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Position Control of Quadrotor using Feedback Linearization Technique

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ABSTRACT: Quadrotor is a type of unmanned aerial vehicle (UAV), and this field has application in the areas such as remote sensing, surveillance, transport, rescue etc. This work aims to control a quadrotor to reach a desired position using altitude and attitude controllers designed using feedback linearization technique. Using Euler-Lagrangian approach the quadrotor is modelled and stability of the designed controller is verified using Lyapunov stability theorem. Simulation results shows the performance of the quadrotor is satisfactory using these controllers.

KEYWORDS: Quadrotor, backstepping, feedback linearization

I. INTRODUCTION

The technology of Unmanned Aerial Vehicle(UAV) has grown in the past decade and this field has application in the areas such as remote sensing, surveillance, transport, rescue, remote inspection and photography. Quadrotor is a type of UAV and it has many abilities such as vertical take-off and landing, hover capability, high maneuverability and agility. A quadrotor can hover in space and have six degrees of freedom. Also, it possesses more advantages than standard helicopters in terms of small size, efficiency and safety. Many control techniques have been developed for the control of quadrotor including back-stepping, sliding mode control, Robust control etc.

II. RELATED WORK

A new nonlinear control technique, back-stepping like feedback linearization is developed in [1] for the position control and stabilize the quadrotor. Linear control techniques like PID and LQR techniques are used in [2], [7] for the control of quadrotor. In [3] a control law was synthesized by sliding mode control based on the back-stepping approach. Based on the developed nonlinear dynamic equations of a quadrotor (named as Qball-X4) UAV (Unmanned Aerial Vehicle), attitude and trajectory tracking control designs based on an inner/outer loop control structure has been proposed in [4]. An integral back-stepping approach was applied into an autonomous flight of the quadrotor system including indoor experiments and a back-stepping control was used to stabilize the quadrotor's attitude system [5]. Nested saturation control algorithm based on the Lyapunov analysis was proposed to track the desired trajectory including experimental tests [6].

1. QUADROTOR MODELLING

The quadrotor model is derived using Euler-Lagrangian method. Let, $q = (x, y, z, \phi, \theta, \psi) \in R^6$ be the generalized coordinates where $\xi = (x, y, z) \in R^3$ denotes the absolute position of the mass of the quadrotor relative to a fixed inertial

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frame. Euler angles, which are the orientation of the quadrotor, are expressed by $\eta = (\phi, \theta, \psi) \in R^3$ where ϕ is the roll angle around the x axis, θ is the pitch angle around the y axis, and ψ is the yaw angle around the z axis.

It is assumed that the Euler angles are bounded as:

$$\begin{aligned} \text{Roll} &: -\frac{\pi}{2} \leq \phi \leq \frac{\pi}{2} \\ \text{Pitch} &: -\frac{\pi}{2} \leq \theta \leq \frac{\pi}{2} \\ \text{Yaw} &: -\pi \leq \psi \leq \pi \end{aligned} \tag{1}$$

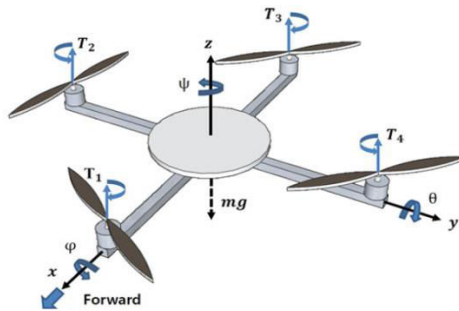


Fig. 1. Quadrotor configuration

The model of quadrotor can be partitioned into translational and rotational coordinates. The translational kinetic energy of the quadrotor is $T_{trans} = \frac{1}{2}m\dot{\xi}^T$, where m is the mass of quadrotor. The rotational kinetic energy is $T_{rot} = \frac{1}{2}I\dot{\eta}^T$. The matrix I is the moment of inertia matrix for the full-rotational kinetic energy of the quadrotor which is expressed directly in terms of the generalized coordinates η . The potential energy is $U = mgz$, where g is the acceleration due to gravity.

