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Robust control of gyro stabilized platform driven by ultrasonic motor☆

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ABSTRACT

In this paper, a two degrees of freedom dynamic model of two axis stabilized platform driven by ultrasonic motor is constructed based on mechanical structure. A robust proportional-integral-differential controller is designed, in which the mechanical resonance, the coupling of inertia moment and torque, nonlinear of ultrasonic motor are considered. The stability of the presented system is analyzed with the method of robust system stability. The presented controller is realized on embedded microcontroller, and the contrast experiments of platform control between the presented controller and the traditional proportional-integral-differential controller are conducted. The experiments has shown that for the stabilized platform driven by ultrasonic motor the presented robust controller has good performance in the dynamic response, isolation, and the whole system has stronger robustness and the anti-jamming ability.

1. Introduction

Gyro stabilized platform is used for image stabilization and tracking control of photoelectric imaging system of motion carrier [1,2]. The traditional gyro stabilized platform is driven by electromagnetic motor (EMM). As the rising requirements of stabilized platform on minimization, lightweight, high precision, fast response and anti-electromagnetic interference [3–5], traditional electromagnetic motor cannot completely meet those requirements. Ultrasonic motor (USM) is a new type of actuator, which based on piezoelectric effect and friction drive, and has obvious advantages on position resolution, power to weight ratio, dynamic response and electromagnetic compatibility [6,7]. The USM utilizing the inverse piezoelectric effect of piezoelectric ceramic to achieve conversion of electrical energy to mechanical energy and through friction drive to realize motion transfer. The USM can achieve high-precision speed control in aerospace systems and can improve the systems effective load for it's simple structure, fast response, high angular resolution, low speed with high speed, self-locking, and without magnetic interference [8–10].

Usually, two axes platform is used to provide stabilization for the load according to the sensor under different disturbances. The most important disturbance sources are the angular motion of the carrier, the dynamics of platform system, and mass unbalance of the gimbal. It is therefore necessary to capture all the dynamics of the plant and express the plant in analytical form before the design and control of the platform is taken up [11,12]. Taking the USM as a driving source, the difficulty of system control is increased due to the nonlinear characteristics of piezoelectric and friction driving of the USM. For two axes platform driven by USMs, each axis should realize the stability by a suitable control algorithm. The traditional proportional-integral- differential (PID) controllers have found extensive industrial applications for its simple structure. The common tuning method of parameters for PID is Ziegler-Nichols (ZN) tuning method [13]. Nevertheless, the ZN related methods might be inadequate in the applications where a high performance is required for plant nonlinear characteristics [14,15]. So how to design proper parameters according to the characteristics and control requirements of the system to achieve the optimal control is always the goal of the researchers.

In this paper, a complete model of two axes gimbal platform driven by USM is derived assuming that gimbals have mass unbalance as well as considering all inertia disturbances and cross coupling. A model of USM is presented for robust control system design. To achieve the stability control of the sensor's line of sight (LOS), a robust PID controller is presented. Then the presented controller is realized on a 32-bits embedded digital signal controller by C langue. At last, experiments comparison between the presented controller and the traditional PID controller are carried out under different disturbance.

2. System modeling

Modeling and analysis is a key step to research and design the control system of gyro stabilized platform. Reasonable platform model is helpful to analyze the source of error and design the

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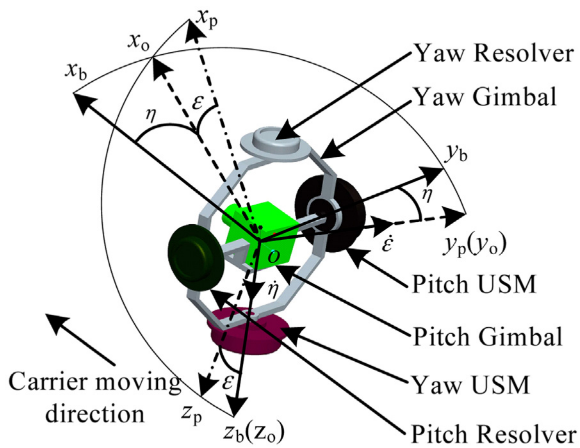

Fig. 1. The coordinates of the platform.

control strategy, which provides the basis for the design of high performance and high precision gyro stabilized platform control system.

2.1. Dynamics modeling of platform

The two axis stabilized platform driven by USMs consists of two gimbals, the driving USM and sensing device. The structure principle and the coordinate system are shown in Fig. 1. In Fig. 1 three coordinates are used to describe the motion relations of the platform, which are the base coordinates system, the outer gimbal coordinates system and the inner gimbal coordinates system.

The base coordinates system ($O_bx_by_bz_b$) connected with the base, can be used to describe the movement of the carrier. The origin of the coordinates system is at the intersection of the yaw and pitch axis. The axis of O_bx_b has the same direction of the carrier, and here we note the direction of motion as positive direction. When the carrier is in a horizontal position, we note the O_bz_b is the positive direction. The positive direction of the O_by_b is defined in terms of the right-handed rule.

