IARJSET

ISSN (Online) 2393-8021
ISSN (Print) 2394-1588

International Advanced Research Journal in Science, Engineering and Technology
National Conference on Emerging Trends in Engineering and Technology (NCETET'16)
Lourdes Matha College of Science & Technology, Thiruvananthapuram
Vol. 3, Special Issue 3, August 2016

Adaptive Backstepping Control of Quadrotor Unmanned Aerial Vehicles

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Abstract: Unmanned Aerial Vehicles (UAVs), also called unmanned aircraft systems, have recently reached unprecedented levels of growth in diverse military and civilian application domains. Quadrotor is basically an underactuated UAV. So control of a quadrotor UAV is difficult owing to the fact that it's a MIMO underactuated system subject to tight coupling and due to the presence of parameter uncertainties. In this work a sliding surface incorporated adaptive backstepping approach is proposed to control and stabilize the quadrotor. The validity of proposed control scheme is demonstrated by simulations using MATLAB simulink with different initial conditions. Simulation results validate the fact that the proposed controller gives better regulation.

Keywords: Quadrotor Unmanned Aerial Vehicle; Dynamics; Lyapunov Method; Sliding Surface based Adaptive Backstepping Contol.

I. INTRODUCTION

Recently, autonomous aerial vehicles such as the quadrotor have attracted considerable amount of interest because of a wide area of applications and a lot of advantages. The quadrotor has many abilities such as the vertical take-off and landing, hover capability, high maneuverability, and agility. The quadrotor also possess more advantages than standard helicopters in terms of small size, efficiency, and safety. Due to these advantages, the quadrotor is eligible for applications like military services, surveillance, rescue, research area, remote inspection, and photography.

For autonomous flight of the quadrotor, one of the most important techniques is an efficient attitude control and stabilization. However, the control of the quadrotor is not easy because of the high nonlinearity, strongly coupled dynamics, and multivariable nature. In addition, the quadrotor system is an underactuated system because the dynamics of a quadrotor have six outputs $(x, y, z, \phi, \theta, \psi)$ while it has only four independent control inputs (U_1, U_2, U_3, U_4). Uncertainties which are associated with physical parameters also bring another challenge for a control design. Thus, it is hard to control the nonlinear and under actuated quadrotor system.

Various nonlinear control methods such as linearization, saturation, backstepping, and sliding mode control were used to control the quadrotor system. For example, a nonlinear controller based on decomposition into a nested structure and feedback linearization has been introduced [6]; a feedback linearization controller involving high-order derivative terms was proposed in [7]. However, in these linearization methods, only higher-level dynamics without consideration of physical parameters were considered.

Robust integral backstepping using sliding mode is another method for the control of quadrotor in the presence of actuator and sensor faults is proposed in [8] here some of the useful nonlinearities gets cancelled. In [9] only attitude control problem is dealt with an adaptive block backstepping controller after considering a 3-DoF design structure. In [10] attitude control by using Zeigler Nichols rule for tuning PD parameter the linearization of nonlinear system is proposed. In [11] model reference adaptive control gives good tracking performance of quadrotor but stability is not guaranteed.

Based on the review, this work will investigate the attitude control design of a quadrotor UAV. Adaptive backstepping technique is adopted to design the controller. The adaptive backstepping controller can asymptotically stabilize the attitude system. The remainder of this paper is organized as follows. In Section 2, the dynamics of the quadrotor, this is obtained by the Lagrange–Euler method. A Sliding surface adaptive backstepping-based control approach is presented in Section 3, and also the stability of closed-loop system is provided. In Section 4, simulation results of the designed control scheme to a quadrotor are presented. Section 5 presents some concluding remarks.

