Optik 125 (2014) 2817–2825

Contents lists available at ScienceDirect

Optik

journal homepage: www.elsevier.de/ijleo

Quad-rotor unmanned helicopter control via novel robust terminal sliding mode controller and under-actuated system sliding mode controller

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ARTICLE INFO

Article history:
Received 14 June 2013
Accepted 16 November 2013

Keywords:
QRUH
Novel robust terminal sliding mode control
Under-actuated systems sliding mode control
Composite control

ABSTRACT

This paper uses the recently developed novel robust terminal sliding mode control (NRTSMC) and under-actuated system sliding mode control (USSMC) approaches to solve the strong coupling and under-actuated problems of a small quad-rotor unmanned helicopter (QRUH). The two controllers have been widely adopted to act as a single control algorithm in many fields, respectively. However, this paper just displays the useful composite application of the two controllers. The QRUH model can be divided into two subsystems, including a fully actuated subsystem (FAS) and an under-actuated subsystem (UAS). For the FAS, the NRTSMC is used to solve the strong coupling problem, it can guarantee the FAS states converge to the desired equilibrium in a very short time, then the states are treated as time invariants and the UAS gets simplified. For the UAS, the USSMC is utilized to solve the under-actuated problem. The obtained simulation results show the applicability of the composite control when faced with external disturbances.

1. Introduction

Nowadays, unmanned aerial vehicles (UAVs) are being used in several typical missions such as, search and rescue missions, surveillance, inspection, mapping, aerial cinematography and law enforcement [1].

UAVs model is a typical multi-input and multi-output (MIMO) system with nonlinear. Many robust control schemes have been developed for the uncertain nonlinear systems. Among these control schemes, the sliding mode control, which has drawn researchers' much attention, has been a useful and efficient control technique for handling systems with large uncertainties, time varying properties, nonlinearities, and bounded external disturbances [2]. The adaptive fuzzy SMC was proposed for nonlinear SISO systems with uncertainties and external disturbances [3]. In [4], a novel high order SMC was given for uncertain nonlinear systems with relative degree three. The observer-based SMC problem was investigated for a class of uncertain nonlinear neutral delay systems [5]. For a certain class of unknown nonlinear dynamic systems in which not all the states were available for measurement, the observer-based indirect adaptive fuzzy SMC with state variable filters was presented [6]. However, the basic SMC cannot guarantee closed-loop system states converge to the desired equilibrium in the finite time.

Compared with conventional SMC with linear sliding surface, TSMC with nonlinear terminal sliding surface provides faster, finite time convergence, and higher control precision. TSMC has been proposed and used in different control problems. In [7], using TSM technique, a relative position/velocity tracking control based on the nonlinear model was developed [8]. The fast terminal dynamic was presented and used in the design of the sliding-mode control for SISO nonlinear dynamical systems [9]. In [10], the derivative and integral TSMC was presented for a class of MIMO nonlinear systems in a unified viewpoint. The nonsingular decoupled TSMC method was proposed for a class of fourth-order nonlinear systems [11]. For the sake of achieving finite time tracking control for the rotor position in the axial direction of a nonlinear thrust active magnetic bearing system, the robust nonsingular TSMC was given [12]. However, the conventional TSMC methods are not the best in the convergence time, the primary reason is that the convergence speed of the nonlinear sliding mode is slower than the linear sliding mode when the system states are close to the equilibrium. A novel TSMC scheme is developed using a function augmented sliding hyperplane for the guarantee that the tracking error converges to zero in finite time [13].

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http://dx.doi.org/10.1016/j.ijleo.2013.11.069

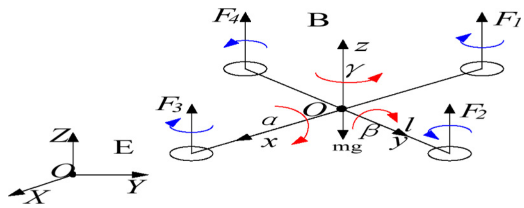

Fig. 1. Quad-rotor unmanned helicopter.

In the area of unmanned quad-rotor, the problem of control design has primarily focused in the following areas:(a)proportional–integral–differential (PID) controllers, PID controllers augmented with angular acceleration feedback and linear quadratic (LQ)-regulators, (b)nonlinear control methods including sliding mode controllers, back-stepping control approaches and integral predictive-nonlinear H_∞ control,(c)dynamic inversion-based techniques, (d)constrained finite time optimal control schemes and (e) model predictive attitude control [14].

