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A Simplified Adaptive Backstepping Control of Aircraft Lateral/Directional Dynamics

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Abstract: A simple approach is proposed in this paper to control lateral/directional dynamics of Unmanned Aerial Vehicles (UAVs). The approach uses backstepping technique to design a lateral/directional controller. As the aerodynamics coefficients are not accurately available for the whole flight regime, we propose an adaptive design to learn and control unknown dynamics. The proposed approach provides satisfactory performance in tracking reference in roll rate using aileron and in maintaining sideslip angle to zero value using rudder. The design is validated on the six degrees of freedom model with the effect of actuator saturation.

Keywords: Flight control system, Nonlinear control, State feedback, Backstepping, Lyapunov stability, Adaptive control.

1. INTRODUCTION

Interest in use of autonomous flight vehicles for defence as well as commercial applications has increased tremendously in recent years. The absence of onboard qualified pilot in case of Unmanned Aerial Vehicles (UAVs) offer the advantage of reduction in weight and cost, and plays a vital role in hazardous environments that are dangerous to human life. However, the field of application of UAVs poses strict requirement on the performance of Flight Control System (FCS) as it acts as brain of these vehicles. Hence, the advantage that UAVs offer comes at the cost of incorporating more robust and reliable control system.

Conventional linear control techniques have been utilized for FCS (McLean [1990]) to exploit well developed linear analysis tools. Although, linear controllers are easy to implement and provide satisfactory performance, their performance degrades if flight condition deviates from the nominal conditions. Various Gain scheduling methods (Nichols et al. [1993], Rugh and Shamma [2000], Shue et al. [1997]) have been developed to include multiple trimmed flight conditions so that control can be achieved throughout the flight envelope. However, computation of multiple controllers is very time consuming and requires estimation of stability and control derivatives for significant number of flight conditions.

Nonlinear control techniques provide advantage of increase in performance as well as reduction in development time by designing a single controller for the whole flight regime rather than designing multiple linear controllers for different operating points. Out of various nonlinear control techniques, feedback linearization is the most widely applied method (Meyer et al. [1984], Lane and Stengel [1986], Ochi and Kanai [1991], and Enns et al. [1994]) which relies on cancellation of all the nonlinearities to transform a nonlinear system into a system with linear dynamics. Extensive research has been done on this technique in the past decades (Isidori [1989], Nijmeijer and van der Schaft [1990]). However, the technique suffers from several drawbacks as it requires complete knowledge of nonlinearities present in the plant and performs cancellation of all the nonlinearities. Due to cancellation, large control input may be required. Another drawback of feedback linerizaion is that the approach is vulnerable to modeling errors and parametric uncertainty. In the case of FCS, a precise aerodynamic and propulsive model is not exactly known, thus the controller must be robust against variations in these parameters. Futhermore, an adpative strategy is required to learn unknown dynamics and to control it.

Variety of robust nonlinear control schemes have been presented in the literature which do not require cancellation of all the nonlinearities. Backstepping is one such approach and has been discussed in Härkegård and Glad [2001] and Ismail et al. [2014]. Backstepping provides a novel way of recursively designing a controller by considering some of the states as virtual control input. In this way, it simplifies the control design process for higher order nonlinear systems such as an aircraft. Thunberg and Robinson [2008] and Knöös et al. [2012] presented comparison between Nonlinear Dynamic Inversion (NDI), backstepping, and other cascade design methods for nonlinear flight controller designs.

A nonlinear control method which incorporates robustness as well as adaptive control approach is adaptive backstepping design (Krstić et al. [1995]). It is a Lyapunov based recursive design that performs online estimation of parameters to deal with parametric uncertainities. Adaptive Backstepping control of longitudinal flight dynamics of UAVs is discussed in Gavilan et al. [2011]. A similar approach along with control allocation has been implemented

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in Härkegård [2003]. A longitudinal along with auto landing control using similar approach has been discussed in Ju and Tsai [2009]. In Gavilan et al. [2014], adaptive Control for aircraft longitudinal dynamics with thrust Saturation has been discussed to incorporate physical limits of the engines. Most of the FCS designs mentioned so far discuss control of longitudinal dynamics. In the case of lateral/directional dynamics, the coupled nature of roll, yaw, and sideslip dynamics poses bigger challenge in designing a control system.

Farrell et al. [2005] developed an adaptive backstepping flight controller using adaptive function approximation based on Lyapunov stability, including the effect of actuator saturaion and rate limits. A nonlinear flight control design using constrained adaptive backstepping for F-16/MATV has been discussed in Sonneveldt et al. [2007] which tracks reference trajectories in total velocity, angle of attack, stability axes roll rate, and sideslip angle. It utilizes the learning capability of neural network to estimate uncertain forces and moments derivatives.

In this paper, an adaptive backstepping scheme is proposed which utilizes mathematical structure of the system under certain assumptions. Since only few aerodynamic coefficients are assumed to be known, a parameter adaptation law is designed for online estimation of remaining parameters. The advantage of this approach is that the resulting control law is explicit and simple, and does not require much onboard computational power.