Then, the Lagrangian model can be defined as:

$$\begin{aligned} L(q, \dot{q}) &= T_{trans} + T_{rot} - U \\ &= \frac{1}{2}m\dot{\xi}^T + \frac{1}{2}I\dot{\eta}^T - mgz \end{aligned} \tag{2}$$

The full quadrotor dynamics can be obtained by Euler Lagrangian equations with external force, $F = (F_\xi, \tau)$ as follows,

$$\frac{d}{dt} \frac{\partial L}{\partial \dot{q}} - \frac{\partial L}{\partial q} = (F_\xi, \tau) \tag{3}$$

where, F_ξ is the translational force applied to the quadrotor and τ is the roll, pitch, and yaw moments. The translational force $F_\xi = RF_R$ is where R is the rotation matrix and F_R is the translational force in the inertial frame. The rotation matrix R equals to $R = R_z R_y R_x$ which is the orientation of the quadrotor. F_R is defined by

$$F_R = \begin{bmatrix} 0 \\ 0 \\ U_1 \end{bmatrix} \tag{4}$$

Then the control vectors can be defined as,

$$\tau = \begin{bmatrix} U_2 \\ U_3 \\ U_4 \end{bmatrix} = \begin{bmatrix} \tau_\phi \\ \tau_\theta \\ \tau_\psi \end{bmatrix} = \begin{bmatrix} bl(\omega_4^2 - \omega_2^2) \\ bl(\omega_3^2 - \omega_1^2) \\ d(\omega_1^2 + \omega_3^2 - \omega_2^2 - \omega_4^2) \end{bmatrix} \tag{5}$$

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The Euler–Lagrangian equation can be partitioned into the translational and rotational co-ordinates. Thus, the final model of the quadrotor can be expressed as

$$m\ddot{\xi} = - \begin{bmatrix} 0 \\ 0 \\ mg \end{bmatrix} + F_{\xi} \tag{6}$$

$$I\ddot{\eta} + \frac{d}{dt}\{I\}\dot{\eta} - \frac{1}{2}\frac{\partial}{\partial \eta}(\dot{\eta}^T I \dot{\eta}) = \tau \tag{7}$$

The Coriolis–centripetal vector is defined by

$$V(\eta, \dot{\eta}) = I\dot{\eta} - \frac{1}{2}\frac{\partial}{\partial \eta}(\dot{\eta}^T I \dot{\eta}) \tag{8}$$

Then,

$$I\ddot{\eta} + V(\eta, \dot{\eta}) = \tau \tag{9}$$

$V(\eta, \dot{\eta})$ can be written as

$$\begin{aligned} V(\eta, \dot{\eta}) &= \left(I - \frac{1}{2}\frac{\partial}{\partial t}(\dot{\eta}^T I) \right) \dot{\eta} \\ &= C(\eta, \dot{\eta})\dot{\eta} \end{aligned} \tag{10}$$

where, $C(\eta, \dot{\eta})$ is referred to as the Coriolis term.

$$m\ddot{\xi} = F_{\xi} - mge_3 \tag{11}$$

$$I\ddot{\eta} = \tau - C(\eta, \dot{\eta})\dot{\eta} \tag{12}$$

Finally, the model of the quadrotor in terms of translation (x, y, z) and rotation (ϕ, θ, ψ) can be written as follows:

$$\begin{bmatrix} \ddot{x} \\ \ddot{y} \\ \ddot{z} \end{bmatrix} = \begin{bmatrix} c_{\phi}s_{\theta}c_{\psi} + s_{\phi}s_{\psi} \\ c_{\phi}s_{\theta}s_{\psi} - s_{\phi}c_{\psi} \\ c_{\phi}c_{\theta} \end{bmatrix} \frac{U_1}{m} + \begin{bmatrix} 0 \\ 0 \\ -g \end{bmatrix} \tag{13}$$

