Fuzzy Logic Controller Design for an Unmanned Aerial Vehicle

R.M. Namal Bandara
Department of Electrical and Computer
Faculty of Engineering
Sri Lanka institute of Information Technology
Malabe, Sri Lanka.
namal.b@sliit.lk

Sujeetha Gaspe
Electrical, Electronic & Aeronautical Engineering Department
Colombo International Nautical & Engineering College
Malabe, Sri Lanka.
sujeetha@cinec.edu

***Abstract*— Aircraft design consists of many steps such as an aerodynamic design, structural analysis and flight control design etc. And flight control is one of the crucial design aspects in modern aircrafts. Modern day aircrafts heavily rely on automatic control system for most of the functions and there is always a persistence demand for efficient controllers. There are many control techniques and methods developed in the field of control Engineering. But there are only a few numbers of controllers that we can be relied on. However the conventional techniques only work efficiently for liner system but in the real world, the air craft dynamics are highly non liner and thus there is the need for a controller which works perfectly for non-liner trajectories. Fuzzy logic controller is a non-liner control technique which uses a linguistic approach for controlling, based on some set of membership functions and rules. This research attempts to design a flight controller using a fuzzy logic system.**

Keywords*— Autopilot, Fuzzy Logic, Pitch Autopilot, Pitch angle, Pitch rate;

I. INTRODUCTION

Wright brothers started the revolution of sky diving by inventing their first aircraft. Since then there were many flying vehicles which used different technologies.

A. Controller design

Designing the controller can be done by using PID control system, LQ control system, PMC control system and Fuzzy logic system.

Even though there are many developed techniques implemented, less amount of techniques are used in real world. The reason behind this is that they are not intuitive. In aerospace where safety is the high priority, unintuitive techniques are not trusted enough to be implemented in real aircrafts. Hence the best option for this implementation is fuzzy logic control system. It has already proven to be more accurate and more efficient than PID controllers and depend on human experience and intuition.

Fuzzy logic controllers (FLC) are non-liner and rule based methods. Therefore no complex model is required. There are two kinds of fuzzy logic systems available.

1. Mamdani Fuzzy logic
2. Takagi-Sugeno (T-S) fuzzy logic.

a. Mamdani Fuzzy Logic

The methodology of Fuzzy PID control has been noticeable in Japan, however it has discovered generally less applications in aviation field. This controller has the extraordinary element of holding the same straight structure as routine PID control, yet the control increases are nonlinear elements of the info signals which make it more productive for nonlinear elements. This kind of controller was utilized for reasonable unmanned flying vehicle (UAV) for longitudinal and parallel autopilots by Institute of Aeronautics and Astronautics, Taiwan in 2011.Here, it was found that the Fuzzy Logic controllers were compelling and fit for waypoint route, direction taking after and even oppose and balance out from wind/blast disturbance [7]. Many different past experimentations have been done utilizing Fuzzy PID blend for control framework assembling a cross breed smart control systems, for example, controller for VTOL quad-rotor steering system, little scale helicopters and so forth.

The greatest point of preference of the half breed Fuzzy PID controller is the strength against clamor, and its simplicity for execution. There were part of examinations and exploration with respect to the execution and utilization of Fuzzy rationale in flight control frameworks from UAVs to significantly contender planes.

b. Takagi-Sugeno Fuzzy Logic

The Mamdani fuzzy control mentioned in controller design lacks the mathematical rigor required to conduct a systematic analysis needed for flight approval although the nonlinear and robust nature of fuzzy control is suited for flight controls. The TS model retains the advantages of the fuzzy control, and it is also constructed in a mathematically rigorous method and as a result, stability and control analysis have been developed.

In T-S fuzzy model, each rule is represented by a linear time invariant system and the fuzzy inference is constructed such that the model is very close to the aircraft nonlinear dynamics. While in the case of T-S fuzzy model the output is computed with a very simple formula (weighted average, weighted sum), Mamdani fuzzy structure require higher computational effort because of large number of rules to comply with defuzzification of membership functions.. This advantage to the T-S approach makes it highly useful in spite of the more intuitive nature of Mamdani fuzzy reasoning in terms of dealing with uncertainty.

