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A Novel Robust Adaptive Backstepping Control Approach For UAV

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Abstract— Robust adaptive backstepping controller is designed for lateral track error control in an unmanned aerial vehicle (UAV). Backstepping method is a systematic design approach and recursive procedure by the choice of Lyapunov function, which guarantees asymptotic stability in the design phase itself. While using adaptive backstepping controller the main limitation is that there are many uncertain controller parameters which have to be estimated during the execution of the control algorithm. Due to parameter adaptation laws, there is very high rate of adaptation which is not all desirable. A robustness scheme is applied on the adaptation laws with the help of continuous σ- switching function to eliminate the problems that arise due to the high rate of adaptation. Software implementation is carried out using MATLAB Simulink. Simulation results show that the controller performs satisfactorily.

Keywords: Unmanned Aerial Vehicle; Lyapunov method; Lateral Track Error; Robust Adaptive Backstepping controller

I. INTRODUCTION

UAV stands for unmanned aerial vehicle which flies with no on-board human pilot and they perform missions that are currently hazardous or can cost lives. UAVs can be either autonomous or semi-autonomous. In autonomous, auto-pilot systems act as vehicle brain to accomplish the mission. In semi-autonomous, the mission is accomplished with the help of human pilot who controls the vehicle using a remote controller. Here a nonlinear model of autonomous UAV is discussed. The main objective is to control the lateral track error of the system. Lateral track error must be as small as possible during the flight.

In last few years, the control of UAV has been of great importance, due to its wide range of application such as remote sensing, forest fire detection, research, commercial, search and rescue operation, Archaeology, environment monitoring etc. It is a highly nonlinear system which will be affected by aerodynamic disturbances and uncertainties. It is very difficult to model the system and designing the controller is always a challenging task for the control engineers. Linearizing the system will cancel out useful nonlinearities, that will remit in an incomplete mode. To overcome the limitations of conventional linear designs, nonlinear design methods were introduced. Many nonlinear controllers were used for controlling the flight such as sliding mode controller, adaptive control and backstepping control. Here robust adaptive backstepping controller is introduced for the control of lateral track error. Backstepping is a systematic design procedure which interlaces the choice of Lyapunov function with the feedback design control will prove the asymptotic stability at the design step itself. Backstepping controller is used to stabilize the system, but the performance requirement will not be met as the time varying parameters in the system are not considered. The varying parameter is adapted to the system by using adaptive controller. Boundedness of closed loop system and convergence of tracking error to zero even in the presence of parametric uncertainties is achieved by using adaptive backstepping approach. The main drawback of this design method is that if the no of estimators are more that will result in a high rate of adaptation. In addition to that, real time implementation of the system will be more complex which is not at all desirable. To mitigate the problems arising due to the high rate of adaptation some kind of robustness measures must be incorporated along with the adaptation laws with the help of continuous switching function [1].

The main aim here is to minimize the cross track error or lateral deviation during the flight. Controlling of air vehicle from one waypoint to another with minimum cross track deviation (y) in the presence of disturbance is a challenging factor. The instantaneous normal displacement of the UAV from the desired track is defined as cross track error or lateral track error. In [2] a nonlinear sliding surface is proposed for lateral track control of aerial vehicle and the stability is guaranteed using the Lyapunov function. The system comprises of outer loop guidance and an inner control loop where the outer loop generates the roll angle command for the inner loop. Adaptive backstepping approach for the control of longitudinal dynamics of the aircraft is discussed in [3]. Velocity and flight path angle is controlled by considering the longitudinal dynamics of the UAV and the stability is verified using the Lyapunov stability theorem. For the tracking control of trajectory and the mission paths of the autonomous UAV, a linear quadratic regulator method is introduced in [4]. Cao Lijia et.al [5] considers the problem of nonlinear system with lump uncertainties and proposes a robust adaptive backstepping control method by using Lyapunov function techniques which is applied to the altitude control of an UAV. A command filtering approach is introduced in the design procedure to avoid the problem of explosion of complexity. The paper is organized as follows: in Section II the system modeling is explained. Adaptive Backstepping controller design and Robust Adaptive Backstepping controller design is presented in section III. In section IV, the simulation discussions about the designed control scheme for the UAV are presented. The section V concludes this paper.

