Measurement 60 (2015) 39–49

Contents lists available at ScienceDirect

Measurement

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

Dynamic lever arm compensation of SINS/GPS integrated system for aerial mapping

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ARTICLE INFO

Article history:
Received 29 December 2013
Received in revised form 9 May 2014
Accepted 19 September 2014
Available online 30 September 2014

Keywords:
Dynamic lever arm
Inertially stabilized platform
Nonlinear estimation
SINS/GPS integrated system
Aerial mapping

ABSTRACT

Strapdown inertial navigation system (SINS)/global positioning system (GPS) integrated system is an important way of accurate measurement of the mapping sensors for high resolution aerial mapping. However, for keeping the mapping sensor level and appointed direction, inertially stabilized platform (ISP) will be applied and rotate its three gimbals. The lever arm between inertial measurement unit (IMU) and GPS antenna will be time-varying. Therefore, the precise compensation of the effect of the dynamic lever arm will be significant for the measurement accuracy of SINS/GPS integrated system. An algorithm which tackles the problem is proposed, the dynamic lever arm is originally considered as the summation of two relative constant lever arms. Then, with the aid of the encoder data of ISP, the algorithm of dynamic lever arm compensation is derived in the paper. As the nonlinearity of the system, the demand of the on-line and off-line processing, unscented Kalman filter and smoother for nonlinear estimation are applied. Finally, the proposed algorithm of dynamic lever arm compensation is applied to a flight data of aerial mapping experiment. It is shown from the experiment results that the proposed algorithm can more effectively compensate the degradation of the measurement information than the traditional algorithm.

1. Introduction

Aerial mapping is a kind of high technology which utilizes aerial mapping sensors to acquire the spatial and geographical information of the surface of earth [1,2]. The ideal motion trajectory of aerial sensors for high quality mapping images is moving along a straight line with constant speed. During the practical aerial mapping, the aerial vehicles will inevitably deviate aerial mapping sensors from the ideal motion trajectory as the effects of gust, air turbulence and the error of flight control. Consequently, the resolution of the mapping images will be degraded. At the same time, as the effects of the drift angle, the images will be obtained in the incorrect direction. Therefore, the demand of the overlapping images will not be satisfied which will result in the failure of the mapping [2]. Therefore, to realize the mapping with high accuracy and efficiency, the isolation of the flight disturbances and motion compensation must be done. To isolate the flight disturbances and the effects of the drift angle, inertially stabilized platform (ISP) is usually utilized which is composed of three gimbals. The mapping sensor is kept level and appointed direction through the servo control of the three gimbals of ISP [3,4]. However, ISP can only isolate the angular disturbances, the motion of translation cannot be eliminated. Therefore, strapdown inertial navigation system (SINS)/global positioning system (GPS) integrated system must be utilized to measure the actual flight trajectory of mapping sensor precisely for motion compensation [5,6].

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http://dx.doi.org/10.1016/j.measurement.2014.09.056
0263-2241/

SINS/GPS integrated system is a sort of multi-sensor data fusion system. SINS has the advantage of independence, high accuracy in short period and high data rate. As there are the bias errors in the gyroscopes and accelerometers, the error of SINS solution will grow unbounded with time elapsing. So aided information must be utilized to correct the errors [7,8]. GPS receiver can receive the signals from GPS satellites, and provide the position and velocity information of the vehicle with error bounded. However, the output rate of GPS is low, and the GPS signals are easily blocked and jammed [8,9]. Therefore, through the integration of the solutions of SINS and GPS, the advantages of both technologies are combined to give an independent, high-bandwidth, complete navigation solution with high long- and short-term accuracy [7,10]. However, it is impossible to have the phase center of GPS antenna coincide with the measurement center of inertial measurement unit (IMU) as the limitation of installation. Generally, the GPS antenna is mounted on the roof of the plane for better visibility of GPS satellites, and IMU is installed inside the cabin of the plane. The displacement of the two points is named lever arm. This spatial separation makes the position and velocity propagations of these two points different from each other during most circumstances. Once the information of SINS and GPS are fused through estimation algorithms directly without remediation, the accuracy of the estimation results will degrade severely, even causing the divergence of the estimator. Therefore, the effect of lever arm must be compensated for SINS/GPS integrated system [11].

