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Comparative controller design of an aerial robot

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ABSTRACT

Flying capability opens novel opportunities in robotic applications, such as search and rescue, surveillance navigations and mapping operations. In this article, considering an aerial robot, i.e. an unmanned aerial vehicle (UAV), a few comparable controllers are designed to manage the system performance during various maneuvers. After introducing a nonlinear dynamics model of the system, an adaptive controller is proposed based on feedback linearization approach and using Lyapunov design method. Next, an optimal controller is designed to compare its performance with the designed adaptive controller. Stability analysis for the designed adaptation law is also studied and discussed. To evaluate the performance of designed controllers for a given aerial robot, a comprehensive simulation program is developed. It is shown that tracking errors for the state variables exponentially converge to zero, even in the presence of parameters uncertainty. In particular, it is shown that the proposed adaptive controller, based on its feedback linearization approach and Lyapunov stabilized characteristics, is able to perform perfect path tracking maneuvers, compared to the optimal controller that contains minor errors due to its feed-forward nature.

1. Introduction

To improve on-orbit servicing capabilities, space free-flying robots (SFFR) in which one or more manipulators are mounted on a thruster-equipped base, have been proposed [2]. It is expected that robotic systems play an important role in future space applications, including servicing, construction, and maintenance of space structures on orbit. Therefore, dynamics modeling and motion control of SFFR have been extensively studied [21,3,13,12,11]. Flying capability opens new opportunities in terrestrial applications as well, in performing field services and tasks like search and rescue, observation and mapping operations [6,14,10]. An aerial robot or unmanned aerial vehicle (UAV) may be defined as an aerial vehicle (mostly without on-board manipulators) that uses aerodynamic forces to support its flight in a desired manner, so that a modern UAV is a fully autonomous flying system. Recent technological advancements in navigation and guidance systems, airframe types, payload varieties, and propulsion systems promise more complex goals to be achievable and yet remain cost-effective. The interaction of the air flows generated by propeller contribute to complex aerodynamic forces that affects the vehicle's motion, and in turn makes the motion control of a UAV a challenging task. The system dynamics is not only coupled and nonlinear, but also difficult to be characterized due to the complexity of the system aerodynamic properties [22].

Despite an ordinary controller, an adaptive controller exploits a mechanism for online adjustment of the controller parameters based on measured variables. There are two main approaches for constructing adaptive controllers. One is the so-called model reference adaptive control method, and the other is the so-called self-tuning method. Various nonlinear control methods, fuzzy, and adaptive laws have been applied to UAVs in case of specific longitudinal and lateral maneuvers [4,17,8,7]. Besides using linear controllers for UAVs [15,23], adaptive controllers with a single hidden layer adaptive element have been successfully used on a number of aircraft [19,18,16].

In this article, various nonlinear adaptive and optimal controllers are proposed for an aerial robot. First, nonlinear dynamics model of longitudinal motion is extracted, which will be used to develop the controller. Stability condition for the designed adaptation law is investigated using Lyapunov method to guarantee the stability of controller. Then, based on feed-forward approach, an optimal controller is designed to compare the performance of these controllers, in terms of system input rate and the state variables errors. To evaluate performance of the designed controllers, a comprehensive simulation program has been prepared. Exploiting this simulation routine, the system is simulated under the proposed control laws, and comparison between state variables errors and trajectory tracking characteristics will be discussed.

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Nomenclature

δ_e	Elevator angle
δ_T	Thrust input
γ_i	Positive constant
λ_i	Positive constant
θ	Pitch angel
$\boldsymbol{\Gamma}$	Adaptive gain matrix
$\boldsymbol{\Psi}$	Filter matrix
$\mathbf{C}_d$	Transformation matrix
g	Gravity acceleration
$\mathbf{k}$	Control law constant
p	Roll rate
q	Pitch rate
r	Yaw rate
u	Velocity in x direction of body
u_0	Velocity along x direction of body coordinates
v	Velocity in y direction of body
w	Velocity in z direction of body
m	Main body mass
$\mathbf{P}$	Parameter
$\mathbf{x}$	State variable
X	Force in x direction
Y	Force in y direction
Z	Force in z direction
$X_u = \partial X/\partial u$	Stability derivatives that defined for each X parameter relative to u

2. Dynamics modeling

Considering the base of aerial robot as a rigid body, its equations of motion are supposed to be ODEs with constant coefficients. Coefficients in these ODEs are representations of aerodynamic stability derivatives of mass and inertia properties of the plane. These equations could be stated as first order ODEs. For instance, using equation of motion for a rigid body and considering Euler angles and gravity and lifting forces, dynamics equation along longitudinal axis of the plane can be written as:

$$X - mg\,\mathrm{Sin}(\theta) = m(\dot{u} + qw - rv) \tag{1}$$

Each variable in this equation is substituted with its initial value added with a perturbed value as:

$$u = u_1 + \Delta u, \quad v = v_1 + \Delta v, \quad w = w_1 + \Delta w$$
$$X = X_1 + \Delta X, \quad q = q_1 + \Delta q, \quad r = r_1 + \Delta r \tag{2}$$