II. Literature Review

Advanced driver assistance systems (ADAS) have been in development for many years and several of them are commercially available today (e.g.: adaptive cruise control, forward collision warning). Typically, these systems are designed to support vehicle drivers in safety-critical situations by providing information and warnings to them, or by automating the longitudinal control of the vehicle (i.e., speed and distance). Recent evaluations of ADAS in the real-world traffic show that these systems are beneficial as they have the potential to reduce the number of crashes as well as to improve fuel and time efficiency.

a. Design of a Stable Flight with a PID Controller using a FPGA (LPC2378) [1].
b. Design of a Control System for an Autonomous Vehicle Based on Adaptive- [2].
c. Fuzzy Logic Based Approach to Design of Flight Control and Navigation Tasks for Autonomous Unmanned Aerial Vehicles [3]

III. Controller Design Theory

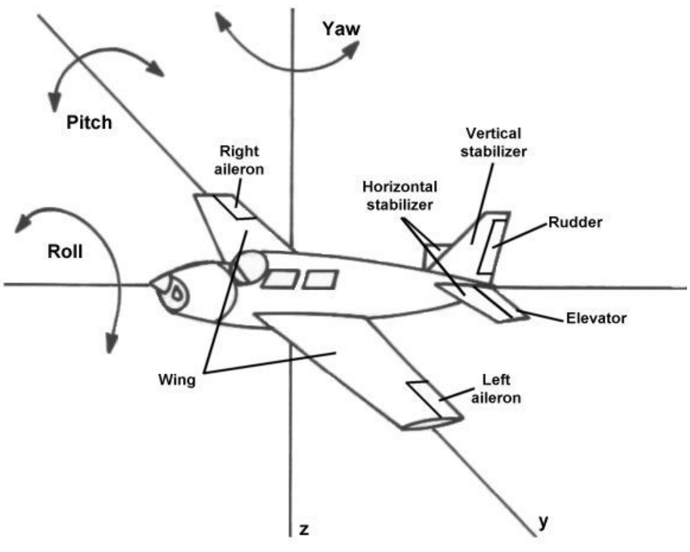

Fig. 1. Longitudinal motion of an aircraft

After deriving following formulas according to the motion of an aircraft [4],[5],[6] the fuzzy logic controller was designed using Matlab software.

$$\boldsymbol{X}=(\dot{v}\boldsymbol{x}-\boldsymbol{rvy}+\boldsymbol{qvz}) \quad (1)$$
$$\boldsymbol{Z}=(\dot{v}\boldsymbol{y}-\boldsymbol{pvz}+\boldsymbol{rvx}) \quad (2)$$
$$\boldsymbol{M}=\boldsymbol{Iy}\dot{\boldsymbol{q}}+(\boldsymbol{Ix}-\boldsymbol{Iz})\boldsymbol{pr}+\boldsymbol{Ixz}(\boldsymbol{p2}-\boldsymbol{r2}) \quad (3)$$

The above mentioned variables are defined below.

X = Aircraft Drag force (force in x* direction) (N)

Z = Aircraft Lift force (force in z* direction) (N)

M = Pitching moment (kgm2s-2)

ma = aircraft mass (kg)

v_x = velocity component in x axis(m/s)

r =yaw rate (rad/s)

v_y = velocity component in y direction (m/s)

q = pitch rate (rad/s)

p = roll rate (rad/s)

v_z = velocity in z direction (m/s)

I_y = moment of inertia about y axis ($kgm2$)

I_x = moment of inertia about x axis ($kgm2$)

I_z = moment of inertia about z axis ($kgm2$)

I_{xz} = moment of inertia about x*z* plane ($kgm2$)

Since the open loop transfer function is not stable for all the models of planes as an example if an Aircraft's controller is based on a OLTF, the variables becomes rigid. When the same controller tries to control a different Aircraft it may need to change the variables according to the shape of the air craft. Therefore closed loop feedback method had to be designed in order to make a control system which has more stability and efficiency. To damp the high amplitude short period oscillation in longitudinal motion a pitch rate (q) damper is introduced through a proportional gain feedback to elevator input (δe).

The block diagram below shows the basic idea of the pitch autopilot

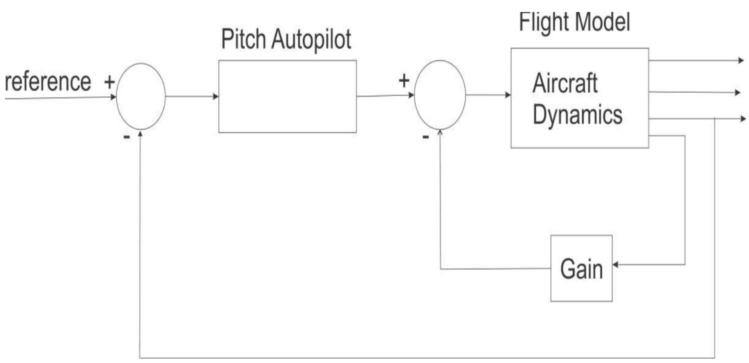

Fig. 2. Pitch autopilot block diagram

The out puts are v_x, α, $\boldsymbol{\theta}$.

