

Fuzzy Based Stabilizer Control System for Quad-Rotor

B. G. Sampath, K. C. R. Perera, W. A. S. I. Wijesuriya, V. P. C. Dassanayake

Abstract—In this paper the design, development and testing of a stabilizer control system for a Quad-rotor is presented which is focused on the maneuverability. The mechanical design is performed along with the design of the controlling algorithm which is devised using fuzzy logic controller. The inputs for the system are the angular positions and angular rates of the Quad-rotor relative to three axes. Then the output data is filtered from an accelerometer and a gyroscope through a Kalman filter. In the development of the stability controlling system Mandani fuzzy model is incorporated. The results prove that the fuzzy based stabilizer control system is superior in high dynamic disturbances compared to the traditional systems which use PID integrated stabilizer control systems.

Keywords—Fuzzy stabilizer, maneuverability, PID, Quad-rotor.

I. INTRODUCTION

STABILIZER control systems are predominantly used for the controlling of the maneuverability of aerial vehicles [1]-[4]. These types of stabilizer control systems are mainly used in the UAVs (Unmanned Aerial Vehicles), mainly because of the fact that UAVs have very sophisticated mechanical systems. It should have complex control system with nonlinear modeling techniques integrated with modern nonlinear theories [21], [25]. Generally UAVs with Vertical Takeoff and Landing (VTOL) possess advanced the control systems [5], where the rotors try to reach a definitive flight and hovering with the use of forces generated by four rotors [6]. These kinds of rotors are highly maneuverable facilitating takeoff, landing and hovering in complex environments [7].

Most of existing stabilizer control systems developed for quad rotors cannot handle quick, accurate and smooth functionality of landing and take-off operations, since the smooth maneuverability is not considered at the design stage. Our research investigates essentials of the stabilizer control system of the quad rotor, its autonomy and its ability to stabilize itself and its navigation on a desired trajectory. In the traditional control system PID technique is used for the stabilizer control system, where the Proportional controller (P), integrative controller (I) and derivative controller (D) is tuned to gain the desired output controlling signal [1],[2],[7].

In this study a Mandani [15]-[22] fuzzy logic based stabilizer control system is designed and developed. It is tested using a developed quad rotor test bed.

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II. DYNAMICS & KINEMATICS OF QUAD-ROTOR

For the design of the stabilizer control system, the dynamics and the kinematics of the quad-rotor should be considered. The following provides a mathematical analysis on the kinematics of the quad-rotor, which supports the development of fuzzy algorithm for the stabilizer control system.

A. Dynamics of Quad-Rotor

A quad rotor consists of four motors with four propellers. When considering the forces acting on the quad rotor, it has its own weight and the prime movers should be able to generate forces more than the weight to raise the quad rotor.

The basic controlling methodology of the quad rotor is a nonlinear – multivariable system [8],[9]. This system has 6-degree of freedom (6-DOF). All the forces required to maneuver the quad rotor are generated through its propellers. The blade angle and the motor speed are important factors for generating the required force. So it is much needed to consider the aerodynamic forces for maneuverability of the quad rotor, because the blade angles directly affect the aerodynamic forces [10].

The propellers generate a lift force that can be used to control pitch and roll angles. The total torque generated by the propeller motors causes the motion of yawing to the body. Therefore, for the prevention of such adversity, two propellers in the system are counter rotating such that the total torque of the system gets balanced.

B. Kinematics of Quad-Rotor

The system which controls the movements of the quad rotor should have the ability to control it in all the 6 directions which are x, y, z directions and rotational movements along those three axes. Movements along x, y and z are called forward-backward, left-right and lifting-landing respectively, while the rotational movements around x, y, z axes are called rolling, pitching and yawing respectively. The motor directions and the thrusts generate from the propeller is illustrated in Fig. 1.

