

ORIGINAL ARTICLES

Disturbance And Noise Rejection Controller Design For Smooth Takeoff / Landing And Altitude Stabilization Of Quad-rotor

M. Hassan Tanveer, S. Faiz Ahmed, D. Hazry, M. Kamran Joyo, Faizan. A. Warsi

Centre of Excellence For Unmanned Aerial Vehicle (COEUAS), Universiti Malaysia Perlis (UniMAP), Perlis, Malaysia.

ABSTRACT

This paper presents a control approach for smooth takeoff / landing i.e altitude controlling of quad-rotor. There are number of failure in UAV projects are recorded because of poor stability and control. In Quad-rotor type Unmanned Aerial Vehicles, smooth takeoff and landing is one of the most critical task and appropriate altitude stabilization controller is essential and necessary part of these type of unmanned systems. Altitude Controlling (i.e. height) under various disturbances conditions (e.g. wind disturbances) has been a challenging research domain for the researchers. This paper presents a simulation based model which takes into account the variation of the aero-dynamical coefficient due to vehicle motion. This paper describes the PID controller feedback structure scheme proposed for altitude control. Besides that Extended Kalman Filter (EKF) is also proposed to filter out the sensor and system noises. Finally, simulations done on MATLAB and results shows the effectiveness of the proposed method and suggest it as a promising way for real time implementation in altitude stabilization performance for quad-rotor.

Key words: Quad-rotor, Takeoff / Landing and Altitude Control, PID, Extended Kalman Filter.

Introduction

One of the prominent rotorcrafts, a quad-rotor has been the area of interest among the researchers in recent years. The quad-rotor helicopter is an unmanned aerial vehicle (UAV) with four propellers attached to four motors placed on a fixed body. A quad-rotor UAV has exceptional advantages like small size and light weight, simple mechanical arrangement.

UAVs are being used in several applications including search and rescue missions (Ryan. A. Hedrick, 2005), wild fire surveillance (Alexis.K, 2009), monitoring over nuclear reactors (Sarris.Z, 2001), power plants inspection (Caprari. G, 2012), agricultural services (Herwitz, S.R., 2004), mapping and photographing (Naval Studies Board, 2005), marine operations (Gray.S., 2003), battle damage assessment (Girard, A., Howell, 2004), border interdiction prevention and law enforcement (Murphy.D. Cycon, 1998). Due to their small size they can be useful in hazardous conditions where human life is at risk and surroundings that are inaccessible to reach.

The applications mentioned influences the demands of unmanned systems regarding the area of control design that are capable of operating in tough surroundings and rough and complex missions. In unmanned aviation, copters and rotorcrafts have proven one of the best solutions because of their essential capabilities such as maneuvering and vertical takeoff and landing, which is our primary concern in this paper. However, quad-rotor UAVs possesses substantial scientific and engineering problems in takeoff /landing and maneuver autonomously and efficiently. These types of machines have complex aerodynamic effects that affect their flight performance and requires effective controller implementation. Besides that onboard sensory systems are noisy which make the control more complex. To overcome these problems, the research work contains EKF technique and PID controller are presented for sensor noise suppression and altitude controlling along with disturbance rejection respectively for quad-rotor type UAV systems.

The organization of the paper is structured as the section 2 refers to the related work. Section 3 follows the Kinematics and Dynamics of quad-rotor. Control technique and Extended Kalman filter has been evaluated in section 4. Experimental results and simulations have been provided in section 5.

Related Work:

In the recent years VTOL and altitude control of quad-rotor has remained an issue due to the kinematic constraints and unstable dynamics. However some of the control techniques have been developed in this area. The X4-Flyer and STARMAC II uses LQR and PID control technique (Anil guclu, 2007), In 2006, Ozguner

Corresponding Author: M. Hassan Tanveer, Centre of Excellence For Unmanned Aerial Vehicle (COEUAS), Universiti Malaysia Perlis (UniMAP), Perlis, Malaysia.

used sliding mode and PID control for the system (R. Xu, 2006). In 2007, Samir Bouabdullah and Ronald Siegwart used a Backstepping method for altitude, attitude and position control of a quad-rotor, the results of this technique showed a flexible control structure. Moreover, showed that quad-rotor was able to perform autonomous hovering with altitude control and autonomous take-off and landing (Samir Bouabdullah, 2007). In 2008, Bouadi presented stabilizing control laws by sliding mode and backstepping approach (H. Bouadi, 2008). In 2011, Keun Uk Lee used Dynamic Surface Control (DSC) method for altitude control (Keun Uk Lee, 2011). This paper introduces modeling of a quad-rotor and a PID control technique for VTOL and altitude control. The proposed algorithm is simulated on (MATLAB). In a real time system, measurement devices and sensors provide noisy data. A filter is introduced in the system in order to reject the noise. The proposed filter is a Kalman filter which could result to be a decent filter for this system. Due to the nonlinear nature of quadrotor system, a simple KF cannot be utilized. The extended version of Kalman Filter is EKF that is used to linearize the states of the system.

Kinematics And Dynamics Of Quad-rotor:

1. Quad-rotor Kinematics:

UAV quad-rotor comprises of four motor out of which two moves clockwise and remaining two moves anticlockwise. Different pairs of propellers attach on the tip of each motor. The rotation of these propellers generate vertical upward lifting force that lifts the quad-rotor body in the air and it can moves in pitch, roll, yaw, hover, take-off and landing positions as shown in fig.1. These different movements can be achieved by changing the combination and speed of the quad-rotor motors described in following section.