II. SYSTEM MODELLING

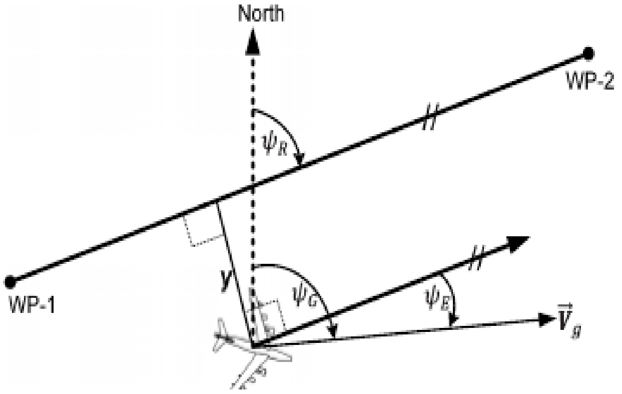

Fig 1: Control problem definition.

In the mission of the UAV, the desired path is defined by using number of waypoints. Here we are discussing about the control of UAV through the given mission. Let WP-1 and WP-2 shown in fig 1, be the two waypoints on the earth surface that describes the desired flight path. Our aim is to minimize the lateral deviation during flight from one way point to the other in the presence of disturbances. The angle of ground velocity V_g with respect to north is the course angle Ψ_G, which is a kinematic variable. It is also called velocity heading angle. In inner/outer loop design procedure, dynamics is considered in the inner loop and kinematics is considered for the outer loop. The desired heading angle Ψ_R be the angle of the line WP-1 and WP-2 with respect to north and the lateral track error is denoted by y. The intercept course or the heading error is the difference between actual velocity heading angle and the desired heading angle, $\Psi_E = \Psi_G - \Psi_R$. The main aim is to minimize the lateral track error y as small as possible i.e. $\Psi_E \approx 0$ when $y \approx 0$. In the circumstance of nonzero y, the control algorithm will handle Ψ_E by banking the vehicle to get y as zero. A component of aerodynamic lift is used by the aerial vehicles to correct the lateral track error by generating lateral acceleration. Rolling or banking of vehicle helps to produce the lateral acceleration.

Let we drop the subscript g from the ground velocity Vg and take only V for ground velocity. Equating vertical component of ground velocity to rate of change of lateral distance

$$\dot{y} = V\sin\Psi_E \qquad (1)$$

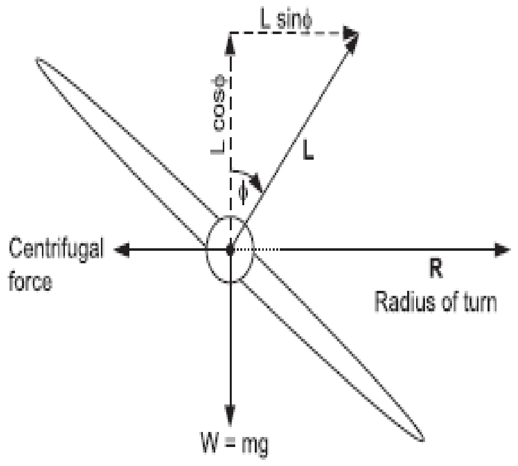

Fig 2: Component of lift during steady flight

During a steady coordinated turn, aircraft is banked at an angle ϕ as shown in fig 2. The vertical component of the lift balances the weight of the aircraft, whereas horizontal component balances the centrifugal force.

$$L\cos\phi = mg \qquad (2a)$$

$$L\sin\phi = \frac{mV^2}{R} \qquad (2b)$$

Where ϕ is the bank angle, L is the lift, m is the mass of the vehicle, g is the gravitational acceleration, V is the ground speed and R is the radius of turn

