Journal of Applied Sciences

ISSN 1812-5654

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OPEN ACCESS **Journal of Applied Sciences**

ISSN 1812-5654
DOI: 10.3923/jas.2016.588.593

Research Article

LQR Based Controller Design for Altitude and Longitudinal Movement of Quad-rotor

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Abstract

Quad-rotor unmanned aerial vehicles have become one of the prominent type of rotorcraft which has been researched massively during the last decade. This study addresses the issue regarding control of quad-rotor under noisy IMU and GPS measurements. Several solutions are provided to resolve the issue of proper controlling of position and altitude of quad-rotor under uncertainties such as noisy measurements but still they are not fully succeeded. This study presents LQR technique for the longitudinal motion control of quad-rotor under noisy sensor measurements. The proposed control technique is simulated on MATLAB. The results of the study show that the applied control technique is effective for altitude and position control of quad-rotor specifically under noisy conditions.

Key words: Quad-rotor, UAV, LQR, altitude, SONAR, GPS, MATLAB

Received: June 03, 2016 Accepted: August 22, 2016 Published: November 15, 2016

Citation: S. Faiz Ahmed, Kushsairy Kadir and M. Kamran Joyo, 2016. LQR based controller design for altitude and longitudinal movement of quad-rotor. J. Applied Sci., 16: 588-593.

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Competing Interest: The authors have declared that no competing interest exists.

Data Availability: All relevant data are within the paper and its supporting information files.

INTRODUCTION

The UAVs have become an eminent subject in the last past years. Rise in their demand is due to their capability of carrying payloads with no life risk. Their ability of spying makes them ideal for military applications. Forces deploy them predominantly for special purpose applications. Their abilities are also utilized in civil applications such as police task force, firefighting, surveillance of pipelines, search and rescue operations, nuclear plant inspections and geo weather surveillance.

Their exist variety of UAVs with different capabilities. Quad-rotor is one of the prominent amongst the rotorcraft type UAVs. It has a simple and unique structural arrangement with distinct functionality as compared to helicopter UAVs. Like helicopters, quad-rotor can hover, Vertically Take Off and Land (VTOL) and can manoeuvre autonomously. Rather than its simple design this UAV has severe issues regarding its dynamic controls due to its nonlinearity. The altitude and position controlling has been an issue over the years. This article introduces a control technique for altitude and position control of a quad-rotor. The proposed control design also minimizes the effect of sensor noises.

In the recent years, altitude and position controlling of quad-rotor has remained a problem due to the constraints of unstable kinematics and dynamics. However, some of the techniques of control were developed in this field. Dynamic Surface Control (DSC) method was used for altitude control and position control[1]. The PID based position control was applied for position control system of quad-rotor[2]. Sliding mode and PID control techniques were also implemented onthequad-rotor system[3]. Adaptive neural controller was used for handling attitude control of quad-rotor[4]. Stabilizing control laws were presented by sliding mode and backstepping approach[5]. Fuzzy logic control was implemented on position, altitude and attitude control of quad-rotor[6]. Backstepping method was used for altitude, attitude and position control of a quad-rotor, the results of this technique showed a flexible control structure. Further quad-rotor was able to perform autonomous hovering with altitude control and autonomous take off and landing[7]. This study presents a control technique based on LQR controller for altitude and position stabilization. The proposed algorithm is simulated on (MATLAB).

MATERIALS AND METHODS

Quad-rotor modelling: The quad-rotor UAV has four fixed pitch rotors mounted on the ends of a simple cross frame structure as shown in Fig. 1. In this figure a pair of motors (Q1 and Q3) rotates clockwise while other pair of motors (Q2 and Q4) rotates counter-clockwise direction to counters the effect of opposite torques produced by motors. By changing the combination and rotor speeds of these motors quad-rotor can perform moves in pitch, roll, yaw, hover, take off and landing positions. Pitch and roll movements can be achieved by changing the speed of any one pair of motors while other motor pair speeds remain constant. Yaw movement is done by altering the speed of both motors pairs in quad-rotor and to perform vertical take off and landing tasks, the rotation speed of all four rotors gradually increased and decreased, respectively.

