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Fuzzy PID Control of a Quadcopter Altitude, Roll and Pitch in the Event of Rotor loss

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ABSTRACT
This scheme presents an adaptive fuzzy PID controller for fault-tolerant control of a quadcopter in the presence of 100 % fault on a single rotor. First, a PID controller is designed as the main controller for the system performance in fault free condition. Then, a fuzzy inference scheme is used to tune in real-time the PID controller gains in the event of an actuator fault. The proposed method computes adaptive PID gains in real time which then compensates for the effects of rotor failure. The fuzzy PID controller reduces the fault on the system by reacting faster and returning the system to its hovering position by varying simultaneously the rotational velocity of the three fault free rotors. Unlike other existing systems in literature, this system does not require a Fault detection and isolation unit. Finally, MATLAB simulations are conducted to evaluate the performance of the proposed Fault Tolerant Controller (FTC). The results prove that the proposed controller is capable of stabilizing a quadcopter in the presence/absence of actuator fault. The performance of the conventional PID technique is then compared with the performance of the FuzzyPID controller.

Key words: Fuzzy Logic, PID control, Quadcopter, Rotor failure

INTRODUCTION

A quadcopter is an aircraft that is lifted and propelled by four rotors in a cross configuration and its basic motions are generated by varying the speeds of all the four rotors. It is a 6 Degree of Freedom (DOF) device with only four actuators, which makes it an under actuated vehicle with unstable dynamics. For an Unmanned Aerial Vehicles (UAV), due to hardware redundancy limitations, design of a reliable control system plays an important role in ensuring acceptable and efficient performance.

Recently there has been a surge of interest in the use of small Unmanned Aerial Vehicles (UAVs) in research and various civilian and military applications [1]. These applications include package delivery, aerial imagery, surveillance, and structural inspection; a common aspect is that these tasks are either in remotely inaccessible locations and require dangerous maneuverability or are in unfriendly environments in case of military operations. Several different UAV platforms exist that have the potential to solve these problems such as fixed-wing airplanes, lighter-than-air blimps, and multirotor aircrafts. A quadcopter has advantages over the fixed wing UAVs in that it has Vertical Take-off and Landing (VTOL) capabilities and can perform maneuvers. Its advantage over other rotary UAVs, such as a helicopter, is that it is mechanically simple; a quadcopter does not need a complex set of mechanical linkages to alter rotor blade angles. Quadcopter helicopters do not require a tail rotor and this allows it to devote all vehicle power to producing lift. This allows for significant payload capacity in relation to vehicle weight.

However, a quadcopter is a six Degrees Of Freedom system with only four actuators, making it under actuated as well as being a highly nonlinear and unstable system [2]. With such a configuration, the entire vehicle must tip in one direction or another in order to direct the rotor thrusts to actuate lateral or longitudinal motion. This could be seen as a potential disadvantage as it does constrain the dynamics of the vehicle in that it cannot cause acceleration forward or back or from side to side while maintaining a given orientation.

It is therefore a bigger challenge to maintain full control of all the attitude states and all the translational states when one of the rotors has failed and the system becomes even further under actuated. This makes the quadcopter non-linear and several uncertainties are encountered during its missions.

