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Adaptive Longitudinal Control of UAVs with Direct Lift Control

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Abstract: In this paper, a nonlinear control technique based on Direct Lift Control (DLC) is proposed to control the longitudinal dynamics of unmanned aerial vehicles. The baseline controller is designed using a nonlinear dynamic inversion technique. As the effectiveness of the baseline controller depends on the knowledge of aircraft dynamic model and aerodynamic coefficients, which is difficult to be found accurately for the whole flight regime, the baseline controller is augmented with a neuro-adaptive controller. The approach uses a single layer neural network to learn the unknown dynamics and an adaptive law is employed to ensure that the UAV behaves in the desired manner. Lyapunov theory is used to show that the approximated dynamics remains bounded. Simulations results are presented to demonstrate the effectiveness of the proposed design on a six degrees of freedom model.

Keywords: DLC, Flap, Dynamic inversion, Adaptive control, Neural network.

1. INTRODUCTION

Over the last few years, there has been a marked rise in the popularity of Unmanned Aerial Vehicles (UAVs). This is primarily due to continuous decline in the prices of electronics hardware due to availability of cheaper technologies for their manufacturing. As a result, more and more people have been using these vehicles as a hobby sport. Due to rising popularity, competitions like SAE Aerodesign, AIAA DBF, etc. have also started which test designing, construction and flying skills of the participants. Though recently quadrotors have also come up as a competitor, fixed wing vehicles are still much simpler both in design and construction. Hence, fixed-wing UAVs are still most widely used. Recently they have also been employed for surveillance, border patrol and criminal investigation by different militaries and also for peaceful purposes like forest fire detection, crop monitoring, etc. For such applications, there is an urgent need of more versatile, resilient, and robust controllers.

To bring out the best in vehicle's performance, it is necessary to use the knowledge of its dynamics. However, nonlinearities in the aircraft dynamic make control design quite challenging. For this reason, variety of controllers have been developed by linearizing the model about several operating points and then combining the different controllers using gain scheduling method. Linear control design such as PID (Graham et al. (1973)), Gain Scheduling (Rugh and Shamma (2000)), and LQR (Hajiyev et al. (2013)) are the widely applied techniques for flight control system design because of the availability of well-established linear analysis tools. However, linear technique requires knowledge of aircraft parameters under different operating conditions and hence makes the control design task very tedious.

Nonlinear control techniques offer advantage over linear techniques as a single controller is designed for whole flight regime considering complete nonlinear dynamics of aircraft and hence it reduces the development time and improves the control performance. Nonlinear dynamic inversion (NDI) is a well-studied technique for flight control design (Enns et al. (1994)). It is one of the best control strategy for vehicles with known dynamics. However, its performance degrades under modeling and parametric uncertainty. Various control techniques have been utilized in the literature to add adaptive capability to the flight control system, such as adaptive backstepping (Härkegård (2003)), constrained adaptive backstepping (Sonneveldt et al. (2007)) and neuro-adaptive (Byoung and Anthony (1997)) etc.

Direct lift control (DLC) refers to the use of flaps in addition to elevator and thrust control for controlling the longitudinal dynamics of an aircraft. Incorporating flap as an additional control mechanism has the advantage that it directly affects the lift on the wings instead of indirectly affecting it through generation of pitching moment or speed (using elevators and throttle) (Fitzgerald (2004)). Although DLC has not been much widely used in practice, it is very effective in terms of control authority (Lee and Johannes (1969)). It also overcomes the problems associated with delay in lift build-up, and excessive pitch rate overshoot associated with the conventional elevator control.

Utilizing the simplicity of dynamic inversion based design and advantage of DLC, we propose a longitudinal controller design for fixed wing UAVs with flaps as well as

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without flaps. As the exact aircraft dynamics and parameters under different operating conditions are not exactly known, which results in degraded control performance, we augment the baseline dynamic inversion controller with neuro-adaptive technique (Padhi et al. (2007)). This provides robustness against parameter uncertainty as it adds online learning capability to learn changes in the UAV dynamics.

The structure of the rest of the paper is as follows. The longitudinal dynamics and problem statement are given in Section 2. The mathematical details of nonlinear dynamic inversion (NDI) and neuro-adaptive techniques are briefly described in Section 3. The control design with and without flap is done in Section 4. The adaptive law for DLC is also developed in this section. Numerical results are presented in Section 5. Finally, concluding remarks are presented in Section 6.

2. PROBLEM STATEMENT

In this section, we initially describe a mathematical model of longitudinal dynamics of a UAV and then formally present the problem statement.

