Contents lists available at ScienceDirect
Aerospace Science and Technology
www.elsevier.com/locate/aescte

# A robust astro-inertial integrated navigation algorithm based on star-coordinate matching

Rong Wang, Zhi Xiong *, Jianye Liu, Lijuan Shi

*Navigation Research Center, College of Automation Engineering, Nanjing University of Aeronautics and Astronautics, Nanjing, 210016, China*

A R T I C L E I N F O

*Article history:*
Received 28 August 2016
Received in revised form 7 August 2017
Accepted 10 September 2017
Available online xxxx

*Keywords:*
Integrated navigation
Robust fusion
Strongly coupled astro-inertial integration framework
Star-coordinate matching
Perturbation-rate statistics
Maximum-likelihood estimation

A B S T R A C T

The astro-inertial integrated navigation system has the characteristic of anti-electromagnetic interference but suffers from aero-optical starlight perturbation when applied to hypersonic cruise vehicles (HCVs). Because there is no strategy in the traditional loosely coupled astro-inertial integration framework for recognising and evaluating skew in star observation, this system cannot adapt to perturbations, and the navigation accuracy tends to degrade. In this study, a strongly coupled framework for an astro-inertial integrated system is designed, and a robust astro-inertial fusion algorithm based on star-coordinate matching is proposed; the skew degree of each observed star is quantified by matching with the virtual star image re-established from INS measurements. Based on star-coordinate matching, a robust weight-tuning rule is designed according to the maximum-likelihood estimation theory, including a method to determine the star-coordinate confidence scope by statistically analysing the astronomical-observation perturbation rate. Compared with the traditional loosely coupled astro-inertial integration framework, the proposed strongly coupled framework and robust astro-inertial integrated navigation algorithm based on star-coordinate matching can significantly improve robustness against perturbations.





## 1. Introduction

Hypersonic cruise vehicles (HCVs), which can cruise at altitudes of 30-50 km with speeds of 5–10 Ma, are of great interest due to their potential ability for rapid global reach [1]. In ultra-high dynamic flight, the reliability of navigation is important for maintaining control stability and flight safety [2,3].

Since the reception of GPS signals is strongly impeded by the plasma sheath around an HCV, researchers have focused on developing an astro-inertial integrated navigation system with the characteristic of anti-electromagnetic interference [4,5]. With the improvement of optoelectronic devices, star sensors are being enhanced from the narrow field of view (NFOV) to wide field of view (WFOV), which enables the observation of multiple stars simultaneously [6,7]. However, uncertain aero-optical effects during hypersonic cruising cause varying degrees of deflection in starlight observations, bringing challenges to the implementation of astro-inertial integrated navigation systems on HCVs [8,9]. Thus, the robustness of the astro-inertial fusion algorithm has significant influence on navigation performance.

Traditional astro-inertial integrated navigation systems are usually based on a loosely coupled framework. Under this framework, the orientation determination of the star sensor is performed independently of an inertial navigation system (INS). Then, the astronomically determined orientation is compared with INS to estimate the INS errors using a Kalman filter [10]. There have been several research studies on astro-inertial fusion methods under the loosely coupled framework. An adaptive SINS/ANS/GNSS fusion algorithm, which adjusts the process-noise and the measurement-noise covariance based on the innovation sequence, has been applied for an air–launch space launcher [11]. A fusion algorithm for GPS/INS/STAR tracker navigation using a software-defined radio was investigated to adapt the filter to process the quaternion updates from the star tracker to enhance a low-cost IMU [12]. An algorithm for astro-inertial navigation in the situation of using CCD star sensors was proposed with the modelling of misalignment of SINS [13]. Moreover, based on modelling the errors in azimuth angle and elevation angle, an INS/CNS integrated filtering algorithm was investigated for airborne applications [14]. The drawback of the loosely coupled astro-inertial integration framework adopted in these works is that the complementary properties of INS and astronomical measurements are not used adequately and that the robustness to perturbation in starlight observation is poor. If the star observation is perturbed, the astronomically

* Corresponding author.
*E-mail address:* xiongzhi@nuaa.edu.cn (Z. Xiong).

