Acta Astronautica 81 (2012) 40–50

Contents lists available at SciVerse ScienceDirect

Acta Astronautica

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

An autonomous navigation scheme based on geomagnetic and starlight for small satellites

Wang Xinlong [a], Wang Bin [a,*], Li Hengnian [b]

[a] School of Astronautics, Beihang University, Beijing 100191, China
[b] State Key Lab of Astronautical Dynamics, Xi'an Satellite Control Center, Xi'an 710043, China

ARTICLE INFO

Article history:
Received 19 April 2012
Received in revised form
9 July 2012
Accepted 15 July 2012
Available online 21 August 2012

Keywords:
Small satellites
Autonomous navigation
Star sensors
Geomagnetic field
UKF

ABSTRACT

According to the characteristics of celestial navigation system (CNS) and geomagnetic navigation system (GNS), a fully autonomous geomagnetic/celestial integrated navigation scheme (GNS/CNS) is proposed for small satellites. By using a large-view-field star sensor to obtain the starlight vectors of multi-stars, CNS can make up the shortcoming of navigation accuracy of GNS. The system model of GNS/CNS is deduced and established in detail, and UKF (unscented Kalman filter) algorithm is used to estimate and obtain high precision navigation parameters. Simulation results show that superior position, velocity and attitude accuracy of small satellites can be obtained by GNS/CNS, and the filter has stronger filtering adaptability and stability, which demonstrate the feasibility and effectiveness of this scheme.

1. Introduction

Small satellites have various characteristics, such as light weight, low cost, short manufacturing period, etc. Small satellite networks will play more and more important roles in the fields of communication, remote sensing, and navigation [1–2]. With the increasing number of low/medium orbit small satellites, traditional ground-based tracking scheme can hardly meet the measurement requirements of small satellite networks.

Satellite autonomous navigation is determining navigation parameters of satellites without the help of ground-based tracking and fulfills the mission only using onboard measurement information [3]. The traditional ground-based navigation method is rather accurate and has been successfully applied to navigate the spacecrafts, but it has high mission costs. For numerous low/medium earth orbit spacecrafts, the domestic networks of ground stations cannot give enough capacity to control these spacecrafts. While in deep space environment, the ground stations are powerless to establish the communication, and the missions may be failed. Autonomous navigation can not only improve the safety and viability of spacecrafts, but also greatly reduce the costs of the ground measurement system [4–6]. Consequently, how to realize autonomous navigation has become a crucial problem in designing small satellite systems.

In recent years, some of satellite navigation methods have been proposed and explored, including inertial navigation system (INS) [7], Global Position System (GPS) [8–9], inter-satellite link [10–11], geomagnetic navigation (GNS) [12–16] and celestial navigation (CNS) [17–20]. INS is an available navigation method, but its navigation error accumulates with time extension. To improve the navigation performance and prevent the increase of errors, INS is usually integrated with GPS or other navigation sensors [21–23]. GPS and inter-satellite link can provide real-time navigation information with high accuracy, but they are only semi-autonomous methods, because they must depend

---

[*] Corresponding author. Tel.: +86 10 82339795.
E-mail address: wangbinbuaa@126.com (W. Bin).

http://dx.doi.org/10.1016/j.actaastro.2012.07.013

Nomenclature

Symbols

$O_iX_iY_iZ_i$	Inertial coordinate system
$O_eX_eY_eZ_e$	Earth-fixed coordinate system
$X_nY_nZ_n$	Geographic coordinate system
$O_sX_sY_sZ_s$	The star sensor coordinate system
$O_pX_pY_p$	Imaging plane coordinate system
$ONET$	Local geographic (north, east, and nadir) coordinate system
C_n^i	Transformation matrix from geographic coordinate system to inertial coordinate system
C_i^b	Transformation matrix from inertial coordinate system to body coordinate system
X,Y,Z	East, north, and down component of geomagnetic field vector (nT)
P_n^m	Legendre functions of degree n and order m in Schmidt quasi-normalized form
B_r,B_θ,B_λ	The field vector components in geomagnetic spherical coordinates (nT)
B	The geomagnetic field vector in geographic coordinate system
ΔB	The error between the measurement and estimate geomagnetic field vector
B_m	The measurement geomagnetic field vector
F	The total intensity of geomagnetic field vector (nT)
D	The declination angle (deg.)
I	The inclination angle (deg.)
β	The angle between starlight vector and measurement geomagnetic field vector (deg.)
U	The starlight vector in star sensor coordinate system
L_m	The starlight vector in satellite body coordinate system
f	=Focal length (mm)
M_V	=The magnitude of star
SNR	Signal to Noise Ratio
FOV	Field of View
A_{cir}	The wide of a circular FOV (deg.)
N_{FOV}	Average number of stars in a FOV
$I_{i,j,m}$	The measurement light intensity for each pixel of the star image
R,V	The position and velocity in initial coordinate system
δR,δV	Satellite position and velocity errors in inertial coordinate system
$\overline{w}_{ob}$	Satellite angular velocity relative to orbit coordinate system (rad/s)
$\overline{w}_{io}$	Orbital angular velocity relative to inertial coordinate system (rad/s)
$\overline{w}$	Satellite angular velocity relative to inertial space (rad/s)
$\Delta\overline{w}$	Satellite angular velocity error relative to inertial space (rad/s)
q	The attitude quaternion
$C_o^b(q)$	Attitude matrix expressed by quaternion
$\Delta\overline{q}$	The vector part of attitude error quaternion
μ	The gravitational constant of the Earth
J_2	The second zonal coefficient
$P(J_2)$	Perturbation acceleration caused by J_2 (m/s^2)
υ_L	The measurement noise of the star sensor ($''$)
υ_{B1}	The magnetometer measurement noise (nT)
υ_{B2}	Geomagnetic field model noise (nT)
υ_β	Angle measurement noise (deg.)

Superscripts and subscripts

$\hat{}$	Estimate value
i	Value in inertial coordinate system
b	Value in satellite body coordinate system
n	Value in geographic coordinate system
j	j-th

on the communication with other satellites. In addition, the jamming may also reduce the navigation accuracy of GPS.

Three-axis magnetometers have the advantages of strong independency and no terrain limitation. It can provide all-weather, continuous measurement information. Most of current satellites have used magnetometers for orbit and attitude determination. However, because of the low precision of geomagnetic field models and magnetometers, GNS has low navigation accuracy and should be integrated with other navigation systems.

Similar to GNS, CNS is another environment-sensitive navigation system. For the advantages of good concealment, high directional precision, and no electromagnetic jamming, etc., CNS has been successfully applied in the navigation systems of most spacecrafts. Owing to the emergence of large-view-field star sensors, it becomes possible for CNS to observe the starlights of more than three guidance stars at the same time and achieve high accuracy attitude determination [24–26]. Although CNS has lower data rate, it can serve as a good complement to GNS. The navigation accuracy of GNS/CNS can be enhanced by using the suitable optimal estimation method.

The main goal of this paper is to present a novel autonomous navigation scheme based on the combination of starlight/geomagnetic information. This scheme makes full use of the starlight and geomagnetic field information, and uses UKF to obtain high accuracy navigation parameters for small satellites. This paper consists of six sections. After this introduction, the geomagnetic field model is described in Section 2. The measurement principle of a large-view-field star sensor is explained in Section 3. The system modeling of GNS/CNS is introduced in Section 4, including the development of the state and measurement equations, and the process of UKF. The simulation results are demonstrated in Section 5. Conclusions are drawn in Section 6.

2. Geomagnetic field model

Near-Earth space has abundant geomagnetic field information, and the potential function of geomagnetic