The primary motivation of this paper is the application of the control scheme using a novel robust TSMC and the SMC of a class of under-actuated systems for a small QRUH. The organization of this paper is arranged as follows. Section 2 presents the QRUH model. The main scheme is proposed in Section 3. In Section 4, simulation results are achieved to highlight the overall validity and the effectiveness of the used controllers, followed by the concluding remarks in Section 5.

2. QRUH model

The attitude angles and velocities are always relative to the special coordinate. In order to describe the motion states of the QRUH clearly, we need to choose the appropriate coordinate. The model of the QRUH will be setted up in this paper by the body-frame $B(Oxyz)$ and the earth-frame $E(OXYZ)$. The two coordinates are presented in Fig. 1. Let the vector $(x, y, z)^T$ denotes the position of the center of the gravity of the QRUH in the earth-frame while the vector $(u, v, w)^T$ denotes its linear velocity in the earth-frame and $(p, q, r)^T$ represents its angular velocity in the body-frame. m is the total mass of the QRUH. g is the acceleration of gravity. l is distance from the center of each rotor to the center of gravity.

The orientation of the QRUH is given by the rotation matrix $R : E \to B$, R depending on the three Euler angles $(\alpha, \beta, \gamma)^T$ representing the roll, the pitch and the yaw, respectively.

$$R(\alpha,\beta,\gamma) = R(z,\gamma)\times R(y,\beta)\times R(x,\alpha)$$
$$= \begin{bmatrix} \cos\gamma & -\sin\gamma & 0 \\ \sin\gamma & \cos\gamma & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} \cos\beta & 0 & \sin\beta \\ 0 & 1 & 0 \\ -\sin\beta & 0 & \cos\beta \end{bmatrix} \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos\alpha & -\sin\alpha \\ 0 & \sin\alpha & \cos\alpha \end{bmatrix}$$
$$= \begin{bmatrix} \cos\gamma\cos\beta & \cos\gamma\sin\beta\sin\alpha - \sin\gamma\cos\alpha & \cos\gamma\sin\beta\cos\alpha + \sin\gamma\sin\alpha \\ \sin\gamma\cos\beta & \sin\gamma\sin\beta\sin\alpha + \cos\gamma\cos\alpha & \sin\gamma\sin\beta\cos\alpha - \cos\gamma\sin\alpha \\ -\sin\beta & \cos\beta\sin\alpha & \cos\beta\cos\alpha \end{bmatrix}$$

The transformation matrix from $(\alpha, \beta, \gamma)^T$ to $(p, q, r)^T$ is given by

$$\begin{bmatrix} p \\ q \\ r \end{bmatrix} = \begin{bmatrix} 1 & 0 & -\sin\beta \\ 0 & \cos\alpha & \sin\alpha\cos\beta \\ 0 & -\sin\alpha & \cos\alpha\cos\beta \end{bmatrix} \begin{bmatrix} \dot\alpha \\ \dot\beta \\ \dot\gamma \end{bmatrix}$$

The dynamic model of the QRUH can be described by the following equation [15]

$$\begin{cases} \ddot{x} = (\cos\alpha\sin\beta\cos\gamma + \sin\alpha\sin\gamma)u_1 - K_1\dot{x}/m \\ \ddot{y} = (\cos\alpha\sin\beta\sin\gamma - \sin\alpha\cos\gamma)u_1 - K_2\dot{y}/m \\ \ddot{z} = (\cos\alpha\cos\beta)u_1 - g - K_3\dot{z}/m \\ \ddot{\alpha} = \dot\beta\dot\gamma\dfrac{I_y - I_z}{I_x} + \dfrac{J_r}{I_x}\dot\beta\Omega_r + u_2 - \dfrac{K_4 l}{I_x}\dot\alpha \\ \ddot{\beta} = \dot\gamma\dot\alpha\dfrac{I_z - I_x}{I_y} - \dfrac{J_r}{I_y}\dot\alpha\Omega_r + u_3 - \dfrac{K_5 l}{I_y}\dot\beta \\ \ddot{\gamma} = \dot\alpha\dot\beta\dfrac{I_x - I_y}{I_z} + u_4 - \dfrac{K_6}{I_z}\dot\gamma \end{cases} \tag{1}$$

where K_i's the drag coefficients and positive constants; $\Omega_r = \Omega_1 - \Omega_2 + \Omega_3 - \Omega_4$ and Ω_i stand for the angular speed of the propeller i; where I_x, I_y, I_z are the inertias of the QRUH; where J_r is the inertia of the propeller; u_1 is the total thrust on the body in the z-axis; u_2 and u_3 are the roll and pitch inputs; u_4 is a yawing moment.