Modeling and Fuzzy Logic Control of a Quadrotor UAV

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Abstract - *Quadrotors have a variety of applications in real time e.g. surveillance, inspection, search, rescue and reducing the human force in undesirable conditions. Quadrotor UAV is equipped with four rotors for the purpose of stability but this will make quadrotor more complex to model and control. In this paper, intelligent controller is designed to control attitude of quadrotor UAV. The paper presents a detailed simulation model for a Quadrotor UAV and Fuzzy logic control strategy is designed to implemented for four basic motions; roll, pitch, yaw, and Z Height. The controller presented in this paper is very simple in structure and it is easy to implement. The main objective of this paper is to get the desired output with respect to the desired input. Simulink model and results are shown at the end of the paper*

Key Words: **Quadrotor, UAV, Fuzzy logic Control, Dynamics, Roll, Pitch, Yaw**

1. INTRODUCTION

A quadrotor or quadcopter can be defined as a "multi-rotor copter with four arms, each of which have a motor and a propeller at their ends" [1].

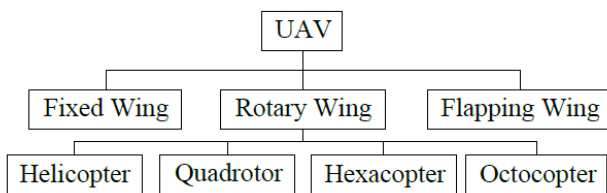UAVs are classified depending upon type of wings as shown in figure 1.

Figure -1: UAV Classification

Quadrotor lies in the category of Rotary wing class of UAVs they are usually used in the applications that required hovering flights such as search and rescue operations, security, journalism, emergency response and in military applications [2].

Quadrotors UAV are different from a helicopter for two main reasons
  a) The way they are controlled i.e. helicopters are not fully autonomous

  b) Second is helicopter can change their blades angle of attack while quadrotor lacks this functionality.

Quadrotors have many advantages over traditional helicopters such as

  a) Quadrotors have Small sizes
  b) They are safe to use for civilians because of small rotor.
  c) Less complex mechanical structure
  d) They are very easy to maintain
  e) Due to their maneuverability, they are safer in hazardous situations

This paper presents different classical and modern control strategies for the control of quadrotor. Simulations result and comparison of all control techniques are presented at the end of this paper.

2. Dynamic Modeling of Quadrotor

Quadrotor UAV flies with the assistance of four motors as shown in figure below. For the purpose of vertical flight two opposite motors rotates in the similar direction. The combination of opposite motors rotates in the similar direction for stabilization on the x-axis other combination of opposite motors keeps it stabilizes on the y-axis [3].
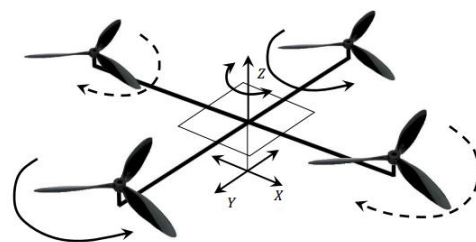

Figure -2: Quadrotor Motion

Quadrotor UAV is a 6 DOF aircraft, so there are 6 variables (x, y, z,$\emptyset$,θ and φ) that are used to express its orientation in space. $\emptyset$, θ, and φ are also known as Euler's angles. Details of each variable are as follows [4]

  • x and y: These variables are used to represent the position of Quadrotor in space.
  • Z: Defines the altitude of quadrotor

- φ: φ or Roll angle it represent angle about the x-axis
- θ : θ or Pitch angle it represent angle about the y-axis
- φ : φ or Yaw angle it represent angle about the z-axis

In this Paper, Newton-Euler formalism is used to derive the dynamics of the quadrotor. Following are the assumptions made for the design [5]

- The Structure is rigid and symmetrical
- The propellers are rigid
- Thrust and drag are proportional to square of propellers speed

