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Engineering Notes

Nonlinear Hierarchical Flight Controller for Unmanned Rotorcraft: Design, Stability, and Experiments

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I. Introduction

ALTHOUGH the research on unmanned aerial vehicles (UAVs) goes back to the last decade, the UAV control has a rich literature with different control techniques. Conventional approaches to UAV flight control involve dynamics linearization about a set of preselected equilibrium conditions or trim points. Then, many linear control techniques, such as proportional integral derivative or linear quadratic regulator controllers, can be applied. However, these approaches suffer from performance degradation when the aircraft moves away from a design trim point. Hence, gain scheduling is usually required to obtain acceptable performance. The main drawback of this approach is the severe tradeoff between control performance and the number of required trim points.

To overcome some of the limitations and drawbacks of the previous linear approaches, a variety of nonlinear flight control techniques have been developed. Among these, feedback linearization [1], model predictive control [2], dynamic inversion [3], adaptive control [4], robust control [5], backstepping [6], and nested saturation [7] techniques have received much of the attention and showed great promise. In actual flight and aerospace applications, the separate inner- and outer-loop approach is more commonly taken because it is usually simpler and results in good flight performance. In designing these practical controllers, the conventional conceptual separation between the position (outer loop) and the orientation (inner loop) is made. Most existing inner- and outer-loop controllers suffer from the lack of stability analysis and robustness with respect to model inversion errors and coupling terms. Our objective is to design a multiple-input/multiple-output nonlinear flight controller that performs well in practice while ensuring the asymptotic stability of the closed-loop system.

In this Note, we present the main steps for designing a hierarchical flight controller using the inner- and outer-loop control scheme. The proposed control system is based on the nonlinear model of rotorcraft UAVs and considers a system's nonlinearities as well as coupling between the rotational and translational dynamics. By exploiting its structural properties, the standard mathematical model of rotorcraft UAVs has been transformed into two cascaded linear subsystems that are coupled by a nonlinear interconnection term. Partial passivation design has been used to synthesize control laws for each subsystem, thereby resulting in an outer loop with slow dynamics that controls the position and an inner loop with fast dynamics that controls the orientation. The asymptotic stability of the entire connected system is proven by exploiting the theories of systems in cascade. The resulting nonlinear controller is thus easy to implement and tune, and it guarantees the asymptotic stability of the closed-loop system.

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II. Nonlinear Hierarchical Controller: Design and Stability

The dynamics of small and lightweight rotorcraft UAVs such as the quadrotor helicopter can be represented by the following mathematical model [7,8], in which rotor dynamics, gyroscopic effects, and blade flapping can be neglected because they do not affect the overall dynamics of the system:

$$\begin{cases} \ddot{\xi} = \frac{1}{m} u R e_z - g e_z \\ M(\eta)\ddot{\eta} + C(\eta, \dot{\eta})\dot{\eta} = \Psi(\eta)^T \tau \end{cases} \tag{1}$$

$\xi = (x, y, z)$ and $\eta = (\phi, \theta, \psi)$ are the rotorcraft position and orientation, respectively. $u \in \mathbb{R}$ and $\tau \in \mathbb{R}^3$ are the applied thrust and torque vector. The body inertia matrix is denoted by $J \in \mathbb{R}^{3\times 3}$ and the mass by $m \in \mathbb{R}$. The pseudoinertial matrix M is defined as $M(\eta) = \Psi(\eta)^T J \Psi(\eta)$, and the matrix C is given by $C(\eta, \dot{\eta}) = -\Psi(\eta)^T J \dot{\Psi}(\eta) + \Psi(\eta)^T sk(\Psi(\eta)\dot{\eta}) J \Psi(\eta)$. The sk operation is defined here from $\mathbb{R}^3$ to $\mathbb{R}^{3\times 3}$, such that $sk(x)$ is a skew-symmetric matrix associated to the vector product $sk(x)y := x \times y$ for any vector $y \in \mathbb{R}^3$. $R \in \mathbb{R}^{3\times 3}$ and $\Psi \in \mathbb{R}^{3\times 3}$ are the rotation matrix and Euler matrix:

$$R = \begin{pmatrix} c\theta c\psi & s\phi s\theta c\psi - c\phi s\psi & c\phi s\theta c\psi + s\phi s\psi \\ c\theta s\psi & s\phi s\theta s\psi + c\phi c\psi & c\phi s\theta s\psi - s\phi c\psi \\ -s\theta & s\phi c\theta & c\phi c\theta \end{pmatrix}$$

and

$$\Psi(\eta) = \begin{pmatrix} 1 & 0 & -\sin\theta \\ 0 & \cos\phi & \cos\theta \sin\phi \\ 0 & -\sin\phi & \cos\theta\cos\phi \end{pmatrix}$$

where $s(x)$ and $c(x)$ are abbreviations for $\sin(x)$ and $\cos(x)$.

Controller design for nonlinear system (1), which is subject to strong coupling, offers both practical significance and theoretical challenges. In this Note, the control design for rotorcraft UAVs is addressed by transforming nonlinear model (1) into two linear systems coupled by a nonlinear term.

Because the attitude dynamics in Eq. (1) is a fully actuated mechanical system for $\theta \neq k\pi/2$, it is exact feedback linearizable. In fact, by considering the following change of variables

$$\tau = J\Psi(\eta)\tilde{\tau} + \Psi^{-1} C(\eta, \dot{\eta})\dot{\eta} \tag{2}$$

system (1) can be written in the following form:

$$\begin{cases} \ddot{x} = \frac{1}{m} u(\cos\phi \sin\theta \cos\psi + \sin\phi \sin\psi), & \ddot{\phi} = \tilde{\tau}_\phi \\ \ddot{y} = \frac{1}{m} u(\cos\phi \sin\theta \sin\psi - \sin\phi \cos\psi), & \ddot{\theta} = \tilde{\tau}_\theta \\ \ddot{z} = \frac{1}{m} u \cos\theta \cos\phi - g, & \ddot{\psi} = \tilde{\tau}_\psi \end{cases} \tag{3}$$

Now we apply the backstepping principle to transform system (3) into two subsystems in cascade. In contrast to the complexity of standard backstepping approaches, the control strategy considered in this Note is very simple and easy to implement and has been effective in a very broad range of aerospace applications.

Let us first define a virtual control vector $\mu \in \mathbb{R}^3$ as follows:

$$\mu = \mathfrak{f}(u, \phi_d, \theta_d, \psi_d) = \frac{1}{m} u R(\phi_d, \theta_d, \psi_d) e_z - g e_z \tag{4}$$