Design and Implementation of Fuzzy Logic Controller for Quad Rotor UAV

K.Senthil Kumar, Mohammad Rasheed, and R.Muthu Madhava Kumar

***Abstract*—**A fuzzy control is designed and implemented to control a simulation model of the quad rotor. Each of the controllers works with the error, derivative of error and the integral of error. The inputs are the desired values of the height, roll, pitch and yaw. The outputs are the power of each of the four rotors that is necessary to reach the desired specifications. Fuzzy controllers have been developed and implemented with the Fuzzy Logic Toolbox of Matlab. The simulation results able to show the efficiency of the Fuzzy logic control strategy and then compared with the experimental results.

***Keywords*—**Intelligent control system, fuzzy control, quad rotor, UAV.

I. Introduction

An Unmanned Air Vehicle (UAV) is defined as a powered, aerial vehicle that does not carry a human operator, uses aerodynamic forces to provide vehicle lift, can fly autonomously or be piloted remotely, can be recoverable, and can carry a lethal or nonlethal payload.

UAVs have far reaching applications.

- Target and decoy - providing ground and aerial gunnery a target that simulates an enemy aircraft or missile.
- Reconnaissance – providing battlefield intelligence.
- Combat – providing attack capability for high-risk missions.
- Logistics – UAVs specifically designed for cargo and logistics operation.
- Research and development.
- Civil and Commercial applications.

II. Quad Rotor Structure

Quad rotor is an aircraft in which lift is generated by four rotors symmetrically fixed around its Centre. Moreover has a simpler configuration for a compact mechanical design. The Quad Rotor layout is shown in the figure 1.

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Maneuvers (i.e. yawing, rolling and pitching) and the vertical or lateral flight are realized by independently varying speeds of the rotors [2][4].

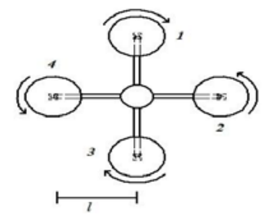

Fig. 1 Quad Rotor Design

There are two arms, each having motors at its ends. The motors 1 and 3, which are mounted on the same arm, rotate in the clockwise direction while the motors 2 and 4, mounted on the second arm, rotate in the anti-clockwise arrangement. This makes the aerodynamic effects and gyroscopic moments to be canceled in a stationary flight. Both motors at opposite ends of the same arm should rotate in same direction to prevent torque imbalance during linear flight [2][4].

III. Quad Rotor Mechanism

A Altitude Motion

The throttle movement is provided by increasing (or decreasing) the speed of all the rotors by the same amount. It leads a vertical force with respect to body-fixed frame which raises or lowers the quad rotor [9][11].

When all actuators are at equal thrust, the craft will either hold in steady hover (assuming no disturbance) or increase/decrease altitude depending on actual thrust value.

B. Roll Motion

The roll movement is provided by increasing (or decreasing) the left rotor's speed and at the same time decreasing (or increasing) the right rotor's speed. It leads to a torque with respect to the central axis which makes the quad rotor to roll. The overall vertical thrust is the same as in hovering.

If one of the actuators is decreased or increased on the roll axis as compared to the other actuator on the same axis, a roll motion will occur. In this instance, the craft would roll towards the right.

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C. Pitch Motion

The pitch movement is provided by increasing (or decreasing) the front rotor's speed and at the same time decreasing (or increasing) the back rotor's speed. It leads to a torque with respect to the central axis. The overall vertical thrust is the same as in hovering.

Similar to the roll axis, if either actuator is changed on the pitch axis, the axis will rotate in the direction of the smaller thrust. In this instance, the craft nose would pitch up due to the differential on the pitch axis.

D. Yaw Motion

The yaw movement is provided by increasing (or decreasing) the front-rear rotor's speed and at the same time decreasing (or increasing) the left-right couple. It leads to a torque which makes the quad rotor turn in horizon level. The overall vertical thrust is the same as in hovering.

If the clockwise spinning actuators are decreased (or the counter clockwise actuators increased), a net torque will be induced on the craft resulting in a yaw angle change. In this instance, a clockwise torque is induced.