The model presented in this Paper is considering following equation of motion

$$\ddot{x} = (\cos\phi \sin\theta \cos\psi + \sin\phi \sin\psi)\frac{1}{m}U_1$$
$$\ddot{y} = (\cos\phi \sin\theta \cos\psi + \sin\phi \sin\psi)\frac{1}{m}U_1$$
$$\ddot{z} = -g + (\cos\phi \cos\theta)\frac{1}{m}U_1$$
$$\ddot{\phi} = \dot{\theta}\dot{\psi}\left(\frac{I_y - I_x}{I_x}\right) - \left(\frac{J_r}{I_x}\right)\dot{\theta}\dot{\Omega} + \frac{l}{I_x}U_2 \quad (1)$$
$$\ddot{\theta} = \dot{\theta}\dot{\phi}\left(\frac{I_z - I_x}{I_y}\right) - \left(\frac{J_r}{I_y}\right)\dot{\phi}\dot{\Omega} + \frac{l}{I_y}U_3$$
$$\ddot{\psi} = \dot{\theta}\dot{\phi}\left(\frac{I_x - I_y}{I_z}\right) - \left(\frac{1}{I_z}\right)U_4$$

In equation (1) *m [kg]* represent the mass of quadrotor helicopter whereas I_{xx} *[Nms²]*, I_{yy}-*[Nms²]*, I_{zz} *[Nms²]* describes the factors of inertia matrix expressed in body system, *J [Nms⁻¹]* is the angular momentum and *Ω [rads⁻¹]* is the speed of propeller. U_1, U_2, U_3, U_4 are the inputs or translation vector factors. Basic motions and the speed of the propeller can be depicted by following equation 2 [6]

$$U_1 = b(\Omega_1^2 + \Omega_2^2 + \Omega_3^2 + \Omega_4^2)$$
$$U_2 = lb(-\Omega_2^2 + \Omega_4^2)$$
$$U_3 = lb(-\Omega_1^2 + \Omega_3^2) \quad (2)$$
$$U_4 = d(-\Omega_1^2 + \Omega_2^2 - \Omega_3^2 + \Omega_4^2)$$
$$\Omega = (-\Omega_1^2 + \Omega_2^2 - \Omega_3^2 + \Omega_4^2)$$

In equation (2) *l[m]*, *b[Ns²]* and *d[Nms²]* describe the distance between propeller center and quadrotors center, lift and drag respectively. Ω_1 *[rads⁻¹]*, Ω_2*[rads⁻¹]*, Ω_3*[rads⁻¹]* and Ω_4*[rads⁻¹]* are front, right, back and left propeller's velocity.

3. Fuzzy Logic Control

In 1965 Lotfi Zadeh developed fuzzy logic as a mathematical tool to deal with uncertainty. Fuzzy logic is based on if-then linguist rules that are easy to define for example variable t is represented as temperature in fan based cooling system the fan should start working at the t>25C so a linguist value of HOT is assigned to t>25. Fuzzy based systems helps to describe the problems that are ill defined in much easier way [7].

The reasons of using fuzzy logic are as follows [8]

1. If you have proper knowledge of the system under consideration Fuzzy Controllers are much easier to implement as compared to the conventional controller.
2. Fuzzy logic based controller are more robust.
3. For the nonlinear systems such as a Quadrotor fuzzy logic can provide more suitable control.

Key Components of FLC

Fuzzy logic Control is divided into five main components [9]

1. Defining of Input variables
2. Fuzzification
3. Fuzzy Rules
4. Defuzzification
5. Defining output variables

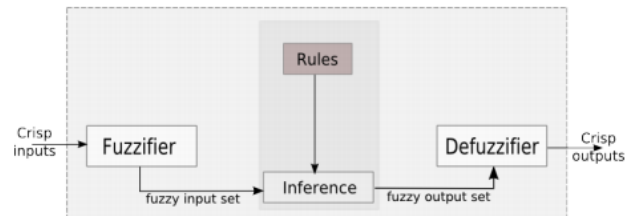A Fuzzy logic system is shown in the figure below

Figure -3: Fuzzy Control System

By experimentation and careful observation following rule base is defined for all four controllers.