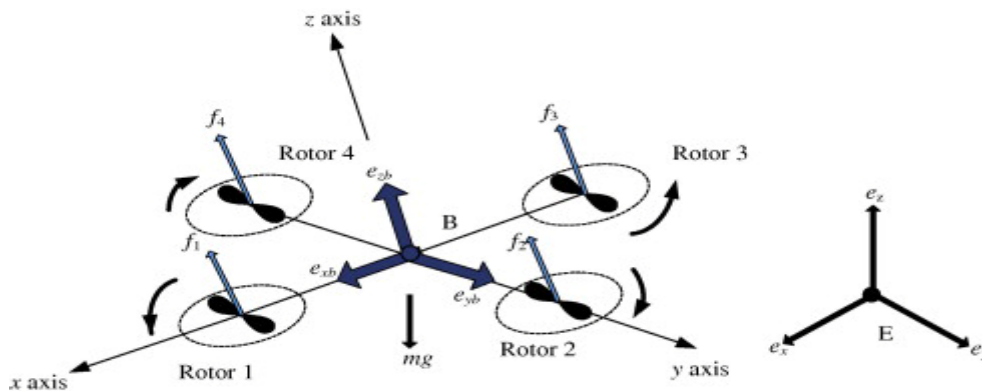


Fig. 1: Quad-rotor UAV with its dimensions

1.1 Hovering, take-off and landing (U1):

To perform hovering, take-off or landing all four propellers rotate with same speed. For take-off the rotation of the propellers must be higher to produce a lifting force greater than the total quad-rotor weight, while for landing, the rotation of the propeller speed gradually decreased to let the quad-rotor getting landed on the ground as shown in fig.2. The hovering can be achieved by producing the lifting force that equal to the total quad-rotor weight. The relation of the movement can be written as:

$$U1 = \pm\omega_1^2 \pm \omega_2^2 \pm \omega_3^2 \pm \omega_4^2$$

Where $\omega_1^2, \omega_2^2, \omega_3^2, \omega_4^2$ are angular velocity or propeller speed produced by motor 1, motor 2, motor 3 and motor 4 respectively.

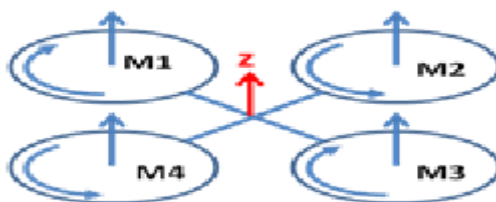


Fig. 2: Hovering, Takeoff and Landing

1.2 Pitch ($U2$):

In pitch movement, the speeds of motor 1 and motor 3 are changed conversely to perform forward and backward movement while other two motors speed must maintain constant to stabilize the quad-rotor as shown in fig.3. To move forward, the speed of motor M3 must be greater than the speed of motor 1 and vice versa for backward move. The relation of the movement can be written as:

$$U2 = \pm\omega_1^2 \mp \omega_3^2$$



Fig. 3: Pitch Movement

1.3 Roll ($U3$):

The method to perform roll movement is same as pitch except that in roll movement the speeds of the motor 2 and 4 are changed for right and left movement as shown in fig.4. The relation of the movement can be written as:

$$U3 = \pm\omega_2^2 \mp \omega_4^2$$

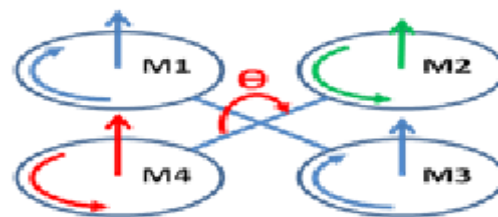


Fig. 4: Roll Movement

1.4 Yaw ($U4$):

To perform the yaw movement, the speeds of the motors in pairs (motor 1 and motor 3) and (motor 2 and motor 4) are changed conversely. To rotate the quad-rotor body to the right, the speeds of motors 2 and 4 must be greater than the speeds of motors 1 and 3 while to rotate it to left, the speed configuration is inverted as shown in fig.5. The relation of the movement can be written as:

$$U4 = \pm\omega_1^2 \pm\omega_3^2 \mp \omega_2^2 \mp \omega_4^2$$

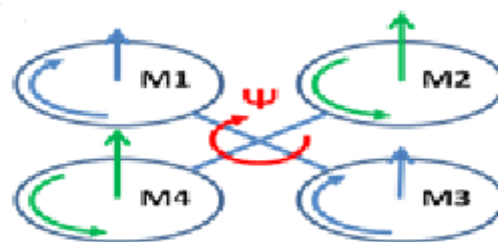


Fig. 5: Yaw Movement

Quad-rotor Dynamics:

2.1 B.L.D.C Dynamics:

As discussed earlier that quad-rotor comprises of four motors which are used to control 6 DOF, so we need to understand its motor dynamics. The motor with propeller dynamics is identified and validated in (N. Guenard

et al, 2006). A first-order transfer function is sufficient to present the dynamics of rotor used in quad-rotor type unmanned systems.

$$G(S) = \frac{0.936}{0.178S+1} \tag{1}$$

For determining dynamics of Quad-rotor, we need to understand Earth Inertial frame (E frame) and quad-rotor fixed-body frame (F frame). The frames are shown in Figure 4.