IV. Mathematical Analysis Of Quad Rotor UAV

The quad rotor has six degrees of freedom that can be divided into two parts:

- Translational – translational motion occurs in x, y, and z directions.
- Rotational – rotational motion occurs about x, y and z directions and named as roll (Φ), pitch (θ), and yaw (ψ).

The frames of reference used are:

- Earth's frame (an inertial frame of reference)
- Body-axis (a non-inertial frame of reference)

A. Assumptions

The mathematical model developed is based on certain basic assumptions as given below:

- Quad rotor body is rigid
- Propellers are rigid.
- There is no friction on quad rotor body.
- Free stream air velocity is zero.
- Drag torque T is proportional to propeller speed with D as drag constant.
- Design is symmetrical.

B. Quadrotor system state

In defining the dynamic behavior of the quadrotor platform, we must have knowledge of the state of the craft. Knowledge of the parameters involved in defining the state describing the craft at any instant in time will help in understanding the derived dynamics. The angles that make up the attitude of the craft with respect to the body coordinate system that is the roll angle, Φ, the pitch angle, θ, and the yaw angle, Ψ, will all be represented in the state vector. Additionally, the angular velocities of these about each axis will be represented using dot notation; Φ, θ, Ψ. These 6 states effectively define the attitude of the craft with respect to its own coordinate system. An additional 6 states are necessary to define the relationship of the craft with respect to the earth fixed coordinate system. These states include the physical location of the craft within the earth fixed system along each of its principal axes, denoted as X, Y, and Z. Additionally, the velocity of the craft in each of these directions is also necessary, and will be denoted as X, Y, and Z.

Together, these 12 state variables make up the state vector of the quadrotor platform. This state vector is provided in equation

$$X = [\,\phi\ \theta\ \psi\ \dot{\phi}\ \dot{\theta}\ \dot{\psi}\ \ X\ Y\ Z\ \dot{X}\ \dot{Y}\ \dot{Z}\ \ ] \tag{1}$$

C. Coordinate system rotations

Two coordinate systems are needed to define the instantaneous state of the platform at any time. First, a body fixed system with the x-axis along the front of the craft, the y-axis to the right, and the z-axis down. Second, an earth fixed inertial system using the North-East-Down convention typical of aviation applications. The rotation of one frame relative to the other can be described using a rotation matrix, comprised of three independent matrices describing the craft rotation about each of the earth frame axes[1]. These rotation matrices are given in equations.

$$R_\phi = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos\phi & \sin\phi \\ 0 & -\sin\phi & \cos\phi \end{bmatrix} \tag{2}$$

$$R_\theta = \begin{bmatrix} \cos\theta & 0 & -\sin\theta \\ 0 & 1 & 0 \\ \sin\theta & 0 & \cos\theta \end{bmatrix} \tag{3}$$

$$R_\psi = \begin{bmatrix} \cos\psi & \sin\psi & 0 \\ -\sin\psi & \cos\psi & 0 \\ 0 & 0 & 1 \end{bmatrix} \tag{4}$$

Using these rotation matrices, the complete orientation of one coordinate system with respect to the other can be calculated. The total rotation matrix equation is provided by the equation below.

$$\theta = R_\phi R_\theta R_\psi \tag{5}$$

D. Forces and moments

The forces and moments are primarily due to gravity and the four propellers. From the reference of the onboard craft coordinate system, the thrusts generated by the motors/propellers are always in the crafts z-direction.

The gravity vector is always in the fixed frame z direction (towards the center of the earth). In this instance the rotation matrix from equation (5) is utilized. Therefore the force of gravity is given by

$$F_g = m\ g\ \begin{bmatrix} -\sin\theta \\ \cos\theta\sin\phi \\ \cos\theta\cos\phi \end{bmatrix}_{body} \tag{6}$$

The force is taken with respect to the craft coordinate system, affixed to the centre of gravity of the quadrotor platform. Along with gravity, the only other forces to be considered are the forces generated by the propeller/motor combos. These forces combined with the force of gravity, allow solving equation for the forces acting on the platform, and determining the acceleration of the craft in terms of the craft fixed frame [1].

$$\begin{bmatrix} \ddot{X} \\ \ddot{Y} \\ \ddot{Z} \end{bmatrix} = -\frac{1}{m} \begin{bmatrix} 0 \\ 0 \\ F_{thrust} \end{bmatrix} + g \begin{bmatrix} -\sin\theta \\ \cos\theta\sin\phi \\ \cos\theta\cos\phi \end{bmatrix} \tag{7}$$

V. Quad Rotor Dynamics

Lifting forces generated by the spinning propeller and the weight, are responsible for all the motion of body, as the external effects such as air friction, wind pressure etc. have been neglected.