The effective input of the system is the summation of the thrusts from all four motors. The gyration along the x-axis is represented from the pitch angle (ϕ). This angle can be attained by changing the speed of motors 1 or 3 (M1 or M3). And the translation along the y-axis is represented by the roll angle (θ) and by varying the speeds of motor 2 or 4 (M2 or M4), the roll angle can be controlled. For the controlling of the yaw angle (ψ), the speed of rotors 1 and 3 (M1 and M3) should not be same as rotors 2 and 4 (M2 and M4). The direction of rotor 1 and 3 have to be opposite of the rotors 2 and 4 to balance the inertia.

Since this is a flying object, it should have two separate coordinate systems which are defined as Body frame

coordinate system and Earth frame coordinate system. It is required to convert the earth frame coordinates to body frame coordinate system to control and position the quad-rotors in an exact manner.

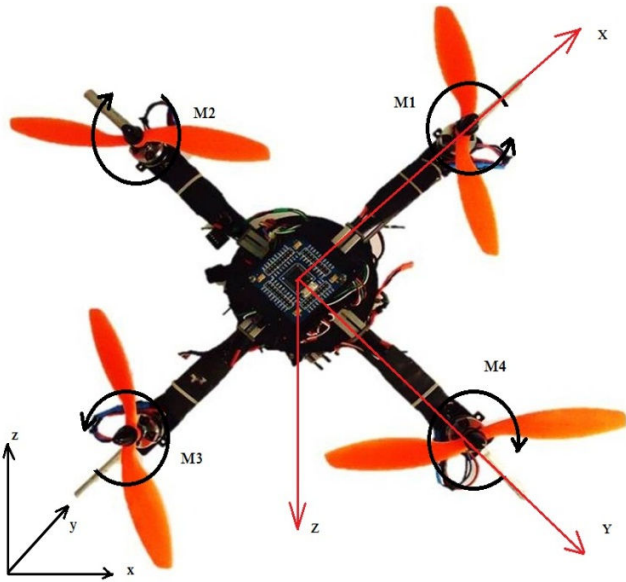


Fig. 1 Quad-rotor Model and Reference Frames

So the mathematical formula to convert those values can be defined as follows [2]. The coordinates systems of quad-rotor, which is inertial and body frame are shown in Fig.1. In here the inertial reference frame is located at the ground, while the body frame located at the center of mass. The quad-rotor has twelve governing state-variable forms in which they are divided into four groups, such as governing equations for the position of the vehicle, governing equations for the velocity of the center of gravity of the vehicle, governing equations of motion of the angular velocity of the vehicle and governing equations of angles of the vehicle with respect to the body frame. It should be noted that all the following derivations will be performed relative to the body frame coordinate system. In order to find the four groups, the linear position of the center of mass of the quad-rotor is determined by the coordinates of the vector between the origin of the body frame and the origin of the earth frame with respect to the inertial frame according to the relations of $P = [x \ y \ z]^T$ and the vehicle's attitude described by $A = [\theta \ \varphi \ \psi]^T$, where θ , φ and ψ denote the vehicle's roll, pitch, and yaw, respectively. The linear velocity of the quad-rotor can be denoted with the following vector, $V = [V_x \ V_y \ V_z]^T$ and to calculate the components of the linear velocity in inertial frame, (1) should be used.

$$\begin{bmatrix} \dot{x}' \\ \dot{y}' \\ \dot{z}' \end{bmatrix} = R_r \begin{bmatrix} u \\ v \\ w \end{bmatrix} \quad (1)$$

In (1), the variables u , v and w represents the absolute velocity components in the body frame and R_r is given as the airframe orientation in the space and can be given by $R_r = R$

$(\psi) \times R(\theta) \times R(\varphi)$, where $R(\varphi)$, $R(\theta)$ and $R(\psi)$ denote the rotation about X axis, Y axis, and Z axis respectively.

