SCIENCE CHINA
Information Sciences

• LETTER •

September 2023, Vol. 66 199201:1–199201:2
https://doi.org/10.1007/s11432-022-3630-1

A new SINS/RCNS integrated navigation method based on star pixel coordinates

Guangxin SONG[1], Yuqing YANG[1], Xiaolin NING[2*], Jiancheng FANG[1] & Weiren WU[3]

[1]*School of Instrumentation Science and Opto-electronics Engineering, Beihang University, Beijing* 100191*, China;*
[2]*School of Research Institute for Frontier Science, Beihang University, Beijing* 100191*, China;*
[3]*Lunar Exploration and Space Program Center, China National Space Administration, Beijing* 100037*, China*

Received 18 April 2022/Revised 17 September 2022/Accepted 11 November 2022/Published online 7 April 2023

Citation Song G X, Yang Y Q, Ning X L, et al. A new SINS/RCNS integrated navigation method based on star pixel coordinates. Sci China Inf Sci, 2023, 66(9): 199201, https://doi.org/10.1007/s11432-022-3630-1

The traditional strapdown inertial navigation system (SINS)/celestial navigation system (CNS) integrated navigation system using the starlight vector or posture difference calculated by SINS and CNS as a measurement can correct the posture error of SINS, but not the position error [1]. The refraction celestial navigation system (RCNS) can independently provide the position information. As a result, SINS/RCNS integrated navigation is an effective method to correct the position error of the SINS. According to Wang et al. [2], the SINS/RCNS integrated navigation method for spacecraft uses the orbital dynamic equations as the state model, and the refraction apparent height as the measurement. The results showed that the position and velocity errors decreased to 87.8% and 39.5% of those of SINS at the reentry point, respectively. However, this method cannot correct the posture error. According to the novel SINS/RCNS integrated navigation method proposed by Qian et al. [3], the state model is established based on the error equations of SINS, and the posture error and refraction apparent height error are taken as measurements. The results showed that the position error could be limited to approximately 250 m and the posture error could be corrected [3]. However, the posture error cannot be corrected directly if only the refraction apparent height is used as the measurement. In contrast to the refraction apparent height and starlight refraction angle, which can only provide refraction angle information, Ning et al.'s new measurement of star pixel coordinates for satellites provides refraction angle and refraction direction information simultaneously. According to the simulations, the satellite positioning accuracy is the best when compared to the refraction apparent height and starlight refraction angle [4].

An innovative SINS/RCNS integrated navigation method based on star pixel coordinates was proposed in this study. The star pixel coordinates were used as a measurement, and the measurement model based on star pixel coordinates was established. We performed comparisons of the performances of SINS and SINS/RCNS integrated navigation based on the refraction apparent height, starlight refraction angle, and star pixel coordinates. The simulations show that the proposed method not only has the best performance in correcting position errors, but also can correct posture errors simultaneously, while the SINS/RCNS integrated navigation based on the refraction apparent height and starlight refraction angle can only correct the position error.

State model. The state model of the SINS/RCNS integrated navigation system is established based on the error equations of SINS and can be expressed as [5]

$$\dot{\boldsymbol{X}}(t) = \boldsymbol{F}(t)\boldsymbol{X}(t) + \boldsymbol{G}(t)\boldsymbol{W}(t), \tag{1}$$

where $\boldsymbol{F}(t)$ represents the state transition matrix, $\boldsymbol{G}(t)$ represents the noise input matrix, $\boldsymbol{X}(t) = [\boldsymbol{\phi}\ \ \delta\boldsymbol{v}_n\ \ \delta\boldsymbol{p}_n\ \ \boldsymbol{\epsilon}\ \ \boldsymbol{\nabla}]^{\mathrm{T}}$ represents the state vector, $\boldsymbol{\phi} = [\phi_E\ \ \phi_N\ \ \phi_U]^{\mathrm{T}}$ represents the misalignment angle, $\delta\boldsymbol{v}_n = [\delta v_E\ \ \delta v_N\ \ \delta v_U]^{\mathrm{T}}$ represents the velocity error, $\delta\boldsymbol{p}_n = [\delta L\ \ \delta\lambda\ \ \delta H]^{\mathrm{T}}$ represents the position error, $\boldsymbol{\epsilon} = [\epsilon_E\ \ \epsilon_N\ \ \epsilon_U]^{\mathrm{T}}$ represents the gyro drift, and $\boldsymbol{\nabla} = [\nabla_E\ \ \nabla_N\ \ \nabla_U]^{\mathrm{T}}$ represents the accelerometer bias.