Linear Acceleration in the X-axis Direction [1][3] is given by

$$\ddot{x} = \frac{u(1)(\sin\psi\sin\phi + \cos\psi\sin\theta\cos\phi)}{m} \tag{8}$$

Linear Acceleration in the Y-axis Direction [1][3] is given by

$$\ddot{y} = \frac{u(1)(\sin\psi\sin\theta\cos\phi + \cos\psi\sin\phi)}{m} \tag{9}$$

Linear Acceleration in the Z-axis Direction [1][3] is given by

$$\ddot{z} = \frac{u(1)\cos\theta\cos\phi - k_3 .\dot{z}}{m} - g \tag{10}$$

Rolling angular Acceleration in the x-axis Direction [1][3] is given by

$$\ddot{\phi} = \frac{u_2 * 1}{I_x} \tag{11}$$

Pitching angular Acceleration in the y-axis Direction [1][3] is given by

$$\ddot{\theta} = \frac{u_3 * 1}{I_y} \tag{12}$$

Yawing angular acceleration in Z-axis Direction [1][3] is given by

$$\ddot{\psi} = \frac{u_4 * 1}{I_z} \tag{13}$$

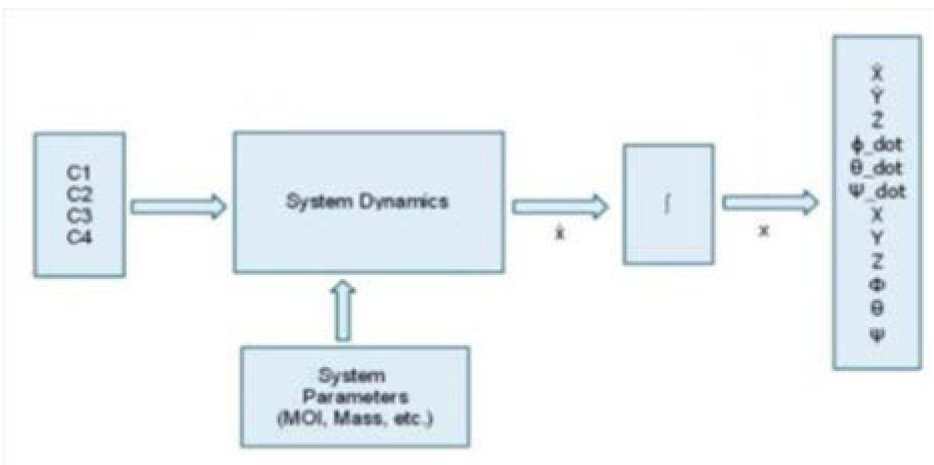

Fig 2 Basic Block Diagram of Simulink Model

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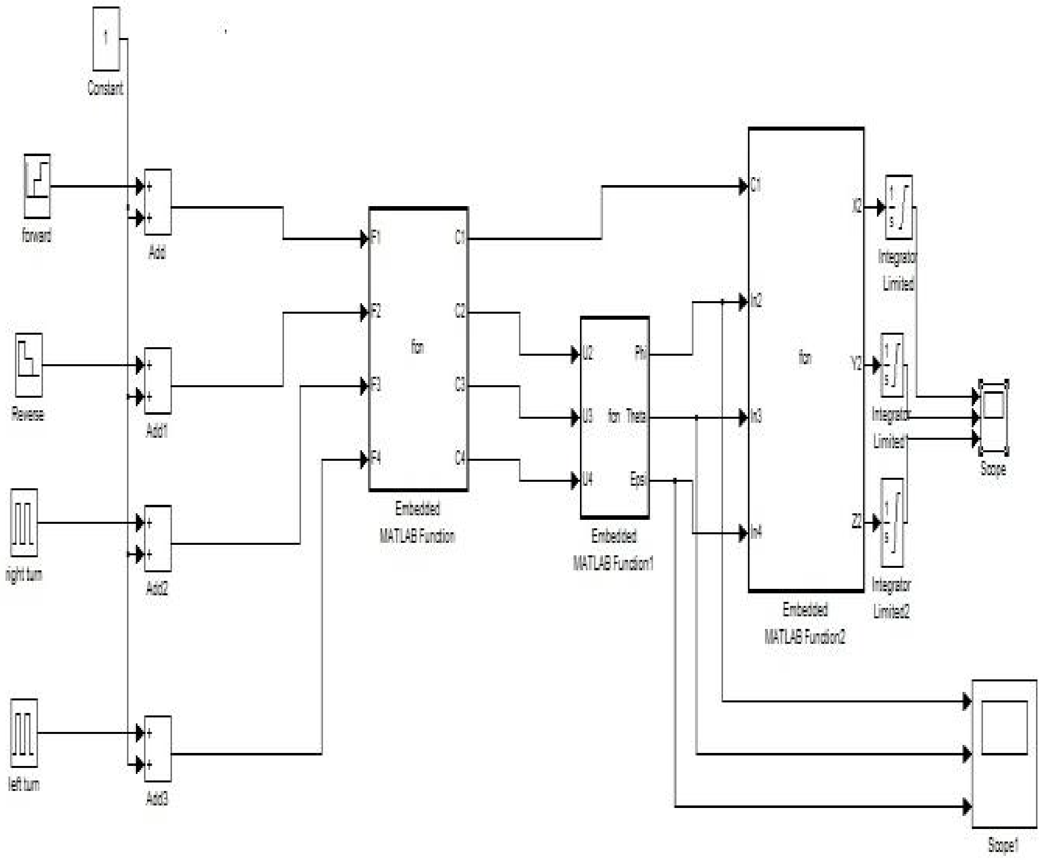

Fig. 3 Simulink Model of Quad Rotor Dynamics

VI. Fuzzy Controller Implementation

The fuzzy control strategy implements the logic used to control the vehicle. The controller decisions are taken based on the desired combination of the four motions: height, pitch, roll and yaw. These actions increase or reduce the power of each of the motors in order to get the specifications and to follow a trajectory.

A. Height controller