In view of the mentioned challenges, several techniques have been proposed in literature to stabilize and safely land a quadcopter with one or more actuator faults. PID control was implemented in design of Quadrotor Controller for stabilization after failure of one of the rotors [3]. Motor 2 is switched off after 37 seconds and the response of the system is simulated. PID linear controller was found to struggle with aggressive maneuvers [4] especially when one of the rotors is faulty. GS-PID is applied in [5] for fault tolerant control of a quadcopter for an 18% of overall loss in power of all motors. Acceptable tracking deviation from the desired square trajectory after the fault occurrence was obtained with the fault injected at 20s. Model Reference Adaptive Controller (MRAC) Direct method is selected in [6] for fault-tolerant control of a quadcopter. The flight was tested for both hovering control and square trajectory tracking controls with fault injection. An MPC strategy is proposed in [7], sacrificing the control on yaw. According to the simulations, the MPC method is able to get the quadrotor UAV in hover position. However, the controller cannot be implemented on hardware for experimental results since the angular velocities are very high and may cause problems therefore there is need to physically validate these simulation results. Farid and co-researchers [8] describes the fault tolerance property of Sliding Mode Control(SMC) and uses it in an FTC. The objective of their work is to land the quadrotor horizontally ($\emptyset = 0$ and $\theta = 0$) when an actuator fault occurs. Amoozgar et al. [9] proposes a two-stage Kalman filter (TSKF) as an observer as a fault detection and isolation unit, its performance is verified by Loss Of control Effectiveness (LOE) in one single motor, in three motors, and in all motors, respectively. However, no fault tolerant control strategies are introduced. Most of the above methods require a Fault Detection and Diagnosis (FDD) scheme to provide the time of fault occurrence as well as the location and the magnitude of the fault during the flight. [10] An adaptive PID controller is proposed for stabilization of a quadcopter helicopter system when one of the actuator motors is faulty. The contribution of this paper therefore lies in the elimination of the FDD and combination of the FLC features such as the ability to deal with nonlinear systems with uncertainties. The combination of these features makes it possible to modify and extend the operating conditions of the baseline PID controller in the event of actuator fault.

DESCRIPTION AND DYNAMICS OF THE QUADCOPTER UAV

The input to the Electronic Speed Controllers (ESCs) is $u = [u_1 u_2 u_3 u_4]^T$ which are Pulse Width Modulation (PWM) signals. The output is the thrust vector $T = [T_1 T_2 T_3 T_4]^T$ generated by four individually controlled motor-driven propellers as illustrated in Fig. 1.

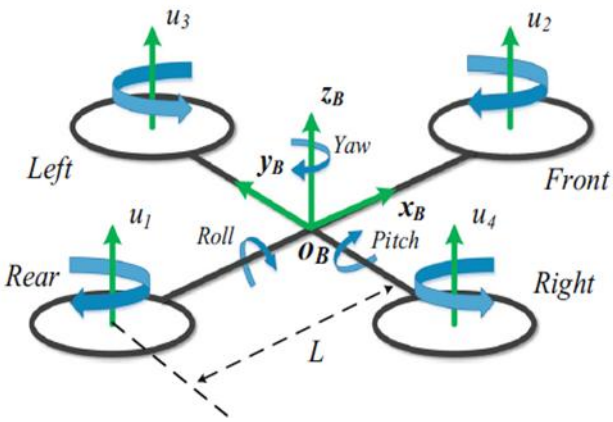

Fig. 1 Schematic representation of a Quadrotor UAV system

In Fig. 1, the two opposing rotors (1, 2) i.e. rear and front rotate clockwise and the other two (3, 4), left and right, rotate counterclockwise. Control of quadcopter is achieved by differential control of the thrust generated by each rotor. Vertical motion is accomplished by simultaneously increasing or decreasing the speed of all four rotors [11].Lateral movement is produced by horizontal translation which requires the quadrotor helicopter to roll or pitch.

DYNAMICAL MODEL OF THE QUADROTOR UAV

From [12] and [13], the commonly employed nonlinear model of the quadrotor UAV is given by:

$$\ddot{x} = \frac{(\sin\psi \sin\phi + \cos\psi \sin\theta \cos\phi)u_1(t) - K_1 \dot{x}}{m}$$

$$\ddot{y} = \frac{(\sin\psi \sin\theta \cos\phi - \cos\psi \sin\phi)u_1(t) - K_2 \dot{y}}{m}$$

$$\ddot{z} = \frac{(\cos\theta \cos\phi)u_z(t) - K_3 \dot{z}}{m} - g \qquad (1)$$

$$\ddot{\phi} = \frac{u_3(t) - K_4 \dot{\phi}}{I_x}$$

$$\ddot{\theta} = \frac{u_2(t) - K_5 \dot{\theta}}{I_y}$$

$$\ddot{\psi} = \frac{u_4(t) - K_6 \dot{\psi}}{I_z}$$

The generated thrust T_i of the i^{TH} motor is related to the i^{TH} PWM input u_i by a first-order linear transfer function:

$$T_i = K \frac{\omega}{s + \omega} u_i; i = 1,....,4 \quad (2)$$

Where;

