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An adaptive decoupling control for three-axis gyro stabilized platform based on neural networks

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ABSTRACT

In order to improve the tracking and stabilization performance of three-axis gyro stabilized platform, an adaptive decoupling control based on neural networks is developed. The dynamic model of three-axis GSP is developed based on traditional Newton–Euler method. The nonlinearity and coupling system is full-state-linearized using feedback linearization, and neural networks are used to compensate for the disturbances and uncertainties. The stability of the proposed scheme is analyzed by the Lyapunov criterion. Comparative simulations and experiments results show the effectiveness of the proposed control approach compared with the conventional control.

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1. Introduction

Gyro stabilized platform (GSP) for airborne observation system is used to stabilize and point the line-of-sight (LOS) of imaging sensors such as cameras and spectrum instruments [1]. Since the angular vibration of airplane and the gale onflow in three directions (azimuth, elevation and roll) seriously degrade stabilization precision of LOS, it is necessary to use three-axis GSP to isolate the undesirable angular motions in three directions [2,3]. While, due to the friction restriction and geometry restriction, there unavoidably exists strong nonlinear coupling disturbance in the dynamic model of three-axis GSP. Moreover, large uncertainties, e.g., unmodeled dynamics, parameter variation, friction force, imbalance, cable and spring torques, gyro and sensor noise, and gear reactions are varied in practice [4,5]. All those disturbance and uncertainties lead to the degradation of tracking and stabilization accuracy of three-axis GSP system in real applications.

Therefore, in order to obtain high motion accuracy of GSP, various decoupling control and disturbance suppression methods have been developed [6–16]. The basic control scheme consisted of the classical PID controllers and three closed servo loops was used for three-axis GSP system in [6]. However, it is very difficult to limit disturbances and uncertainties rapidly if adopting this linear control method. In [7,8], a decoupled controller based on feedback linearization with extra information from an inertial angular rate sensor for inertially stabilized double gimbal platform was proposed. A feed-forward vibration rejection control based on accelerometer for inertially stabilized double gimbal platform was presented in [9]. The disturbing torque, which can be measured, was fed forward to the two direct drive motors after being filtered. However, these methods are limited to measured disturbances. To compensate for the disturbance of GSP, a reduced-order observer was designed in [10]. The method can be simply completed, but requires an accurate system model to achieve satisfactory performance. An internal-loop compensator based on a disturbance observer was introduced in [11] to estimate the disturbance of GSP. However, this method is also dependent on the accurate system model. For decreasing the effect of uncertainties and other probable variation, a robust enhancer compensator was designed for inertial stabilization platform in [12]. However, the inverse of model of system is needed in this method. An extended-state-observer was used to estimate disturbance for a floated inertial platform in [13]. However, due to the need of adjusting many parameters, the method is hard to obtain optimal parameters tuning. Based on PI disturbance observer, an integral sliding mode controller was presented for three-axis inertial platform in [14]. The sliding mode control is used to improve the robustness of system, but the parameters of control system are without auto-tuning in the process of control. In order to attenuate the platform disturbance, two degree of freedom internal model controller (IMC) was used in [15]. The IMC method has robustness on parameter perturbation, but the disturbance structure is needed to be known. The design and implementation of two different control structures

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were presented for two-degree-of-freedom gyroscopic platform in [16]. One was a switching control law proved to be appropriate for position control mode; the other was a master–slave structure for the velocity control mode.

To deal with the nonlinearity of GSP system, input–output feedback linearization (FL) is of great interest. This technique is based on the idea of transforming the nonlinearities of the system to a pseudo-linear system through introducing new input. Some industrial applications have been reported [17–20]: in [17] the state-feedback linearization was used to transform the nonlinear dynamic to a linear state space model for the nonlinear 5-DOF flywheel, and then a linear controller based on the linearized model was designed to stabilize the rotor of the magnetic suspension flywheel; in [18], the feedback linearization theory was applied to reduce coupling effects stemmed from system dynamics of the parallel robot via incorporating force–velocity control with cross-coupling precompensations; in [19], a nonlinear speed tracking controller was introduced for three-phase synchronous reluctance motor on the basis of input–output feedback linearization; in [20], a decoupling feedback linearization algorithm and an adaptive strategy were introduced respectively to design the synchronization controllers for two FitzHugh–Nagumo neurons.

To deal with unknown disturbances, neural networks (NNs) have received considerable attentions for disturbance compensation in control systems, since they have distinct advantages of learning and approximating nonlinear functions, and are independent of the system model or disturbance structure [21–23]. In [21], the neural network feedback–feedforward and feedforward compensation methods were developed, each of which incorporated the output feedback control and the neural network compensator based on measured accelerometer signals. A novel high-performance classification system based on the S-transform and a probabilistic neural network was proposed for classifying power quality disturbances in [22]. In [23], an adaptive recurrent neural networks controller suitable was designed, developed and implemented for real-time manipulator control applications. The algorithm focused on fast and efficient optimization by weighting parameters of inverse recurrent neural models.

Therefore, an adaptive decoupling controller based on neural networks for three-axis GSP is proposed in this paper. First, the dynamic model of three-axis GSP is developed based on traditional Newton–Euler method, and kinematic relations for angular rates for three gimbals are analyzed. Then, the nonlinearity and coupling are resolved by input–output feedback linearization, and the uncertainties and disturbance such as unmodeled dynamics, parameter variation, friction force, imbalance, cable and spring torques, gyro and sensor noise, and gear reactions are estimated by radial basis function (RBF) neural networks. At last, the stability of the proposed scheme is analyzed by the Lyapunov criterion. Experimental results demonstrate the effectiveness of the proposed controller.