II. QUADROTOR DYNAMICS

The dynamics of quadrotor helicopters have been studied in detail by several groups [1],[14]. A simple, rigid-body model of the quadrotor is given,

$$\ddot{x} = (\cos\phi\sin\theta\cos\psi + \sin\phi\sin\psi)\frac{U_1}{m}$$

$$\ddot{y} = (\cos\phi\sin\theta\sin\psi - \sin\phi\cos\psi)\frac{U_1}{m}$$

ISSN (Online) 2393-8021
ISSN (Print) 2394-1588

$$\ddot{z} = -g + (\cos\phi\cos\theta)\frac{U_1}{m}$$
$$\ddot{\phi} = \dot{\theta}\dot{\psi}\left(\frac{I_y - I_z}{I_x}\right) - \frac{J_r}{I_x}\dot{\theta}\omega_R + \frac{L}{I_x}U_2$$
$$\ddot{\theta} = \dot{\phi}\dot{\psi}\left(\frac{I_z - I_x}{I_y}\right) + \frac{J_r}{I_y}\dot{\phi}\omega_R + \frac{L}{I_y}U_3$$
$$\ddot{\psi} = \dot{\phi}\dot{\theta}\left(\frac{I_x - I_y}{I_z}\right) + \frac{1}{I_z}U_4 \qquad (1)$$

where x, y, and z are the position of the center of mass in the inertial frame; ϕ, θ and ψ are the Euler angles, which describe the orientation of the body-fixed frame with respect to the inertial frame; m, I_x, I_y and I_z are the mass and moments of inertia of the quadrotor, respectively; L is the length from the rotors to the center of mass; and J_r and ω_R are the moments of inertia and angular velocity of the propeller blades. U_1, U_2, U_3 and U_4 are the collective, roll, pitch, and yaw forces generated by the four propellers.

To simplify equation (1)

$$a_1 = \frac{I_{yy} - I_{zz}}{I_{xx}} \quad a_3 = \frac{I_{zz} - I_{xx}}{I_{yy}} \quad a_5 = \frac{I_{xx} - I_{yy}}{I_{zz}}$$
$$a_2 = \frac{J_r}{I_{xx}} \quad a_4 = \frac{J_r}{I_{yy}} \quad b_1 = \frac{l}{I_{xx}}$$
$$b_2 = \frac{l}{I_{yy}} \quad b_3 = \frac{l}{I_{zz}}$$

Then state space representation is (2)

Where $x_1 \rightarrow x_6$ that correspond to $\phi, \dot{\phi}, \theta, \dot{\theta}, \psi, \dot{\psi}$ respectively.

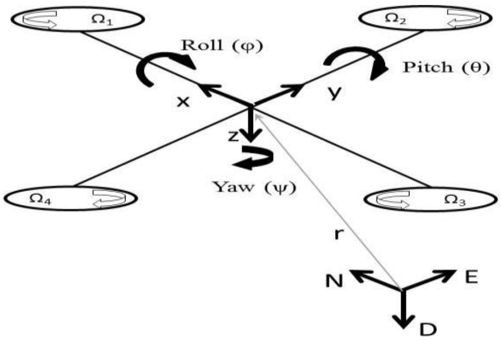

Fig1: Euler angles for Quadrotor UAV

$$\dot{x}_1 = \dot{\phi} = x_2$$
$$\dot{x}_2 = \ddot{\phi} = x_4 x_6 a_1 - x_4 \Omega_r a_2 + b_1 U_2$$
$$\dot{x}_3 = \dot{\theta} = x_4$$
$$\dot{x}_4 = \ddot{\theta} = x_2 x_6 a_3 + x_2 \Omega_r a_4 + b_2 U_3$$
$$\dot{x}_5 = \dot{\psi} = x_6$$
$$\dot{x}_6 = \ddot{\psi} = x_2 x_4 a_5 + b_3 U_4$$
$$\dot{x}_7 = \dot{z} = x_8$$
$$\dot{x}_8 = \ddot{z} = g - \frac{U_1}{m}(\cos x_1 \cos x_3)$$
$$\dot{x}_9 = \dot{x} = x_{10} \qquad (2)$$
$$\dot{x}_{10} = \ddot{x} = \frac{-U_1}{m}(\sin x_1 \sin x_5 + \cos x_1 \sin x_3 \cos x_5)$$
$$\dot{x}_{11} = \dot{y} = x_{12}$$
$$\dot{x}_{12} = \ddot{y} = \frac{U_1}{m}(\sin x_1 \cos x_5 - \cos x_1 \sin x_3 \sin x_5)$$