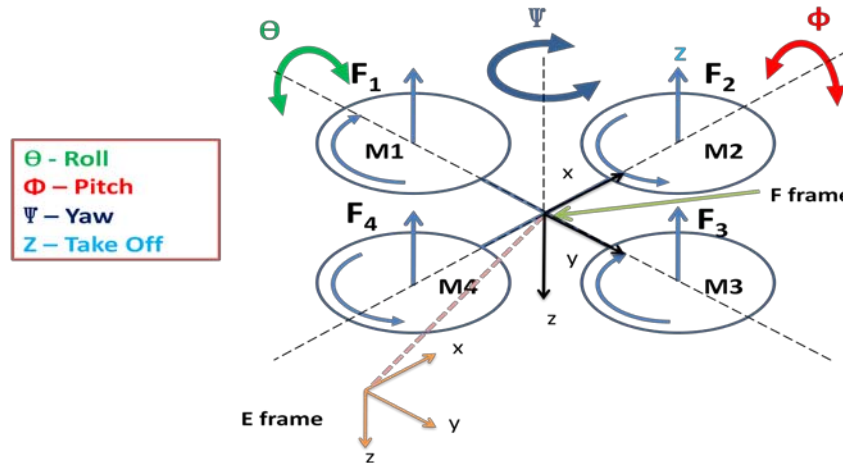


Fig. 6: Quad-rotor Body and Earth Inertial Frame

The Quad-rotor orientation (ϕ, θ, ψ) and position (x, y, z) can be defined by Newton Euler Method.

2.2 Newton Euler Method:

Newton Euler technique can be used to derive the quad-rotor 6 DOF equation. From the fig.(6), two frames earth and body frame have been given. Eq. (2) describes the kinematics of a generic 6 DOF rigid body.

$$\dot{\xi} = J_{\Theta} v \tag{2}$$

- Where
- ' ξ ' is a generalized velocity vector with respect to E-frame.
- ' v ' is a generalized velocity vector with respect to B-frame.
- ' J_{Θ} ' is a generalized matrix

As defined in the Eq. (3), ' ξ ' is composed of a quad-rotor linear ' Γ^E ' and angular ' Θ^E ' position vectors with respect to earth fixed frame.

$$\xi = [\Gamma^E \ \Theta^E]^T = [X \ Y \ Z \ p \ q \ r]^T \tag{3}$$

Likewise, in eq. (4) ' v ' is composed of quad-rotor linear ' V^B ' and angular ' ω^B ' velocity vectors with respect to body fixed frame.

$$v = [V^B \ \omega^B]^T = [u \ v \ w \ \square \ \theta \ \psi]^T \tag{4}$$

The generalised matrix ' J_{Θ} ' is made from 4 sub-matrices according to the eq. (5).

$$J_{\Theta} = \begin{bmatrix} R_{\Theta} & 0_{3 \times 3} \\ 0_{3 \times 3} & T_{\Theta} \end{bmatrix} \tag{5}$$

The notation $0_{3 \times 3}$ means a sub-matrix with dimension 3 times 3 filled with all zeros while the rotation R_{Θ} matrix is defined according to equation (6).

$$R_{\Theta} = \begin{bmatrix} c_{\psi}c_{\theta} & -s_{\psi}c_{\theta} & +c_{\psi}s_{\theta}s_{\phi} & s_{\psi}s_{\theta} & +c_{\psi}s_{\theta}c_{\phi} \\ s_{\psi}c_{\theta} & c_{\psi}c_{\theta} & +s_{\psi}s_{\theta}s_{\phi} & -c_{\psi}s_{\theta} & +s_{\psi}s_{\theta}c_{\phi} \\ -s_{\theta} & c_{\theta} & & & \\ & & c_{\theta}s_{\phi} & & c_{\theta}c_{\phi} \end{bmatrix} \tag{6}$$

Where the notations:

ck = cos k,

sk = sin k,

tk = tan k.

The dynamics of a generic 6 DOF rigid-body takes into account the body mass 'm' and the inertial matrix 'I'. The dynamics is described by equation (7).

$$\begin{bmatrix} mI_{3 \times 3} & 0_{3 \times 3} \\ 0_{3 \times 3} & I \end{bmatrix} \begin{bmatrix} \dot{V}^B \\ \dot{\omega}^B \end{bmatrix} + \begin{bmatrix} \omega^B \times (mV^B) \\ \omega^B \times (I\omega^B) \end{bmatrix} = \begin{bmatrix} F^B \\ \tau^B \end{bmatrix} \quad (7)$$

Where the notation ' $I_{3 \times 3}$ ' is a identity matrix. ' \dot{V}^B ' is the quad-rotor linear acceleration vector with respect to B-frame while ' $\dot{\omega}^B$ ' is the quad-rotor angular acceleration vector with respect to a B-frame. In addition, ' F^B ' is the quad-rotor forces vector with respect to B-frame and ' τ^B ' is the quad-rotor torques vector WRT B-frame.

$$\zeta = [r^E \ \omega^B] = [\dot{X} \ \dot{Y} \ \dot{Z} \ \dot{\phi} \ \dot{\theta} \ \dot{\psi}]^T \quad (8)$$

The quad-rotor dynamic system in equation (10) refers to a new frame. The system is composed of linear equations with respect to E-frame and angular equations with respect to B-frame. Hence the eq. (8) is expressed in the new frame called H-frame. Equation (9) shows the quad-rotor generalized velocity vector with respect to H-Frame.