$$\begin{bmatrix} \ddot{\phi} \\ \ddot{\theta} \\ \ddot{\psi} \end{bmatrix} = f(\phi, \theta, \psi) + g(\phi, \theta, \psi)\tau_U \tag{14}$$

where c_{ϕ} is $\cos \phi$, s_{ϕ} is $\sin \phi$, and

$$f(\phi, \theta, \psi) = \begin{bmatrix} \dot{\theta}\dot{\psi} \left(\frac{I_y - I_z}{I_x} \right) - \frac{I_x}{I_x} \dot{\theta}\dot{\Omega} \\ \dot{\phi}\dot{\psi} \left(\frac{I_z - I_x}{I_y} \right) + \frac{I_x}{I_y} \dot{\phi}\dot{\Omega} \\ \dot{\phi}\dot{\theta} \left(\frac{I_x - I_y}{I_z} \right) \end{bmatrix} \tag{15}$$

$$g(\phi, \theta, \psi) = \begin{bmatrix} \frac{1}{I_x} & 0 & 0 \\ 0 & \frac{1}{I_y} & 0 \\ 0 & 0 & \frac{1}{I_z} \end{bmatrix} \tag{16}$$

The control inputs U_1, U_2, U_3, U_4 can be defined as,

$$U_1 = b(\omega_1^2 + \omega_2^2 + \omega_3^2 + \omega_4^2) \tag{17}$$

$$\tau_U = \begin{bmatrix} U_2 \\ U_3 \\ U_4 \end{bmatrix} = \begin{bmatrix} bl(\omega_4^2 - \omega_2^2) \\ bl(\omega_3^2 - \omega_1^2) \\ d(\omega_1^2 + \omega_3^2 - \omega_2^2 - \omega_4^2) \end{bmatrix} \tag{18}$$

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where U_1 is essentially used to make the altitude reach the desired value, U_2 is used to control the roll and horizontal displacement, U_3 is used to control the pitch and vertical movement, U_4 is used to set the yaw displacement, $I_{x,y,z}$ are the moment of inertia of quadrotor, J_r is the moment of inertia of rotor, and $\Omega = \omega_1 - \omega_2 + \omega_3 - \omega_4$.

Figure 2 shows the control schematic of the quadrotor. x, y, z are the translational coordinates of the quadrotor model. x_d, y_d, z_d are the desired translational coordinates. The z coordinate of the quadrotor model is compared with the desired z coordinate and a control vector U_1 is computed using feedback linearization technique. But in-order to make a movement along x and y direction, its attitude must be changed, that is roll and pitch angles. From x_d, y_d the desired Euler angles ϕ_d, θ_d are calculated using position control and it is compared with quadrotor model ϕ and θ , then control vector U_2, U_3 are computed using feedback linearization technique.

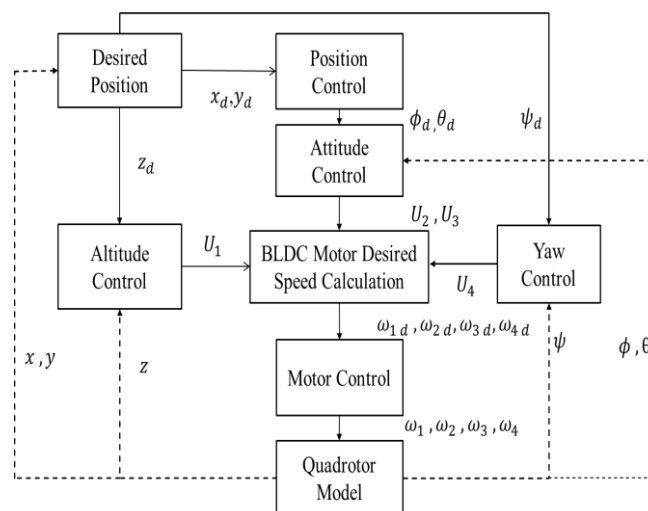


Fig. 2. Control scheme of quadrotor

Similarly, the yaw angle of the quadrotor model is compared with the desired yaw angle and a control vector U_4 is computed using feedback linearization technique.