In this research the Mamdani Fuzzy system will be used in order to come up with a controller.

The Mamdani Fuzzy Logic controller designed for pitch autopilot has two parts. The feedback inputs pass through fuzzy controller and the output of fuzzy controller is the input for PID controller. The block diagram shown in Figure (3) demonstrates the basic structural setup of the system where the Theta reference is the input of the system and there are two feedback paths to the system input.

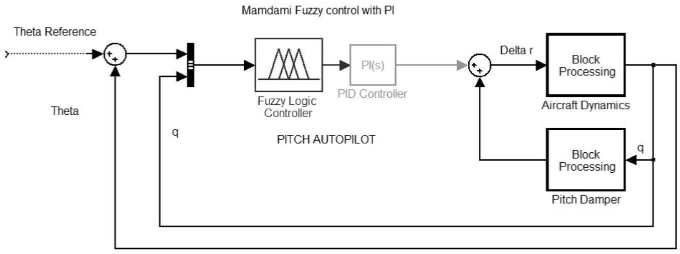

Fig. 3. Fuzzy logic system block diagram block diagram

The fuzzy controller was designed in Matlab using the inbuilt fuzzy interface system. The fuzzy inference engine needs two inputs: error and change in error. In the longitudinal system, the two inputs were pitch angle (θ) and pitch-rate (q) and the output of the fuzzy inference engine was the elevator deflection angle (δe). The Fuzzy interface system in Matlab is shown below.

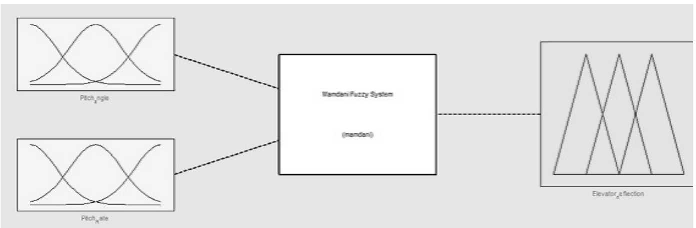

Fig. 4. Fuzzy interface block diagram showing the connections between input and output

The membership functions used were simple triangular functions with different range of angles for inputs and output.

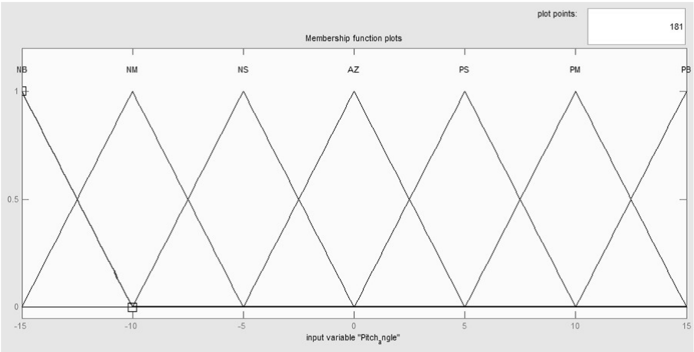

Fig. 5. The membership functions of the Pitch angle

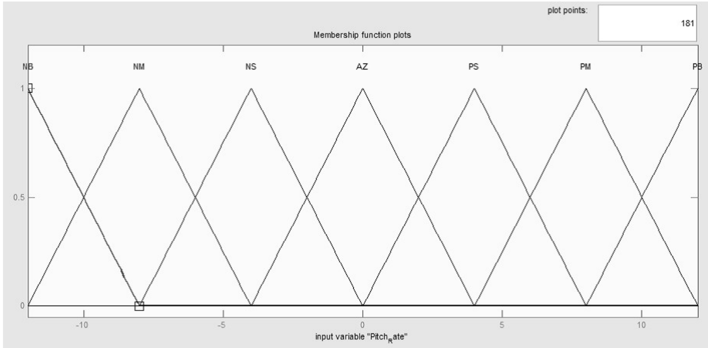

Fig. 6. The membership functions of the Pitch rate

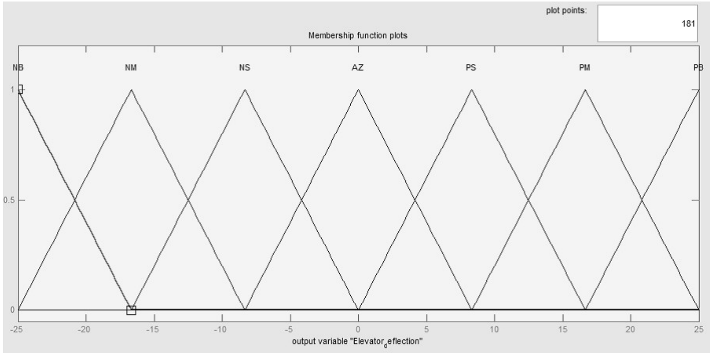

Fig. 7. The membership functions of the elevator reflection.

