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Sliding mode tracking control for miniature unmanned helicopters

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Abstract A sliding mode control design for a miniature unmanned helicopter is presented. The control objective is to let the helicopter track some predefined velocity and yaw trajectories. A new sliding mode control design method is developed based on a linearized dynamic model. In order to facilitate the control design, the helicopter's dynamic model is divided into two subsystems, such as the longitudinal-lateral and the heading-heave subsystem. The proposed controller employs sliding mode control technique to compensate for the immeasurable flapping angles' dynamic effects and external disturbances. The global asymptotic stability (GAS) of the closed-loop system is proved by the Lyapunov based stability analysis. Numerical simulations demonstrate that the proposed controller can achieve superior tracking performance compared with the proportional-integral-derivative (PID) and linear-quadratic regulator (LQR) cascaded controller in the presence of wind gust disturbances.

1. Introduction

Compared with the fixed-wing unmanned aerial vehicles (UAVs), unmanned helicopters have significant advantageous characteristics of hovering, take-off and landing vertically, low altitude flight and multi-attitude flight. These qualities have made them suitable for a variety of military and civilian applications. The unmanned helicopter is a special vehicle, which is a dynamic system of 6 degrees of freedom (6-DOF), underactuated, multiple-input multiple-output (MIMO), strong coupling and nonlinear UAV. Consequently, the development of reliable unmanned helicopter flight control system has become a very challenging topic in academic communities recently.[1]

Most of high-performance flight control systems are model-based control architecture which depends on the accurate dynamics of the helicopter. In most studies that exist in the literature,[2–4] the proposed designs are developed based on specific helicopter platforms. The nonlinear model based on first-principle modeling approach is not suitable for flight control design. In comparison with the nonlinear model, the linearized model is more suitable for the controller synthesis in practical autonomous flight. Cai et al.[5] attained a parameterized dynamic model of helicopters by combining

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the first-principles with the system identification approach. Lyapunov-based control design method[6] is applied to proceed on the controller synthesis in Refs.[7–9] However, the control design proposed by these literatures does not consider the model uncertainties and external perturbations. Besides, many previous work focuses on the stability analysis of closed-loop dynamics, but very few works have considered the influence of wind gusts, whereas it is a crucial problem for out-door application. Recently, researchers are beginning to realize that preserving stability in the presence of exogenous disturbances is one of the critical issues. Cai et al.[10] used H_∞ control technique to yield good robust properties with respect to external disturbances. Leonard et al.[11] designed an active disturbance rejection control based on extended state observer and used it to suppress the lateral and vertical wind gust disturbances.

In this paper, a new sliding mode controller for a class of unmanned helicopter which involves immeasurable flapping angles dynamics and external disturbances is proposed. Sliding mode control[12–14] has the advantages of fast response, no online identification and easy to implement. It is also proposed to stabilize underactuated systems which are in cascaded form. The linearized dynamics model structure is used for the flight control development. In order to facilitate the control design, the helicopter model is divided into two subsystems, such as the longitudinal-lateral subsystem and the heading-heave subsystem. Since there is no strong coupling between the two subsystems, the controllers can be designed respectively. Sliding mode control technique is applied to compensate for the influence of immeasurable flapping angles' dynamic effects and external perturbations. The global asymptotic stability (GAS) of the closed-loop error system is proved by the Lyapunov-based stability analysis. Numerical simulation is performed to demonstrate that the controller can achieve superior tracking performance and robustness compared with the proportional-integral-derivative (PID) and linear-quadratic regulator (LQR) cascaded controller in the presence of external disturbances.

2. Dynamic model of an unmanned helicopter

The motion variables of unmanned helicopter are expressed with respect to a body-fixed reference frame defined as $\mathcal{F}_\mathrm{B} = \{O_\mathrm{B}, x_\mathrm{B}, y_\mathrm{B}, z_\mathrm{B}\}$, where the center O_B is located at the center of gravity (CG) of the helicopter. The directions of the body frame orthonormal vectors are shown in Fig. 1. The linear velocity and angular velocity vectors are denoted by $\boldsymbol{v}^\mathrm{B} = [u, \ v, \ w]^\mathrm{T}$ and $\boldsymbol{\omega}^\mathrm{B} = [p, \ q, \ r]^\mathrm{T}$, where u, v and w represent longitudinal velocity, lateral velocity and vertical velocity respectively, p, q and r represent roll angle velocity, pitch angle velocity and yaw angle velocity respectively. The orientation vector is given by $\boldsymbol{\Theta} = [\phi, \ \theta, \ \psi]^\mathrm{T}$, with ϕ, θ and ψ the roll angle, pitch angle and yaw angle. $\boldsymbol{T}_\mathrm{M}$ and $\boldsymbol{T}_\mathrm{T}$ denote thrust vector of the main rotor and tail rotor, respectively. The flapping angles a and b, which represent the tilt of the tip-path-plane (TPP) at the longitudinal and lateral axis respectively, are also depicted in Fig. 1. In the following, we will give the dynamics model of the helicopter.[5,8,15,16]

Generally, the 11-state nonlinear dynamics for unmanned helicopter is given as

$$\dot{\boldsymbol{x}}(t) = \boldsymbol{f}(\boldsymbol{x}(t), \boldsymbol{u}_\mathrm{c}(t), \boldsymbol{d}_\mathrm{w}(t)) \tag{1}$$

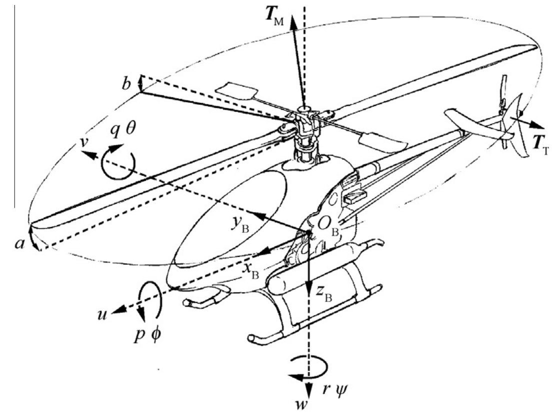

Fig. 1 Helicopter's body-fixed frame.