The outer gimbal coordinates system ($O_ox_oy_oz_o$) is used to describe the movement of the yaw. The outer gimbal coordinates system has the same origin of the base coordinates system. The O_oz_o axis is along with the direction of the inner gimbal rotating, and we note the pointing to the yaw USM is the positive direction. The O_oy_o axis is along with the direction of the outer gimbal rotating, and we note the pointing to the pitch USM is the positive direction. The positive direction of the O_ox_o is defined in terms of the right-handed rule.

The inner gimbal coordinates system ($O_px_py_pz_p$) is used to describe the movement of the pitch. The inner gimbal coordinates system has the same origin of the base coordinates system. At the initial position the inner gimbal and the outer gimbal have a same plane. The axis of O_px_p is the LOS, and we note the pointing to the front of the carrier is the positive direction. The axis of O_py_p is along with the direction of the inner gimbal rotating, and to the right is positive. The positive direction of the O_pz_p is defined in terms of the right-handed rule.

All the above origin of the coordinate system are taken at the intersection of the two axes, so their origin is coincident, here we note as $O_b = O_o = O_p = O$.

In order to achieve stability and tracking of the platform it is necessary to control the rotation of each gimbal, which will produce a coordinate transformation. Take the rotation angle of outer gimbal to the base is η. The transformation matrix of the base coordinates system to the outer gimbal coordinates system is

$$T_{ob} = \begin{bmatrix} \cos\eta & \sin\eta & 0 \\ -\sin\eta & \cos\eta & 0 \\ 0 & 0 & 1 \end{bmatrix} \tag{1}$$

Take the rotation angle of inner gimbal to the outer gimbal is ε. The transformation matrix of the outer coordinates system to the inner gimbal coordinates system is

$$T_{po} = \begin{bmatrix} \cos\varepsilon & 0 & -\sin\varepsilon \\ 0 & 1 & 0 \\ \sin\varepsilon & 0 & \cos\varepsilon \end{bmatrix} \tag{2}$$

Let the angular velocity of the carrier is $\omega_b = [p\ q\ r]^T$, and the angular velocity of the carrier can be transformed into the outer coordinate system by the coordinate conversion (1)

$$\omega_{ob} = T_{ob}\omega_b \tag{3}$$

The outer gimbal has an angular velocity vector respect to the carrier, which is the description of outer gimbal deflection angular velocity itself in the outer gimbal coordinate system.

$$\dot{\eta} = \begin{bmatrix} 0 & 0 & \dot{\eta} \end{bmatrix}^T \tag{4}$$

From (3) and (4) we can get the outer gimbal angular velocity vector described in the outer gimbal coordinate system

$$\begin{aligned} \omega_o &= \omega_{ob} + \dot{\eta} = T_{ob}\omega_b + \dot{\eta} \\ &= \begin{bmatrix} p\cos\eta + q\sin\eta & -p\sin\eta + q\cos\eta & r + \dot{\eta} \end{bmatrix}^T \end{aligned} \tag{5}$$

The outer gimbal angular velocity can be transformed into the inner coordinate system by the coordinate conversion (2)

$$\omega_{po} = T_{po}T_{ob}\omega_b + T_{po}\dot{\eta} \tag{6}$$

The inner gimbal has an angular velocity vector respect to the outer gimbal, which is the description of the inner gimbal deflection angular velocity itself in the inner gimbal coordinate system.

$$\dot{\varepsilon} = \begin{bmatrix} 0 & \dot{\varepsilon} & 0 \end{bmatrix}^T \tag{7}$$

The LOS coordinate system is the inner gimbal coordinate system, and the LOS and the inner gimbal system have the same motion parameters. So from (6) and (7) the inner gimbal angular velocity in the inner gimbal system can be described as

$$\begin{aligned} \omega_p &= T_{po}T_{ob}\omega_b + T_{po}\dot{\eta} + \dot{\varepsilon} \\ &= \begin{bmatrix} (p\cos\eta + q\sin\eta)\cos\varepsilon - (r + \dot{\eta})\sin\varepsilon \\ -p\sin\eta + q\cos\eta + \dot{\varepsilon} \\ (p\cos\eta + q\sin\eta)\sin\varepsilon + (r + \dot{\eta})\cos\varepsilon \end{bmatrix} \end{aligned} \tag{8}$$

If all the factors of driving and influence of the optical axis motion are considered the dynamic model of the platform will be complex. In general engineering applications, some appropriate measures could avoid or reduce the interference, so the model can be simplified. The simplifications: the inertia of each frame in the two axes of the respective coordinate system are very close to or the same by increasing the machining and assembly, installation and adjust the weight of the mechanical parts [16]. According to Newton's laws of motion the dynamic model of the platform is

$$\begin{cases} M_{el} - M_{imb\ py} - M_{dp} = J_{py}\dot{\omega}_{py} \\ M_{az} - M_{imb\ oz} - M_{do} = J_{oz}\dot{\omega}_{oz} - J_{px}\dot{\omega}_{px}\sin\varepsilon + J_{pz}\dot{\omega}_{pz}\cos\varepsilon \end{cases} \tag{9}$$

where M_{el} is the driving torque of inner gimbal motor, M_{az} is the driving torque of outer gimbal motor, M_{fp} is the inner disturbance torque generated by friction, M_{fo} is the outer disturbance