ISA Transactions 63 (2016) 288–298

Contents lists available at ScienceDirect

ISA Transactions

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

Research Article

Dual-rate-loop control based on disturbance observer of angular acceleration for a three-axis aerial inertially stabilized platform

Xiangyang Zhou*, Yuan Jia, Qiang Zhao, Tongtong Cai

School of Instrumentation Science & Opto-electronics Engineering, Beihang University (BUAA), Beijing 100191, China

ARTICLE INFO

Article history:
Received 18 December 2014
Received in revised form
4 January 2016
Accepted 27 February 2016
Available online 23 March 2016

Keywords:
Dual-rate-loop
Disturbance observer
Inertially stabilized platform
Kalman filter
Tracking-differentiator

ABSTRACT

This paper presents a dual-rate-loop control method based on disturbance observer (DOB) of angular acceleration for a three-axis ISP for aerial remote sensing applications, by which the control accuracy and stabilization of ISP are improved obviously. In stabilization loop of ISP, a dual-rate-loop strategy is designed through constituting inner rate loop and the outer rate loop, by which the capability of disturbance rejection is advanced. Further, a DOB-based on angular acceleration is proposed to attenuate the influences of the main disturbances on stabilization accuracy. Particularly, an information fusion method is suggested to obtain accurate angular acceleration in DOB design, which is the key for the disturbance compensation. The proposed methods are theoretically analyzed and experimentally validated to illustrate the effectiveness.

1. Introduction

Aerial remote sensing plays an increasingly important role in lots of fields closely related to the national economy and the people's livelihood, such as surveying and mapping, resources exploration, disaster monitoring, and so on. In an aerial remote sensing system, the axis of optical sensor must be accurately pointed from a movable base to a fixed or moving target. However, due to the serious effects of internal and external disturbances, the movement of the aircraft is not ideal that makes the sensor's line of sight (LOS) jitter, eventually resulting in the degradation of images quality [1–8]. For an aerial remote sensing system, inertially stabilized platform (ISP) is a key component, which is used to hold and control the LOS of the imaging sensor to keep steady relative to inertial space or maintaining sensor's orientation toward a target [1,2]. In order to obtain high-resolution images and satisfy the requirements of high photo overlapping ratio, the sensor's LOS must be strictly controlled. Therefore, the high-precision ISP, which is typically mounted on a movable platform, is indispensable to isolate disturbances derived from diverse sources [3,4], particularly for the case of swings of three angular attitudes of aircraft. The best-known application of ISP is the stabilization and control of payloads particularly for electro-optical sensors. When applied, it provides a physical interface between imaging sensors and the aviation platform. 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. In [5,6], three-axis ISP that can improve greatly the image quality through controlling the sensor's LOS to achieve accurate pointing and stabilizing is systematically introduced, especially when the target is in highly dynamic.

The first fundamental objective of an ISP is to help imaging sensors to obtain good quality images of the target or target region [6]. 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 [5]. Disturbances that affect the pointing vector arise from platform angular motion or maneuvers, and external loads such as wind and air-stream inducing torque. Disturbances arise from diverse sources, for example, platform linear motion and vibration generate disturbance torques due to mass imbalance and gimbal geometry. In [5], the common ISP disturbances are summarized systematically. Among them, friction, imbalance, vehicle motion kinematic coupling and sensor noise are predominant [7,8]. They can be further divided into two categories [9]: The first category contains stochastic disturbances, which are normally characterized by statistical properties, such as mean value, covariance and power spectral density. The second category contains waveform-structured signals, which show distinguishable patterns, at least over short time intervals.Typically, the aerial ISP control system is configured as a high-bandwidth

* Corresponding author. Tel.: +86-10-82317396.
E-mail addresses: xyzhou@buaa.edu.cn (X. Zhou), jiayuan@buaa.edu.cn (Y. Jia), zhaoqiangbuaa@163.com (Q. Zhao), cttnszbdhz@163.com (T. Cai).