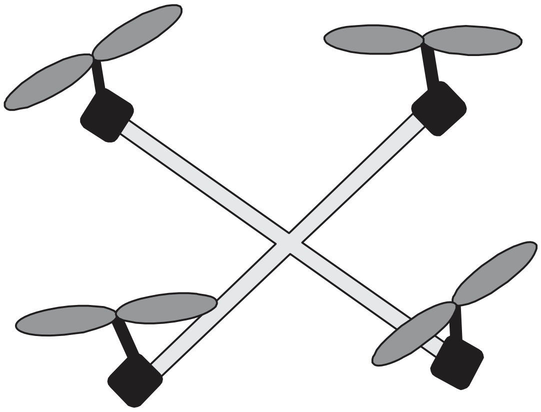

Fig. 1: Quad-rotor body

The motors which rotate quad-rotors propellers are brushless DC motors and its dynamics cab be define by its aerodynamics and geometric structure described in[8]:

$$G(s) = \frac{K_M}{\tau s + 1} \quad (1)$$

where, K_M and τ are motor constant and motor time constant, respectively.

To understand quad-rotor dynamic model, two frames must be defined as a reference which are earth inertial frame (E frame) and quad-rotor fixed-body frame (F frame) as shown in Fig. 2. The quad-rotor orientation and translation vectors are define by three Euler angles $\Omega T = (\phi, \theta, \psi)$ and vector $qT = (x, y, z)$ in the inertial frame. The transformation of vectors of the fixed frame to the inertial frame is given by the resultant transformation matrix of z, y and x axis.

The movements of quad-rotor are achieved by changing the combination and varying the speeds of the motors described as:

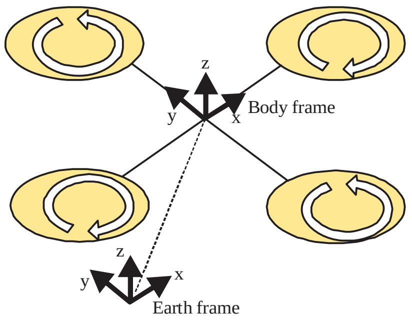

Fig. 2: Quad-rotor body with earth and body frame

$$\left.\begin{aligned} u_1 &= b\left(\omega_1^2+\omega_2^2+\omega_3^2+\omega_4^2\right)\\ u_2 &= b\left(\omega_4^2-\omega_2^2\right)\\ u_3 &= b\left(\omega_3^2-\omega_1^2\right)\\ u_4 &= d\left(\omega_2^2+\omega_4^2-\omega_1^2-\omega_3^2\right)\end{aligned}\right\} \tag{2}$$

where, u_1, u_2, u_3 and u_4 are the thrust force, roll torque, pitch torque and yaw torque, respectively.

Finally the mathematical modeling of quad-rotor is extracted from above mentioned frames defined in the study[9,10]:

$$\left.\begin{aligned} \ddot{x} &= -\left(\cos\phi\sin\theta\cos\psi+\sin\phi\sin\psi\right).\frac{u_1}{m}\\ \ddot{y} &= -\left(\cos\phi\sin\theta\sin\psi-\sin\phi\cos\psi\right).\frac{u_1}{m}\\ \ddot{z} &= g-\left(\cos\phi\cos\theta\right).\frac{u_1}{m}\\ \ddot{\phi} &= \dot{\theta}\dot{\psi}\left(\frac{1_{yy}-1_{zz}}{1_{xx}}\right)-\frac{1_M}{1_{xx}}\dot{\theta}g(u)+\frac{L}{1_{xx}}u_2\\ \ddot{\theta} &= \dot{\phi}\dot{\psi}\left(\frac{lzz-l_{xx}}{l_{yy}}\right)-\frac{l_M}{l_{yy}}\dot{\phi}g(u)+\frac{L}{l_{yy}}u_3\\ \ddot{\psi} &= \dot{\theta}\dot{\phi}\left(\frac{l_{xx}-l_{yy}}{l_{zz}}\right)-\frac{1}{l_{zz}}u_4\end{aligned}\right\} \tag{3}$$

Proposed controller design: In this study optimed gain LQR controller is presented for better stabalization and improving the flight quality specially for position and altitude controlling of quad-rotor under uncertanity conditions such sensor and system noises which makes systm unstable[11,12].