θ is the Pitch angle
$\emptyset$ is the Roll angle
Ψ is the Yaw angle
x, y, z are the coordinates of the quadcopter
I_x, I_y, I_Z are the moments of inertial along x, y, z directions
T is the generated Thrust
K is the Drag coefficient related to aerodynamic force
u_i is the thrust of each motor
g is the Acceleration of gravity
m is the Mass of the quadcopter

A linearized model of the quadrotor UAV can be obtained by assuming hovering conditions which implies that the $u_z \approx mg$ in the vertical direction with no yawing $\varphi = 0$ and small roll and pitch angles i.e. $\sin \emptyset = \emptyset$ *and* $\sin \theta = \theta$ [14].

A simplified linear model is therefore given by:

$$\ddot{x} = \theta g$$

$$\ddot{y} = -\phi g$$

$$\ddot{z} = u_z(t)/m - g$$

$$I_x \ddot{\theta} = u_\theta(t)$$

$$I_y \ddot{\phi} = u_\phi(t)$$

$$I_z \ddot{\psi} = u_\psi(t) \quad (3)$$

By setting $Ti \approx Kui$ from (2), the relation between the lift/torques and the thrusts/accelerations is:

$$\begin{bmatrix} u_z \\ u_\theta \\ u_\phi \\ u_\psi \end{bmatrix} = \begin{bmatrix} K & K & K & K \\ KL & -KL & 0 & 0 \\ 0 & 0 & KL & -KL \\ KK_\psi & KK_\psi & -KK_\psi & -KK_\psi \end{bmatrix} \begin{bmatrix} u_1 \\ u_2 \\ u_3 \\ u_4 \end{bmatrix} \quad (4)$$

QUADCOPTER SYSTEM MODEL UNDER ACTUATOR FAULTS

Power systems optimization is an important area in Power Systems Engineering because it has contributed to savings in terms of fuel cost, improved operational reliability and system security.

The control signal in the presence of actuator fault can be written as

$$u_{fi}(t) = l_{fi} u_i(t) \quad (5)$$

Where l_{fi} is the effectiveness of a particular actuator with l_{fi} =1 as partial actuator failure and l_{fi} =0 as the complete actuator failure.

For the quadcopter UAV, the effectiveness of four actuators can be expressed as:

$$u_f(t) = L_f u(t) \tag{6}$$

where $L_f = diag\{l_{f1},....,l_{f4}\}$ as the effectiveness factors written in a diagonal matrix, $u_f(t) = [u_{f1}(t),...,u_{f4}(t)]^T$ as the faulty control input vector and $u(t) = [u_1(t),...,u_4(t)]^T$ the control actions on fault free quadcopter UAV.

In state space representation, (3) and (4) can be written as:

$$\begin{aligned} \dot{x}(t) &= Ax(t) + Bu(t) \\ y &= Cx(t) \end{aligned} \tag{7}$$

From (6), the system with actuator fault can be described as

$$\begin{aligned} \dot{x}(t) &= Ax(t) + B_f u(t) \\ y &= Cx(t) \end{aligned} \tag{8}$$

where $B_f = BL_f$ is the post fault control input matrix, the state vector and control input are taken as $x(t) = \begin{bmatrix} x & \dot{x} & y & \dot{y} & z & \dot{z} & \theta & \dot{\theta} & \phi & \dot{\phi} & \psi & \dot{\psi} \end{bmatrix}^T$ and $u(t) = \begin{bmatrix} u_z & u_\theta & u_\phi & u_\psi \end{bmatrix}^T$ respectively.