$$R(\psi) = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos(\psi) & \sin(\psi) \\ 0 & -\sin(\psi) & \cos(\psi) \end{bmatrix} \quad (2)$$

$$R(\theta) = \begin{bmatrix} \cos(\theta) & 0 & -\sin(\theta) \\ 0 & 1 & 0 \\ \sin(\theta) & 0 & \cos(\theta) \end{bmatrix} \quad (3)$$

$$R(\varphi) = \begin{bmatrix} \cos(\varphi) & \sin(\varphi) & 0 \\ -\sin(\varphi) & \cos(\varphi) & 0 \\ 0 & 0 & 1 \end{bmatrix} \quad (4)$$

$$R_r = \begin{bmatrix} c\theta c\varphi & s\theta c\varphi s\psi - s\varphi c\psi & c\varphi s\theta c\psi + s\varphi s\psi \\ s\varphi c\theta & c\varphi s\theta s\psi + c\varphi c\psi & s\varphi s\theta c\psi - c\varphi s\psi \\ -s\theta & c\theta s\psi & c\theta c\psi \end{bmatrix} \quad (5)$$

where $r = \cos$, $s = \sin$

The dynamic model of the quad rotor can be obtained through the Lagrangian approach and it can be provided as follows with (6)-(9);

$$u_1 = \frac{F_1 + F_2 + F_3 + F_4}{m} \quad (6)$$

$$u_2 = \frac{\bar{F}_1 + F_2 + F_3 \pm F_4}{J_1} \quad (7)$$

$$u_3 = \frac{F_1 \pm F_2 + F_3 \mp F_4}{J_2} \quad (8)$$

$$u_4 = \frac{C(F_1 - F_2 + F_3 - F_4)}{J_3} \quad (9)$$

In above equations $F_i(0.03875 \text{ g/rpm})$, where $i = 1,2,3,4$ are the forces up-thrust generated by each propeller [2]-[5]. The variable u_1 represents the total upward thrust which is going to move the quad rotor vertically upwards. The variable J_i , where $i = 1,2,3$ is the moment of inertia relative to each axes and C is the force to moment scaling factor. Ultimately u_1 represents the total thrust on z direction while u_2 , u_3 , u_4 are pitch, roll and yaw moments respectively. Therefore with the defined four inputs, set of equations for the acceleration can be derived as in (10):

$$\begin{aligned} \ddot{x} &= u_1(\cos\varphi \sin\theta \cos\psi + \sin\varphi \sin\psi) & \ddot{\theta} &= u_2 l \\ \ddot{y} &= u_1(\sin\varphi \sin\theta \cos\psi - \cos\varphi \sin\psi) & \ddot{\psi} &= u_3 l \\ \ddot{z} &= u_1(\cos\theta \cos\psi) & \ddot{\varphi} &= u_4 \end{aligned} \quad (10)$$

III. QUAD-ROTOR TEST BED

When considering the hardware parameters, it is very important to configure the physical parameters of the quad rotor. The main structure of the quad rotor consists of a cross bar frame including four motors at each end. The brushless DC (BLDC) motors with 22,000 maximum rpm, which is controlled with Electronic Speed Control (ESC) motor controllers, were used for the tested system. The quad rotor

weighs 625g of weight and it is able to provide a weight-to-thrust ratio of 1:4. It has four 9-inch long propellers where the distance between outer tips of the opposite propellers is 55cm. Then a Lithium ion polymer battery of 2000 mAh with a weight of 150g is used as the main power source for the quad rotor flying unit. Quad rotor mechanical system has been optimized to make burst landing and take-off as well as trajectory navigation according to mentioned parameters above.

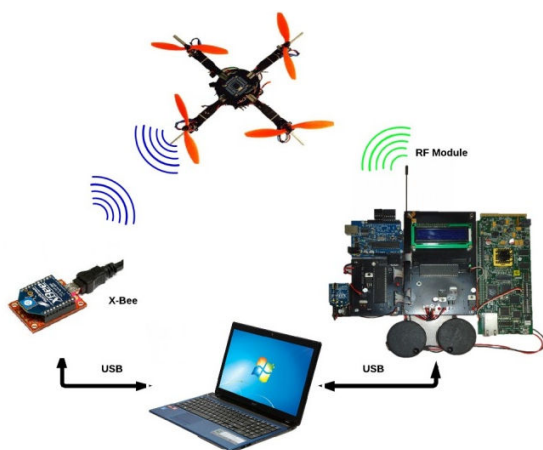


Fig. 2 Communication System

The system has main two hardware units called, Quad-rotor flying unit and Quad-rotor pilot station which are depicted in Figs. 2 and 3, respectively. These units are two separate hardware systems and communicate with each other using a RF module.