The mechanization and compensation method of the lever arm between IMU and GPS are analyzed in [10,12,13]. However, the lever arm is difficult to be measured in some situations. The estimation of the lever arm and corresponding observability analysis are tackled in [14,15]. Besides considering the effect of lever arm between the IMU and GPS, the lever arm between IMU and odometer is also taken into accounted in [16]. So more accurate results of the system are obtained for the navigation of land vehicles. The effect of lever arm between Locata antenna and IMU is compensated for Locata/SINS integrated system to replace the vulnerable GPS for maritime application in [17]. Several kinds of lever arms of SINS/GPS integrated system are examined in [11], the impacts on the accuracy of the system is also studied with the conclusion that the effect of lever arm is an important factor to the precision of the system. Furthermore, the effect of lever arm is also critical for transfer alignment between two or more IMUs, the effect must be compensated precisely for effective transfer alignment [15,18,19].

To keep the mapping sensor level and appointed direction in the process of aerial mapping, ISP need to rotate the three gimbals. Consequently, the lever arm between the measurement center of IMU and the phase center of GPS antenna will change. The problem is named dynamic lever arm compensation in the paper. As the traditional lever arm compensation does not consider the change of the lever arm, the measurement information from GPS will deteriorate after the traditional lever arm compensation. Therefore, the accuracy of the integrated system will become worse correspondingly. A new algorithm which tackles the problem of dynamic lever arm compensation is proposed in the paper.

The paper is organized as follows. The error model of nonlinear SINS/GPS integrated system and problem statement are presented in Section 2. The principle of dynamic lever arm compensation and estimator for nonlinear SINS/GPS integrated system are discussed in Section 3. In Section 4, a flight data of aerial mapping experiment is utilized to demonstrate the effectiveness of the proposed algorithm. Finally, Section 5 concludes the paper.

2. System description and problem statement

2.1. System description

SINS and GPS are very complementary in the error characteristics. Therefore, operating the two systems together yields benefits over operating either system alone. SINS/GPS integrated system discussed here is a loosely coupled system, the position and velocity of SINS and GPS solutions are compared, the resulting differences forming the measurement inputs to an estimator. As SINS provides more information than GPS, and it is more independent. SINS is chosen as the reference solution of the integrated systems, GPS will provide the error bounded data of position and velocity to aid SINS. The error model of SINS/GPS integrated system is fundamental for the integrated estimation which will be presented in the following.

2.1.1. State equation

Since SINS is the reference solution, the error equation of SINS forms the state model of the integrated system. The east-north-up local-level frame is chosen as the navigation frame. Also, the widely used 15-dimension state model is applied in this paper. To obtain more accurate estimation results, the nonlinear error model of SINS/GPS integrated system is utilized which is presented in detail in the following.

The differential equation of orientation errors is given by

$$\dot{\varphi}^n = (I_3 - C_n^p)\omega_{in}^n + \delta\omega_{in}^n - C_b^n\varepsilon^b - C_b^n\omega_\varepsilon^b \tag{1}$$

where $\varphi^n = [\varphi_E, \varphi_N, \varphi_U]^T$ denotes the orientation error vector, the superscript T denotes the transpose. ω_{in}^n denotes the angular rate of the navigation frame with respect to the inertial frame, $\delta\omega_{in}^n$ denotes the angular rate error of ω_{in}^n. $\varepsilon^b = [\varepsilon_x, \varepsilon_y, \varepsilon_z]^T$ is the constant drift vector of gyroscopes, ω_ε^b is the noise vector of gyroscopes, I_3 denotes the 3×3 identity matrix, C_n^p is the orientation error matrix, C_b^n is the coordinate transformation matrix from the body frame to the navigation frame.

The differential equation of velocity errors is presented as

$$\begin{aligned}\delta\dot{v}^n = {} & (I_3 - C_p^n)C_b^n f^b - (2\delta\omega_{ie}^n + \delta\omega_{en}^n) \times v^n - (2\omega_{ie}^n \\ & + \omega_{en}^n) \times \delta v^n + C_b^n\nabla^b + C_b^n\omega_\nabla^b\end{aligned} \tag{2}$$

where $\delta v^n = [\delta v_E, \delta v_N, \delta v_U]^T$ is the velocity error vector, f^b is the specific force vector obtained by accelerometers, ω_{ie}^n is the angular rate of the earth frame with respect to the