The height controller returns the power required by each engine to correct the error in height. The output of the controller must be the same for each rotor, either increasing or decreasing; otherwise it would produce a drift. That means that if we want to go up, the input for each engine must be the same and positive, and if the quad rotor has to go down, the power of the four rotors should be decremented the same quantity [7][10]. The controller gives only one value as output, *fz*, and this value is applied to the four motors.

$$\mu_z = f1 + f2 + f3 + f4 = 4fz \tag{14}$$

B. Roll controller

The roll controller acts on the motors M2 and M4. For rotation around x-axis, the front and back motors (M1 and M3) must be kept without changes [7][10]. The increment in one of the rotors must be compensate with the same decrement in the other one, to maintain the support force (μ_{roll}) constant and in order not to destabilize the quad rotor. The fuzzy controller returns a single value that should be added to M2 and be subtracted from M4 force.

A positive value means a rotation clockwise (right) and a negative value means anti-clockwise (left). That is, for right rotation it is necessary that the left rotor (M2) had more power than the right one (M4) and vice versa.

$$F_2 = f_z + \Delta_{roll} \tag{15}$$

$$F_4 = f_z - \Delta_{roll} \tag{16}$$

C. Pitch controller

The pitch controller operates on the front and back motors M1 and M3. It turns around y-axis, so M1 and M3 must be modified, and rotors M2 and M4 must be kept constant. The value calculated by the pitch fuzzy control is Δ_{pitch}, which is added or subtracted in order to pitch up or down. The pitch controller also returns a single value of output [7][10].