2. Problem description

In this section, the gimbal configuration of three-axis GSP is introduced first. Then the kinematics of angular rates for three gimbals is analyzed. Finally, the dynamic model of three-axis GSP is derived.

2.1. Gimbal Configuration

To isolate the imaging payload from disturbances of three degrees-of-freedom, the configuration of GSP consisting of three nested gimbals is shown in Fig. 1. All payload components requiring stabilization are mounted on the azimuth gimbal, which is the innermost gimbal. The elevation gimbal is outside the azimuth gimbal. The roll gimbal is the outermost gimbal.

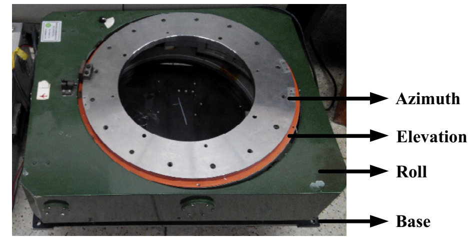

Fig. 1. The configuration of GSP.

2.2. Kinematic description for angular rates

2.2.1. Gimbal coordinates definition

An orthogonal coordinate system is defined rotating with each member of the gimbaled system: azimuth gimbal (x_a, y_a, z_a), elevation gimbal (x_e, y_e, z_e), roll gimbal (x_r, y_r, z_r), and base (x_b, y_b, z_b), as shown in Fig. 2.

θ_a and $\dot{\theta}_a$ are the relative angular and relative angular rate between the azimuth gimbal and the elevation gimbal, respectively.

θ_e and $\dot{\theta}_e$ are the relative angular and relative angular rate between the elevation gimbal and the roll gimbal, respectively.

θ_r and $\dot{\theta}_r$ are the relative angular and relative angular rate between the roll gimbal and the base, respectively.

2.2.2. Angular rates of three gimbals

The kinematics of three gimbals angular rates in terms of relative angular rates and the angular rates of base is given by

$$\begin{aligned}
&\begin{pmatrix}\omega^r_{irx} & \omega^r_{iry} & \omega^r_{irz}\end{pmatrix}^T = C^r_b\begin{pmatrix}\omega^b_{ibx} & \omega^b_{iby} & \omega^b_{ibz}\end{pmatrix}^T + \begin{pmatrix}0 & \dot{\theta}_r & 0\end{pmatrix}^T \\
&\begin{pmatrix}\omega^e_{iex} & \omega^e_{iey} & \omega^e_{iez}\end{pmatrix}^T = C^e_r C^r_b\begin{pmatrix}\omega^b_{ibx} & \omega^b_{iby} & \omega^b_{ibz}\end{pmatrix}^T + C^e_r\begin{pmatrix}0 & \dot{\theta}_r & 0\end{pmatrix}^T + \begin{pmatrix}\dot{\theta}_e & 0 & 0\end{pmatrix}^T \\
&\begin{pmatrix}\omega^a_{iax} & \omega^a_{iay} & \omega^a_{iaz}\end{pmatrix}^T = C^a_e C^e_r C^r_b\begin{pmatrix}\omega^b_{ibx} & \omega^b_{iby} & \omega^b_{ibz}\end{pmatrix}^T + C^a_e C^e_r\begin{pmatrix}0 & \dot{\theta}_r & 0\end{pmatrix}^T \\
&\qquad + C^a_e\begin{pmatrix}\dot{\theta}_e & 0 & 0\end{pmatrix}^T + \begin{pmatrix}0 & 0 & \dot{\theta}_a\end{pmatrix}^T
\end{aligned} \tag{1}$$

where $\begin{pmatrix}\omega^b_{ibx} & \omega^b_{iby} & \omega^b_{ibz}\end{pmatrix}$ is the base angular rate; $\begin{pmatrix}\omega^r_{irx} & \omega^r_{iry} & \omega^r_{irz}\end{pmatrix}$ is the angular rate of roll gimbal; $\begin{pmatrix}\omega^e_{iex} & \omega^e_{iey} & \omega^e_{iez}\end{pmatrix}$ is the angular rate of elevation gimbal; $\begin{pmatrix}\omega^a_{iax} & \omega^a_{iay} & \omega^a_{iaz}\end{pmatrix}$ is the angular rate of azimuth gimbal; and

$$C^r_b = \begin{pmatrix}\cos\theta_r & 0 & -\sin\theta_r \\ 0 & 1 & 0 \\ \sin\theta_r & 0 & \sin\theta_r\end{pmatrix}, \quad C^e_r = \begin{pmatrix}1 & 0 & 0 \\ 0 & \cos\theta_e & \sin\theta_e \\ 0 & -\sin\theta_e & \cos\theta_e\end{pmatrix},$$

$$C^a_e = \begin{pmatrix}\cos\theta_a & \sin\theta_a & 0 \\ -\sin\theta_a & \cos\theta_a & 0 \\ 0 & 0 & 1\end{pmatrix} \tag{2}$$

are the transformations from the base coordinate to the roll coordinate, the roll coordinate to the elevation coordinate, and the elevation coordinate to the azimuth coordinate, respectively.

It is obviously observed that the angular rates of roll gimbal are coupled by base angular rates transforming once, angular rates of elevation gimbal are coupled by base angular rates transforming twice and $\dot{\theta}_r$ transforming once, and angular rates of azimuth gimbal are coupled by base angular rates transforming thrice, $\dot{\theta}_r$ transforming twice and $\dot{\theta}_e$ transforming once.

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