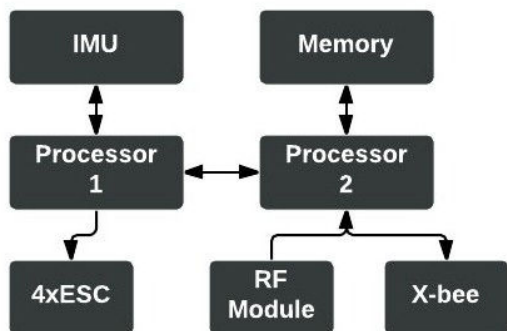


Fig. 3 Quad-rotor Flying Controller

The Quad-rotor flying unit consists of two processors, four motor controllers (ESC), Inertia Measurement Unit (IMU), memory card and a communication unit. IMU module has 4 independent sensors of gyroscope, accelerometer, a compass and a barometric pressure sensor.

The pilot station at the ground includes two microprocessors, one communication link module, three joystick controls, one LCD display and a Graphical user Interface (GUI) for the PC. Processor 1 in pilot station is programmed to communicate with the quad rotor via RF

signal, while the user can control the hovering of the rotor to desired position using the joystick.

Processor 2 in pilot station communicates with processor 1 and receives the feedback from quad rotor flying unit. After receiving feedback and data such as altitude, velocity, acceleration, processor 2 directly forward it to the software which installed in the PC.

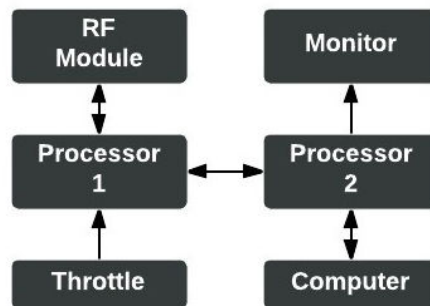


Fig. 4 Quad-rotor Test Bed Ground Station

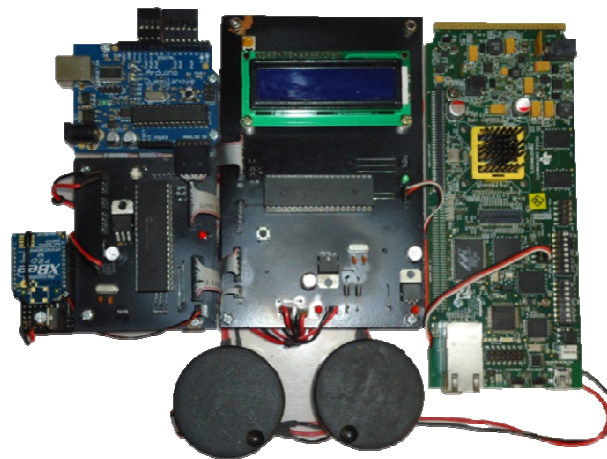


Fig. 5 Quad-rotor Test Bed Ground Station Circuit

Since the model of the quad-rotor is nonlinear, a fuzzy logic controller was designed and implemented by trial and error method. The IMU module inputs signals and data, such as angular velocity, acceleration, altitude to the processor of flying unit and the conditioning of the signal is fulfilled by filtering out the noise. Upon receiving these data, processor analyzes those data and determines the rotational speeds of the individual motors separately.

While keeping the stabilization of the quad-rotor using above method, the system performs data communication with pilot station via Radio Frequency (RF) module. The trajectory analyzer guides the quad-rotor to navigate on a given path.