$$F_1 = f_z + \Delta_{pitch} \tag{17}$$

$$F_3 = f_z - \Delta_{pitch} \tag{18}$$

D. Yaw controller

The yaw controller acts on the four motors, M1, M2, M3 and M4. It turns around the z-axis. Regarding the yaw movement, the rotors are grouped in pairs: the left and right rotor M2 and M4 turn in one direction, and the front and back rotors M1 and M3 change in the other direction. Furthermore, if the support force is kept constant, anything that increases/decremented the power engine in one pair should produce the opposite effect on the other pair. This fuzzy controller gives the value $+\Delta\mu_{yaw}$ *as* output. Yaw Controller returns a positive power if it rotates clockwise (right) and a negative power if it rotates anticlockwise (left). It acts like roll-controller [7][10].

$$F_1 = f_z + \Delta_{yaw} \tag{19}$$

$$F_2 = f_z - \Delta_{yaw} \tag{20}$$

$$F_3 = f_z + \Delta_{yaw} \tag{21}$$

$$F_4 = f_z - \Delta_{yaw} \tag{22}$$

VII. Fuzzy Logic Controller

The input is the error (difference between the desired and the present one), its derivative and its integral. The output is the control value of the power to be applied to the four motors [8]. Fuzzy controllers have been developed and implemented with the Fuzzy Logic Toolbox of Matlab. All of them have these following commons characteristics:

- Mamdani inference.
- The central membership function is triangular and the rest are trapezoidal.
- Defuzzification method: centroid.

The three fuzzy sets for each of the input error, derivate error and for the integral error are LOW, MEDIUM and HIGH [5][6][10].

The output has five fuzzy sets : VERY SMALL, SMALL, MEDIUM, LARGE and VERY LARGE [5][6][10]. Table I shows the control actions of the possible combinations of the three input values. Although the number of rules is 27, they have been reduced to 11, joining the ones that produce the same output [5][6][10].

TABLE I
Fuzzy Inference Rules of the Controller

DE – IE / E	**LOW**	**MEDIUM**	**HIGH**
LOW-LOW	Very Small	Small	Medium
LOW-MEDIUM	Very Small	Small	Medium
LOW-HIGH	Very Small	Small	Medium
MEDIUM- LOW	Small	Medium	Large
MEDIUM-MEDIUM	Small	Medium	Large
MEDIUM-HIGH	Small	Medium	Large
HIGH- LOW	Medium	Large	Very Large
HIGH- MEDIUM	Medium	Large	Very Large
HIGH- HIGH	Medium	Large	Very Large

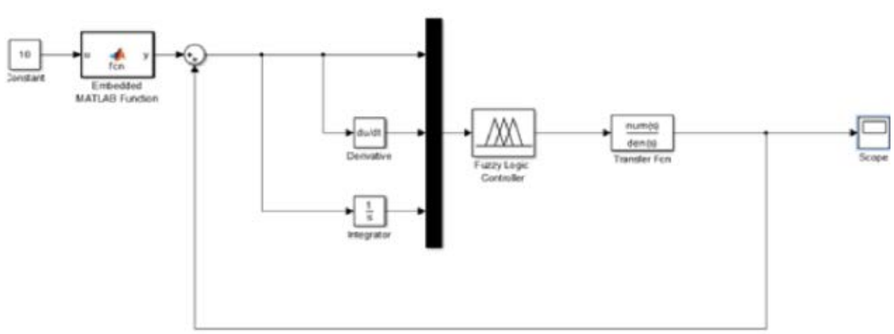

Fig 4 Simulation Block Diagram using MATLAB SIMULINK

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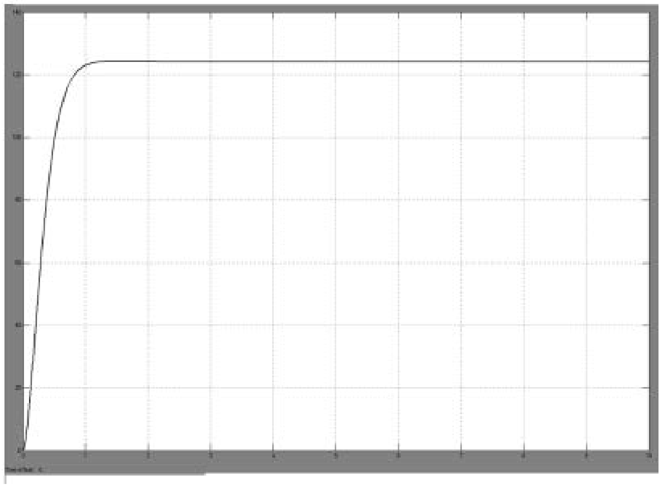

