid autopilot (PID-FLC + PID) with the control signal (U_c in Fig. 6) from PID-FLC as input to the PID controller, proved abortive. Rather this was achieved by algebraically adding the outputs of the two control blocks.

After subjecting the Intelligent hybrid autopilot to the same investigation, it's time response characteristic were found to be completely acceptable.

7. FUTURE WORK

The mathematical model for a typical aircraft system is highly nonlinear and flexible, it is intended that in future a nonlinear flexible mathematical model for an aircraft and also a nonlinear actuator model will be used to implement the hybrid autopilot. Also, other proposed scheme(s) of the PID-FLC controllers will be investigated and compared with the one implemented here. The type-2 fuzzy logic which extends the use of fuzzy logic to a higher order will be explored for possible implementation of the proposed PID-FLC controller scheme.

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COMPETING INTERESTS

Authors have declared that no competing interests exist.

REFERENCES

1. Blakelock John H. Automatic Control of Aircraft and Missiles, second Edition, John Wiley & Sons;1991. Inc. ISBN 0-471-50651-6.
2. Jan Roskam. Airplane Dynamics and Automatic Flight Controls. Design, Analysis and Research Corporation;2001. ISBN 1-884885-17-9.
3. Cook MV. Flight Dynamic Principles: A Linear system Approach to Aircraft Stability and Control. Second Edition;2007. ISBN: 978-0-7506-6927-6.
4. Uy-Loi Ly. Stability and Control of Flight Vehicle. Department of Aeronautics and Astronautics, Box 352400 University of Washington Seattle;1997. WA98195.
5. Bernard EtkinLioyd Duff Reid. Dynamics of Flight, Stability and Control, third Edition John Wiley & Sons;1996. Inc ISBN 0-47 1-0341 8-5.
6. Donald McLean. Automatic Flight Control Systems. Prentice Hall;1990. ISBN 0-13-0540080.
7. Nurbaiti Wahid, Rahmat MF, Jusoff K. Comparative Assessment Using LQR and Fuzzy Logic Controller for a Pitch Control System**.** European Journal of Scientific Research. 2010;42(2):184-194.
8. Sivanandam SN, Sumathi S, Deepa SN. Introduction to Fuzzy Logic using MATLAB. Springer Berlin Heidelberg New York. 2007;ISBN-10 3-540-35780-7.
9. Wahid N. Hassan, Rahmat MF, Mansor S. Application of Intelligent Controller in Feedback Control Loop for Aircraft Pitch Control**.** Australian Journal of Basic and Applied Sciences. 2011;5(12):1065-1074.
10. Aliyu Bhar Kisabo. Expendable Launch Vehicle Control: Design and Simulation Using MATLAB/Simulink. Lambert Academic Publishers, Germany. 2011;ISBN 978-3-8443-2729-8.
11. Chen G. Guanrong and Trung Tat Pham. Introduction to Fuzzy Sets, Fuzzy Logic and Fuzzy Control Systems. CRC Press USA, 2000;ISBN 0-8493-1658-8.
12. Aliyu B. Kisabo, Osheku, CA, Adetoro MAL, Funmilayo AA. Fuzzy Logic Control for an Expendable Launch Vehicle Autopilot. European Journal of Scientific Research. 2011;59(2):226-240.

13. Aliyu B. Kisabo, Osheku CA, Adetoro MAL, Funmilayo AA. Ordinary Differential Equations: MATLAB/Simulink® Solutions. International Journal of Scientific & Engineering Research. 2012;3(8):1.
14. Shashikala Narasimha Murthy. Implementation of unmanned vehicle control on FPGA based platform using system generator. University of South Florida, Master of Science in Electrical Engineering thesis. 2007; http://scholarcommons.usf.edu/etd/2297.
15. Lazic Dragan V, Waqar Shahid. FPGA Based Longitudinal and Lateral Controller Implementation for a Small UAV. World Academy of Science, Engineering and Technology. 2012;46.
16. Alvis W, S Murthy S, Valavanis K, Moreno W, Katkoori S. FPGA Based Flexible Autopilot Platform for Unmanned Systems. Proceedings of the 15th Mediterranean Conference on Control & Automation, July 27-29, 2007, Athens-Greece.
17. Lloyd R. Jenkinson, James F. Marchman III. Aircraft Design Projects, for Engineering Students. Butterworth-Heinemann, 2003;UK. ISBN 0 7506 5772 3.

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