http://dx.doi.org/10.1016/j.ast.2017.09.013

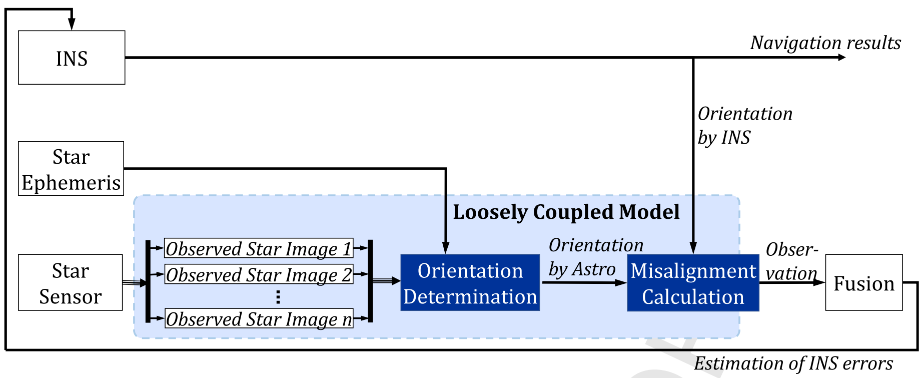


**Fig. 1.** Framework of the classic astro-inertial integration model.

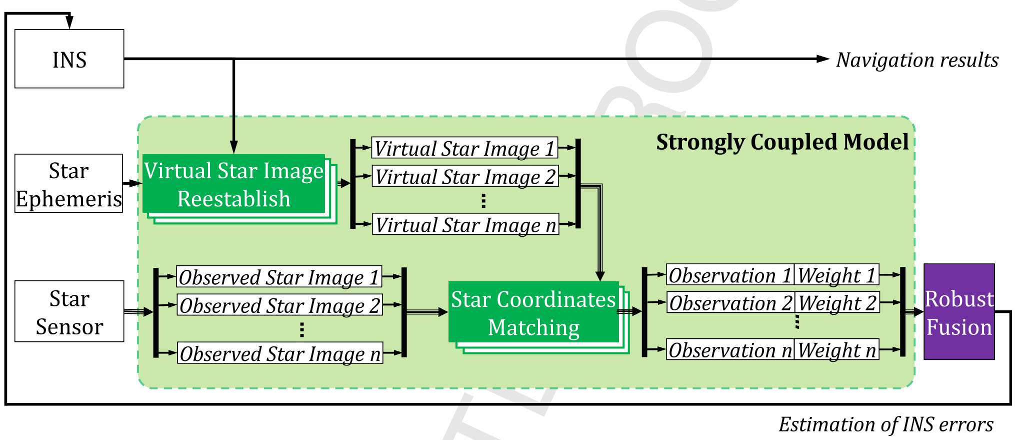


**Fig. 2.** Framework of the proposed strongly coupled astro-inertial integration model.

determined orientation will be skewed. Furthermore, the influences of perturbation on different stars may be unequal during hypersonic cruise, resulting in the variable change of a characteristic in astronomical-observation noise. Since no strategy exists in the loosely coupled framework for recognising and evaluating the skew in star observation, the astro-inertial integrated system cannot adapt to perturbation, and the navigation accuracy will degrade.

To overcome these problems, in this study, a strongly coupled framework for the astro-inertial integrated system is designed, and a robust astro-inertial fusion algorithm based on star-coordinate matching is proposed. In contrast to the traditional loosely coupled astro-inertial integration framework, the original astronomical measurements are fused with INS directly without astronomical-orientation determination in the designed strongly coupled framework. The benefit of this framework is that the skew degree of each observed star can be quantified by matching with the virtual star image re-established from INS measurements. Based on star-coordinate matching, a robust weight-tuning rule is designed according to maximum-likelihood estimation theory, along with a method to determine the star-coordinate confidence interval by statistically analysing the astronomical-observation perturbation rate. In section 2, the novel strongly coupled astro-inertial integration framework and corresponding model are proposed. In section 3, a robust astro-inertial fusion algorithm based on star-coordinate matching is proposed, which is designed in combination with the novel strongly coupled framework. The simulation in section 4 validates the effectiveness of the proposed model and algorithm.

## 2. Novel strongly coupled astro-inertial integration model

### *2.1. Classic astro-inertial integration framework*

The framework of the traditional astro-inertial system is shown in Fig. 1.

In Fig. 1, both the INS and star sensor are mounted to the vehicle body. According to the INS-sensitive vehicle dynamic parameters, the inertial-based attitude can be calculated along with the velocity and position. In addition, the starlight observe through the WFOV lens of the star sensor are projected onto the star-image plane to obtain the original astronomical measurements. In the traditional loosely coupled mode, these original astronomical measurements are used during positioning by an iteration algorithm and then linked with inertia-based position resolutions. Clearly, for the traditional strap-down astro-inertial system, the astronomical measurements are considered reliable; thus, the robustness of the astro-inertial system to deflections in astronomical measurements is limited.

### *2.2. A novel, strongly coupled astro-inertial integration framework*

To improve the navigation performance of the astro-inertial system with respect to the effects of deflection in the hypersonic flight of the HCV, a strongly coupled mode for the astro-inertial system is proposed, as shown in Fig. 2.

In this proposed framework, a virtual star image is re-established, which is calculated according to the attitude and position provided by INS and the star ephemeris. Then, using the virtual star image as a reference, the physically observed star images are compared, and the star-coordinate biases are obtained. The star-coordinate matching degrees, which are evaluated according to the star-coordinate bias and its statistical bound, are used to identify



Please cite this article in press as: R. Wang et al., A robust astro-inertial integrated navigation algorithm based on star-coordinate matching, Aerosp. Sci. Technol. (2017), http://dx.doi.org/10.1016/j.ast.2017.09.013