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Decoupling control for two-axis inertially stabilized platform based on an inverse system and internal model control

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ABSTRACT

This paper describes a decoupling control scheme for a two-axis inertially stabilized platform (ISP) used in the airborne power line inspection system. The dynamic model of the ISP has been obtained by using the Newton–Euler equation first. The inverse system method combining with the internal model control has been proposed to deal with the nonlinearity and coupling of the ISP. The key idea is to design an inverse system with measured system states such as angular positions, rates and accelerations. Then a pseudo-linear system is constructed when the inverse system is connected with the original system in series. As a result, the coupled nonlinear MIMO (Multiple-Input Multiple-Output) system is converted to two linear decoupled SISO (Single-Input Single-Output) subsystems. Model uncertainties or unmeasurable disturbances existing objectively can be solved by introducing internal model control. Better decoupling effect and disturbance rejecting ability are demonstrated by numerical simulations and experiments carried out on a two-axis ISP system.

1. Introduction

In the airborne power line inspection (APLI) system, an unmanned helicopter carries imaging sensors such as CCD camera and infrared scanner to move along the power line. So, conditions of the power line could be estimated based on obtained images. The basic control task for the ISP is to make the line of sight (LOS) tracking the command and keeping steady even in presence of various disturbing phenomena like vibration, turbulence, gust and so on. As a result, the multi-axis inertially stabilized platform mounted between aviation platforms and imaging sensors has been widely used to isolate those disturbances [1–3]. However, the dynamic model of the multi-axis ISP is coupled and nonlinear. Furthermore, mechanism drawbacks such as machining accuracy and assembly error usually enhance the coupling and nonlinear characteristics. These coupling and nonlinear factors deteriorate the static and dynamic performances of the APLI system and make the ISP control more complex. Obviously, the decoupling technology for the ISP becomes critical in improving the stability and precision of the APLI system.

Various decoupling control methods have been studied for a better control performance of ISP, and they can mainly be divided into two groups. In the first group, all of the coupling factors are considered as disturbances, and the defined decoupling control is disturbance rejecting control. Traditionally, the designed decoupling controllers are always based on typical three-loop control. In which the inner loop compensates for disturbances and the outer track loop ensures the sensor LOS pointing toward the target [1,4]. For example, feed forward approaches in inner velocity loop have been employed to counter kinematic coupling in [2]. A model-based feed forward compensation approach for the fast and precise positioning of a rotary table system is presented in [5], where the interference model as well as the disturbance model is mathematically modeled and applied in the model-based feed forward compensation. An image-based feedback control idea of enhancing the intuitive decoupled controller structure with measurements of the camera inertial angular rate around its optical axis is described in [6]. For the coupling vibration rejection in ISP, an acceleration feed forward method is proposed in [7], where the linear acceleration of the carrier can be measured, filtered and fed forward to the two direct drive motors. Nonlinear coupling disturbance is analyzed and anti-disturbance compensation control algorithm based on adaptive robust control idea is studied for three-axis swing turntable system in [8].

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In the second group, the decoupling controller is designed based on the MIMO system dynamic model, and it is the truly meaningful decoupling design. For example, a general coupling mathematical model of multi-DOF servo system is established, and then its inverse system is obtained by using Singh algorithm. Finally, according to the desired nominal linear transfer function, a decoupling control law is developed in [9]. The nonlinear coupling characteristic among frames of the gyro stabilized turntable was analyzed and the dynamic model of the system was founded. Using nonlinear differential geometry means, the input–output decoupling control method was described in details. Using mode-tracking sliding mode variable structure method, the nonlinear disturbances of the system were eliminated in [10]. A method based on α-th order inverse system theory is used to realize dynamic decoupling control, and the state feedback linearization method is used to decouple and linearize the system, and then linear control system techniques are applied to these linearization subsystems to synthesize and simulate [11].

In this paper, the dynamic model of the two-axis ISP is developed by using traditional Newton–Euler method first. According to the model, the nonlinearity and coupling caused by angular movement of aviation (base) and ISP's gimbals are evaluated sequentially. And then, the nonlinearity and coupling are resolved by inverse system method which belongs to feedback linearization [12,13]. Then the coupled MIMO nonlinear dynamic model is converted to two decoupled SISO linear subsystems. However, it is well known that uncertainties and model errors such as friction, gear gaps, unbalance and delay exist but they are ignored. These uncertainties and errors degrade the performance of decoupling control and even make system unstable. Therefore, the 2-DOF internal model control (IMC) based on the inverse system is proposed to improve the performance of the ISP [14–16].

