ISA Transactions ∎ (∎∎∎∎) ∎∎∎–∎∎∎

Contents lists available at ScienceDirect

ISA Transactions

journal homepage: www.elsevier.com/locate/isatrans

Research article

A compound scheme on parameters identification and adaptive compensation of nonlinear friction disturbance for the aerial inertially stabilized platform

Xiangyang Zhou [a,*], Beilei Zhao [a], Wei Liu [b], Haixiao Yue [a], Ruixia Yu [c], Yulong Zhao [d]

[a] School of Instrumentation Science & Opto-electronics Engineering, Beihang University, No. 37 Xueyuan Rd., Haidian District, Beijing 100191, China
[b] Institute of Navigation and Control Technology, No. 10 Chedaogou Rd., Haidian District, Beijing 100089, China
[c] Pera Corporation Ltd., No. 1 Balizhuangdongli Park, Chaoyang District, Beijing 100025, China.
[d] State Key Laboratory for Manufacturing Systems Engineering, Xi'an Jiaotong University, No. 28 Xianning West Road, Xi'an 710049, Shaanxi, China

ARTICLE INFO

Article history:
Received 16 March 2016
Received in revised form
4 December 2016
Accepted 1 January 2017

Keywords:
Adaptive compensation
Aerial remote sensing
Nonlinear friction disturbance
Inertially stabilized platform
Parameters identification

ABSTRACT

A compound scheme is proposed to compensate the effect of nonlinear friction disturbance on the control precision of a three-axis inertially stabilized platform (ISP) for aerial remote sensing applications. The scheme consists of friction parameters identification and adaptive compensation. A LuGre model-based ISP friction model is first developed. Then, a comprehensive experimental scheme is proposed to obtain the static friction parameters. Further, the dynamic parameters are identified by experiments and dynamic optimization. On the basis of identified parameters and Lyapunov stability theory, a back-stepping integral adaptive compensator is designed to compensate the nonlinear friction disturbance. Simulations and experiments are carried out to validate the scheme. The results show that the compound scheme can accurately obtain the friction parameters and improve the control precision and stability of ISP.

1. Introduction

Inertially Stabilized Platform (ISP) is a key component for an aerial remote sensing system, which is used to hold and control the line of sight (LOS) of the imaging sensors keeping steady in inertial space [1–6]. For an aerial remote sensing system, in order to obtain high-resolution images and satisfy the requirements of high photo overlapping ratio, the high-precision ISP is indispensable to isolate disturbances derived from diverse sources [3,4], particularly for the swings of three attitude angles of aircraft. Due to the serious effects of internal and external disturbances, the movement of aircraft is not ideal that makes the LOS jitter, eventually resulting in the degradation of images quality [5,6]. The first fundamental objective of an ISP is to help imaging sensors to obtain good quality images of the target region. Therefore, the most critical performance metric for an ISP is torque disturbance rejection. It is a principal issue for the control system of ISP that how to minimize the effects of disturbances introduced on the ISP [2].

For the aerial surveying and mapping applications, the ISP is generally required to provide three rotational degrees of freedom (DOFs) to achieve better isolation from the angular motions of aircraft. Therefore, the structures with three-axis are commonly used when ISP is designed. Since the maximum required velocity of an ISP is usually low, rarely exceeds 100 degrees per second, gearing can be considered in an attempt to reduce the size and weight of the actuator, particularly when the torque requirements are demanding [1]. Thus, to meet the requirements with capacity of high driving torque, heavy load and small size, etc., three gimbals are often designed to be rotated by indirect drive motors linked to each gimbal through gear trains. To satisfy the high quality imaging requirements, the ISP needs to realize high pointing precision without jitter under lower tracking speed. However, since most gearing arrangements inevitably introduce additional friction and torsional resonances in the system, the reaction torque from a geared actuator constitutes an equivalent torque disturbance that can degrade stabilization performance [1,2]. As we know, for a mechano-electronic system with the characteristic of low speed, the control system performance is mainly affected by factors such as friction torque, motor fluctuations torque, measurement system error etc. Among these factors, the friction torque is predominant over others, which directly affects the control accuracy and movement stability [3,4].

Friction plays a major role in control systems. The effects of friction can be alleviated to some extent by friction compensation [7]. In most applications, friction is a major disturbance and frictional torques can be particularly troublesome, bearings and seals

* Corresponding author.
E-mail addresses: xyzhou@buaa.edu.cn (X. Zhou), zhaobeilei1992@buaa.edu.cn (B. Zhao), liuwbuaa@126.com (W. Liu), victor_yue@buaa.edu.cn (H. Yue), yrx_nx@163.com (R. Yu), zhaoyulong@mail.xjtu.edu.cn (Y. Zhao).

http://dx.doi.org/10.1016/j.isatra.2017.01.003
0019-0578/

on the gimbal assemblies are typically the major contributor to friction levels [2,4]. Friction has been shown to be one of the major contributing factors for problem associated with accuracy in motion control systems [8]. Such a physical phenomenon may result in some negative effects on system performance, for instance, self-excited vibration, steady-state limit cycle, poor tracking performance, and friction-induced instabilities [9]. It limits the precision of positioning and pointing systems and can give rise to instabilities. Since friction is nonlinear, it may produce steady state errors and transmission accuracy errors. In addition, due to the static frictional force, the elastic deformations may occur on the contact surfaces of transmission gears, which will produce position error. Particularly, when the motion is reversed the return error will occur [10]. These friction errors make imaging resolution and repeatability decrease, which seriously influence the quality and efficiency of an aerial remote sensing task. Therefore, it is crucial for an ISP to conduct friction compensation to reach high control precision.