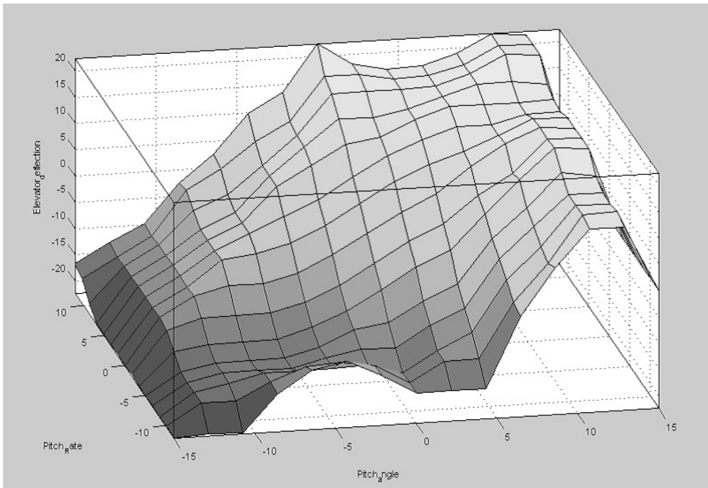

Fig. 8. The surface view of the Mamdani fuzzy logic system

The second part of the system which is a PI controller was designed as follows.

In order to design a PI control, a given State-Space model of the nonlinear dynamics was used. The State-Space model is given in *equation (1)* below:

$$\dot{x} = Ax + Bu \qquad (4)$$

$$\text{Where } A = \begin{bmatrix} X_{vx} & X_a & X_q & X_\theta \\ Z_{vx} & Z_a & Z_q & Z_\theta \\ M_{vx} & M_a & M_q & M_\theta \\ 0 & 0 & 1 & 0 \end{bmatrix} \qquad B = \begin{bmatrix} X_{\delta e} \\ Z_{\delta e} \\ M_{\delta e} \\ 0 \end{bmatrix}$$

The main function of the pitch damper is to damp the high amplitude short period oscillations caused by random disturbances or guts or pilot input. A feedback from Pitch Rate is passed through a gain/filter and fed back into elevator input. The Open Loop transfer function (OLTF) of assumed SISO system is shown in *equation (2)* below.

$$OLTF(s) = \frac{-8.7833s\,(s+0.8354)(s+0.09973)}{(s^2+0.05156s+0.005346)(s^2+1.893s+7.419)}$$

$$\frac{-8.7833s^3-8.21352s^5-0.73173s}{s^4+1.94456s^3+7.710346s^2+0.392639s+0.03966} \qquad (5)$$

This synthesis was done using the Root-locus method of the system shown in equation above considering it to be a SISO. The Root-locus plot and Bode plot of the damper are shown below in figure 9 and 10, as it shows that poles are moved to higher stability region.