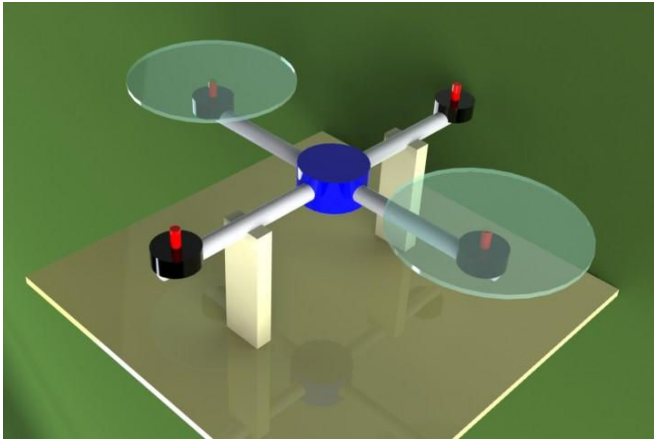


Fig. 6 Quad-rotor Test Bed

IV. DEVELOPMENT OF THE ALGORITHM

A. Filtering Out Sensor Data

The accelerometer of the IMU produces a lot of noise due to vibrations. Gyroscope output is also subjected to drift and bias. As shown in Fig. 4, to filter out those noises low pass filters are used. Those two outputs from low pass filters are then sent to the complementary filter. The output of complementary filter and low pass filter of accelerometer are then sent to 'Kalman' filter. Filtered angle data is taken from the output of 'Kalman' filter.

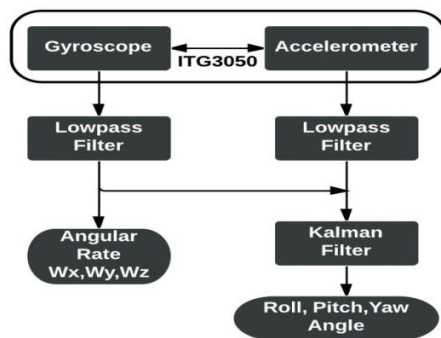


Fig. 7 Flow Chart for filtering out noises of gyroscope and accelerometer

The components of angular velocity of the robot in the body frame are ω_x, ω_y and ω_z . These values are related to the derivatives of the roll, pitch, and yaw angles according to (11) [2].

$$\begin{bmatrix} \omega_x \\ \omega_y \\ \omega_z \end{bmatrix} = \begin{bmatrix} \cos\theta & 0 & -\cos\phi\sin\theta \\ 0 & 1 & \sin\phi \\ \sin\theta & 0 & \cos\phi\cos\theta \end{bmatrix} \begin{bmatrix} \dot{\phi} \\ \dot{\theta} \\ \dot{\psi} \end{bmatrix} \quad (11)$$