III SLIDING SURFACE ADAPTIVE BACKSTEPPING CONTROL DESIGN

In this section, a sliding surface is introduced into the adaptive back stepping approach is presented. This is because; quadrotor is an under-actuated system because it has six degrees of freedom but only four actual inputs. The six degrees of freedom include translational motion in three directions and rotational motion around three axes. The schematic configuration of a quadrotor is shown in fig: 1

For an underactuated system the adaptive backstepping control technique fails to stabilize the system. So a sliding surface is introduced, which forces the system to eliminate the disturbance then asymptotically stabilize the system.

(1) To obtain control input U_1

$$\dot{x}_7 = x_8$$
$$\dot{x}_8 = \hat{\phi}_9 - \hat{\phi}_{10} \cos x_1 \cos x_3 U_1$$

First Lyapunov function for the subsystem is

$$V_7 = \frac{1}{2}x_7^2 \qquad (3)$$

First derivative of the Lyapunov function is

$$\dot{V}_7 = x_7 \dot{x}_7 \qquad (4)$$

According to theory, system is asymptotically stable, the first derivative of Lyapunov function should be negative definite. So,

IARJSET

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ISSN (Print) 2394-1588

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$$\dot{x}_7 = x_8^{des} = -c_7 x_7 \quad (5)$$

Then (5) in (4)

$$\dot{V}_7 = -c_7 x_7^2 < 0 \quad (6)$$

Augmenting the Lyapunov function by adding the error variable and sliding surface

$$V_8(x,\tilde{\phi},s) = \frac{1}{2}x_7^2 + \frac{1}{2}x_8^2 + \frac{1}{2\gamma_9}\tilde{\phi}_9^2 + \frac{1}{2\gamma_{10}}\tilde{\phi}_{10}^2 + \frac{1}{2}s_4^2 \quad (7)$$

where,

$$s_4 = \frac{1}{2}e^2 \qquad e = x_7^{act} - x_7^{des}$$

$$\tilde{\phi}_9 = \phi_9 act - \hat{\phi}_9$$

$$\tilde{\phi}_{10} = \phi_{10} act - \hat{\phi}_{10}$$

By taking the derivative,

$$\dot{V}_8 = x_7\dot{x}_7 + x_8\dot{x}_8 + \frac{\tilde{\phi}_9\dot{\tilde{\phi}}_9}{\gamma_9} + \frac{\tilde{\phi}_{10}\dot{\tilde{\phi}}_{10}}{\gamma_{10}} + e\dot{e} \quad (8)$$

Where,

$$\dot{\tilde{\phi}}_9 = -\dot{\hat{\phi}}_9$$

$$\dot{\tilde{\phi}}_{10} = -\dot{\hat{\phi}}_{10}$$

Then the parameter adaptation laws are

$$\dot{\hat{\phi}}_9 = \gamma_9 x_8 \quad (9)$$

$$\dot{\hat{\phi}}_{10} = \gamma_{10} x_8 \cos x_1 \cos x_3 U_1$$

By proper selection of U_1, the overall Lyapunov function V_8 becomes negative definite which implies that x_7 tends to zero, then error also tends to zero asymptotically. Therefore,

$$U_1 = \frac{1}{\hat{\phi}_{10}\cos x_1 \cos x_3}[-\hat{\phi}_9 - x_7^{act} + x_7^{des} - c_8 x_8] \quad (10)$$

So,

$$\dot{V}_8 = -c_7 x_7^2 - c_8 x_8^2 < 0$$

(2) To obtain control input U_2

$$\dot{x}_1 = x_2$$

$$\dot{x}_2 = \hat{\phi}_1 U_2 - \hat{\phi}_2 x_4 \Omega_r + \hat{\phi}_3 x_4 x_6$$