Various control methods have been proposed to compensate the friction effects. The methods for friction compensation can be divided into two categories: the model-based and the nonmodel-based compensations [11]. On the one hand, nonmodel-based methods are widely investigated that have the advantages in such as decreasing the required information on complex dynamics in advance [12–14]. For examples, a recursive model free controller (RMFC) based friction compensation scheme is proposed that uses only the robot position measurement and does not require knowledge of the electromechanical system parameters [13]. A model-free control scheme with the elasto-plastic friction observer is presented for robust and high-precision positioning of a robot manipulator [14]. On the other hand, over past decades, researchers have proposed many models [7,8,15–21] to describe the nonlinear friction behavior. In general, friction models can be divided into two regimes: static-friction models and dynamic-friction models [9]. Models designed to characterize the stick-slip phenomenon mainly include those such as Reset-Integrator, Bristle, Karnopp, Dahl, and Walrath [21], and so on. Friction phenomena such as pre-displacement, rate dependence, and hysteresis have been observed experimentally and are reproduced only by dynamic models [7]. Friction models have been developed to complex dynamic models containing multiple parameters from simple static models which cannot describe the friction dynamic characteristics [22,23]. Dynamic friction models mainly include the LuGre model and the Bristle model. Relatively, the dynamic LuGre friction model describes the friction effects more accurately and addresses low velocities and velocity reversals [9]. The LuGre friction model is a more complete dynamic friction model, was proposed by C. Canudas de Wit in 1995 [24], has been confirmed to contain virtually all of the static and dynamic friction characteristics and can be used in the design of friction compensation program. Due to its simpler form and the ability to capture major dynamic friction behaviors, the LuGre model has been widely employed in high precision servo control systems with dynamic friction compensations [25]. Therefore, it is important to investigate the friction compensation methods based on LuGre model to realize higher accuracy [26].

In this paper, to compensate the friction disturbances of a three-axis ISP for aerial remote sensing application, the investigation on the friction modeling, parameters identification and adaptive compensation are carried out. The related methods are accordingly proposed under considering both of performance and application, and further validated by experiments.

2. Basic background

2.1. Aerial remote sensing system

Fig. 1 shows the schematic diagram of an aerial remote sensing system. An aerial remote sensing system is generally composed of four main components, i.e., a three-axis ISP, an imaging sensor, a Position and Orientation System (POS) and the aircraft vehicle. The role of the ISP is to act as a physical and intelligent interface between the imaging sensor and the aircraft. With the help of ISP, the influences of various disturbances either inside or outside the aircraft on imaging sensors are initiatively isolated and hence leading to high-resolution images. The POS, which is mainly composed of three main components, inertial measurement unit (IMU), GPS receiving antenna and data processing system [27], is used to provide an accurate reference of position and attitude in inertial space for control system of ISP and imaging sensor through measuring the angular movement of imaging sensor. The IMU is mounted on the top of the imaging sensor's phase center.

As shown in Fig. 1, the three-axis ISP is mounted on the floor of aircraft, and the imaging sensor and POS are mounted on inner azimuth gimbal of the ISP. When the aircraft rotates or jitters, the control system of three-axis ISP gets the high-precision attitude reference information measured by POS and then routinely control the LOS of imaging sensor to achieve accurate pointing and stabilizing relative to ground level and flight track.

2.2. Working principle of three-axis ISP system

Fig. 2 shows the schematic diagram of the three-axis ISP's principle. We can see that the ISP consists of three gimbals, which are azimuth gimbal (A-gimbal), pitch gimbal (P-gimbal) and roll gimbal (R-gimbal). Among them, the A-gimbal is assembled on the P-gimbal, and can rotate around Z_a axis. Likewise, the P-gimbal is assembled on the R-gimbal, and can rotate around X_p axis. The R-gimbal is assembled on the basement, and can rotate around Y_r axis.

From Fig. 2, we can see the relationships between three gimbals: G_p, G_r and G_a respectively stand for rate gyro that measures inertial angular rate of P-gimbal, R-gimbal and A-gimbal. E_r, E_p and E_a respectively stand for photoelectric encoder which measures relative angular between gimbals. M_r, M_p and M_a respectively stand for gimbal servo motor which drives R-gimbal, P-gimbal and A-gimbal to keep these three gimbals steady in inertial space.

2.3. Three closed-loop control system

Fig. 3 shows the block diagram of traditional three-loop control system for ISP. The three closed-loop control strategy, composed of current loop, speed loop and position loop, is widely employed in the control of ISP. The inner current loop is used to reduce the influence of voltage fluctuation from power supply or motor back electromotive force (EMF). The middle rate loop uses a rate gyro to measure the angular rate of the gimbal in the inertial space, which is used to compensate the difference between the rate command input and the angular rate of the gimbal, and then improve the steady-state precision. As to the main feedback path, the outer position loop takes the attitude angle measured by POS as accurate references to ensure the accurate pointing of the LOS.

In Fig. 3, the blocks of G-pos, G-spe and G-cur separately represent the controllers in the position loop, speed loop and current loop; the PWM block represents the power amplification used for the current amplify to drive the torque motor; the symbol L represents the inductance of a torque motor, R is the resistance, K_t is the torque coefficient of the motor and N is the transition ratio from the torque motor to the gimbals; J_m is the moment of inertia

Please cite this article as: Zhou X, et al. A compound scheme on parameters identification and adaptive compensation of nonlinear friction disturbance for the aerial inertially stabilized platform. ISA Transactions (2017), http://dx.doi.org/10.1016/j.isatra.2017.01.003