ADAPTIVE FAULT TOLERANT CONTROLLER DESIGN

PID controllers are control loop feedback mechanisms that directly adjust control values with a closed-form formula based on derivative, integral, and proportional gains [15] as shown in (9).

$$G(s) = K_p + \frac{K_i}{s} + K_d S \tag{9}$$

Where K_p, K_i, and K_d are the proportional, integral, and derivative gains, respectively. PID controllers are frequently used in a number of industrial applications because of their simplicity and due to the fact that they do not need an accurate mathematical model of the controlled process [16]

PID controllers applied in a fault free quadcopter system provides satisfactory attitude and altitude control. However, there is no certain way for choosing the control parameters which guarantees the good performance. Moreover, their performance may also be affected by structural changes and uncertainties in the system parameters such as an unpredicted rotor failure. Therefore, there is need to fine-tune the PID gains in real time to overcome these shortcomings. Fuzzy logic is proposed in this work to tune the PID gains (baseline controller) online where the tracking error and the change of the tracking error are used to determine control parameters.

The fuzzy logic control method is chosen for the following reasons: 1) it can deal with nonlinear systems with uncertainties; 2) controller design and implementation is easy and simple [17] and 3) actuator faults result in a wide range of working environments, an effective fault tolerant control strategy is therefore demanded for adapting the faulty model online. The fuzzy controller is capable of adjusting the parameters of the baseline controller in order to achieve the desired performance even in the presence of actuator faults.

PID control

First, the baseline PID controller was designed in MATLAB using trial and error method. The PID values used are as shown in Table-1

Table -1 Initial PID values selected for simulation

	Roll	Pitch	Altitude
K_p	10	10	1.5
K_i	0.05	0.05	1
K_d	0	0	1.8

The PID control diagram for altitude, Roll and Pitch is as shown in Fig. 2**.**

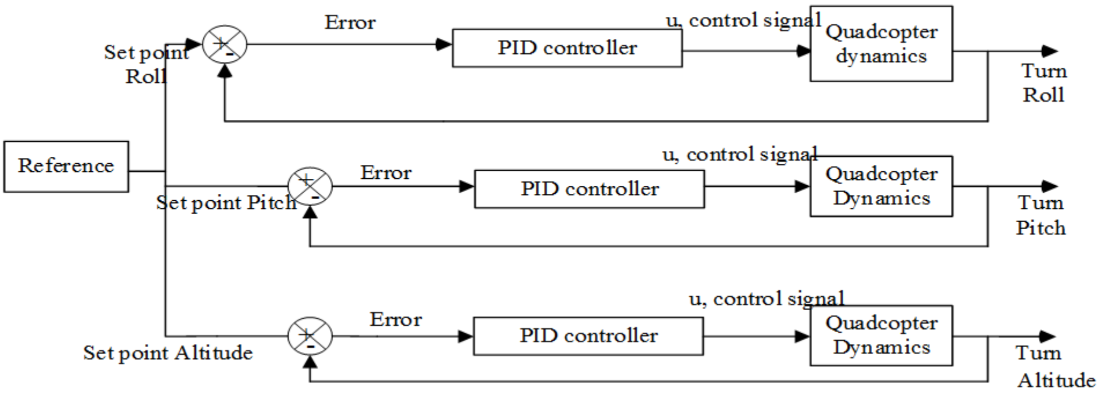

Fig. 2 PID control block diagram

Fuzzy PID control

Triangular membership function and Mamdani inferencing system with centroid defuzzification method was used for the FLC as in Fig. 3.