Fig 5 Response Result in MATLAB SIMULINK

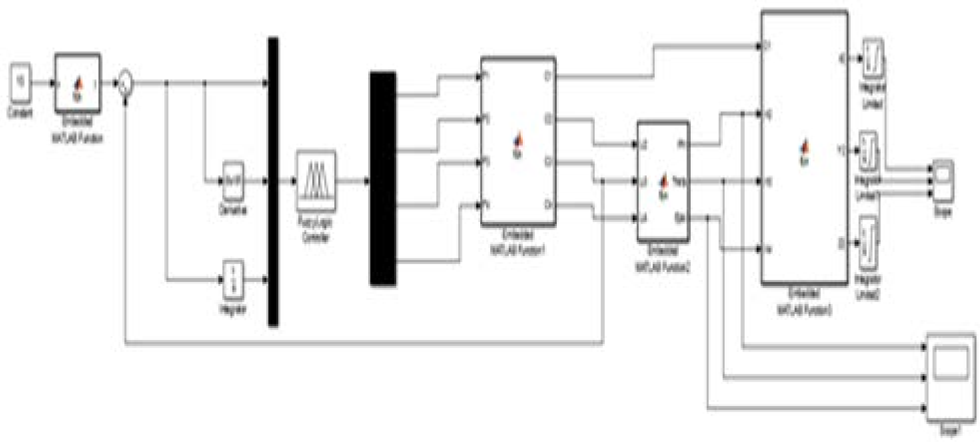

Fig 6 Simulation Block Diagram using Quad rotor Dynamics in MATLAB SIMULINK

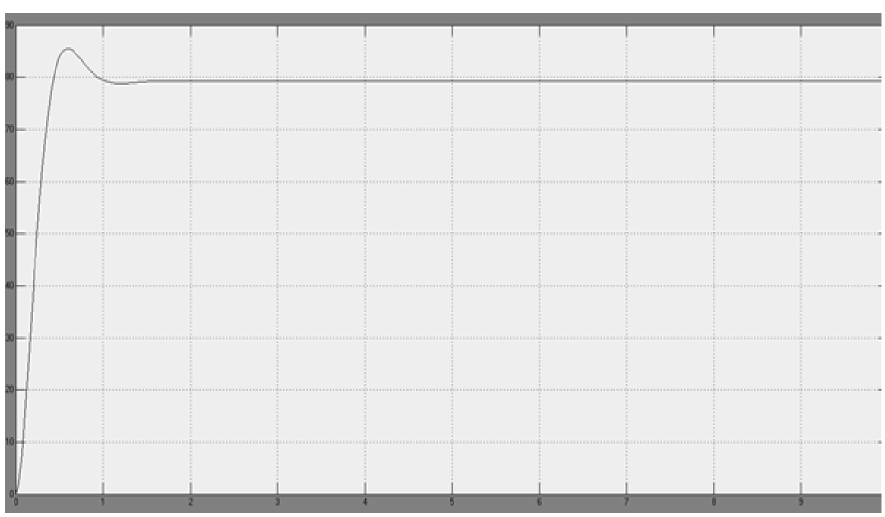

Fig 7: Response Result in MATLAB SIMULINK

TABLE II
COMPARISON TABLE WITH FUZZY LOGIC AND PID CONTROLLER

	PID Controller	**Fuzzy Logic Controller**
Rise Time	0.835 s	0.496 s
Settling Time	1.6 s	1.1 s
Peak Over Shoot	7.77 %	5.30%
Peak Value	1.08	1.055

VI. CONCLUSION

The application of intelligent strategy fuzzy logic in the design of control systems allows flexibility and efficiency. The knowledge about the behavior of the system helps to deal with complex model and control.

In this work, an intelligent system based on fuzzy logic has been designed and implemented in order to control a quad rotor. This vehicle has a complex dynamics because of the coupling of the different variables that represent the motion. The simulation results obtained for different tests are quite promising and compared with real time quad rotor performance.

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