2. Modeling of two-axis ISP

2.1. The two-axis ISP system

The APLI system showed in Fig. 1 is widely used in power grid maintenance and overhaul task. Unmanned helicopter is usually chosen as mobile aviation which can take off and land freely in the complex geographic environment. Inspecting imaging sensors such as CCD camera, infrared scanner and ultraviolet scanner are carried by the ISP which is mounted between sensors and aviation platform, and they are assembled as a pod system hanging below the helicopter. The pod system can communicate with a supervisory computer. The control system of ISP can get information from the supervisory computer and other inertial sensors to realize stabilizing function for the LOS of camera.

As shown in Fig. 2, the ISP considered in this article is a two-axis system. The inner gimbal allows elevation of the payload, and the outer gimbal allows a rotation in azimuth angle. The payload consists of two CCD cameras, an infrared scanner, an ultraviolet scanner, and a laser scanner. Torque motors are used as drive system for two gimbals. Two fiber-optic gyroscopes, one Position and Orientation System (POS), and two encoders are attached to the payload to measure rotation angles, rates and accelerations.

The elevation and azimuth gimbals will not keep steady in inertial space because of angular movement of aviation and gimbals. So, the LOS of imaging sensors will not keep steady which leads to bad image quality. Therefore, the ISP plays an important role in improving the image quality. Working principle of the ISP is shown in Fig. 3.

2.2. Notation for coordinate frames and their rotations

This section mainly expresses rotating relations among several coordinate frames. The triads of vectors $[x, y, z]$ represent the right-handed rule coordinate frames and those vectors are assumed to share a common origin for simplicity. Coordinate frames and their symbols are shown in Fig. 2 and they are defined as follows. The inertial coordinate frame $[\boldsymbol{I}]$ represents the inertial space. The base (aviation) coordinate frame $[\boldsymbol{B}]$ represents a frame attached to the body of the aviation. The azimuth coordinate frame $[\boldsymbol{A}]$ represents a frame attached to the outer (azimuth) gimbal which can rotate with respect to the base around the $z_B = z_A$ axis. The elevation coordinate frame $[\boldsymbol{E}]$ represents a frame attached to the inner (elevation) gimbal which can rotate with respect to the azimuth gimbal around $x_A = x_E$ axis [1,6,17]. Rotations expressing the pose of the elevation gimbal with respect to the base are given by

$$\boldsymbol{C}_{\boldsymbol{B}}^{\boldsymbol{A}} = \begin{bmatrix} \cos\theta_a & \sin\theta_a & 0 \\ -\sin\theta_a & \cos\theta_a & 0 \\ 0 & 0 & 1 \end{bmatrix} \tag{1}$$

and

$$\boldsymbol{C}_{\boldsymbol{A}}^{\boldsymbol{E}} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_e & \sin\theta_e \\ 0 & -\sin\theta_e & \cos\theta_e \end{bmatrix} \tag{2}$$

where the subscripts and superscripts are used here as "rotation matrix expressing the coordinate triade of the frame $[\boldsymbol{B}]$ within

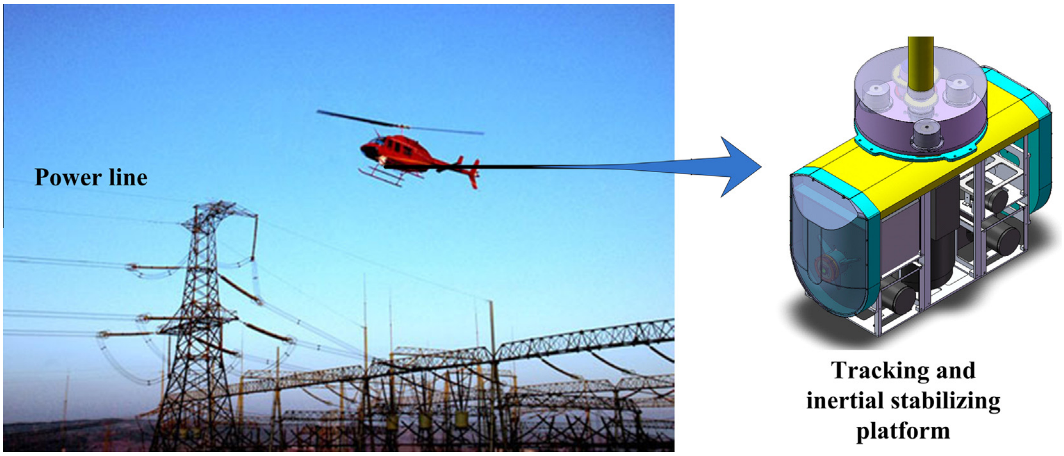

Fig. 1. APLI system.