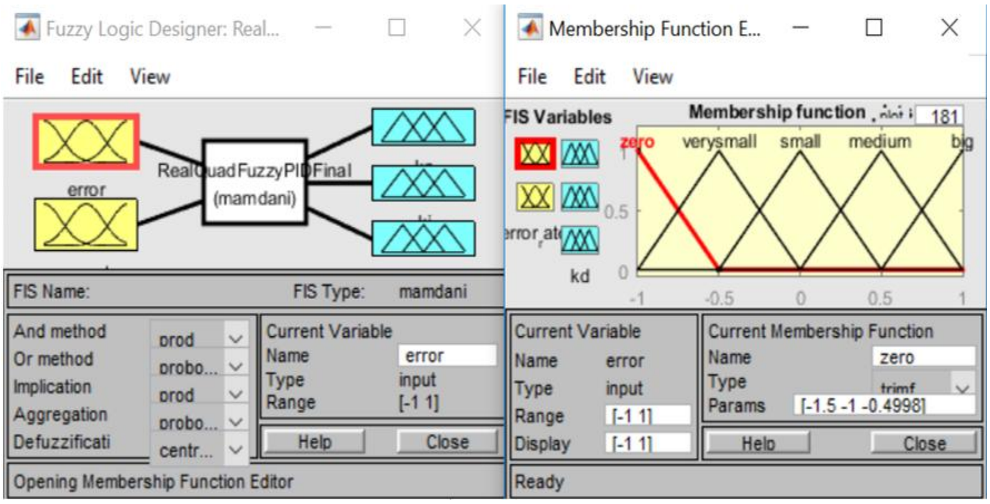

Fig. 3 Fuzzy inference system used

Table- 2 Matrix table used for generating fuzzy rules

e(t)/de(t)	**Z**	**VS**	**S**	**M**	**B**
Z	**VS B M**	**VS B M**	**Z B M**	**Z B B**	**Z B B**
VS	**VS B S**	**VS B M**	**VS B M**	**Z M M**	**Z M B**
S	**S M VS**	**S M VS**	**S M VS**	**VS S S**	**VS S S**
M	**M Z Z**	**M Z Z**	**M VS VS**	**S VS VS**	**S VS VS**
B	**B Z Z**	**B Z Z**	**B Z Z**	**B Z Z**	**M Z Z**

From the fuzzy matrix table, IF THEN rules were constructed with “VS” implying very small, “S” as small, “Z” zero, “M” medium and “B” as big.

The additional regulating gains are generated according to the FLC controller in Fig. 4

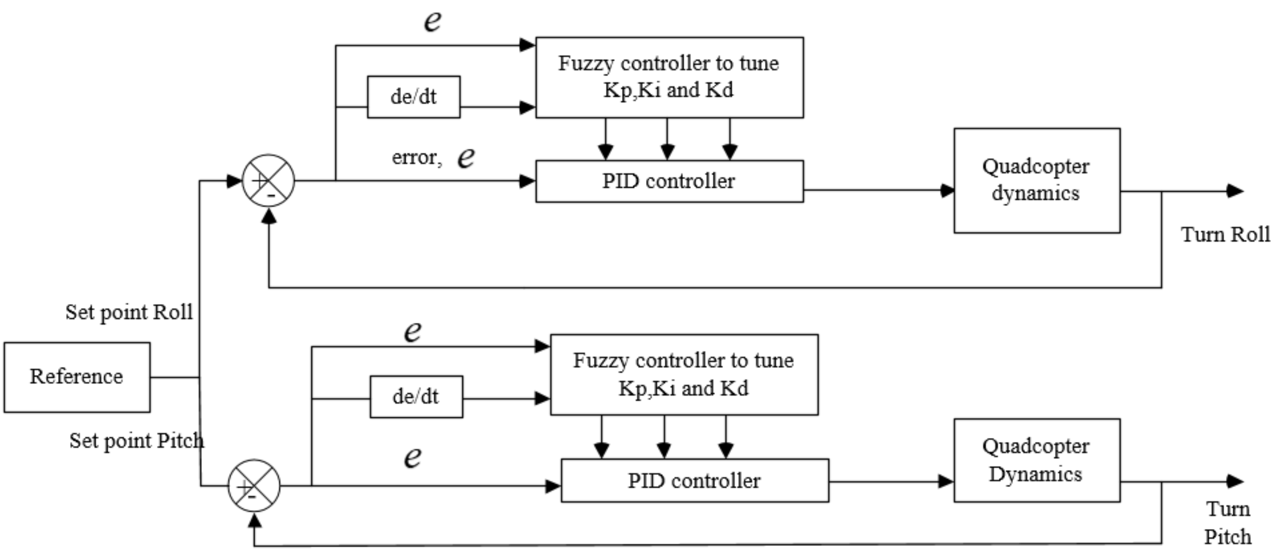

Fig. 4 FuzzyPID control

RESULTS AND DISCUSSION

A fault (complete rotor loss), was introduced at 12.0 seconds (randomly chosen) during simulation and the performance of the PID and Fuzzy PID controller for roll and pitch compared.