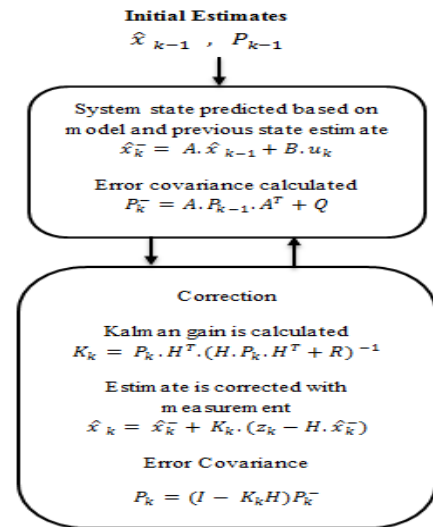


Fig. 8 Flow Chart for Kalman Filter

The defined x, \dot{x} are true states at time t and time derivative for continuous time. The value of the true state is unknown and the filter estimates it in line with x_k the true state at time t which is the discrete time (unknown). The variable u_k is the state transition matrix which describes the changes in state due to system dynamics only. The effects of noise disturbances are not included in u_k . The change of state occurs across the discrete-time interval from t_k to t_{k+1} . The variable z_k is the measurement at time t_k , while H_k is the measurement matrix which relates the state to measurement when the value is 1. In this case no noise effects are included. The variable P_k is the covariance matrix of the error in the state estimate and the value is updated on-line with $P_k = E[e_k e_k^T]$, where x, \dot{x} are true states at time t and time derivative for continuous-time. The value of the true state is unknown and the filter estimates it on-line with x_k which is true state at time t , discrete-time (unknown). Then u_k is the state transition matrix describing changes in state due to system dynamics only. The effects of noise disturbances are not included in u_k . The change of state occurs across the discrete-time interval from t_k to t_{k+1} . z_k and the measurement at time t_k . Where e_k is the error in state estimate $e_k = x_k - \hat{x}_k$ at time t_k . The variable R_k is the covariance matrix of measurement noise and E represent expected value of noise. Q is the covariance matrix of process noise and the value is zero.

B. Fuzzy Algorithm

The balance of the system is kept using a fuzzy stabilizer. The design of the Mamdani fuzzy model [15]-[22] and the 121 fuzzy rules were defined, according to the experimental data. Fig. 9 shows the fuzzy membership of the angle error which is defined for each x, y , and z axes. The fuzzy subset [11]-[15], [17], [19]-[22] was determined using experimental data and Matlab simulations. The defining of fuzzy rules and the generation of input-output membership functions were done, identifying each and every limit of control variables (upper bound, high dynamic working range around mid-point and

lower bound) [21]-[27]. The shape (gradient) of the membership function can be adjusted manually when it is running on the test bed and following shapes are obtained according to the real time data when controller delivers maximum acceptable performance.

$$\text{Angle error} = \text{Desired angle} - \text{Measured angle}$$

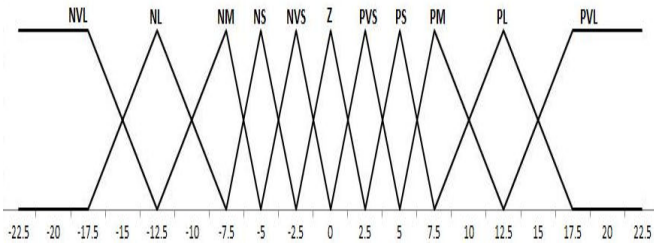


Fig. 9 Fuzzy membership of angle error

Fig. 10 shows the fuzzy membership of rate of angle error, which is also defined for each x, y, and z axes and the fuzzy subset is determined using the experimental data.

$$\frac{d(\text{Angle error})}{dt} = \text{Angular rate}$$

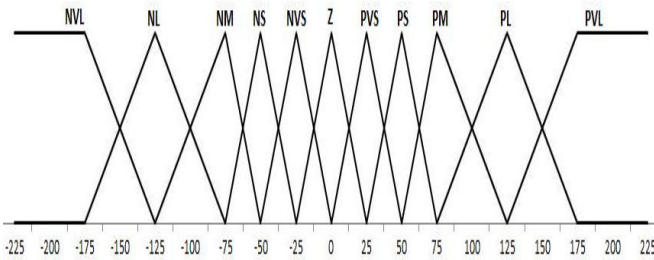


Fig. 10 Fuzzy Membership of Rate Change of Angle Error

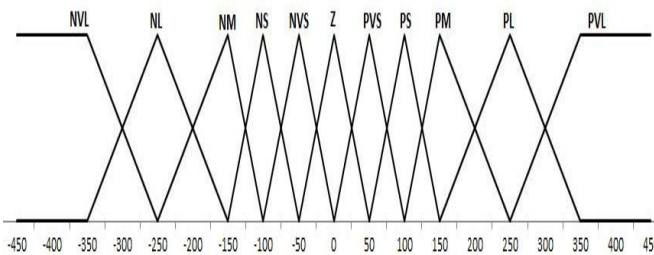


Fig. 11 Fuzzy Membership of Output

The terms defined in the fuzzy rules can be elaborate as NVL-Negative very large, NL- Negative large, NM- negative medium, NS- Negative small, NVS- Negative very small, Z-zero, PVS-Positive very small, PS- Positive small, PM-Positive medium, PL-Positive large, PVL-positive very large.