First Lyapunov function for the subsystem is,

$$V_1 = \frac{1}{2}x_1^2 \quad (11)$$

First derivative of the Lyapunov function is

$$\dot{V}_1 = x_1\dot{x}_1 \quad (12)$$

Then to make derivative as negative definite,

$$\dot{x}_1 = x_2^{des} = -c_1 x_1 \quad (13)$$

Then (13) in (12) gives

$$\dot{V}_1 = -c_1 x_1^2 < 0 \quad (14)$$

Augmenting the Lyapunov function by adding the error variable and sliding surface

$$V_2(x,\tilde{\phi},s) = \frac{1}{2}x_1^2 + \frac{1}{2}x_2^2 + \frac{1}{2\gamma_1}\tilde{\phi}_1^2 + \frac{1}{2\gamma_2}\tilde{\phi}_2^2 + \frac{1}{2\gamma_3}\tilde{\phi}_3^2 + \frac{1}{2}s_1^2 \quad (15)$$

Where,

$$s_1 = \frac{1}{2}e^2 \qquad e = x_1^{act} - x_1^{des}$$

$$\tilde{\phi}_1 = \phi_1 act - \hat{\phi}_1$$

$$\tilde{\phi}_2 = \phi_2 act - \hat{\phi}_2$$

$$\tilde{\phi}_3 = \phi_3 act - \hat{\phi}_3$$

By taking the derivative,

$$\dot{V}_2 = x_1\dot{x}_1 + x_2\dot{x}_2 + \frac{\tilde{\phi}_1\dot{\tilde{\phi}}_1}{\gamma_1} + \frac{\tilde{\phi}_2\dot{\tilde{\phi}}_2}{\gamma_2} + \frac{\tilde{\phi}_3\dot{\tilde{\phi}}_3}{\gamma_3} + e\dot{e} \quad (16)$$

Where,

$$\dot{\tilde{\phi}}_1 = -\dot{\hat{\phi}}_1$$

$$\dot{\tilde{\phi}}_2 = -\dot{\hat{\phi}}_2$$

$$\dot{\tilde{\phi}}_3 = -\dot{\hat{\phi}}_3$$

Then the parameter adaptation laws are

$$\dot{\hat{\phi}}_1 = \gamma_1 x_2 U_2$$

$$\dot{\hat{\phi}}_2 = -\gamma_2 x_2 x_4 \Omega \quad (17)$$

$$\dot{\hat{\phi}}_3 = \gamma_3 x_2 x_4 x_6$$

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By proper selection of U_2, the overall Lyapunov function V_2 becomes negative definite which implies that x_1 tends to zero, then error also tends to zero asymptotically. Therefore,

$$U_2 = \frac{1}{\hat{\phi}_1}[\hat{\phi}_2 x_4 \Omega_r - \hat{\phi}_3 x_4 x_6 - x_1^{act} + x_1^{des} - c_2 x_2]$$

So,

$$\dot{V}_2 = -c_1 x_1^2 - c_2 x_2^2 < 0 \qquad (18)$$

(3) To obtain control input U_3

$$\dot{x}_3 = x_4$$

$$\dot{x}_4 = \hat{\phi}_4 - \hat{\phi}_5 x_2 \Omega_r + \hat{\phi}_6 x_2 x_6$$

First Lyapunov function for the subsystem is,

$$V_3 = \frac{1}{2} x_3^2 \qquad (19)$$

First derivative of the Lyapunov function is

$$\dot{V}_3 = x_3 \dot{x}_3 \qquad (20)$$

Then to make derivative as negative definite,

$$\dot{x}_3 = x_4^{des} = -c_3 x_3 \qquad (21)$$

Then (21) in (20) gives,

$$\dot{V}_3 = -c_3 x_3^2 < 0 \qquad (22)$$

Augmenting the Lyapunov function by adding the error variable and sliding surface

$$V_4(x,\tilde{\phi},s) = \frac{1}{2}x_3^2 + \frac{1}{2}x_4^2 + \frac{1}{2\gamma_4}\tilde{\phi}_4^2 + \frac{1}{2\gamma_5}\tilde{\phi}_5^2 + \frac{1}{2\gamma_6}\tilde{\phi}_6^2 + \frac{1}{2}s_2^2 \qquad (23)$$