$$\begin{cases} \ddot{X} = (\sin \psi \sin \phi + \cos \psi \sin \theta \cos \phi) \frac{U_1}{m} \\ \ddot{Y} = (-\cos \psi \sin \phi + \sin \psi \sin \theta \cos \phi) \frac{U_1}{m} \\ \ddot{Z} = -g + (\cos \theta \cos \phi) \frac{U_1}{m} \\ \dot{\phi} = \frac{I_{YY} - I_{ZZ}}{I_{XX}} \theta \psi - \frac{J_{TP}}{I_{XX}} \theta \omega + \frac{U_2}{I_{XX}} \\ \dot{\theta} = \frac{I_{ZZ} - I_{XX}}{I_{YY}} \theta \psi - \frac{J_{TP}}{I_{YY}} \theta \omega + \frac{U_3}{I_{YY}} \\ \dot{\psi} = \frac{I_{XX} - I_{YY}}{I_{ZZ}} \theta \psi - \frac{U_4}{I_{ZZ}} \end{cases} \quad (9)$$

$$\begin{cases} U_1 = b(\omega_1^2 + \omega_2^2 + \omega_3^2 + \omega_4^2) \\ U_2 = lb(-\omega_2^2 + \omega_4^2) \\ U_3 = lb(\omega_1^2 + \omega_3^2) \\ U_4 = d(-\omega_1^2 + \omega_2^2 - \omega_3^2 + \omega_4^2) \end{cases} \quad (10)$$

Where 'l' is the distance between the center of the quad-rotor and the center of a propeller. U1, U2, U3 and U4 are the movement vector components. Their relation with the propellers' speeds comes from aerodynamic calculus [15].

For Altitude and hovering controlling only 4 DOF out of 6 DOF will be taken in account illustrated in Equation (11),

$$\begin{cases} \ddot{Z} = -g + (\cos \theta \cos \phi) \frac{U_1}{m} \\ \dot{\phi} = \frac{I_{YY} - I_{ZZ}}{I_{XX}} \theta \psi - \frac{J_{TP}}{I_{XX}} \theta \Omega + \frac{U_2}{I_{XX}} \\ \dot{\theta} = \frac{I_{ZZ} - I_{XX}}{I_{YY}} \theta \psi - \frac{J_{TP}}{I_{YY}} \theta \Omega + \frac{U_3}{I_{YY}} \\ \dot{\psi} = \frac{I_{XX} - I_{YY}}{I_{ZZ}} \theta \psi - \frac{U_4}{I_{ZZ}} \end{cases} \quad (11)$$

Proposed Controller Design:

In this Paper PID controller technique is proposed for its proper altitude controllability of quad-rotor under the disturbance condition. Besides that EKF is also proposed to filter out the noise caused by sensor and system.

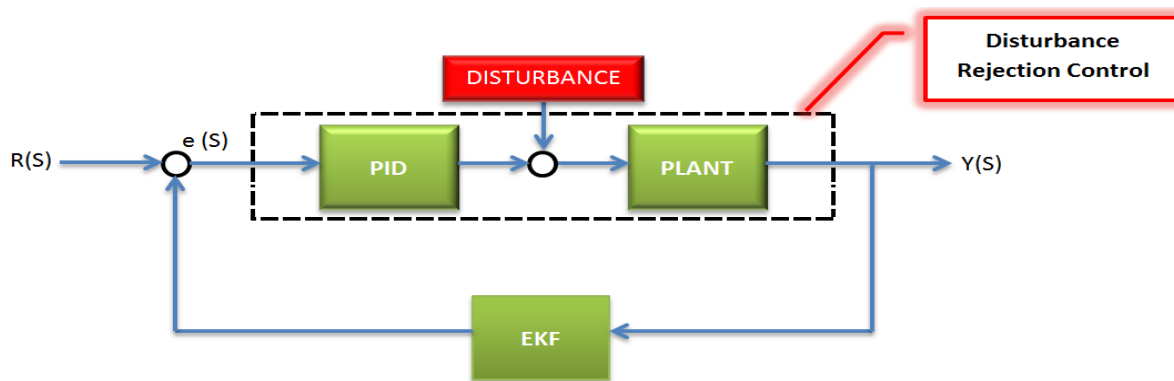


Fig. 7: Proposed Control System

Fig.7 shows the overall block diagram of Proposed Control Algorithm, altitude Stabilization of controlling quad-rotor. For smooth VTOL quad-rotor always follows z-axis, so suitable altitude controller is necessary.

The main objective of this research is to design Controller which makes quad-rotor stable under the circumstances of disturbance. In order to deal with this major issue an appropriate PID Auto tune Controller is proposed for making this system stabilize under the various air disturbance during flying.

The other common problem in quad-rotor is that basically during sensor data is distorted due to noise, to overcome this problem hence Extended Kalman Filter is introduced.

1. Extended Kalman for noise Rejection:

Fig.8 is the subsystem of EKF with MATLAB function defining all parameters of EKF given in equations below. The kalman filter states the general problem of finding the estimates of the discrete time process of a linear system while EKF is used if the dynamics of the system or output of the system is nonlinear. In our case quad-rotor is linear system so we must adapt EKF to filter out the noisy sensor data. EKF lies on the principles of linearization of the current estimation error mean and covariance [16].

Considering a standard state space model of a nonlinear system,

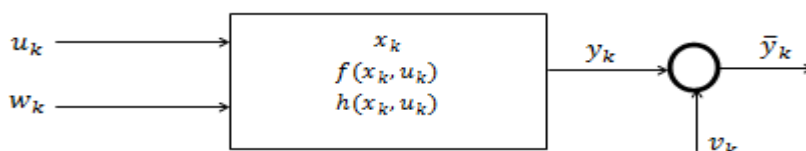


Fig. 7: Nonlinear system, with input and a measurement noise

$$x_{k+1} = f(x_k, u_k) + w_k \tag{12}$$

$$\bar{y}_k = h(x_k) + v_k \tag{13}$$

Where, 'x_k' is a state vector in equation (12), 'y_k' is a measured process output in equation (13), 'w_k' and 'v_k' are the process and measurement noises respectively. f(.) and h(.) Are generic nonlinear functions.