Table I shows the optimized fuzzy rules matrix. Here the figures are determined by trial and error method focusing on the reduction of the steady state error and the overshoot.

TABLE I
 OPTIMIZED FUZZY RULES

θ_0	NVL	NL	NM	NS	NVS	Z	PVS	PS	PM	PL	PVL
NVL	NVL	NVL	NL	NM	NVS	NVS	PVS	PS	PM	PL	PL
NL	NVL	NVL	NL	NM	NVS	NVS	PVS	PS	PM	PL	PL
NM	NVL	NVL	NL	NM	NVS	NVS	PVS	PS	PM	PL	PL
NS	NVL	NVL	NL	NS	NVS	NVS	PVS	PS	PM	PL	PL
NVS	NVL	NVL	NL	NS	NVS	Z	PVS	PS	PM	PL	PL
Z	NVL	NL	NM	NS	Z	Z	Z	PS	PM	PL	PVL
PVS	NL	NL	NM	NS	NVS	Z	PVS	PM	PL	PVL	PVL
PS	NL	NL	NM	NS	NVS	PVS	PS	PM	PL	PVL	PVL
M	NL	NL	NM	NS	NVS	PVS	PS	PM	PL	PVL	PVL
PL	NL	NL	NM	NS	NVS	PVS	PS	PM	PL	PVL	PVL
PVL	NL	NL	NM	NS	NVS	PVS	PS	PM	PL	PVL	PVL

Here the motor speed is determined by de-fuzzification using weighted average method using (12):

$$\Delta\omega = \frac{\sum_{i=0}^3 \omega_i x_i y_i}{\sum x_i y_i} \quad (12)$$

In (12), the variable $\Delta\omega$ is the predicted amount of variation of speed, ω_i is the rotor speed defined by fuzzy rules, x_i is the output of the membership of angle error (Fig. 9) and y_i is the output of the membership of rate change of angle error (Fig. 10).

$$\begin{bmatrix} \omega_{1_des} \\ \omega_{2_des} \\ \omega_{3_des} \\ \omega_{4_des} \end{bmatrix} = \begin{bmatrix} 1 & 0 & -1 & 1 \\ 1 & 1 & 0 & -1 \\ 1 & 0 & 1 & 1 \\ 1 & -1 & 0 & -1 \end{bmatrix} \begin{bmatrix} \omega_h + \Delta\omega_F \\ \Delta\omega_\phi \\ \Delta\omega_\theta \\ \Delta\omega_\psi \end{bmatrix} \quad (13)$$

In (13), the variable ω_h is the rotor speed needed to hover in steady state and the $\Delta\omega_F$, $\Delta\omega_\phi$, and $\Delta\omega_\theta$ are the deviations from this nominal vector $\Delta\omega_\psi$. The variable $\Delta\omega_F$ results in a net force along the z_B axis and $\Delta\omega_\phi$, $\Delta\omega_\theta$, and $\Delta\omega_\psi$ are the moments producing roll, pitch, and yaw, respectively. The current orientation of the Quad-rotor is sent to ground control center through wireless communication and the Quad-rotor estimates its current position through its sensing system incorporating Kalman filters. The coordinates as well as IMU data is shown in the PC user interface which is connected to ground pilot station.

V. RESULTS AND DISCUSSION

The test bed results indicate that the proposed control system has high dynamic response, which is less than traditional PID controller in stabilizing. Figs. 12-15 illustrate the results of the fuzzy based stabilizer control system within less overshoot limits than PID controller, which is clearly shown by real time results of the test bed.