Where,

$$s_2 = \frac{1}{2}e^2 \qquad e = x_3^{act} - x_3^{des}$$

$$\tilde{\phi}_4 = \phi_4 act - \hat{\phi}_4$$

$$\tilde{\phi}_5 = \phi_5 act - \hat{\phi}_5$$

$$\tilde{\phi}_6 = \phi_6 act - \hat{\phi}_6$$

By taking the derivative,

$$\dot{V}_4 = x_3 \dot{x}_3 + x_4 \dot{x}_4 + \frac{\tilde{\phi}_4 \dot{\tilde{\phi}}_4}{\gamma_4} + \frac{\tilde{\phi}_5 \dot{\tilde{\phi}}_5}{\gamma_5} + \frac{\tilde{\phi}_6 \dot{\tilde{\phi}}_6}{\gamma_6} + e\dot{e} \qquad (24)$$

where,

$$\dot{\tilde{\phi}}_4 = -\dot{\hat{\phi}}_4$$

$$\dot{\tilde{\phi}}_5 = -\dot{\hat{\phi}}_5$$

$$\dot{\tilde{\phi}}_6 = -\dot{\hat{\phi}}_6$$

Then the parameter adaptation laws are

$$\dot{\hat{\phi}}_4 = \gamma_4 x_4 U_3$$

$$\dot{\hat{\phi}}_5 = -\gamma_5 x_2 x_4 \Omega_r \qquad (25)$$

$$\dot{\hat{\phi}}_6 = \gamma_6 x_2 x_4 x_6$$

By proper selection of U_3, the overall Lyapunov function V_4 becomes negative definite which implies that x_3 tends to zero, then error also tends to zero asymptotically. Therefore,

$$U_3 = \frac{1}{\hat{\phi}_4}[\hat{\phi}_5 x_2 \Omega_r - \hat{\phi}_6 x_2 x_6 - x_3^{act} + x_3^{des} - c_4 x_4] \qquad (26)$$

So,

$$\dot{V}_4 = -c_3 x_3^2 - c_4 x_4^2 < 0$$

(4) To obtain control input U_4

$$\dot{x}_5 = x_6$$

$$\dot{x}_6 = \hat{\phi}_7 U_4 + \hat{\phi}_8 x_2 x_4$$

First Lyapunov function for the subsystem is,

$$V_5 = \frac{1}{2} x_5^2 \qquad (27)$$

First derivative of the Lyapunov function is

$$\dot{V}_5 = x_5 \dot{x}_5 \qquad (28)$$

Then to make derivative as negative definite,

$$\dot{x}_5 = x_6^{des} = -c_5 x_5 \qquad (29)$$

Then (29) in (28) gives

$$\dot{V}_5 = -c_5 x_5^2 < 0 \qquad (30)$$

Augmenting the Lyapunov function by adding the error variable and sliding surface

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$$V_6(x,\tilde{\phi},s)=\frac{1}{2}x_5^2+\frac{1}{2}x_6^2+\frac{1}{2\gamma_7}\tilde{\phi}_7^2+\frac{1}{2\gamma_8}\tilde{\phi}_8^2+\frac{1}{2}s_3^2 \quad (31)$$

Where,

$$s_3=\frac{1}{2}e^2 \qquad e=x_5^{act}-x_5^{des}$$

$$\tilde{\phi}_7=\phi_7act-\hat{\phi}_7$$

$$\tilde{\phi}_8=\phi_8act-\hat{\phi}_8$$

By taking the derivative,

$$\dot{V}_6=x_5\dot{x}_5+x_6\dot{x}_6+\frac{\tilde{\phi}_7\dot{\tilde{\phi}}_7}{\gamma_7}+\frac{\tilde{\phi}_8\dot{\tilde{\phi}}_8}{\gamma_8}+e\dot{e} \quad (32)$$

where,

$$\dot{\tilde{\phi}}_7=-\dot{\hat{\phi}}_7$$

$$\dot{\tilde{\phi}}_8=-\dot{\hat{\phi}}_8$$

Then the parameter adaptation laws are

$$\dot{\hat{\phi}}_7=\gamma_7x_6U_4$$
$$\dot{\hat{\phi}}_8=\gamma_8x_2x_4x_6 \quad (33)$$

By proper selection of U_4, the overall Lyapunov function V_6 becomes negative definite which implies that x_5 tends to zero, then error also tends to zero asymptotically.