So, it is obtained:

$$\begin{aligned} &X_1 + \Delta X - mg\,\mathrm{Sin}(\theta_1 + \Delta\theta) \\ &\quad = m\bigg(\frac{d}{dt}(u_1 + \Delta u) + (q_1 + \Delta q).(w_1 + \Delta w) \\ &\qquad - (r_1 + \Delta r).(v_1 + \Delta v)\bigg) \end{aligned} \tag{3}$$

The force ΔX indicates a change in thrust and aerodynamic forces along x direction, which can be presented as a Taylor series in terms of perturbed variables. Assuming ΔX as a function of u, w, δ_e, δ_T parameters then ΔX can be written as:

$$\Delta X = \frac{\partial X}{\partial u}\Delta u + \frac{\partial X}{\partial w}\Delta w + \frac{\partial X}{\partial \delta_e}\Delta\delta_e + \frac{\partial X}{\partial \delta_T}\Delta\delta_T \tag{4}$$

where $\partial X/\partial u$, $\partial X/\partial w$, $\partial X/\partial\delta_e$, $\partial X/\partial\delta_T$ are known as stability derivatives and their values are defined in the reference flight condition. The variables δ_e and δ_T define the elevator angle and the fuel gate attitude. Eq. (1) for the initial flight condition is written as:

$$X_1 - mg\,\mathrm{Sin}(\theta_1) = m(\dot{u}_1 + q_1 w_1 - r_1 v_1) \tag{5}$$

Assuming symmetric flight conditions yields:

$$v_1, w_1, q_1, r_1 \approx 0 \tag{6}$$

By subtracting Eq. (3) from previous equation and substituting ΔX while reformatting the result, the nonlinear equation of rigid body motion along x direction is obtained as:

$$\begin{aligned} &\left(\frac{d}{dt} - X_u\right)\Delta u - X_w \Delta w + g.S_\theta + \Delta q.\Delta w - \Delta r.\Delta v \\ &\quad = X_{\delta_e}\Delta\delta_e + X_{\delta_T}\Delta\delta_T \end{aligned} \tag{7}$$

where $X_w = \partial X/\partial w/m$ and $X_u = \partial X/\partial u/m$. For the two remained equations of longitudinal motion a similar approach is performed and the following equations will be obtained:

$$\begin{aligned} &-Z_u\Delta u + \left((1 - Z_{\dot{w}})\frac{d}{dt} - Z_w\right)\Delta w \\ &\quad - \left((u_0 + Z_q)\frac{d}{dt} - g\sin\theta_0\right)\Delta\theta \\ &\quad + \Delta p.\Delta v - \Delta q.\Delta u = Z_{\delta_e}\Delta\delta_e + Z_{\delta_T}\Delta\delta_T \end{aligned} \tag{8}$$

$$\begin{aligned} &-M_u\Delta u - \left(M_{\dot{w}}\frac{d}{dt} + M_w\right)\Delta w \\ &\quad + \left(\frac{d^2}{dt^2} - M_q\frac{d}{dt}\right)\Delta\theta + \left(\frac{I_x - I_z}{I_y}\right)\Delta r.\Delta p \\ &\quad + \left(\frac{I_{xz}}{I_y}\right)\Delta p^2 - \left(\frac{I_{xz}}{I_y}\right)\Delta r^2 = M_{\delta_e}\Delta\delta_e + M_{\delta_T}\Delta\delta_T \end{aligned} \tag{9}$$

These nonlinear equations are used to design the controller. Thus, according to two inputs of the system, feedback linearization controller will be designed:

$$\begin{aligned} \Delta\dot{u} &= X_u.\Delta u + X_w.\Delta w - g.\Delta\theta - \Delta q.\Delta w \\ &\quad + X_{\delta_e}.\Delta\delta_e + X_{\delta_T}.\Delta\delta_T \end{aligned} \tag{10}$$

$$\begin{aligned} \Delta\dot{w} &= Z_u.\Delta u + Z_w.\Delta w + u_0.\Delta q + \Delta q.\Delta u + Z_{\delta_e}.\Delta\delta_e \\ &\quad + Z_{\delta_T}.\Delta\delta_T \end{aligned} \tag{11}$$

3. Nonlinear controller design

Various approaches have been proposed for nonlinear controller design, which include feedback linearization, robust control, adaptive control and gain scheduling, and each of these are most suitable for a specific kind of control problem. Feedback linearization has attracted a great deal of research interests in recent years. The idea of simplifying the form of a system's dynamics by choosing a different state representation is not entirely unfamiliar. In mechanics, for instance, it is well known that the form and complexity of a system model depends considerably on the choice of reference frames or coordinate systems. Feedback linearization techniques can be viewed as way of transforming original system models into equivalent models of a simpler form. Thus, they can also be used in the development of robust or adaptive nonlinear controllers.