where $\boldsymbol{x} = [u, \ v, \ w, \ p, \ q, \ r, \ \phi, \ \theta, \ \psi, \ a, \ b]^\mathrm{T}$ is the state vector; $\boldsymbol{u}_\mathrm{c} = [u_\mathrm{lon}, \ u_\mathrm{lat}, \ u_\mathrm{ped}, \ u_\mathrm{col}]^\mathrm{T}$ is the control input, with u_lon and u_lat the cyclic control inputs which control the inclination of the TPP in the longitudinal and lateral directions, u_ped and u_col are the collective control inputs; $\boldsymbol{d}_\mathrm{w} = [d_1, \ d_2, \ d_3]^\mathrm{T}$ denotes the unknown time-varying external wind disturbance. The nonlinear dynamics equations can be expressed as

$$\begin{cases} m\dot{\boldsymbol{v}}^\mathrm{B} = -m\boldsymbol{S}(\boldsymbol{\omega}^\mathrm{B})\boldsymbol{v}^\mathrm{B} + mg\boldsymbol{R}(\boldsymbol{\Theta})^\mathrm{T}\boldsymbol{e}_3 + \boldsymbol{T}_\mathrm{M} + \boldsymbol{d}_\mathrm{w} \\ \dot{\boldsymbol{\Theta}} = \boldsymbol{\Psi}(\boldsymbol{\Theta})\boldsymbol{\omega}^\mathrm{B} \\ \boldsymbol{J}\dot{\boldsymbol{\omega}}^\mathrm{B} = -\boldsymbol{S}(\boldsymbol{\omega}^\mathrm{B})\boldsymbol{J}\boldsymbol{\omega}^\mathrm{B} + \boldsymbol{M}(T_\mathrm{mr})\boldsymbol{v}_\mathrm{c} + \boldsymbol{N}(T_\mathrm{mr}) \\ \dot{a} = -q - \dfrac{1}{\tau_\mathrm{f}}a + A_b b + A_\mathrm{lon}u_\mathrm{lon} \\ \dot{b} = -p + B_a a - \dfrac{1}{\tau_\mathrm{f}}b + B_\mathrm{lat}u_\mathrm{lat} \end{cases} \tag{2}$$

where m represents the mass of the helicopter; g is the acceleration of gravity; $\boldsymbol{J} = \mathrm{diag}(J_{xx}, J_{yy}, J_{zz})$ denotes inertia matrix of the helicopter with J_{xx}, J_{yy} and J_{zz} the rolling inertia moment, pitching inertia moment and yawing inertia moment; $\boldsymbol{S}(\boldsymbol{\omega}^\mathrm{B})$ denotes the skew symmetric matrix of vector $\boldsymbol{\omega}^\mathrm{B}$; $\boldsymbol{R}(\boldsymbol{\Theta}) \in SO(3)$ is the rotation matrix representing the orientation of the body frame $\mathcal{F}_\mathrm{B}$ with respect to the inertia frame $\mathcal{F}_\mathrm{I}$; $\boldsymbol{e}_3 = [0, \ 0, \ 1]^\mathrm{T}$ is a unit vector; $\boldsymbol{\Psi}(\boldsymbol{\Theta})$ represents the angular velocity transfer matrix. $\boldsymbol{T}_\mathrm{M} = [-T_\mathrm{mr}a, \ T_\mathrm{mr}b, \ -T_\mathrm{mr}]^\mathrm{T}$; $\boldsymbol{T}_\mathrm{T} = [0, \ -T_\mathrm{tr}, \ 0]^\mathrm{T}$; $\boldsymbol{v}_\mathrm{c} = [b, \ a, \ T_\mathrm{tr}]^\mathrm{T}$; $\boldsymbol{M}(T_\mathrm{mr}) \in \mathbf{R}^{3\times3}$ represents an invertible matrix for T_mr and $\boldsymbol{N}(T_\mathrm{mr}) \in \mathbf{R}^3$ represents a parameter vector for T_mr; $T_\mathrm{mr} = K_\mathrm{m}u_\mathrm{col} + B_\mathrm{m}$ and $T_\mathrm{tr} = K_\mathrm{t}u_\mathrm{ped} + B_\mathrm{t}$ are the magnitudes of the generated thrusts, with $K_\mathrm{m}, K_\mathrm{t}, B_\mathrm{m}$ and B_t are constants; τ_f is the main rotor time constant; A_b and B_a account for the cross-coupling effects occurring at the level of rotor itself; A_lon and B_lat are the input derivatives.

To derive the control law, the dynamics in Eq. (1) are linearized around the trim flight condition. The following state-space expressions are obtained:

$$\begin{cases} \dot{\boldsymbol{x}}(t) = \boldsymbol{A}\boldsymbol{x}(t) + \boldsymbol{B}\boldsymbol{u}_\mathrm{c}(t) + \boldsymbol{E}\boldsymbol{d}_\mathrm{w}(t) \\ \boldsymbol{y}(t) = \boldsymbol{C}\boldsymbol{x}(t) \end{cases} \tag{3}$$

where $\boldsymbol{y} = [u, \ v, \ w, \ \psi]^\mathrm{T}$ is the output vector. The Jacobian matrices of $\boldsymbol{A} \in \mathbf{R}^{11\times11}$ and $\boldsymbol{B} \in \mathbf{R}^{11\times4}$ for hover fight condition are given as