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Nonlinear empirical mode predictive drift extraction on fiber optical gyroscope

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ABSTRACT

The integration drift of inertial unit is a fatal error on navigation and attitude determination system. Many approaches have been developed to extract and eliminate it. A novel fiber optical gyroscope drift extraction algorithm was proposed in this paper to ameliorate the performance of fiber optical gyroscope by extracting the trend component as the compensation. In this algorithm, the attitude quaternion of stellar sensor and the output of fiber optical gyroscope were imported into a nonlinear empirical mode predictive algorithm to extract the drift component of gyroscope. Combing the advantages of predictive filter and empirical mode decomposition in nonlinear signal processing, our proposal is more precise in drift extraction and data approximation. Software simulation and hardware verifications on gyroscope were launched, in which the results had proven the capability of the algorithm.
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1. Introduction

With the development of human technique in aerospace exploration, many kinds of spacecrafts have been constructed, which include satellites, space shuttles, space ships and space stations [1]. The related technology is being the most attractive realm of human science. In the voyage of a spacecraft, Gyroscope, which works as a key device for angular velocity detection, had played an important role in inertial navigation system. Because of gyroscope's important responsibility, many modifications have been undertaken to improve its performance [2,3]. However, the drift of gyroscope, which accumulates with time, is hard to be eliminated due to the inherent flaw of inertial sensors themselves [4]. Since the gyroscope drift is a main error source in inertial system, many research works had been deployed for exploring an alternative solution of decreasing the drift of gyroscope [5,6].

As a gyroscope is a self-contained and no radiating navigation system, its error propagation cannot be separated by merely improving the precision of the sensor itself [7]. The common approach is to compensate the integration drift of gyroscope by importing the external reference information obtained from other navigation or attitude determination sensors. The Inertial Rate Sensor (IRS)/Celestial Vector Sensor (CVS) or Global Position System (GPS)/IRS joint attitude determination algorithms have been proposed. With the advantage of no drift accumulation in CVS and GPS, the integration drift could be impaired in these joint attitude determination systems [8,9].

Amongst these joint attitude determination approaches, the attitude determination based on stellar sensor (ADSS) is enchanting as the merits of stellar sensor in the application of inter-planetary spacecraft voyage are obvious. Compared with the other CVS devices, the stellar sensor is advantageous for its high precision, solid state, high stable and wide workable range, which makes it suitable for deep space exploration [10].

In this paper, a novel fiber optical gyroscope (FOG) drift extraction algorithm is proposed. This proposal imports the stellar sensor output as the reference, and extract the drift component from FOG through a Nonlinear Empirical Mode Predictive (NEMP) process. This NEMP architecture had blended the advantage of nonlinear predictive algorithm in nonlinear data approximation and the merits of empirical mode calculation in trend component analysis.

This paper has consisted of five sections. In Section 2, the related works are introduced. The NEMP algorithm on FOG drift extraction is discussed in Section 3. The verification and the simulation are listed in Section 4, and conclusion is drawn in Section 5.

2. Related works

The related works are introduced in this section. In the traditional attitude determination, the Kalman filter has been proven to be extremely useful for attitude estimation using vector attitude measurements and gyro measurements. For spacecraft attitude

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estimation, the Kalman filter is most applicable to spacecraft attitude determination with three axis gyroscopes [11]. In the application of Gyroless SAD, the analytical models of rate motion was used [12]. This approach has been successfully used in a Real-Time Sequential Filter (RTSF) algorithm which propagates state estimates and error covariance using a dynamic model [12,13]. However, the RTSF is essentially a Kalman filter in which the gyro bias is modeled as a Gaussian process with known covariance. Also, fairly accurate models of angular momentum are required in order to obtain accurate estimates. Subsequently, the design process for choosing the model error covariance becomes difficult [13,14].

A new method of performing optimal state estimation in the presence of significant model error has been proposed by Mook and Junkins [15]. This method, called the Minimum Model Error (MME) estimator, is different from most filter and smoother algorithms, does not presume that the model error is represented by a Gaussian process. Instead, the model error is determined during the MME estimation process [16]. Therefore, accurate state estimates can be determined without the use of precise system representations in the assumed model. This algorithm has been successfully used to estimate the attitude of an actual spacecraft without the utilization of gyro measurements [16]. However, the MME estimator is a batch (off-line) estimator which must utilize post experiment measurements [16].

Another approach in Gyroless application SAD is the nonlinear predictive filter, which combines the good qualities of both the Kalman filter and the MME estimator [14]. The new algorithm is based on a predictive tracking scheme introduced by Prof. Lu in his publication [17]. The predictive filter algorithm developed in Prof. J. Crassidis's paper is reformulated as a filter and estimator with a stochastic measurement process [14].

