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Design of robust sliding mode control with disturbance observer for multi-axis coordinated traveling system

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A R T I C L E I N F O

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A B S T R A C T

This paper deals with the robust control strategy for multi-axis coordinated motion system. Firstly, the adjacent cross-coupling error control method was introduced to reduce the synchronization error. Then, the sliding mode control (SMC) law based on the mathematical model of the plant was adopted for restraining parameter perturbation. Furthermore, addressing the unknown torque disturbance, a disturbance observer was proposed. The switching gain of the robust control algorithm can be set as a smaller value so that the chattering on the sliding mode plane can be decreased. The simulation results have proved the effectiveness of the proposed control algorithm.

1. Introduction

Multi-axle systems are widely used in industrial fields such as the multi-motor system in numerical control machines, robotics, and the multi-hydraulic-motor system in the driving system of construction machineries. In mostly application the coordinated motion means generally the synchronization motion. So in a multi-axis coordinated motion system, the elimination of the synchronization errors is an important problem.

The synchronization errors among different axes are caused by many reasons, such as the different initial values, the different parameters, and the different disturbance in each plant. The cross coupling strategy is introduced for synchronization control by Koren [1] and Perez-Pinal [2], but it is too complicated to use this basic cross-coupling strategy to the systems with more than 2 motors. Sun and Mills proposed the adjacent cross-coupling strategy in robotic synchronization control, which has simplified the structure of the cross-coupling strategy [3,4]. Cao et al. [5], and Zhang et al. [6] respectively studied proportional-synthesized type of and proportional-integral-synthesized type of adjacent coupling error sliding mode control law to be used in the synchronized control of multi-induction-motor systems. Li et al. [7] proposed an adjacent coupling error total sliding mode control used to multi-induction-motors, which can guarantee no sliding mode approaching stage so as to enhance the robustness of the multi-axis coordinated control system. Kempf and Kobayashi studied the design of the disturbance observer in the high-speed-drive-positioning table, and put forward a solution with the feed-forward compensation, disturbance observer, and Q-filter [8]. Kim and Chung [9] proposed a kind of advanced disturbance observer with Q-filer and applied this control law to the mechanical positioning system. Li investigated the design of the disturbance-observer of the electro-hydraulic simulator and proposed a hybrid control strategy [10]. Pai and Yau [11] focused the parameters uncertainty and disturbance in the chaotic control system with SMC law and proposed a kind of the compensation method by using an augment state variable. Chung and Chen addressed the linear system subject to periodic disturbance and designed an adaptive disturbance/state observer [12]. Liang et al. [13] studied the friction compensation issues in the servo systems. Horng and Lee [14] designed a sliding observer for friction compensation in a linear-motor-driven motion system, and this method can acquire a higher precision than that of the

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disturbance observer (DOB) compensation or without friction compensation. Chen and Li [15] designed a kind of adaptive iteration learning control law based on an observer for a robotic system tracking problem. Liu [16] designed a state observer to estimate the disturbance in a servo system. Shi et al. [17] proposed a stable adaptive fuzzy control law for a nonlinear system, and this control method can increase the ability of the system to reject the disturbance.

For the traveling system with multi-axis driving, obviously, the cross-coupling and the external torque disturbance simultaneously exist. So, in order to improve the coordinated performance of the system, we need to consider the influence of the cross-coupling and the torque disturbance. Addressing this problem, this paper proposed a robust control algorithm which can simultaneously restrain the cross-coupling error and the external torque disturbance.

The rest of the paper is arranged as follows. Firstly, in the next section, a mathematical model to describe the dynamic characteristics of the multi-axis rotational speed system was established and the forward adjacent coupling error strategy was introduced. In Section 3, an SMC law with the disturbance observer compensation was designed for restraining uncertainties of the plant, so that we can select the smaller value of the switching gain of the SMC law and decrease the chattering on the sliding mode plane. Finally, the main conclusions of the paper are summarized.

2. Problem statement

2.1. The objective of multi-axis coordinated motion system

Consider a multi-axis coordinated motion system in [18]. Note that all of the wheels make the steering center while steering, the synchronized relationships among of the rotational speeds of the motors to combine the traveling system are as follows

$$\frac{\omega_1}{R_1}\frac{r_d}{i_{tr}} = \frac{\omega_2}{R_2}\frac{r_d}{i_{tr}} = \cdots = \frac{\omega_n}{R_n}\frac{r_d}{i_{tr}} \tag{1}$$

where, i_{tr}, r_w, R_i $(i = 1, 2, \ldots, n)$, and ω_i $(i = 1, 2, \ldots, n)$ are the transmission ratio of the rotational speeds from the driving motor to the vehicle wheel, the rolling radius of the wheel, the steering radius of the i-th wheel rotating the steering center, and the rotational angle speed of the i-th wheel, respectively. Supposing that the traveling velocity of the transporter at the geometric center is v_{d0}, and defining $\omega_d = \frac{v_{d0}}{r_w i_{tr}}$, $x_d = \frac{\omega_d}{R_0} = \frac{v_{d0}}{i_{tr} r_w R_0}$ and $x_{di} = \frac{\omega_{di}}{R_i}$, then from the pure-rolling conditions of the vehicle steering kinematics we can derive the following kinematical relationships as

$$x_{d1} = x_{d2} \cdots = x_{dn} = x_d \tag{2}$$

where R_0 and ω_{di} represent the steering radius of the transporter geometric center, and the desired angle speed of the i-th transporter wheel, respectively.

Using Newton's second motion law for each motor yields the dynamic model of each axis of the multi-axis system can be described as

$$J_i\dot{\omega}_i + B_i\omega_i + T_{Li} = T_{ei}. \tag{3}$$

In (3), J_i is the rotary inertia of the i-th axis, B_i is the damping coefficient of the i-th axis, T_{Li} is the unknown torque disturbance, and T_{ei} is the driving torque.

Let $x_i = \frac{\omega_i}{R_i}$, $b_i = \frac{B_i}{J_iR_i}$, $d_i = \frac{T_{Li}}{J_iR_i}$, $u_i = \frac{T_{ei}}{J_iR_i}$, and to substitute them into (3) yields

$$\dot{x}_i + b_ix_i + d_i = u_i. \tag{4}$$

Defining the tracking error of each axis of the multi-hydraulic motors system as

$$e_i = x_d - x_i. \tag{5}$$

Then we can give the goal of the control system described by Eq. (4) is to realize the multi-axis coordinated motion control and the tracking of x_i to x_{di}, and its expressions are as follows

$$x_1 = x_2 = \cdots = x_n = x_d. \tag{6}$$

Note that $R_1 = R_2 = \cdots = R_n = \infty$ for the synchronization line traveling problem, i.e. all of the wheels have the same wheel velocity, so we may let $x_i = \omega_i$, $b_i = \frac{B_i}{J_i}$, $d_i = \frac{T_{Li}}{J_i}$, $u_i = \frac{T_{ei}}{J_i}$ in Eq. (4).

2.2. The forward adjacent error strategy

In order to guarantee the coordinated control of the multi-hydraulic-motor traveling system, we must consider the influence of the different characteristics amount on every hydraulic motor driving sub-system. For this goal, we put forward