2. CONTROLLER DESIGN

Non-linear controller of the quadrotor includes attitude control altitude control. The main objective of designed controller is to ensure that the position of quadrotor (x, y, z, ψ) tracks the desired trajectory (x_d, y_d, z_d, ψ_d) . The attitude controller is to design control inputs $U_2 \sim U_4$. The altitude controller, attitude controller is designed using feedback linearization technique.

A) Attitude Controller

This section aims to design the attitude control vector $U_2 \sim U_4$. The errors associated with the attitude dynamics of the quadrotor are as follows:

$$e_1 = \phi - \phi_d \tag{19}$$

$$e_2 = \dot{\phi} - \dot{\phi}_d + k_1 e_1 \tag{20}$$

$$e_3 = \theta - \theta_d \tag{21}$$

$$e_4 = \dot{\theta} - \dot{\theta}_d + k_3 e_3 \tag{22}$$

$$e_5 = \psi - \psi_d \tag{23}$$

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$$e_6 = \dot{\psi} - \dot{\psi}_d + k_5 e_5 \quad (24)$$

To check the stability of the attitude controller Lyapunov function can be used.

Let, the Lyapunov candidate V_1 can be taken as:

$$V_1 = \frac{1}{2} \{e_1^2 + e_2^2 + e_3^2 + e_4^2 + e_5^2 + e_6^2\} \quad (25)$$

where the Lyapunov candidate V_1 is positive definite and the time derivative of the Lyapunov candidate V_1 is obtained by

$$\dot{V}_1 = e_1 \dot{e}_1 + e_2 \dot{e}_2 + e_3 \dot{e}_3 + e_4 \dot{e}_4 + e_5 \dot{e}_5 + e_6 \dot{e}_6 \quad (26)$$

For the system to be stable, Lyapunov candidate V_1 should be positive definite and \dot{V}_1 should be negative semi definite.

The time derivative of the Lyapunov function can be obtained as follows:

$$\dot{V}_1 = e_1(e_2 - k_1 e_1) + e_2(\dot{\phi} - \dot{\phi}_d + k_1 e_1) + e_3(e_4 - k_3 e_3) + e_4(\ddot{\theta} - \ddot{\theta}_d + k_3 e_3) + e_5(e_6 - k_5 e_5) + e_6(\dot{\psi} - \dot{\psi}_d + k_5 e_5) \quad (27)$$

Assuming the time derivatives of desired angular rates as zero. ($\dot{\phi}_d = \ddot{\theta}_d = \dot{\psi}_d = 0$) then (29) becomes,

$$\dot{V}_1 = e_1(e_2 - k_1 e_1) + e_3(e_4 - k_3 e_3) + e_5(e_6 - k_5 e_5) + e_2 \left\{ \dot{\theta} \dot{\psi} \left(\frac{I_y - I_z}{I_x} \right) - \frac{J_r}{I_x} \dot{\theta} \Omega + \frac{l}{I_x} U_2 + k_1(e_2 - k_1 e_1) \right\} + e_4 \left\{ \dot{\phi} \dot{\theta} \left(\frac{I_x - I_y}{I_z} \right) + \frac{J_r}{I_y} \dot{\phi} \Omega + \frac{l}{I_y} U_3 + k_3(e_4 - k_3 e_3) \right\} + e_6 \left\{ \dot{\phi} \dot{\theta} \left(\frac{I_x - I_y}{I_z} \right) + \frac{1}{I_z} U_4 + k_5(e_6 - k_5 e_5) \right\} \quad (28)$$