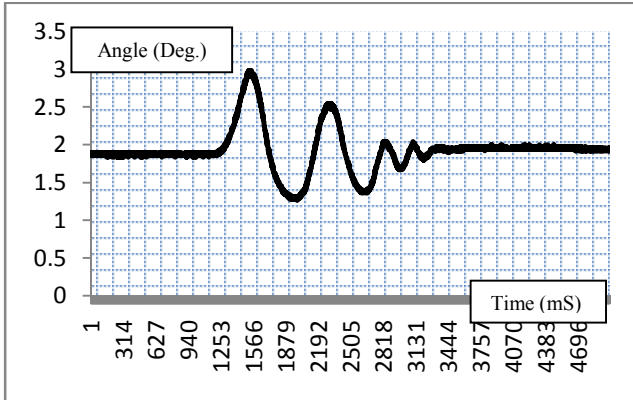


Fig. 12 Tuning Process Using PID Controller

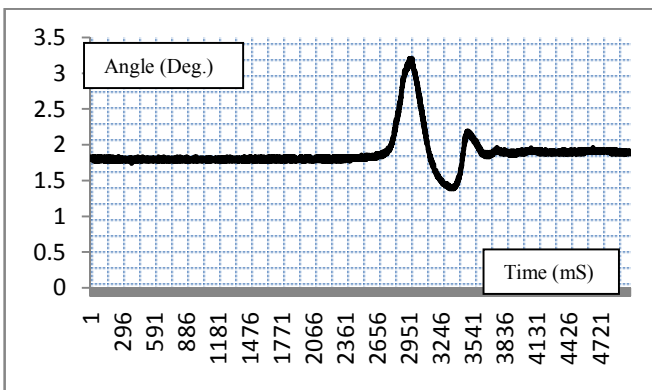


Fig. 13 Tuning Process Using Fuzzy Controller

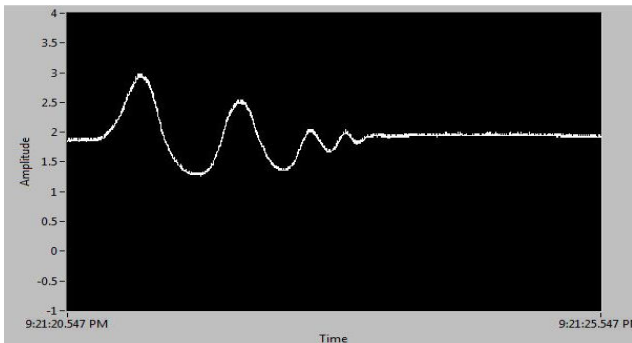


Fig. 14 Output control signal from PID based stabilizer control system

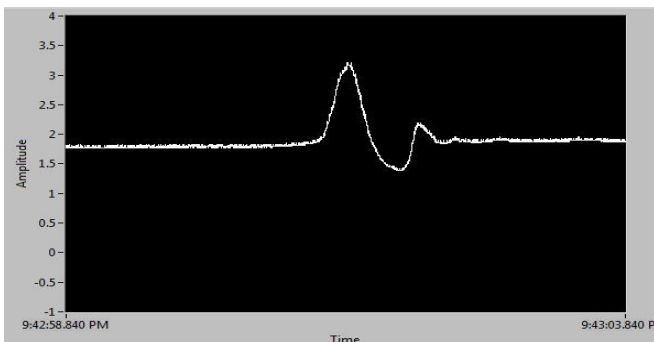


Fig. 15 Output control signal from fuzzy based stabilizer control system

VI. CONCLUSION

The objective of the study is to define a stabilizer model for a physical quad-rotor constructed by the authors. Since the physical device is such constructed the authors are very much in control of its design specifications while defining the controller parameters, all results are obtained via operating the quad-rotor in real time, on a test bed in order to obtain results relative to each axis.

Military rescue missions, Fire and rescue operations and other rescue operations related to natural or man-made disasters are the key applications which are considered with the development of the stabilizer control system, which is solely used for quad-rotor UAVs. Thus the fuzzy based stabilizer control system provides high precision in high dynamic conditions.

In the future, it is proposed to further modify the quad-rotor to be operated in indoor compounds by using a motion capture camera system such that the device can identify obstacles on its path.

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