As the drift of gyroscope is a nonlinear, non-stationary random process, it is hard to be extracted by stationary separation approaches [5]. For the non-stationary signal extraction, the common used approach is regression algorithm, which builds the trend model by analyzing many sub-components' trend. These characters make the regression algorithm complex and imprecise [18]. With the development in wavelet study, some novel gyroscope drift extraction algorithms based on wavelet analysis were proposed [19]. The wavelet transform related drift extraction algorithms need multi-size decomposition and low frequency component verification in drift extraction process, which also make it complicated in process [20]. To resolve these problems, a kind of Empirical Mode Decomposition (EMD) algorithm, which was proposed by Dr. Norden E. Huang, is adopted in gyroscope drift extraction [21,22]. Unlike other signal decomposition techniques, which map the signal space onto a space spanned by a predefined basis, the idea behind this method is to decompose a general data set into a number of basis functions termed intrinsic mode functions (IMFs), which are derived directly from the data, in a natural way [21,23].

3. Algorithm architecture

The architecture of stellar sensor based FOG drift extraction system is introduced in this section, which includes an angular velocity generation block and a FOG drift extraction block. The angular velocity generation block is based on a regression process, which relies on the attitude quaternion from stellar sensor, and the FOG initial output. The generated spacecraft angular velocity was sent to the FOG drift extraction block to extract the drift trend component from FOG output. This drift extraction block is based on the NEMP algorithm to complete the calculation of error separation and drift trend extraction. The architecture of the system is shown in Fig. 1.

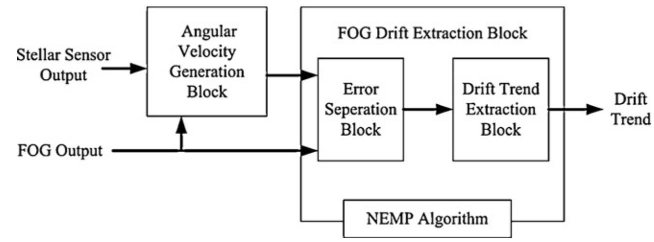

Fig. 1. The system architecture.

3.1. Stellar sensor

The stellar sensor we used was a mature production. The field of view is 8.5° × 8.5°; the line of sight Accuracy is 10 arcsec; and the Update rate is 10 Frames/s. The output of the stellar sensor is a quaternion sequence, which represent the attitude variation from the stellar sensor body coordinates system to the ECICS.

3.2. Reference coordinates system

The RCS mentioned in the paper is J2000 Reference Coordinates, which is a sub-type of ECICS and defined as the *X* and *Z* axes point toward the mean vernal equinox and mean rotation axes of the Earth on January 1, 2000 at 12:00:00.00 Universal Time Coordinated (UTC). J2000.0 = 2000 January 1.5 = JD 2451545.0 Terrestrial Dynamical Time (TDT) [24].

3.3. Angular velocity generation algorithm

As the satellite attitude update is described by the satellite rotation angular velocity under Satellite Body Coordinates System (SBCS), which contains the components in three dimensions and should be measured by at least three gyroscopes. Based on this principle, the reference rotation angular velocity revived from stellar sensor should be mirrored on the reference frame of FOG.

The stellar sensor, which exported the data under the control of synchronous trigger, outputted the satellite attitude as the quaternion vector $q(i)$, $q(i) = [q_0(i), q_1(i), q_2(i), q_3(i)]^T$. Similarly, the FOG outputted the vehicle rotation angular velocity in its reference frame, expressed as $\omega(i) = [\omega_x(i), \omega_y(i), \omega_z(i)]^T$. Firstly, an installation error compensation for both the FOG and the stellar sensor needed to be conducted to guarantee the data obtained from these two sensors are in high precision mode.

Express the FOG output data at initial time t_0 as the vector $\omega(0) = [\omega_x(0), \omega_y(0), \omega_z(0)]^T$, where *x*, *y*, *z* represent the three axes of FOG output. The generated angular velocity of spacecraft is $\hat{\omega}(i)$, $\hat{\omega}(i) = [\hat{\omega}_x(i), \hat{\omega}_y(i), \hat{\omega}_z(i)]^T$, which was calculated in this block.

Before the start of the angular velocity reconstruction regression process, some initial calculations needed to be completed by using the initial measurement parameters.

The initial reference angular velocity Modulus $|\omega(0)|$ was calculated as follows:

$$|\omega(0)| = \sqrt{\omega_x(0)^2 + \omega_y(0)^2 + \omega_z(0)^2} \quad (1)$$

The initial cosine parameter and the sine parameter were also obtained:

$$\begin{cases} c(0) = \cos\left(\dfrac{|\omega(0)|}{2}\right) \\ s(0) = \dfrac{\sin(|\omega(0)|/2)}{|\omega(0)|} \end{cases} \quad (2)$$

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