From (30) the control vectors $U_2 \sim U_4$ can be obtained as follows:

$$U_2 = \frac{I_x}{l} \left\{ -\dot{\theta} \dot{\psi} \left(\frac{I_y - I_z}{I_x} \right) + \frac{J_r}{I_x} \dot{\theta} \Omega + (k_1^2 - 1)e_1 - (k_1 + k_2)e_2 \right\}$$

$$U_3 = \frac{I_y}{l} \left\{ -\dot{\phi} \dot{\theta} \left(\frac{I_z - I_x}{I_y} \right) - \frac{J_r}{I_y} \dot{\phi} \Omega + (k_3^2 - 1)e_3 - (k_3 + k_4)e_4 \right\}$$

$$U_4 = I_z \left\{ -\dot{\phi} \dot{\theta} \left(\frac{I_x - I_y}{I_z} \right) + (k_5^2 - 1)e_5 - (k_5 + k_6)e_6 \right\} \quad (29)$$

where $k_1 \sim k_6$ are control parameters which are positive constants.

Substituting (29) in (28) \dot{V}_1 becomes, $\dot{V}_1 = -k_1 e_1^2 - k_2 e_2^2 - k_3 e_3^2 - k_4 e_4^2 - k_5 e_5^2 - k_6 e_6^2 \leq 0$

B) Altitude Controller

The altitude of the system is controlled by the vertical force control input U_1 . Let the altitude error e_7 and e_8 as follows:

$$e_7 = z - z_d \quad (30)$$

$$e_8 = \dot{z} - \dot{z}_d + k_7 e_7 \quad (31)$$

where k_7 is the control parameter which is positive constant.

The Lyapunov candidate V_2 can be defined as:

$$V_2 = \frac{1}{2} (e_7^2 + e_8^2) \quad (32)$$

Then, the time derivative of Lyapunov candidate can be obtained as,

$$\dot{V}_2 = e_7(e_8 - k_7 e_7) + e_8 \left\{ (\cos \phi \cos \theta) \frac{1}{m} U_1 - g - \ddot{z}_d + k_7(e_8 - k_7 e_7) \right\} \quad (33)$$

Assuming, the time derivative of desired velocity of the altitude is zero ($\ddot{z}_d = 0$).

The control input U_1 can be defined as follows:

$$U_1 = \frac{m \{ g + (k_7^2 - 1)e_7 - (k_7 + k_8)e_8 \}}{\cos \phi \cos \theta} \quad (34)$$

Therefore, the altitude control becomes stable.

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c) Position Controller

The variation in the x, y position of the quadrotor depends on the roll and pitch angles.

Let, the x, y errors be,

$$e_9 = x - x_d \quad (35)$$

$$e_{10} = \dot{x} - \dot{x}_d + k_9 e_9 \quad (36)$$

$$e_{11} = y - y_d \quad (37)$$

$$e_{12} = \dot{y} - \dot{y}_d + k_{11} e_{11} \quad (38)$$

Therefore, the altitude control is asymptotically stable.

Let, the Lyapunov candidate be,

$$V_3 = \frac{1}{2} (\zeta_1 e_9^2 + \zeta_2 e_{10}^2 + \zeta_3 e_{11}^2 + \zeta_4 e_{12}^2) \quad (39)$$

The time derivative of the Lyapunov function becomes,

$$\dot{V}_3 = \zeta_1 e_9 (\dot{e}_{10} - k_9 e_9) + \zeta_3 e_{11} (\dot{e}_{12} - k_{11} e_{11}) + \zeta_2 e_{10} \{\ddot{x} - \ddot{x}_d + k_9 (e_{10} - k_9 e_9)\} + \zeta_4 e_{12} \{\ddot{y} - \ddot{y}_d + k_{11} (e_{12} - k_{11} e_{11})\} \quad (40)$$

