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An autonomous navigation scheme based on starlight, geomagnetic and gyros with information fusion for small satellites

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ABSTRACT

To improve the precision of autonomous navigation for small satellites, an innovative integrated navigation scheme based on starlight, geomagnetic and gyros is proposed. The accurate starlight vectors measured by star sensors can make up the inaccuracy of gyros and magnetometers, and the real-time information exported by gyros can compensate the shortcoming of low date rate in star sensors. The integrated system model is deduced and established with orbital dynamics, attitude kinematics and measurement models, and the information fusion algorithm based on self-adaptive Extended Kalman Filter (EKF) is applied to get high accurate navigation parameters. Simulation results demonstrate that this autonomous navigation scheme can achieve high accurate position, velocity and attitude, which can improve the precision for small satellites.

1. Introduction

Compared with large satellites, small satellites have the advantages of short manufacturing period, low cost, launch flexibility, high integration and high reliability [1–4]. Furthermore, small satellites have extensive application in the field of satellite communication, marine surveillance, meteorological sounding, and space research, etc. [5–10]. More and more researchers are getting involved in the development of small satellites. Autonomous navigation can effectively reduce the costs of the mission, which is important especially for low-budget small satellites, and many kinds of autonomous navigation systems have been explored. In most cases the accuracy of these systems, ranging from a few hundred meters to a few kilometers, is sufficient for small satellites. Military accuracy requirements, however, such as those of the Strategic Defense Initiative (SDI), are more severe [14]. These accuracies can be realized using the Global Navigation Satellite System (GNSS), including the U.S.'s modernized GPS-IIF and planned GPS-III, Russia's restored GLONASS, and the coming European Union's GALILEO system and China's Beidou/COMPASS system, but this method is semiautonomous because it relies on communication with other satellites. Consequently, the precision of autonomous navigation systems has become a pressing problem.

Magnetometers possess the merits of low cost, low power consumption and high reliability, which makes them become one of the preferred sensors for small satellites [11–16]. But, the accuracy of the geomagnetic field model is not very high, and magnetometers are susceptible to the remanence (the magnetization left behind in a ferromagnetic material after an external magnetic field is removed) in the satellites. Hence the navigation scheme using only the magnetometer and star sensors to estimate the satellite orbit and attitude is not accurate enough [17]. To improve the precision, magnetometers should be integrated with other sensors.

Star sensors are the most accurate attitude sensors, which can obtain attitude parameters of satellites with high precision. Moreover, star sensors can be integrated with magnetometers to determine the orbit, reducing

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Nomenclature

Symbols

V	The potential function of geomagnetic field
$\tilde{P}_n^m$	Schmidt quasi-normalized associated Legendre functions of degree $n$and order m.
$\boldsymbol{B}$	The geomagnetic field vector (nT)
$\boldsymbol{B}_b$	The real geomagnetic field vector in body coordinates (nT)
F	The total intensity (nT)
I	The inclination angle (deg)
D	The declination angle (deg)
$\boldsymbol{C}_i^b$	Transformation matrix from inertial geocentric coordinates to body coordinates
$\boldsymbol{C}_i^o$	Transformation matrix from inertial geocentric coordinates to orbit coordinates
$\boldsymbol{s}_b$	The unit starlight vectors in the body coordinates
$\boldsymbol{q}$	The output quaternion of star sensors
$\Delta\overline{\boldsymbol{q}}_{bo}$	The error quaternion
$\Delta\boldsymbol{q}$	The vector part of the error quaternion
ω_o	The orbital rate (rad/s)
$\boldsymbol{\omega}_{bo}$	The angular rates from body coordinates to orbit coordinates (rad/s)
$\boldsymbol{\omega}_{bi}$	The angular rates from body coordinates to inertial coordinates (rad/s)
$\boldsymbol{\omega}_g$	The output vector of gyros (rad/s)
$\boldsymbol{b}$	Constant drift
$\boldsymbol{v}$	The position vector
$\boldsymbol{r}$	The velocity vector
$\boldsymbol{v}_g$	The measurement noise of gyros (°/h)
$\boldsymbol{v}_{gb}$	Gyro drift driving noise (°/h)
$\boldsymbol{v}_s$	The measurement noise of the star sensors (″)
$\boldsymbol{v}_b$	The magnetometer measurement noise (nT)
$\boldsymbol{v}_\alpha$	The angle measurement noise (deg)