Figure 3 shows the overall block diagram of proposed control algorithm for stabilizing quad-rotor position/altitude control. The control law for LQR is derived and shown in Fig. 3. The system defined as:

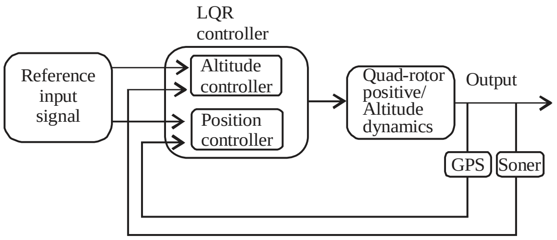

Fig. 3: LQR based controller

$$\dot{x} = Ax+Bu,\ y = Cx,\ z = Gx+Hu \tag{4}$$

The state-feedback controller can be defined as:

$$u = -Kx \tag{5}$$

Further LQG state-estimator is constructed:

$$\dot{\overline{X}} = (A-LC)\overline{X}+Bu+Ly \tag{6}$$

The output feedback controller can be obtained by using estimated state rather than true state.

$$\dot{\overline{X}} = (ALC-BK)\overline{X}+Ly \tag{7}$$

Hence, the control law can be defined as:

$$u = K\overline{X} \tag{8}$$

The output equation will become:

$$Y_{new} = CX \tag{9}$$

Altitude stabilization controller: The altitude controller ensures that the quad-rotorfly at desired distance from the ground. While evaluating altitude, only z-axis equation from Eq. 3 is taken into account with an addition of noise effect on it while other axes are considered to be constant.

$$\ddot{z} = g-\left(\cos\phi\cos\theta\right).\frac{u_1}{m}+\zeta \tag{10}$$

For hovering condition, ϕ and θ are kept equivalent to 0 while g and $\frac{u_1}{m}$ are constant values at each instant, 'ζ' is the noise factor which is generated by the sensors. Taking constants as $g-\frac{U_1}{m}-K_z$ and taking laplace transformation the system will become:

$$Z(S)\,\frac{K_Z}{S^2}+\zeta \qquad (11)$$

By adding rotor dynamics, the system becomes:

$$Z(S)\left(\frac{K_Z}{S^2}\right)\left(\frac{K_M}{\tau s+1}\right)^2+\zeta \qquad (12)$$

The close loop transfer function can thus be defined as:

$$G_Z(S)\,\frac{Z(s).u}{1+Z(s).u}+\zeta \qquad (13)$$

Position controller: Position controller, controls quad-rotor maneuvering in x and y direction as per desired action, these movements are obtain by rolling and pitching the quad-rotor, respectively. For position controlling only X and Y equations will be taken in account from Eq. 3 with considering the system and sensor noise effect on it:

$$\left.\begin{aligned}\ddot{X} &= (\sin\psi\,\sin\phi+\cos\psi\sin\theta\cos\phi)\frac{U_1}{m}+\zeta\\ \ddot{Y} &= (-\cos\psi\sin\phi+\sin\psi\sin\phi\cos\phi)\,\frac{U_1}{m}+\zeta\end{aligned}\right\} \qquad (14)$$

Table 1: Control and system parameters

Item	Symbols	Values
Control parameters	K	[0.0649 0.8928 -0.20818 -1.1046 0.0227]
System parameters	K_M	0.936
	τ	0.178
	g	9.8
	m	0.65
	b	3.13E-05
	d	7.5w−07

For position controlling we take $\psi = 0$ and by considering rotor dynamics and propeller rotation action on translational motion equations and also using small angle approximation and then write it in laplase domain, we can get:

$$\left.\begin{aligned}X(s) &= \left(\frac{K_X}{S^2}\right)\left(\frac{K_M}{\tau s+1}\right)^2+\zeta\\ Y(s) &= \left(\frac{K_Y}{S^2}\right)\left(\frac{K_M}{\tau s+1}\right)^2+\zeta\end{aligned}\right\} \qquad (15)$$