The extended Kalman filter is used to estimate unmeasured states and the actual process outputs. The figure (8) shows the estimated state " and " estimated measured output.

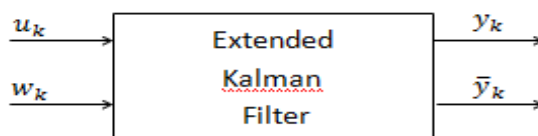


Fig. 8: EKF system

Likewise the standard kalman filter, the EKF also uses two step prediction and correction algorithm. The time update equations of EKF are

$$\hat{x}_{k+1} = f(\hat{x}_k, u_k) \quad (14)$$

$$P_{k+1} = A_k P_k A_k^T + Q \quad (15)$$

Where ' \hat{x}_{k+1} ' is prior state estimate in equation (14). The time update equations project the state and covariance estimate ' P_{k+1} ' from previous time step 'k' to the current time step 'k+1'. The measurement update equations of EKF are

$$K_k = P_k C_k^T (C_k P_k C_k^T + R)^{-1} \quad (16)$$

$$\hat{x}_{k+1} = f(\hat{x}_k, u_k) + K_k [\bar{y}_k - h(\hat{x}_k)] \quad (17)$$

$$P_{k+1} = A_k (1 - K_k C_k) P_k \quad (18)$$

Where 'K' is the correction Kalman gain vector and ' A_k ' and ' C_k ' cannot be used directly. With this type of limitation either Taylor series is applied or Jacobian is used. The Jacobians are defined as

$$A_k = f'(\hat{x}_k, u_k) \quad (19)$$

$$C_k = h'(\hat{x}_k) \quad (20)$$

Where $f(\cdot)$ can be evaluated as in the eq.(21).

$$f'(x) = \begin{bmatrix} \frac{df_1}{dx_1} & \dots & \dots & \dots & \frac{df_1}{dx_n} \\ & & \cdot & & \\ & & \cdot & & \\ & & \cdot & & \\ & & \cdot & & \\ & & \cdot & & \\ & & \cdot & & \\ \frac{df_n}{dx_1} & \dots & \dots & \dots & \frac{df_n}{dx_n} \end{bmatrix} \quad (21)$$

2. PID For Disturbance Rejection:

After getting the noiseless signal from EKF. Feedback signal and Reference Signal produces error signal which go to PID contro block as shown in fig.(7).

PID control over here is tuned by using auto-tune method and its range is between 0 to 1 for all parameters of PID. By Using this Controller for the control-laws synthesis, all the tracking errors are approximately simplified. For achieveing desired task only the main requirement is to work on quad-rotor Z axis and remaining all axis constant with respect to origin. Only requirement is a system that provides the dynamics of Z axis which represents the vertical position of quad-rotor shown in figure 5.

After solving Z from equation (9) it gives constant value, taking all constants as

$$g - (\cos \phi \cos \theta) \frac{U_1}{m} = K_1 \text{ and applying laplace Transform system will become:}$$

$$\ddot{z} = g - (\cos \phi \cos \theta) \frac{U_1}{m}$$

. In above equation g and $\frac{U_1}{m}$ are constant values where with respect of time ϕ and θ change their values and giving a constant value at a particular time so above equation can be rewrite as:

$$\ddot{z} = \frac{K_1}{s^2} \quad (22)$$

So for above plant PID control law can be chosen as:

$$U(S) = K_p e(S) + \frac{K_i}{S} e(S) + K_d S e(S) \quad (23)$$

K_p , K_i and K_d can be selected by Auto tuning method.

Therefore close loop transfer function for the complete system will become:

$$\frac{Y(S)}{R(S)} = \frac{K_d K_1 S^2 + S K_p K_1 + K_i K_1}{S^3 + K_d K_1 S^2 + (S K_p + K_i) K_1} \tag{24}$$

Equation (24) is the controller equation, which gives actual linearize and controlled output.

Simulation Results:

In this section, system simulink model implemented in MATLAB and simulation results are shown in terms of time history demonstrates the validity of control method for the smooth takeoff / landing and altitude control of quad-rotor. PID parameters chosen after auto-tune is illustrated in Table-2. Physical Parameters of quad-rotor are chosen as mention in Table-1. Initial Value of altitude z(0) is set to origin 0.

Table 1: Quad-rotor Calibration Data

Parameter Name	Symbol	Value	Unit
Rotational Inertia Along Z-axis	I	0.0013	kg. m ²
Total Mass	m	0.65	kg
Thrust Constant	b	3.13e ⁻⁵	N. s ²
Drag Constant	d	7.50e ⁻⁷	N. s ²
Arm Length	l	0.23	m