Superscripts and subscripts

$\wedge$	Estimate value
i	Value in inertial coordinate system
b	Value in satellite body coordinate system
m	Value in geocentric spherical coordinate system

navigation parameter errors that are caused by magnetometers measurement noise [20–22]. However, star sensors need extensive star catalogs for determination, which should be performed by special computers, causing a lower data rate, that is star sensors cannot export real-time attitude. Although star sensors have the demerits of high cost, heavy weight and high power consumption, they are always installed on small satellites to obtain high accurate attitudes [23]. Recently, many researchers have been involved in the miniaturization of star sensors, getting promising results [18,19].

Gyros can offer real-time angular velocity as the inertial basis to the attitude determination system, which can deduce the attitude parameters. Nonetheless, gyro drift is unavoidable, and attitude errors caused by gyro drift increase with time. Gyros cannot be used exclusively for long time, and the drift must be corrected by other measurements regularly. In general, star sensors are always applied to compensate gyro drift [24–26], and gyros offer attitude information in short periods. This integrated method can offset weaknesses in sensors to reach high precision requirement of attitude determination. With the development of Micro-electromechanical Systems (MEMS), MEMS gyros that have advantages of small volume, light weight and low power consumption, are promising for small satellites in the future [27].

In order to improve the precision of autonomous navigation for small satellites, a scheme based on starlight, geomagnetic and gyros is proposed. This scheme takes advantage of the information measured by sensors and obtains high accurate navigation information. The rest of this paper consists of three sections plus conclusions. (Section 2) describes how the measurement models are established in detail, and then system model is developed in Section 3. In the ensuing, simulation is implemented in Section 4.

2. Measurement models

2.1. Geomagnetic field model

The earth magnetic field is practically a stationary field whose intensity and direction are functions of position. The potential function of geomagnetic field is [28]

$$V(r,\theta,\phi)=a\sum_{n=1}^{\infty}\sum_{m=0}^{n}(r)^{n+1}(g_n^m\cos m\phi+h_n^m\sin m\phi)\tilde{P}_n^m(\cos\theta) \quad (1)$$

where a and $r$denote the magnetic reference spherical radius and the radial distance from the center of the Earth, respectively. ϕ denotes the geodetic longitude. $\theta=(\pi/2)-\phi$ is the geocentric colatitude. $g_n^m$and h_n^m are time-dependent Gauss coefficients, and the term$\tilde{P}_n^m(\cos\theta)$ are Schmidt quasi-normalized associated Legendre functions of degree n and order m.

The geomagnetic field vector $\boldsymbol{B}_m$ can be written as the negative spatial gradient of V

$$\boldsymbol{B}_m=-\nabla V \quad (2)$$

Three components of $\boldsymbol{B}_m$ in geocentric spherical coordinates can be deduced from Eqs. (1) and (2)

$$\begin{cases} B_r=-\frac{\partial V}{\partial r}=\sum\limits_{n=1}^{k}(n+1)\left(\frac{a}{r}\right)^{n+2}\sum\limits_{m=0}^{n}(g_n^m\cos m\varphi+h_n^m\sin m\varphi)\tilde{P}_n^m(\cos\theta) \\ B_\theta=\frac{1}{r}\frac{\partial V}{\partial\theta}=\sum\limits_{n=1}^{k}\left(\frac{a}{r}\right)^{n+2}\sum\limits_{m=0}^{n}(g_n^m\cos m\varphi+h_n^m\sin m\varphi)\frac{\partial\tilde{P}_n^m(\cos\theta)}{\partial\theta} \\ B_\varphi=-\frac{1}{r\sin\theta}\frac{\partial V}{\partial\varphi}=\frac{1}{\sin\theta}\sum\limits_{n=1}^{k}\left(\frac{a}{r}\right)^{n+2}\sum\limits_{m=0}^{n}m(g_n^m\sin m\varphi-h_n^m\cos m\varphi)\tilde{P}_n^m(\cos\theta) \end{cases} . \quad (3)$$

Fig. 1 shows that the geomagnetic field vector $\boldsymbol{B}_m$ can also be described by 7 elements in the ellipsoidal reference frame: the northerly intensity X', the easterly intensity Y',