Therefore,

$$U_4=\frac{1}{\hat{\phi}_7}[-\hat{\phi}_8x_4x_2-x_5^{act}+x_5^{des}-c_6x_6] \quad (34)$$

So,

$$\dot{V}_6=-c_5x_5^2-c_6x_6^2<0$$

IV. SIMULATION RESULTS

In this section, the results of simulation are presented in order to demonstrate the performance of the proposed controller. The simulation parameters are given in the table 1.

Table1: Quadrotor UAV model parameters

Parameters	Description	Value	Units
g	Gravity	9.81	m/s^2
m	Mass	.65	kg
L	Distance	.23	m
I_x	Roll Inertia	$7.5*10^{-3}$	kgm^2
I_y	Pitch Inertia	$7.5*10^{-3}$	kgm^2
I_z	Yaw Inertia	$1.3*10^{-3}$	kgm^2
J_r	Rotor Inertia	$6.5*10^{-5}$	kgm^2
b	Thrust factor	$3.13*10^{-5}$	
d	Drag factor	$7.5*10^{-7}$	

The simulation of roll angle variation with respect to time for the initial condition 0.1 is shown in fig 2. The simulation is done for $c_2=2, c_4=c_6=c_8=.01$ and $\gamma_1=\gamma_2=\gamma_3=\gamma_4=\gamma_5=\gamma_6=\gamma_7=\gamma_8=\gamma_9=\gamma_{10}=.01$.

The results show that, the controller forces the system to eliminate disturbance and system is regulated with 0.4% error. Similarly the roll angle variation with respect to time for the different initial conditions (0.2,0.3) are shown in fig 3 and fig 4 with same initial conditions gives better regulation with 0.4% error

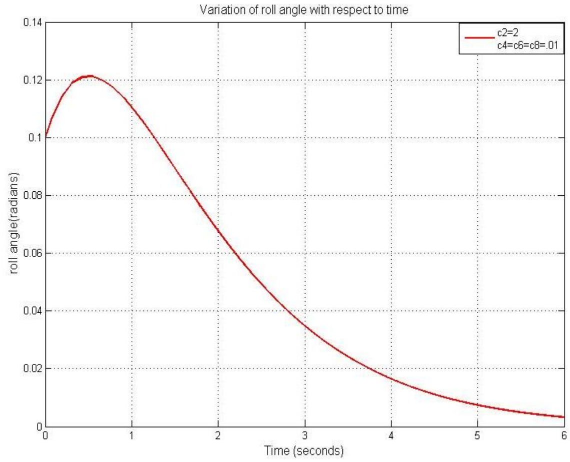

Fig2: Variation of roll angle with respect to time

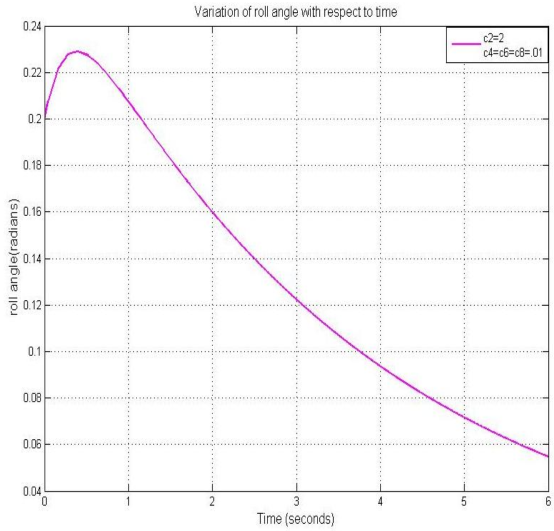

FIG3: Variation of Roll Angle With Respect To Time

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ISSN (Online) 2393-8021
ISSN (Print) 2394-1588