The paper is structured as follows. Aircraft dynamics model and control objective are discussed in Section 2. The control strategy is presented in Section 3, which begins with the discussion of adaptive backstepping approach, then derivation of sideslip and roll rate controllers are presented. Section 4 presents simulation results. Section 5 concludes the paper and discusses some future avenues.

2. UAV DYNAMICS AND CONTROL OBJECTIVES

In this section, we initially give equations of motion for lateral/directional dynamics. Then, we define the control objective to maintain aircraft in cruise and then coordinated turn.

Let $(v, \phi, p, r) \in \mathbb{R}^4$ be the state vector where v is the body fixed component of the total velocity along body fixed Y-axis, ϕ is the bank angle, and p and r are the body axis roll and yaw rates, respectively. Let $(\delta_a, \delta_r) \in \mathbb{R}^2$ be the control input vector where δ_a and δ_r are the aileron and rudder control surfaces deflections, respectively. Fig. 1 represents the definition of axes system and angles used.

The equations of motion for lateral/directional dynamics are as follows (Stevens and Lewis [2003])

$$\dot{v} = -ru + pw + g\sin\phi\cos\theta + \frac{Y}{m} \tag{1}$$

$$\dot{\phi} = p + \tan\theta(q\sin\phi + r\cos\phi) \tag{2}$$

$$\dot{p} = (c_1 r + c_2 p)q + c_3\bar{L} + c_4 N \tag{3}$$

$$\dot{r} = (c_8 p - c_2 r)q + c_4\bar{L} + C_9 N \tag{4}$$

where m represents the mass of aircraft, V is the total velocity, α is the angle of attack, θ is the pitch angle, Y, $\bar{L}$, and N are the aerodynamic side force, rolling, and yawing moment respectively, and

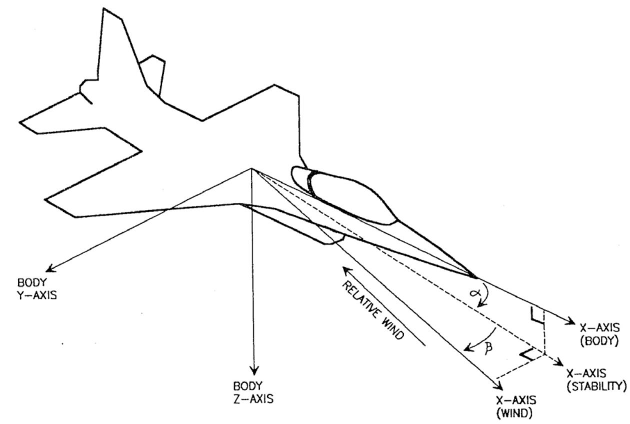

Fig. 1. Definition of aircraft axes and angles

$$c_1 = (I_y - I_z)I_z - I_{xz}^2/\Delta, \quad c_2 = (I_x - I_y + I_z)I_{xz}/\Delta$$
$$c_3 = I_z/\Delta, \quad c_4 = I_{xz}/\Delta, \quad c_8 = (I_x - I_y)I_x + I_{xz}^2/\Delta$$
$$c_9 = I_x/\Delta \quad \text{and} \quad \Delta = I_x I_z - I_{xz}^2$$

where I_x, I_y, I_z and I_{xz} represents moments of inertia about body fixed x, y, z axes and cross-product of inertia respectively.

The body fixed components of velocity i.e. u, v, and w are related to α, β, and V as follows

$$u = V\cos\alpha\cos\beta, \quad v = V\sin\beta, \quad w = V\sin\alpha\cos\beta$$

In this paper, we consider designing a lateral/directional controller for an aircraft/UAV performing coordinated turns. Thus, the control objective is to make aircraft follow references in sideslip angle and roll rate command. However, we aim here to design a simplified nonlinear lateral/directional controller which gives satisfactory performance in sideslip and roll rate dynamics when applied to complete six-degree of freedom (six-DOF) aircraft model. In this work, we propose a control law design using adaptive backstepping scheme (Krstić et al. [1995]). To utilize the recursive design approach of backstepping, we need to represent the dynamic equations in a strict feedback form. For this purpose, we make the following assumptions.

Assumption 1. i). Aerodynamic angles i.e. α and β remain small such that $\sin(x) \approx x$ and $\cos(x) \approx 1$. ii). Roll rate p remains small. iii). Total velocity V is maintained constant. iv). Pitch rate q remains very small during lateral/directional maneuver. v). I_{xz} is small.

Under Assumption 1, the equations of motion (1)-(4) can be written as

$$\dot{\phi} = p + r\tan\theta\cos\phi \tag{5}$$

$$\dot{p} = c_3\bar{L}(\delta_a) \tag{6}$$

$$\dot{\beta} = -r + \frac{1}{V}\left[g\sin\phi\cos\theta + \frac{Y(\beta)}{m}\right] \tag{7}$$

$$\dot{r} = C_9 N(\delta_r) \tag{8}$$

The aerodynamic forces and moments are computed through their non-dimensional coefficients as