http://dx.doi.org/10.1016/j.isatra.2016.02.021
0019-0578/

rate loop inside a lower bandwith pointing or tracking position loop. The ISP might be viewed as a means for removing high-frequency disturbances and controlling the LOS, whereas the pointing and tracking loops have the task of removing the lower frequency parallatic motion and perhaps any bias or drift in the ISP rate loop [6]. Therefore, in practical application, the aerial ISP control systems mostly adopt traditional PID three-closed-loop compound control scheme, which is composed of current loop, speed loop and position loop [10]. 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 improve the steady-state precision. As to the main feedback path, the outer position loop takes the attitude angle measured by position and orientation system (POS) as accurate reference to ensure the accurate pointing of the LOS. However, the performances of simple single-loop control mode are not satisfactory under parameter variation, nonlinearity, large supply and load disturbances [11]. Particularly, accompanying with the increasing requirements of high stabilization accuracy of ISP arising from aerial remote sensing applications, the single-rate-loop mode has gradually lost the good stabilization ability to simultaneously reject internal disturbances and external carrier turbulence, as well as decrease effectively the effects of nonlinear disturbances on system performance under low speed servo condition, which no longer satisfies the need of aerial remote sensing system. Therefore, the dual-rate-loop cascade control structure [11–15] is proposed and applied widely in various mechanical and electrical systems, which shows the excellent capability of rejecting disturbances comparing with the single-rate-loop mode. In [11], considering the shortcomings of single-rate-loop servo control composed of rate gyro for LOS stabilization of opto-electronic tracking platform system, a dual-rate-loop cascade control structure using the DC tachometer motor to constitute the inner speed loop, and using the rate gyro to constitute the digital outer stabilization loop is presented. In [12], a novel series cascade control structure to enhance the closed loop performance is proposed for integrating and time delay processes, which gives significant improvement in the closed-loop performances with less number of controllers. In [13], a novel closed-loop tuning method for cascade control systems is presented, in which both primary and secondary controllers are tuned simultaneously. In [14], a new hybrid finite-time robust three-axis cascade attitude control approach is proposed in the spacecraft modeling and analysis of the control scheme. In [15], a cascade control is developed for the Sander automation system to actively reject the internal disturbance.

In addition, there are continuous interests for researchers to investigate the control methods with higher accuracy and stability by various disturbances rejection. Disturbance observer (DOB) is an effective method. DOB-based control algorithms first appeared in the late 1980 s, which now has been successfully employed in the industry including ISPs [9,16–24] thanks to its powerful ability to attenuate disturbances and compensate for plant uncertainties. DOB is capable of fulfilling the fundamental objectives in the feedback system design including robust stability and disturbance rejection [8]. By this approach, the magnitude of the disturbance is estimated and then be used to improve the performance of a literally any control algorithms [16]. One interesting feature of DOB is that it can be used as an inner-loop controller so that a real uncertain plant, in the presence of disturbances, is forced to behave like a nominal plant in a disturbance-free environment [17]. In [18], the generalized disturbance compensation framework named the robust internal-loop compensator (RIC) is introduced and an advanced design method of DOB is proposed based on the RIC. In [19], a DOB is constructed to estimate the disturbance with partially-known information, based on which, a DOB-based disturbance attenuation control scheme is proposed. In [20], DOB is used as a means for disturbance rejection to stabilize the position error for a high-precision motion control of a nanopositioning stage driven by a piezoelectric stack actuator (PSA). In [21], two kinds of DOB-based controllers are compared in terms of stability of inertia variation for a two-wheel wheelchair system. In [22], an uncalibrated visual servoing scheme with optimal disturbance rejection performance is proposed based on DOB. In [23], an uncertainty and disturbance estimator (UDE) is used to estimate the composite disturbance of three-axis ISP, which is used to robustify feedback linearization based controller designed for nominal system. In [24], to compensate the disturbances of ISP such as vibrations, frictions and couplings, a sliding mode controller based on a proportional integral (PI) disturbance observer is presented. For the ISPs' control system, the angular accelerometer output signal of gimbals relative to inertial space is a time-varied parameter [25] which is related closely to the external disturbances. Therefore, it is necessary to adopt angular acceleration-based DOB to estimate and compensate the disturbance torques.

Therefore, in this paper, to achieve the high stabilization accuracy of a three-axis ISP for aerial remote sensing applications, a compound control scheme is proposed, which combines both advantages of the dual-rate-loop control structure and DOB in disturbances rejecting. Firstly, in the design of stabilization loop of ISP, a dual-rate-loop strategy is proposed through constituting inner rate loop and the outer rate loop respectively. By this way, the functions of rejecting internal disturbance of ISP and insulating external disturbances of carrier turbulence are separated. As a result, the capability of disturbance rejection is promoted significantly. Secondly, on the basis of dual-rate-loop control structure, to further attenuate the influences of the main disturbances on stabilization accuracy, a DOB based on angular acceleration is proposed in stabilization loop meanwhile. In DOB design, particularly, an information fusion method is proposed to obtain accurate angular acceleration for disturbances compensation, in which Kalman filter is used in combination with tracking-differentiator. To verify the performance of proposed scheme, a series of experiments are carried out. The results validates that the compound control scheme is effective that can improve obviously the stabilization accuracy of ISP.

The rest of this paper is organized as follows: Section 2 introduces the basic principle of three-axis ISP for aerial remote sensing applications. Section 3 presents the design of dual-rate-loop control structure of three-axis ISP and analyzes its performance in disturbance rejection. Section 4 describes the design of DOB based on angular acceleration in stabilization loop and proposes an information fusion method to accurately estimate the angular acceleration for DOB-based disturbance compensation. Section 5 conducts the experiments to validate the methods and discusses the experimental results. Finally, the conclusions are given in Section 6.

2. Principle of the three-axis ISP

2.1. Constitution of aerial remote sensing system

Fig. 1 shows the schematic diagram of an aerial remote sensing system. Generally, an aerial remote sensing system consists of four main components [10], i.e., the three-axis ISP, remote sensing sensor, POS and aviation platform. When applied, the three-axis ISP is mounted on the aviation platform, and the imaging sensor