From (2a) and (2b)

$$\tan\phi = \frac{V^2}{Rg} \qquad (3)$$

During the steady turn, relation between angular velocity and tangential velocity in a circular motion is given by

$$V = R\Psi_G \qquad (4)$$

$$\tan\phi = \frac{V\dot{\psi}_G}{g} \qquad (5)$$

Assuming inner control loop dynamics will be faster than outer loop, $\phi \approx \phi_R$ and reference path course will not change quickly i.e. $\dot{\Psi}_R \approx 0$; $\dot{\Psi}_E = \dot{\Psi}_G$. Therefore the equation (5) become

$$\tan\phi_r = \frac{V\dot{\Psi}_E}{g} \qquad (6)$$

Let u = $\tan\phi_r$ be the control input.

$$u = \frac{V\dot{\psi}_E}{g} \qquad (6a)$$

Then the state equations are

$$\dot{y} = V\sin\Psi_E \qquad (7)$$

$$\dot{\Psi}_E = \frac{g}{V}u \qquad (8)$$

III.ROBUST ADAPTIVE BACKSTEPPING CONTROLLER DESIGN

(1) Adaptive backstepping controller design

$$\dot{x}_1 = V\sin x_2 \qquad (9)$$

$$\dot{x}_2 = \frac{g}{V}u \qquad (10)$$

Assigning $\frac{g}{V}$ a constant but unknown parameter as ϕ therefore equation (10) becomes

$$\dot{x}_2 = \phi u \qquad (11)$$

Let Lyapunov function be

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

$$\dot{V}_1(x) = x_1\dot{x}_1 = x_1 V\sin x_2$$

$$x_2^{des} = \sin^{-1}\frac{1}{V}(-c_1x_1)$$

Therefore $\dot{V}_1(x) = -c_1x_1^2 < 0$

Since the first derivative of the Lyapunov function for the subsystem is negative definite, asymptotic stability is guaranteed by design.

Here, $x_2^{des} = \propto(x)$ is called as the stabilizing function. Let an error variable defined as $z = x_2 - x_2^{des}$ for a change of coordinates and let $\tilde{\phi}$ be the estimation error, ϕ be the actual value, $\hat{\phi}$ is the estimate & γ is the adaptation gain.

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

Let the augmented Lyapunov function be

$$V_2(x) = \frac{1}{2}x_1^2 + \frac{1}{2}z^2 + \frac{1}{2\gamma}\tilde{\phi}^2$$

$$\dot{V}_2(x) = x_1\dot{x}_1 + z\dot{z} + \frac{1}{\gamma}\tilde{\phi}\dot{\tilde{\phi}}$$

$$\dot{V}_2(x) = -c_1x_1^2 + z\left(u\hat{\phi} + \frac{c_1}{V\sqrt{1-x_1^2}}\right) + \frac{\tilde{\phi}}{\gamma}\left(z.u.\gamma - \dot{\hat{\phi}}\right)$$

The parameter adaptation law is given by

$$\dot{\hat{\phi}} = z.u.\gamma \qquad (12)$$

and the control input is given by

$$u = -c_2z - \frac{c_1}{V\sqrt{1-x_1^2}} \qquad (13)$$

With the help of (12) and (13), the first derivative of the augmented Lyapunov function becomes negative definite.

$$\dot{V}_2(x) = -c_1x_1^2 - c_2z^2 \qquad (14)$$

Equation 12 & 13 will ensure the stability of the system.

(2) Robust adaptive backstepping controller design

Even though Adaptive backstepping controller provides an effective tool for dealing with the uncertainties of the system, low frequency disturbance as well as high frequency measurement noises may still take a roll on the performance of the system. The stability of the system is affected due to the high rate of adaptation and these disturbances. To eliminate the problems arising, a continuous $\sigma-$ switching surface is in cooperated with the parameter adaptation law as

$$\dot{\hat{\phi}} = z.u.\gamma - \gamma\sigma_{\phi s}\hat{\phi} \qquad (15)$$

Where

$$\sigma_{\phi s} = f(x)\begin{cases} 0, & if\ |\hat{\phi}| < \phi_0 \\ \sigma_{\phi 0}\left[\frac{|\hat{\phi}|-\phi_0}{|\hat{\phi}|}\right], & if\ \phi_0 < |\hat{\phi}| < 2\phi_0 \\ \sigma_{\phi 0}, & if\ |\hat{\phi}| \geq 2\phi_0 \end{cases} \qquad (16)$$