Table 2: PID Auto-tune Parameter

Kp	0.0007482940731823
Ki	0.000007482940731823
Kd	0.000844205739401302

1. Disturbance Rejection:

1.1 Simulink Implementation and Simulation Results:

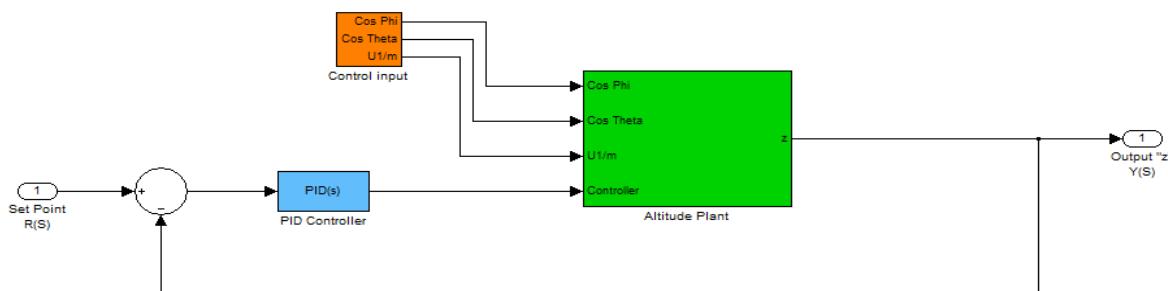


Fig. 9: Simulink model for disturbance Rejection

Figure 9 represents the overall altitude Control system for disturbance rejection. Figures 10 and 11 shows the response of control system tracking the actual path without disturbance and the UAV could track the actual path with almost minimal tracking error. Figure 12 shows the disturbance in system and the PID controlled System output. However, Controller responding time is very quick and stabilizing the system. Figures 13 and 14, shows the complete effect on system when disturbance added as shown in figure 12.