International Advanced Research Journal in Science, Engineering and Technology

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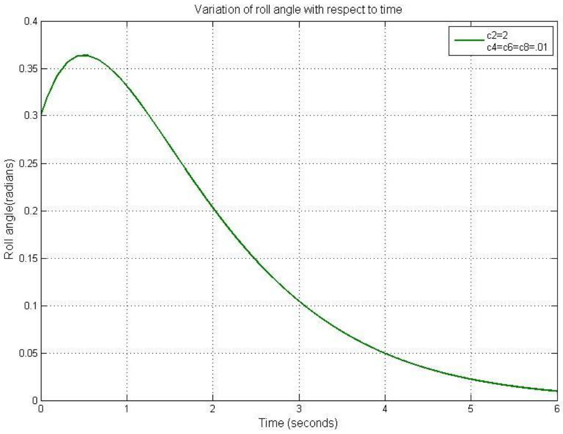

Fig4: Variation of roll angle with respect to time

The simulation of pitch angle variation with respect to time for the initial condition 0.1 is shown in fig 5. The simulation is done for $c_2 = c_4 = c_6 = 2, c_8 = .01$ and $\gamma_1 = \gamma_2 = \gamma_3 = \gamma_4 = \gamma_5 = \gamma_6 = \gamma_7 = \gamma_8 = \gamma_9 = \gamma_{10} = .01$. The result shows that, the controller forces the system to eliminate disturbance and system is regulated with .1% error. Similarly the pitch angle variation with respect to time for the different initial conditions(0.2,0.3)are shown in fig 6 and fig 7 with same initial conditions gives better regulation with 0.1% error.

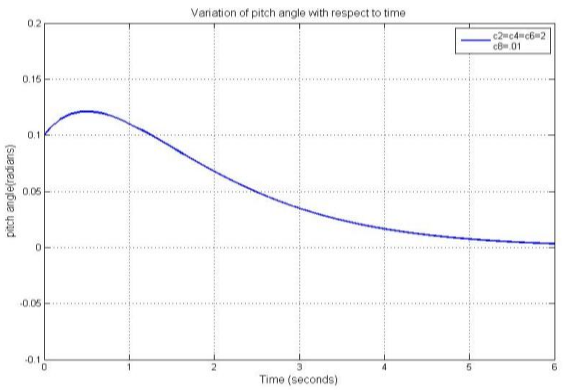

Fig5: Variation of pitch angle with respect to time

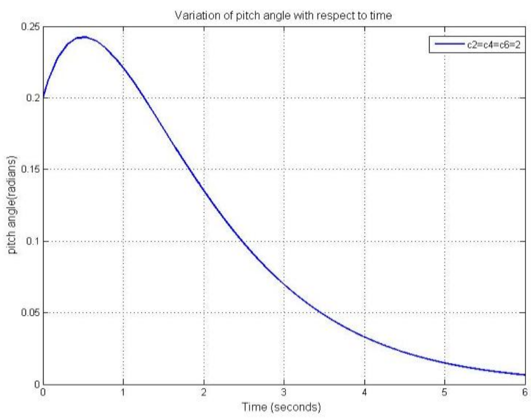

Fig6: Variation of Pitch angle with respect to time

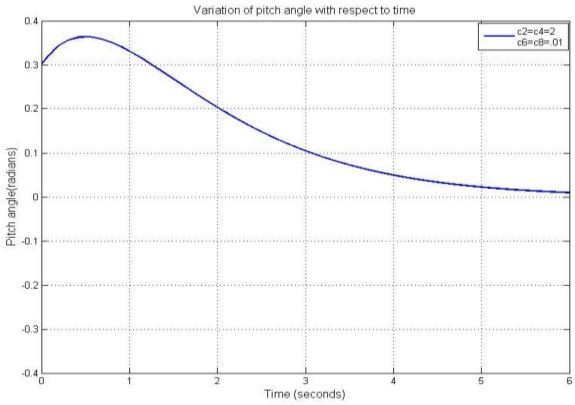

Fig7: Variation of Pitch angle with respect to time

The simulation of yaw angle variation with respect to time for the initial condition 0.1 is shown in fig 8. The simulation is done for $c_2 = c_4 = c_6 = 2, c_8 = .01$ and $\gamma_1 = \gamma_2 = \gamma_3 = \gamma_4 = \gamma_5 = \gamma_6 = \gamma_7 = \gamma_8 = \gamma_9 = \gamma_{10} = .01$. The results show that, the controller forces the system to eliminate disturbance and system is regulated with .1% error. Similarly the pitch angle variation with respect to time for the different initial conditions(0.2,0.3)are shown in fig 9 and fig 10 with same initial conditions gives better regulation with 0.1% error.