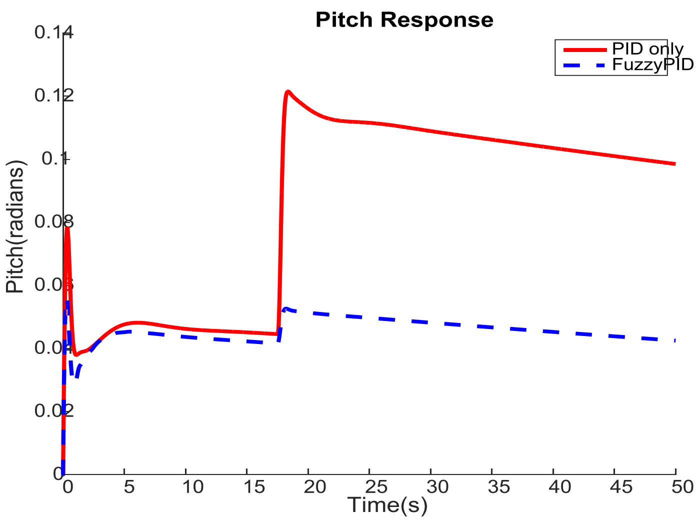

Fig. 5 Pitch response for PID and FuzzyPID control

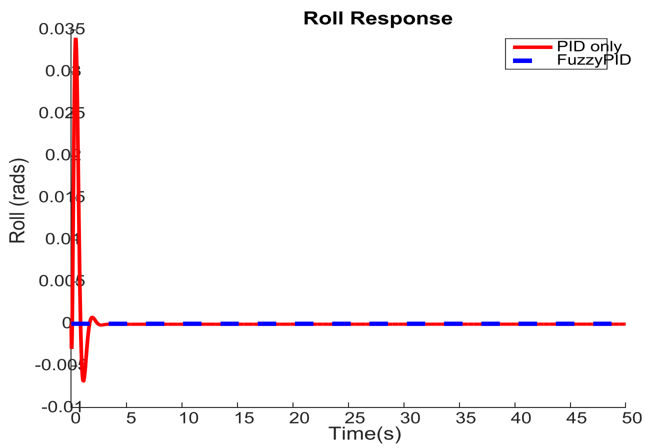

Fig. 6 Roll response for PID and FuzzyPID control

Similarly, the performance of the PID and Fuzzy PID controller was investigated for a complete rotor loss at 12.0 secs for the altitude, *z*.

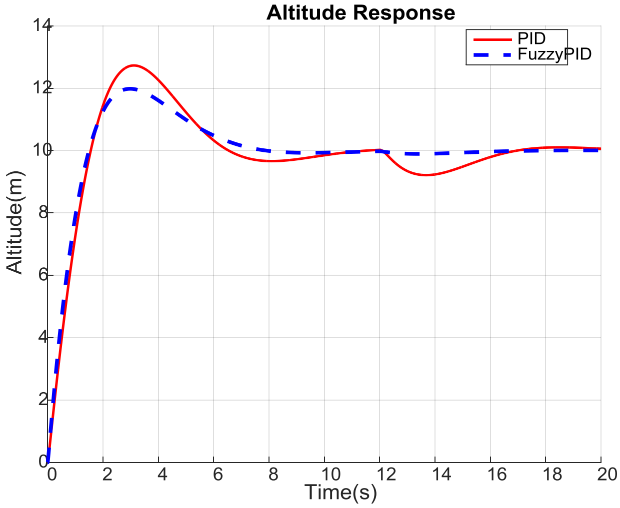

Fig. 7 Altitude response for PID and FuzzyPID control

It can be observed from Fig. 7 that the fault at 12.0 seconds is barely noticeable for altitude response under FuzzyPID controller whereas for the conventional PID the fault recovery time after the fault is 6.0 seconds. The overshoot is 20% for FuzzyPID while it is 30% for the conventional PID.

CONCLUSION

FuzzyPID controller was able to stabilize the quadcopter by reacting faster than the conventional PID controller during fault. The designed FLC was able to regulate the PID gains to withstand the unpredictable structural disturbance. Future work will involve the optimization of the FLC parameters in real time using Extended Kalman Filter for the regulation of PID gains online.

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