Measurement model. There are three commonly used measurements related to starlight refraction: the refraction apparent height, starlight refraction angle, and star pixel coordinates. The establishment process of the measurement model is given in the following.

First, refraction apparent height. According to the geometric relationship of the starlight atmospheric refraction, the measurement model based on the refraction apparent height can be expressed as

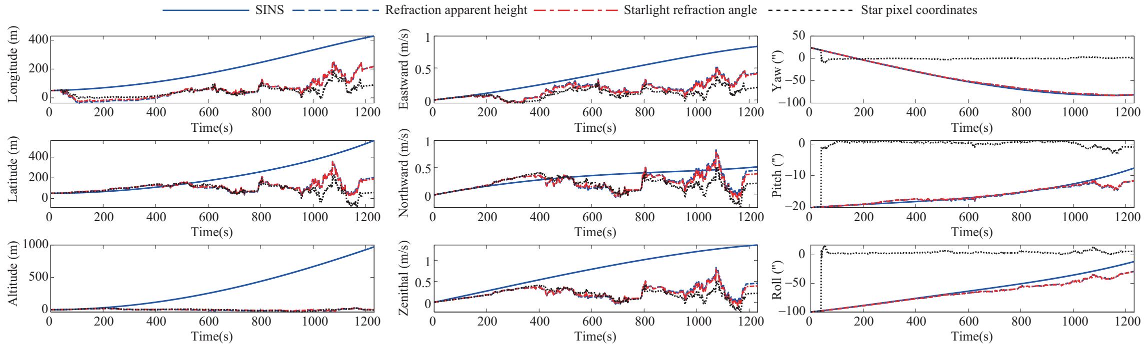
$$h_a = \sqrt{r^2 - u^2} + u \tan R - R_e, \tag{2}$$

where R_e is the Earth's radius, $r = |\boldsymbol{r}|$, $u = |\boldsymbol{u}| = |\boldsymbol{r} \cdot \boldsymbol{S}_i|$, $\boldsymbol{r}$ represents the position vector of the spacecraft in the geocentric inertial frame, and $\boldsymbol{S}_i$ represents the unit starlight vector before refraction in the geocentric inertial frame.

Second, starlight refraction angle. According to the starlight atmospheric refraction model and its empirical formulas, the refraction apparent height can also be expressed

---

[*] Corresponding author (email: ningxiaolin@buaa.edu.cn)



(a) (b) (c)

Figure 1 (Color online) Comparisons of the different navigation methods. (a) Position error; (b) velocity error; (c) posture error.

as

$$h_a = 69.21177057R^{0.9805} - 6.441326\ln R - 21.74089877. \tag{3}$$

By combining (2) and (3), the measurement model of the starlight refraction angle can be expressed as

$$\begin{aligned} &69.21177057R^{0.9805} - 6.441326\ln R - 21.74089877 \\ &\quad = \sqrt{r^2 - u^2} + u\tan R - R_e. \end{aligned} \tag{4}$$

Third, star pixel coordinates. According to the starlight vector $\boldsymbol{S}_i$ and position vector $\boldsymbol{r}$, we can obtain the normal vector $\boldsymbol{n}$ of the refraction plane. By taking the normal vector $\boldsymbol{n}$ of the refraction plane as the rotation axis and rotating $\boldsymbol{S}_i$ for R in the refraction plane, we can obtain the unit starlight vector $\boldsymbol{S}_r$ of the refracted star in the geocentric inertial frame. Then we can obtain the star pixel coordinates by converting $\boldsymbol{S}_r$ in the geocentric inertial frame into $\boldsymbol{S}_c$ in the star sensor frame. The establishment process of the measurement model is shown in Appendix A.