The close loop transfer function can thus be defined as:

$$G_x = \frac{x(s).u}{1+x(s).u}+\zeta \qquad (16)$$

Similar approach for y-axis may be followed in order to develop the system transfer function:

$$G_Y = \frac{Y(s).u}{1+Y(s).u}+\zeta \qquad (17)$$

RESULTS AND DISCUSSION

In the simulations a complete flight path followed by quad-rotor is demonstrated. Noise is introduced in the system which is due to the GPS and SONAR sensors which are measuring position and altitude, respectively. Under noisy conditions quad-rotor response becomes uncertain and challenging for controller to understand the abrupt response. Figure 4 shows the response of a quad-rotor equipped with LQR controller under noisy conditions. The noise added in the system is also shown in Fig. 4. By applying the proposed LQR controller the response is improved and noise is eliminated to high extent.

For simulation purposes the system and control parameters are chosen as in Table 1.

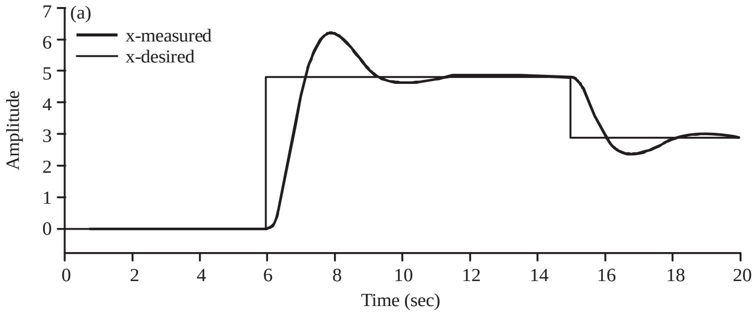

Fig. 4(a-c): Continue

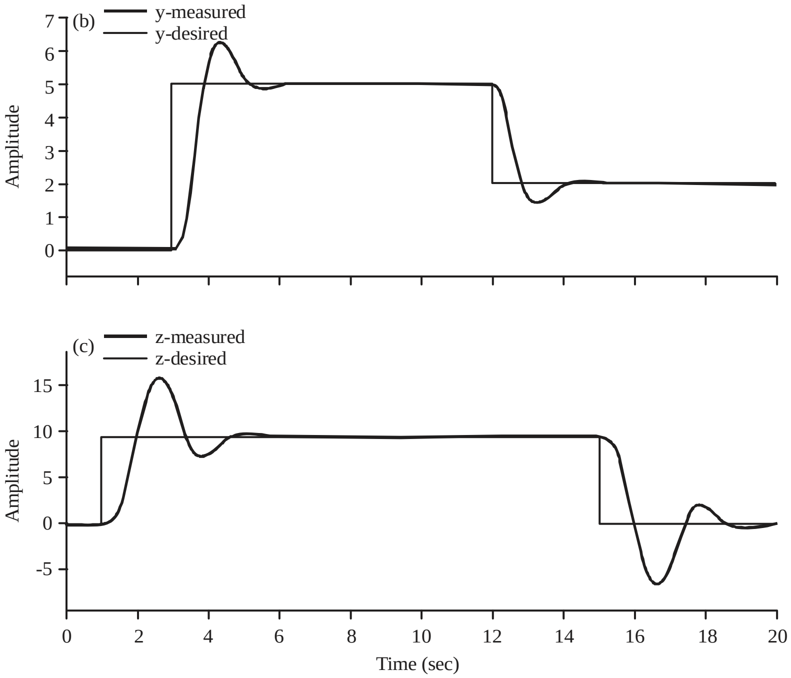

Fig. 4(a-c): LQR controller response in x, y and z direction under noisy data measurements

CONCLUSION

In this study the issue regarding quad-rotor position and altitude controlling is elaborated. Due to the effect of system and sensor noises the performance of quad-rotor is degraded. The LQR control technique is proposed inorder to suppress the noises and follow the trajectory smoothly. It was observed that under noisy conditions quad-rotor was able to maneuver smoothly and noises were suppressed by controller itself.

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