Assuming, second derivative of the desired x and y position as zero and substituting for \ddot{x}, \ddot{y}

$$\dot{V}_3 = \zeta_1 e_9 \dot{e}_{10} - \zeta_1 k_9 e_9^2 + \zeta_3 e_{11} \dot{e}_{12} - \zeta_3 k_{11} e_{11}^2 + \zeta_2 e_{10} \gamma_1 \frac{U_1}{m} + \zeta_2 k_9 e_{10}^2 - \zeta_2 k_9^2 e_9 e_{10} + \zeta_4 e_{12} \gamma_2 \frac{U_1}{m} + \zeta_4 k_{11} e_{12}^2 - \zeta_4 k_{11}^2 e_{11} e_{12} \quad (41)$$

where, $\gamma_1 = \cos \phi \sin \theta \cos \psi + \sin \phi \sin \psi$, (42)

$$\gamma_2 = \cos \phi \sin \theta \sin \psi - \sin \phi \cos \psi \quad (43)$$

Choosing, $\zeta_1 = \zeta_2 k_9^2$, $\zeta_3 = \zeta_4 k_{11}^2$

$$\dot{V}_3 = \zeta_2 e_{10} \gamma_1 \frac{U_1}{m} + \zeta_2 k_9 e_{10}^2 - \zeta_2 k_9^3 e_9^2 + \zeta_4 e_{12} \gamma_2 \frac{U_1}{m} + \zeta_4 k_{11} e_{12}^2 - \zeta_4 k_{11}^3 e_{11}^2 \leq 0 \quad (44)$$

If $k_9 e_{10}^2 - k_9^3 e_9^2 < 0$ and $k_{11} e_{12}^2 - k_{11}^3 e_{11}^2 < 0$, Then the following condition should be satisfied to ensure the stability.

$$\dot{V}_3 = \zeta_2 e_{10} \gamma_1 \frac{U_1}{m} + \zeta_4 e_{12} \gamma_2 \frac{U_1}{m} \leq 0 \quad (45)$$

Depending the sign of errors e_{10} and e_{12} , γ_1^{sol} and γ_2^{sol} can be obtained as (46) (47), and by solving (42), (43) the required roll, pitch angles can be calculated.

$$\gamma_1^{sol} = \begin{cases} -\gamma_1^{max} & \text{if } e_{10} \geq 0 \\ \gamma_1^{max} & \text{if } e_{10} < 0 \end{cases} \quad (46)$$

$$\gamma_2^{sol} = \begin{cases} -\gamma_2^{max} & \text{if } e_{12} \geq 0 \\ \gamma_2^{max} & \text{if } e_{12} < 0 \end{cases} \quad (47)$$

Also, assuming that $|\gamma_1| \leq |\gamma_1^{sol}|$, $|\gamma_2| \leq |\gamma_2^{sol}|$.

According to the assumption of Euler angles, γ_1 and γ_2 are bounded as follows:

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$$\begin{cases} -1 \leq \gamma_1 \leq 1 \\ -1 \leq \gamma_2 \leq 1 \end{cases} \quad (48)$$

By subtracting $\gamma_2 * \frac{1}{\sin \psi}$ from $\gamma_1 * \frac{1}{\cos \psi}$; $\sin \phi \left(\frac{\sin \psi}{\cos \psi} + \frac{\cos \psi}{\sin \psi} \right) = \gamma_1^{sol} \frac{1}{\cos \psi} + \gamma_2^{sol} \frac{1}{\sin \psi}$

where, $\gamma_1^{sol} = \sin \phi \sin \psi$, $\gamma_2^{sol} = \sin \phi \cos \psi$

Since, $\sin \phi$ is bounded between -1 and 1, $(\gamma_1^{sol})^2 + (\gamma_2^{sol})^2 \geq \sin^2 \phi$

When $(\gamma_1^{sol})^2 = (\gamma_2^{sol})^2$, $\gamma_1^{sol} \leq |0.7071|$, $\gamma_2^{sol} \leq |0.7071|$.

By choosing $\gamma_1^{sol} \leq |0.7071|$, $\gamma_2^{sol} \leq |0.7071|$ the desired roll and pitch angles can be obtained to track the desired position.

3. SIMULATION RESULTS

Here, the desired position is given as [10, 10, 10]. From fig 3 it is clear that the quadrotor tracks the desired altitude 10. This means the quadrotor moves vertically upwards. At that time all the Euler angles, roll, pitch and yaw remains zero. Also, x, y positions remains zero. Only z direction movement will be there. The z response has very less overshoot and less settling time.