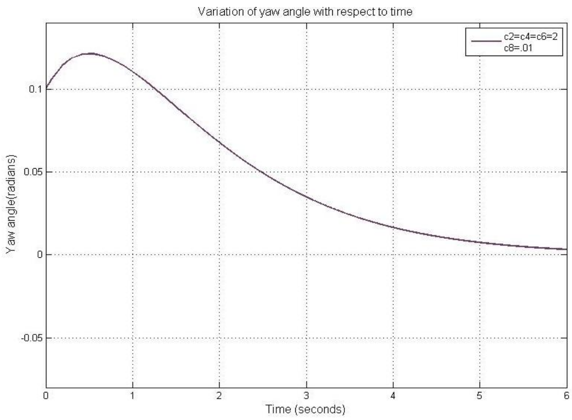

Fig8: Variation of yaw angle with respect to time

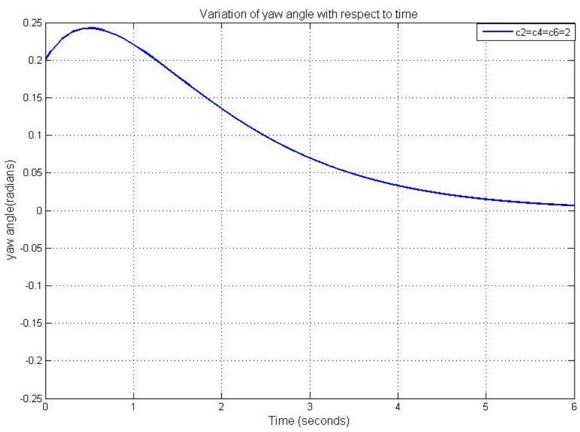

Fig9: Variation of yaw angle with respect to time

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ISSN (Online) 2393-8021
ISSN (Print) 2394-1588
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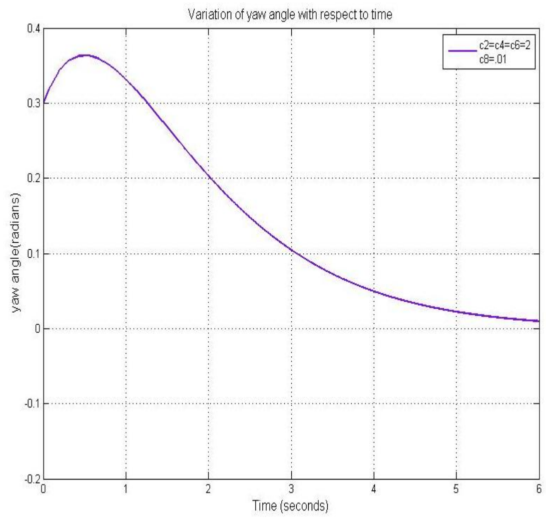

Fig10: Variation of yaw angle with respect to time

From the simulation results it is clear that, by using a sliding surface in to the adaptive backstepping approach, to control the quadrotor UAV gives better results. The error is very less and the system regulates with a steady-state error which is less than 1% for various initial conditions. So compared to simple adaptive backstepping approach [1] sliding surface in corporated adaptive backstepping is good.

V. CONCLUSION

A sliding surface- adaptive back stepping approach is employed to control and stabilize an under actuated quadrotor UAV system with unknown parameters. Based on Lyapunov stability theorem adaptive backstepping control laws are designed to ensure asymptotic stability of the system. A sliding surface is also incorporated into the system, to ensure better regulation. Validate the fact that the controller regulate satisfactorily. The steady-state error of 1% can be eliminated by an integral action.

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