IV. SIMULATION RESULTS AND DISCUSSIONS

In this section the performance of robust adaptive backstepping controller for the lateral track error control has been verified in the simulation studies. In table 1 the values of parameters which are used for the simulation is shown

Table 1: Simulation Parameter Values

Parameter	Description	Value	units
m	Aircraft Mass	0.568	Kg
Q	Dynamic pressure	80.05	
S	Wing area	0.2712	m^2
I_x	Moment of inertia around x-axis	0.14641	$K_g.m^2$
I_y	Moment of inertia around y-axis	0.11995	$K_g.m^2$
I_z	Moment of inertia around z-axis	0.26547	$K_g.m^2$
g	Acceleration due to gravity	9.8	m/s^2
m_a	Empty weight	0.0568	Kg
AR	Aspect ratio	2.42	
V_a	Aircraft velocity	11.432	m/s

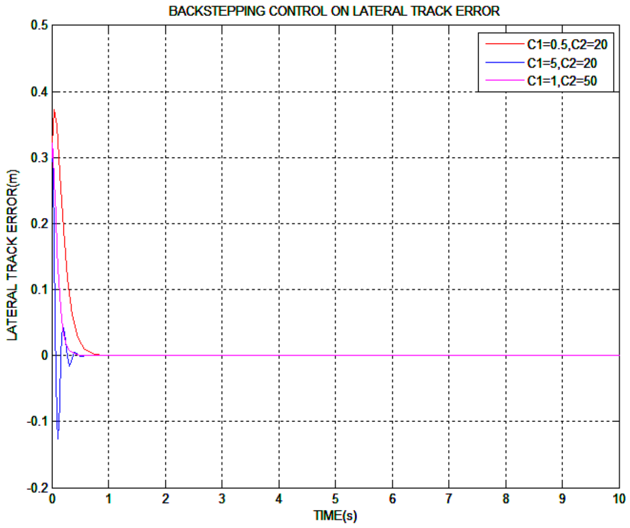

Fig 3: Variation of lateral track error with respect to time (BC)

The simulation of backstepping control lateral track error variation with respect to time with the initial condition 0.3 is shown in the fig 3. From the figure we can infer that there is 60% overshoot about the mean equilibrium position for low values of gain (C1= 0.5,C2=20) and if we increase the gain value to (C1=1,C2=50) the performance is satisfactory. As we goes on increasing the gain value to (C1=5,C2=20) undershoots and oscillations also increases.

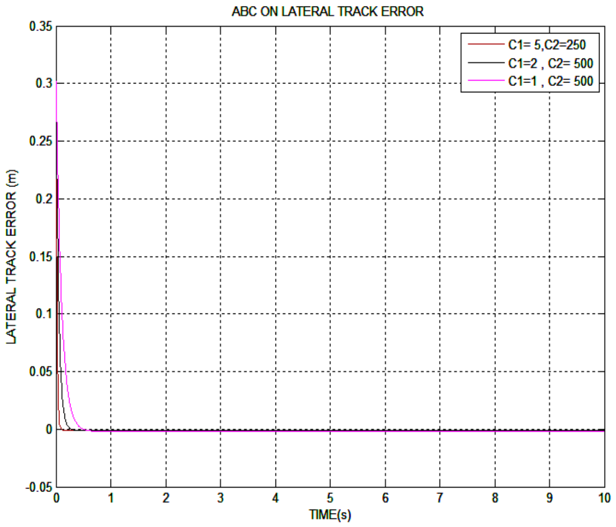

Fig 4: Variation of lateral track error with respect to time (ABC)

The overshoots and undershoots can be neglected by using adaptive backstepping controller as shown in fig4 where 0.3 is the initial condition. From the simulation results, we can say that the system converges to zero. i.e. regulation holds good. And we can obtain better performance while increasing the gain values.