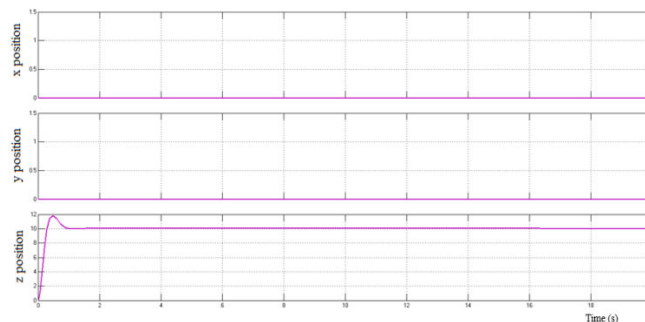


Fig. 3. Response of positions with altitude controller

Fig 4 shows the response of x, y, z positions with attitude controller. Here, randomly, the Euler angles are given. Since the x, y positions depends on the Euler angles roll and pitch, variation in these angles results in variation in x, y positions. Here, for the given roll and pitch angles, quadrotor tracks the desired position.

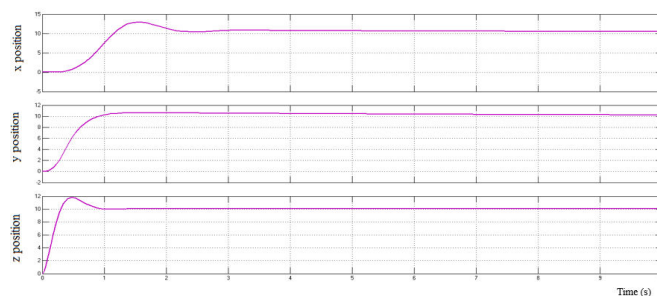


Fig. 4. Response of positions with attitude controller

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Fig 5 shows the response of x, y, z position with position controller. The position controller calculates the roll, pitch angles to reach the desired position. From fig 5 it is clear that the quadrotor tracks the desired position with these Euler angles. Response has less overshoot, less settling time.

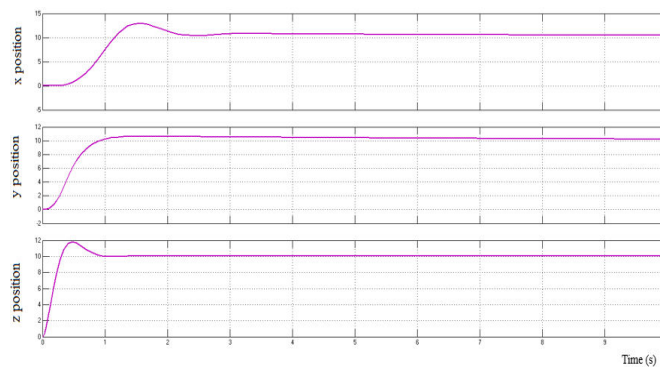


Fig. 5. Response of positions with position controller

Table 1 shows the time domain analysis of the system with feedback linearization technique. From the table it is clear that the response has less rise time, less overshoot and less settling time. Comparatively, x response has less rise time, less overshoot. But z response has very less settling time.

TABLE I
RESPONSE ANALYSIS

Position	Rise time	Peak overshoot	Settling time
X	0.852 s	7.4 %	10 s
Y	0.926 s	5.66 %	10 s
z	1 s	15.2 %	1.96

IV. CONCLUSION

A non-linear control technique, feedback linearization has been used to track the desired position of the quadrotor. Using Euler-Lagrangian approach the quadrotor is modelled and the stability of the system is verified by Lyapunov's stability theorem. The control inputs designed using feedback linearization technique, stabilizes the system and leads to the control of altitude and attitude. The desired roll and pitch angles to track the desired x and y position are calculated using feedback linearization technique. The simulation results show the quadrotor tracks the desired position.

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