Simulation results. The performance of the traditional SINS and the SINS/RCNS integrated navigation based on the refraction apparent height, starlight refraction angle, and star pixel coordinates is given.

Figure 1 shows the navigation performance of the SINS and SINS/RCNS integrated navigation based on the refraction apparent height, starlight refraction angle, and star pixel coordinates. The Monte-Carlo simulation results of the four navigation methods at the final moment are shown in Appendix B. The position errors at the final moment of the four navigation methods are $[428.80 \;\; 561.47 \;\; 970.36]$ m, $[161.96 \;\; 148.24 \;\; 8.16]$ m, $[161.33 \;\; 144.59 \;\; 8.32]$ m, and $[154.96 \;\; 133.89 \;\; 11.87]$ m; the velocity errors at the final moment of the four navigation methods are $[0.84 \;\; 0.52 \;\; 1.36]$ m/s, $[0.28 \;\; 0.29 \;\; 0.14]$ m/s, $[0.27 \;\; 0.26 \;\; 0.14]$ m/s, and $[0.25 \;\; 0.25 \;\; 0.13]$ m/s; and the posture errors are $[81.53'' \;\; 7.62'' \;\; 11.76'']$, $[82.58'' \;\; 11.44'' \;\; 35.56'']$, $[82.54'' \;\; 11.49'' \;\; 35.87'']$, and $[1.75'' \;\; 2.08'' \;\; 6.94'']$. The simulation results indicate that the SINS/RCNS integrated navigation based on the star pixel coordinates has the best performance in correcting the position and velocity errors and can correct the posture error simultaneously. This is because the measurement model based on the star pixel coordinates is simultaneously related to the position and posture of the spacecraft. Howerver, because the measurement models of the refraction apparent height and starlight refraction angle are only related to the position of the spacecraft, the integrated navigation method can only correct the position error.

Conclusion. This study proposed a SINS/RCNS integrated navigation method based on star pixel coordinates. The star pixel coordinates provide both the refraction angle and refraction direction information, so the proposed method not only has the best performance in correcting the position error, but also can correct posture error simultaneously. The simulations show that the longitude, latitude, and altitude errors are reduced to approximately 36%, 23%, and 1.2% of those of SINS at the final moment; the eastern velocity, northern velocity, and zenithal velocity errors are reduced to approximately 30%, 48%, and 9.6%, respectively. Furthermore, the yaw, pitch, and roll errors are reduced to approximately 2%, 27%, and 59% of those of SINS.

Supporting information Appendixes A and B. The supporting information is available online at info.scichina.com and link.springer.com. The supporting materials are published as submitted, without typesetting or editing. The responsibility for scientific accuracy and content remains entirely with the authors.

References

1 He Z, Wang X L, Fang J C. An innovative high-precision SINS/CNS deep integrated navigation scheme for the Mars rover. Aerospace Sci Tech, 2014, 39: 559–566

2 Wang H Y, Gao Z Q, Wang T F, et al. Study on command attitude law for refracted starlight observation in SINS/RCNS integrated navigation. Adv Space Res, 2018, 62: 721–731

3 Qian H M, Sun L, Cai J N, et al. A novel navigation method used in a ballistic missile. Meas Sci Technol, 2013, 24: 105011

4 Ning X L, Sun X H, Fang J C, et al. Satellite stellar refraction navigation using star pixel coordinates. Navigation, 2019, 66: 129–138

5 Zhu J F, Wang X L, Li H N, et al. A high-accuracy SINS/CNS integrated navigation scheme based on overall optimal correction. J Navigation, 2018, 71: 1567–1588