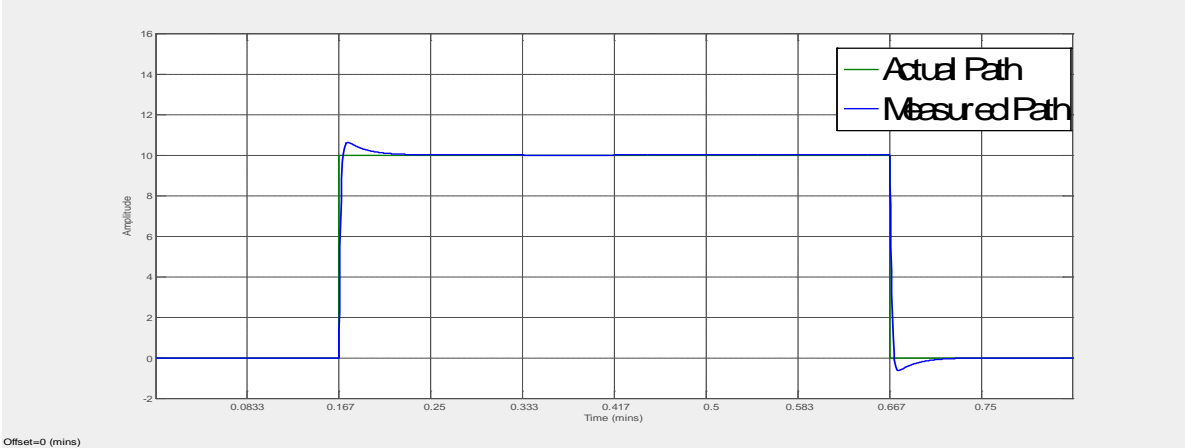


Fig. 10: Path Followed By Using PID Control Algorithm

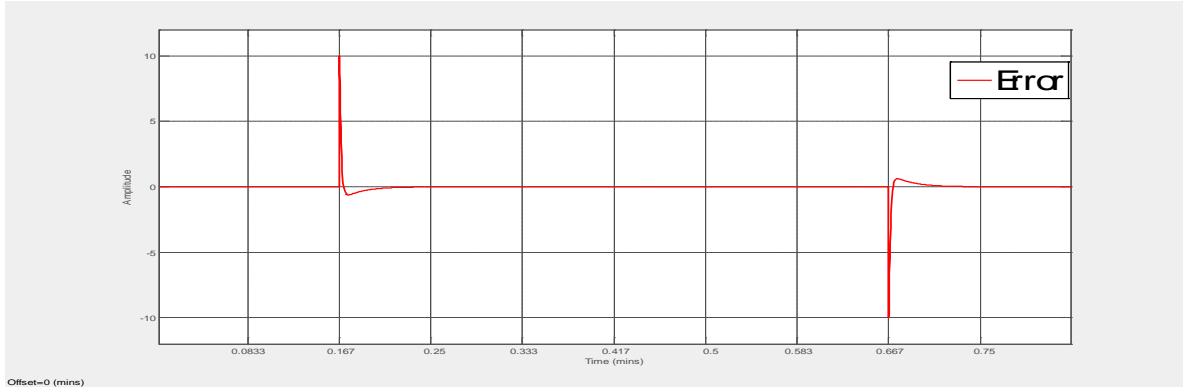


Fig. 11: Path Followed Error Traced

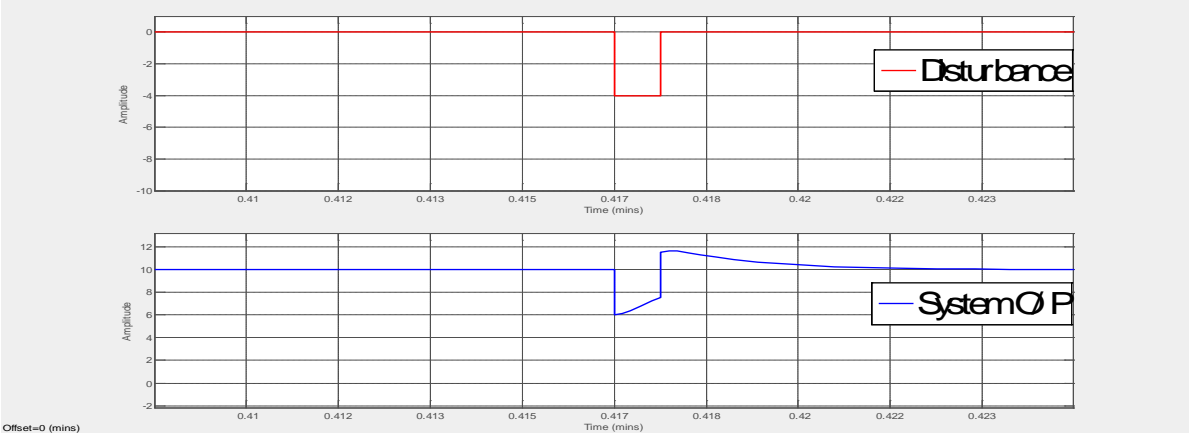


Fig. 12: Addition of Disturbance and System Response

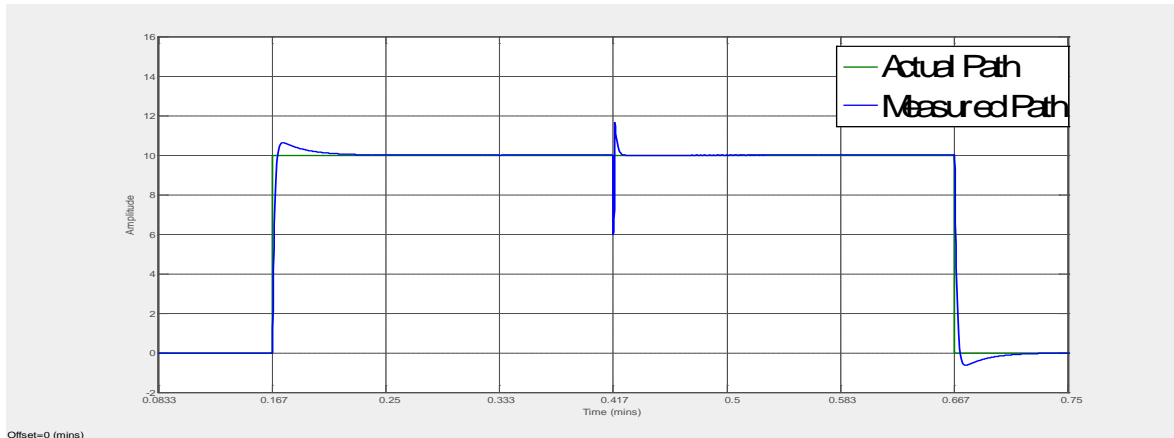


Fig. 13: Disturbance Rejection Path Followed By Using PID Control Algorithm

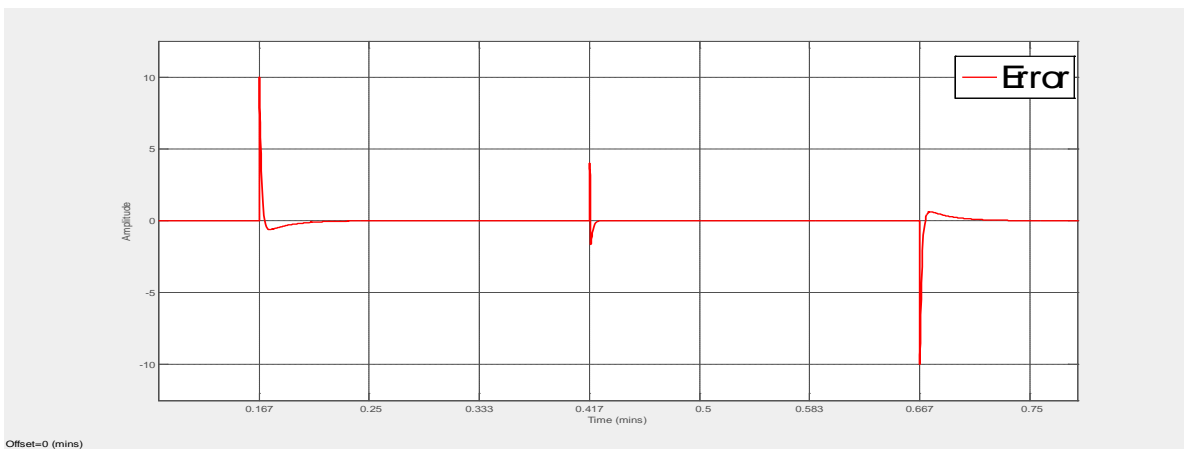


Fig. 14: Disturbance and Path Followed Error Traced

2. Noise Rejection:

2.1 Simulink Implementation and Simulation Results:

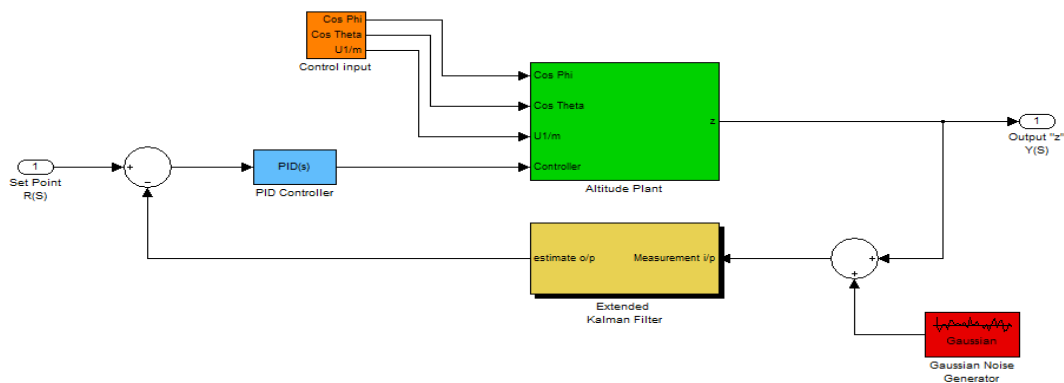


Fig. 15: Simulink Model For Noise Rejection

Figure 15 shows the complete altitude stabilization and noise rejection model. This part shows the trajectory estimation of EKF, figure 18 shows the Gaussian noise added in actual trajectory path and to evaluate the performance of EKF figure 17 shows the actual and measured path of the particular system with the rejection of noise.