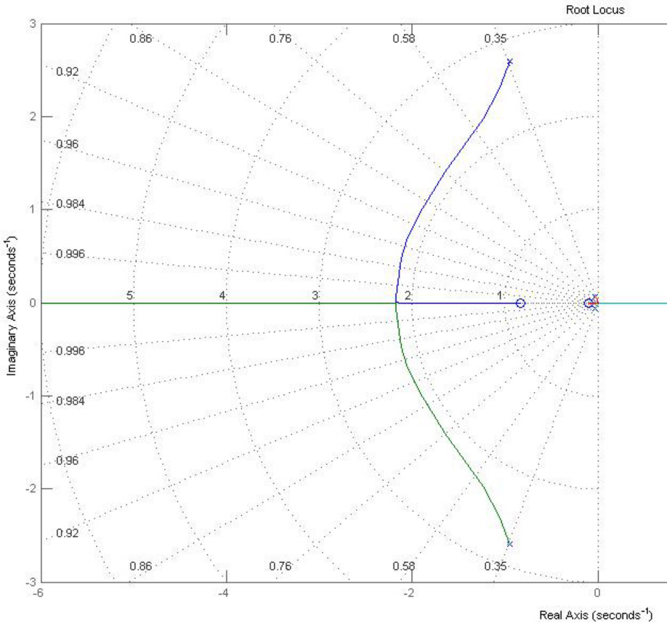

Fig. 9. The root locus of the OLTF

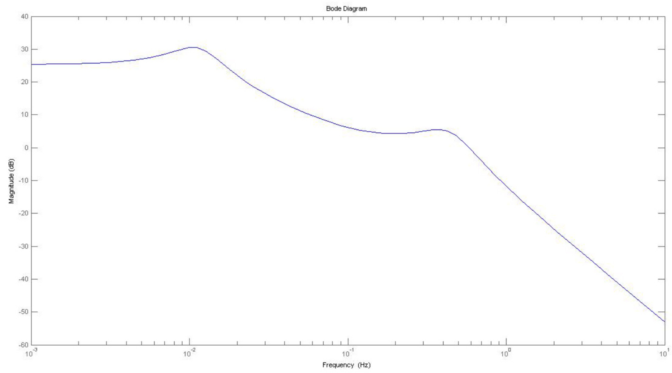

Fig. 10. Bode diagram of OLTF

Hence the CLTF can be obtained as follows (*eq. 3)*.

$$\text{Transfer Function} = \frac{-8.7833s\,(s+0.8354)(s+0.09973)(s+0.5)}{(s+7.5651)(s+1.511)(s+0.3592)(s^2+0.4022s+0.004833)} \qquad (6)$$

Now, based on the new system with pitch damper, a Pitch Autopilot was designed with feedback from θ and using the Root-locus method once again considering a SISO system with θ as output and δe as the input, a PI compensator was designed and the transfer function is shown below in equation (4) below.

$$PI(s) - \frac{1.25+0.5s}{s} \qquad (7)$$

Then the complex poles can be brought very close to the imaginary axis and they represent the long Phugoid motion which is hard to control in reality. But when using the Fuzzy system described above with this PI controller the system becomes easy to control.

IV. CONCLUTION & FUTURE WORKS

This paper's main objective was to design a Fuzzy logic controller for an autonomous unmanned aerial vehicle.

The system is a combination of a Fuzzy and PID. The fuzzy controller was designed in Matlab using the inbuilt fuzzy interface system. The fuzzy inference engine needs two inputs: error and change in error. In the longitudinal system, the two inputs were pitch angle (θ) and pitch-rate (q) and the output of the fuzzy inference engine is the elevator deflection angle (δe). The second part of the system is the PI controller. Using a State space model of the nonlinear dynamics an open loop transfer function was created. Then by using the OLTF a new CLTF was designed to make the maximum optimization of the system.

The controller that was designed was tested on a model UAV. It was in the air for a considerable time without a human interference even though there were some difficulties when there was strong wind.

For further enhancements the controller can be designed using Takagi-Sugeno Fuzzy logic. Even though it is more complex than the Mamdani Fuzzy logic, it may give better stability.

V. ACKNOWLEDGMENT

This work has been supported by the University of Wolverhampton, Wolverhampton WV1 1LY, United Kingdom and Colombo International Nautical and Engineering College, Malabe, Sri Lanka.

VI. REFERENCE

[1] Stephen Wong and Jennifer Yu, "*Autonomous Stable Flight with a PID Controller*", *Cornell University*.

[2] Pan Zhao, Jiajia Chen, Yan Song, Xiang Tao, Tiejuan Xu, Tao Mei, "*Design of a Control System for an Autonomous Vehicle Based on Adaptive-PID*", ISSN 1729-8806: July 25, 2012

[3] Sefer Kurnaz, Omer Cetin, Okyay Kaynak "*Fuzzy Logic Based Approach to Design of Flight Control and Navigation Tasks for Autonomous Unmanned Aerial Vehicles*", J Intell Robot Syst, 2009

[4] EAFB CA, "*equations of motion-chapter 4*", USAF test pilot school., vo2. flying qualities phase, pp. 4.2, October 1988

[5] EAFB CA, "*equations of motion-chapter 4*", USAF test pilot school., vo2. flying qualities phase, pp. 4.2, October 1988

[6] EAFB CA, "*equations of motion-chapter 4*", USAF test pilot school., vo2. flying qualities phase, pp. 4.2, October 1988

[7] C.C. Lee, "*Fuzzy logic in control systems: Fuzzy logic controller. II*", IEEE Transactions on Systems, Man, and Cybernetics ISSN 1729-8806: July 25, 2012