Table -1: Fuzzy Rules

Height					
$\frac{dE}{dt}$ E	NB	N	Z	P	PB
N	GDM	GD	GD	S	GU
Z	GUM	GD	S	GU	GUM
P	GD	S	GU	GUM	GUM

For quadrotor control triangular, trapezoid and Gaussian membership functions are used. Input range is from [-2, 2] whereas output variable lies in the range of [-15, 15]. Following are the membership defined for each controller.
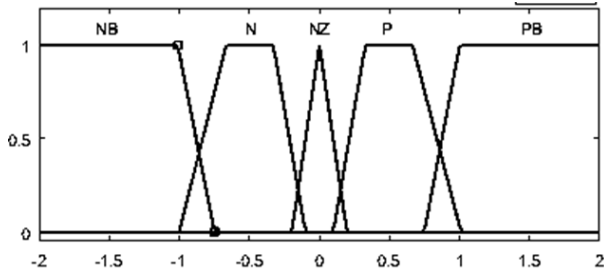

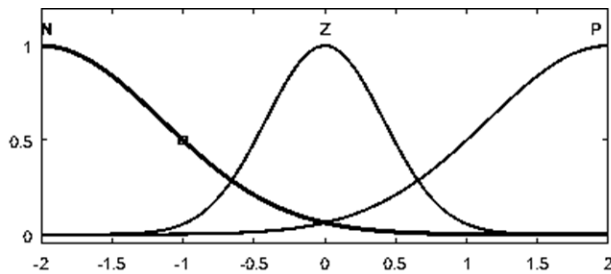**Figure -4**: *Error Input Membership Function*

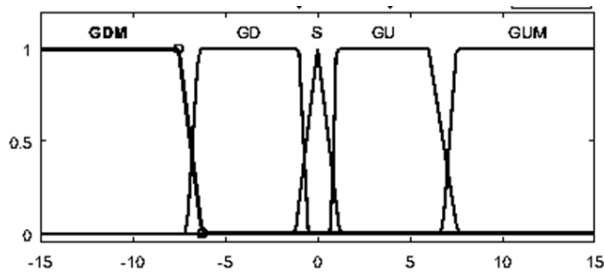**Figure -5:** *Derivative of Error Input Membership Function*

Figure -6: *Output Membership Function*

The simulation in this paper is using the parameters as mentioned in **Bouabdallah** PHD thesis as shown in table below [**5**].

Table -2: Quadrotor Parameters

I_{XX}	0.0075
I_{YY}	0.0075
I_{ZZ}	0.0130
J_r	6.50×10^{-5}
B	3.13×10^{-5}
D	7.50×10^{-5}
L	0.23
M	0.65

Simulink is used to develop the controller. For the control of quadrotor four Fuzzy type controllers are used in order

Where
N: Negative   *Z: Zero*
P: Positive   *GUM: Go Up Much*
GU: Go Up   *S: Stand*
GDM: Go Down Much   *GD: Go Down*
NB: Negative Big   *PB: Positive Big*

to achieve the desired output. In this paper we are only going to discuss the Roll Controller and rest remains similar.

For the purpose to control the roll angle of the quadrotor control input can be defined as [**10**]

$$U_2=K_p.(\phi_d-\phi)+K_d.(\phi^{\cdot}_d-\phi^{\cdot}) \tag{3}$$

Where

U_2: Control Input K_p: Proportional Gain
K_d: Derivative Gain ϕ_d: Roll Desired
ϕ: Actual Roll

The equation above can be implemented in Simulink as shown in figure below. Saturation blocks are used in the design of the controller to avoid the any situation that can take value out of the defined range.
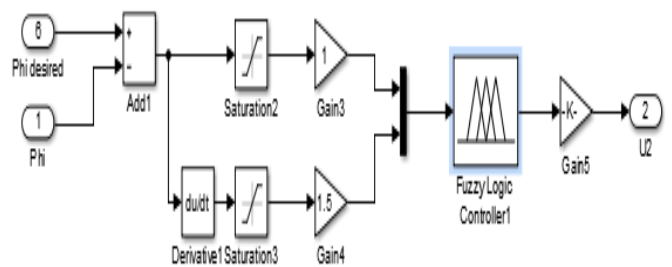

Figure -7: *Fuzzy Roll Controller*

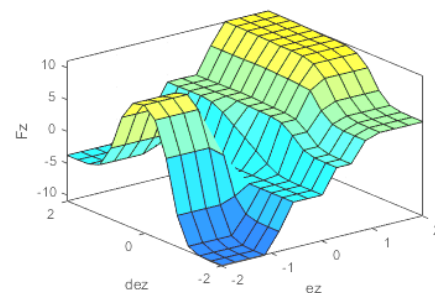Fuzzy rules surface can be seen in the figure below