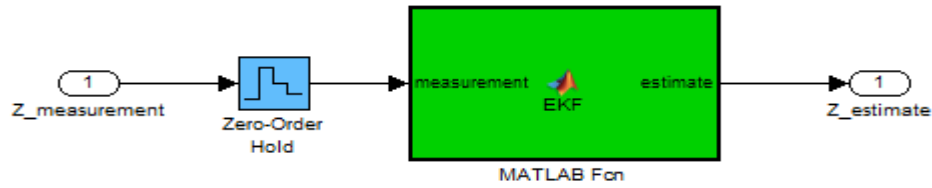


Fig. 16: Block diagram of EKF as a Subsystem

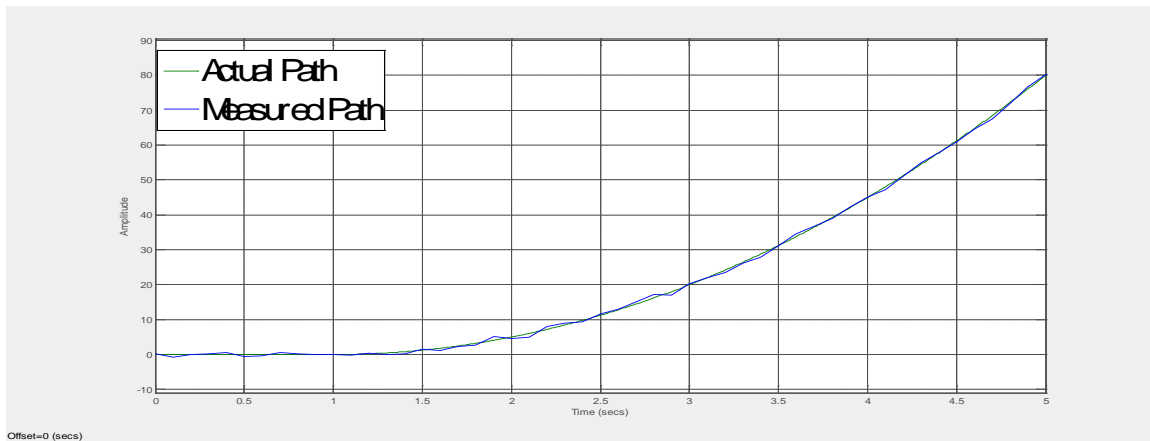


Fig. 17: Noise Rejection By Using Extended Kalman Filter

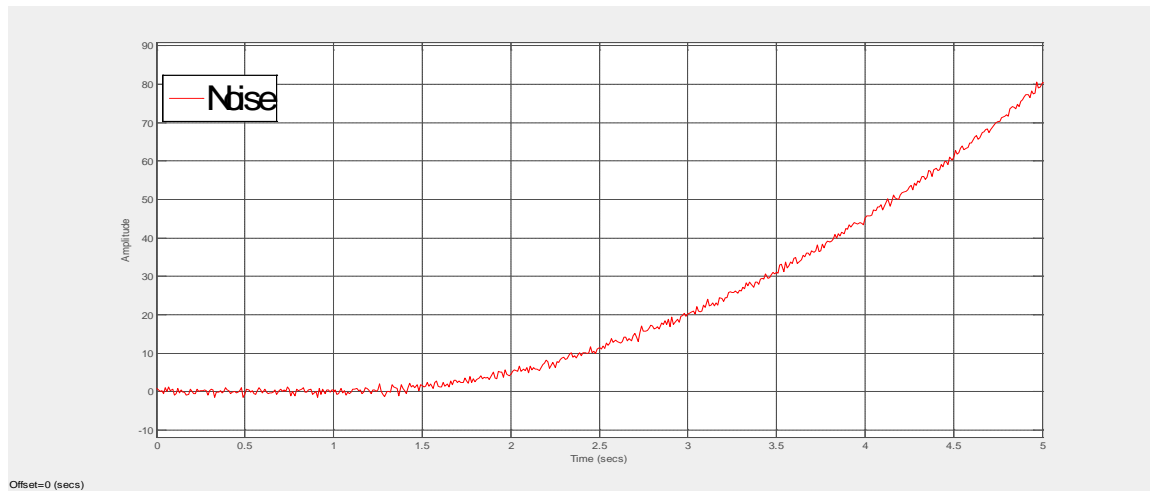


Fig. 18: Noise Traced

Conclusion:

This paper presents the efficient auto-tuned PID controller with Extended Kalman Filter (EKF) for Disturbance and Noise Rejection in Smooth Takeoff / Landing and Altitude Stabilization of Quad-rotor. The simulations are performed on mathematical modeling of quad-rotor UAV using Matlab under different disturbance and noisy conditions. Simulation results shows that proposed auto-tuned PID controller with EKF works very well for altitude stabilization, and quickly become stable when external disturbances are applied on it. From the simulation results, we can conclude that proposed method works efficiently and makes the system stable under the circumstance where there is any kind of disturbance imposed on it.

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