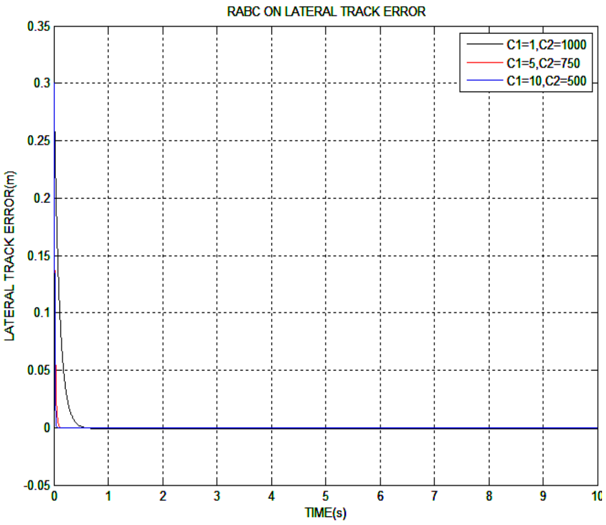

Fig 5: Variation of lateral track error with respect to time (RABC)

Regulation graph of robust adaptive backstepping controller for the control of lateral track error is shown in fig 5 with initial condition 0.3. Fig 6 and fig 7 shows that the system can track a reference input. The initial condition is given as 0.3 for both ABC and RABC, and plotted for different gain values.

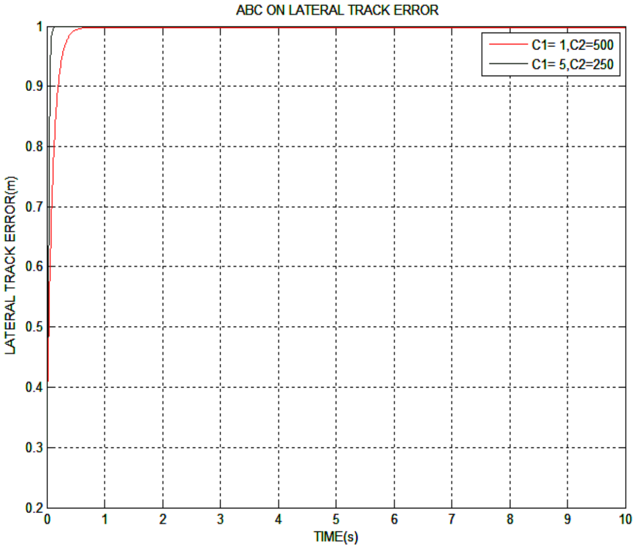

Fig 6: Variation of lateral track error with respect to time (ABC)

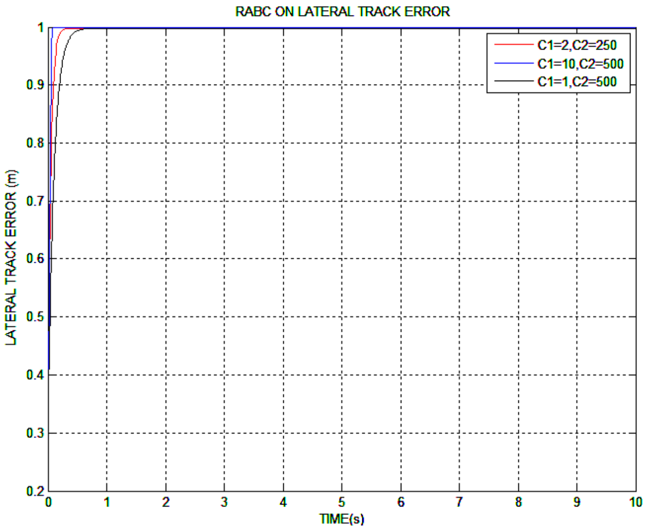

Fig 7: Variation of lateral track error with respect to time (RABC)

V.CONCLUSIONS

The UAV is a highly coupled, nonlinear system which is stabilized by using the robust adaptive backstepping controller. The lateral track error is minimized even in the presence of external disturbances and uncertainties. Simulation results show that the proposed controller performs well than the backstepping controller and adaptive backstepping controller. Proposed controller ensures better regulation and tracking.

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