Figure -8: *Fuzzy rules surface*

4. Simulation and Results

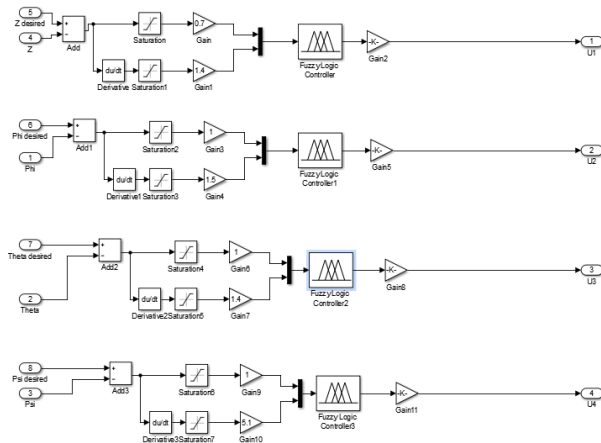General Scheme of all controllers in Matlab is shown in the picture below

Figure -9: Controller Block Diagram

Here in this case the desired input is unit step and desired output is also unit step. Simulation results with respect to the desired input is shown in the figures below
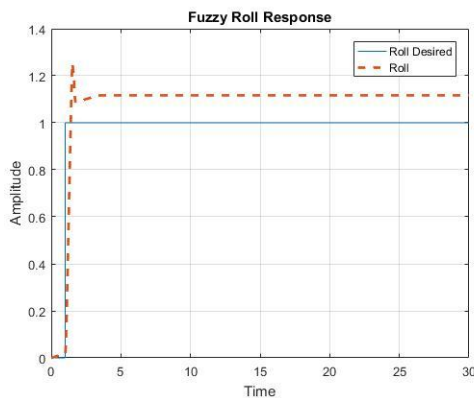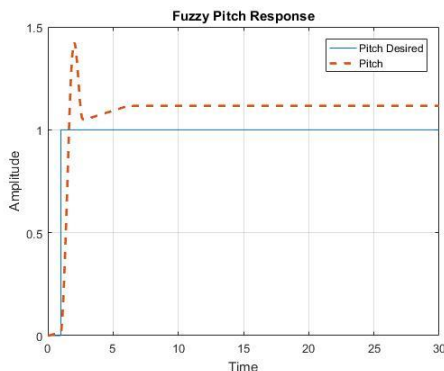

Figure -10: PHI Response

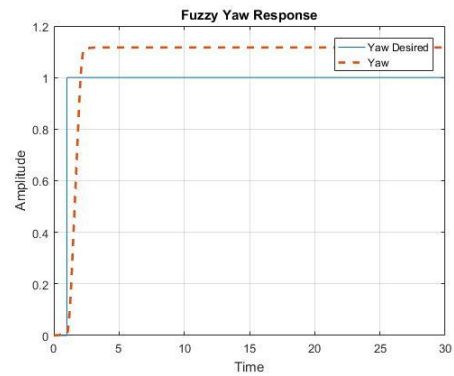

Figure -11: Theta Response
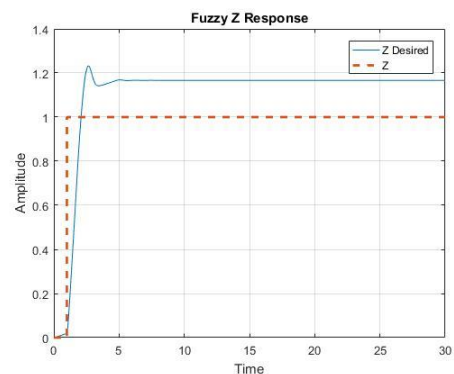

Figure -12: PSI Response

Figure -13: Z/Altitude Response

5. CONCLUSIONS

In this paper a nonlinear mathematical model of quadrotor is presented and implementation of the presented model is done through Matlab/Simulink. The presented model also considered rotor dynamics and aerodynamic effects which in most of the literatures are not considered during modeling. By looking at the responses shown in figures above we can observe that the behavior of Roll, Pitch, Yaw and Z are almost the same as the provided input. Further investigation can be made by using the same controller design and implement it on hardware.

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BIOGRAPHIES

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Dr Abdulla Ismail obtained his B.Sc. ('80), M.Sc. ('83), and Ph.D. ('86) degrees, all in electrical engineering, from the University of Arizona, U.S.A. Currently, he a full professor of Electrical Engineering and assistant to the President at the Rochester Institute of Technology, Dubai, UAE