Let (v, γ, θ, h) be the state vector, where v is the absolute air speed, γ is the flight path angle, θ is the pitch angle, and h is the height (or altitude). The following are the equations of motion of the UAV (Stevens and Lewis (2003)):

$$\dot{v} = \frac{1}{m}(F_T \cos\alpha - D - W \sin\gamma) \tag{1}$$

$$\dot{\gamma} = \frac{1}{mv}(L + F_T \sin\alpha - W \cos\gamma) \tag{2}$$

$$\ddot{\theta} = \frac{1}{I_{yy}}(M) \tag{3}$$

$$\dot{h} = v \sin\gamma \tag{4}$$

where, F_T is the thrust, while L, D, and M are aerodynamic Lift, Drag and Pitching Moment (about y-axis), respectively. m and I_{yy} are the mass and inertia of the aircraft and α represents the angle of attack.

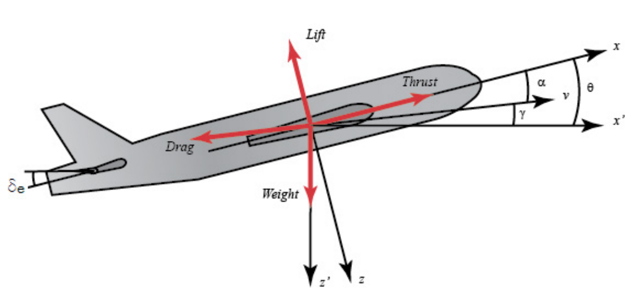

Fig. 1. Definition of forces, moment and angles

As known, L, D, and M are expressed by the following aerodynamic equations.

$$L = QSC_L, \quad D = QSC_D, \quad M = QS\bar{c}C_M \tag{5}$$

where, $Q = \frac{1}{2}\rho v^2$ is the dynamic pressure, S is the projected wing area, and $\bar{c}$ is the mean chord. C_L, C_D, and C_M are the non-dimensional lift, drag, and pitching moment coefficients, respectively, which are approximated by the following equations for an aircraft with flaps.

$$C_L = C_{L_0} + C_{L_\alpha}\alpha + C_{L_{\delta_e}}\delta_e + C_{L_{\delta_f}}\delta_f \tag{6}$$

$$C_D = C_{D_0} + kC_L^2 \tag{7}$$

$$C_M = C_{M_0} + C_{M_\alpha}\alpha + C_{M_q}\frac{q\bar{c}}{2v} + C_{M_{\delta_e}}\delta_e + C_{M_{\delta_f}}\delta_f \tag{8}$$

where, δ_e and δ_f are the elevator and flap deflection angle respectively. In case of aircraft with no flaps, the aerodynamic model for Lift and Pitching Moment do not contain δ_f term.

For thrust (F_T) we use the following model, which is valid for propeller driven electric aircrafts.

$$F_T = \frac{1}{2}Th(\rho S_{prop}C_{prop} + v^2/{k_{motor}}^2) \tag{9}$$

where, Th is the throttle input, S_{prop} and C_{prop} are propeller parameters, and k_{motor} is motor parameter.

The objective is to design a longitudinal control to follow the references velocity and altitude commands precisely under the parameters uncertainty of the UAV model.

3. PRELIMINARY

In this section, we present general theory of nonlinear dynamic inversion(NDI)(Enns et al. (1994)) and neuro-adaptive approach (Padhi et al. (2007)) in brief. The approaches will be use in the next section to develop an adaptive longitudinal controller of UAVs.

3.1 Nonlinear Dynamic Inversion (NDI)

Dynamic inversion is a well-established nonlinear control technique to design controllers for nonlinear systems. Consider a class of nonlinear dynamical system given as follows

$$\begin{aligned} \dot{X} &= f(X) + [g(X)]\,U \\ Y &= h(X) \end{aligned} \tag{10}$$

This form of state equations is known as control affine form as control appears linearly in the state equation. It is observed that the UAV dynamics can be written in the control-affine form of Eq. (10). In general, the objective is to control a subset of the state and/or a combination of states. Toward this, we write the output dynamics as

$$\dot{Y} = f_Y(X) + g_Y(X)\; U \tag{11}$$

where $f_Y(X) \triangleq \left[\frac{\partial h}{\partial X} f(X)\right]$ and $g_Y(X) \triangleq \left[\frac{\partial h}{\partial X}\right][g(X)]$. Generally, the objective of control to drive the output state, Y, to some desired state, Y^*. For this purpose, the control is synthesized by choosing the first order stable error dynamics as follows

$$\dot{E} + KE = 0 \tag{12}$$

where $E(t) \triangleq [Y(t) - Y^*(t)]$ and K is a fixed gain matrix. Note that one of relatively easy way to choose K = $\text{diag}\left[\frac{1}{\tau_1}, \frac{1}{\tau_2}....\frac{1}{\tau_i}....\frac{1}{\tau_p}\right]$, here τ_i is the time constant.

Substituting Eq.(11) in Eq.(12) and carrying out the necessary algebra to solve for control, we get

$$U = [g_Y(X)]^{-1}\left(\dot{Y}^* - K(Y - Y^*) - f_Y(X)\right) \tag{13}$$

Note that the dynamic inversion approach requires complete knowledge of the system model. If there are modeling