Available online at www.sciencedirect.com

ScienceDirect

Advances in Space Research 60 (2017) 2751–2762

ADVANCES IN SPACE RESEARCH (a COSPAR publication)

www.elsevier.com/locate/asr

A real-time airborne terrain aided inertial navigation system and its performance analysis

Q.Q. Zhang [b], L. Zhao [a,b,*], J.H. Zhou [a,b,c], B.H. Wang [c], Y.P. Zhang [d]

[a] Science and Technology on Aircraft Control Laboratory, Beihang University, Beijing 100191, China
[b] Digital Navigation Center, Beihang University, Beijing 100191, China
[c] Beijing Satellites Navigation Center, Beijing 100094, China
[d] School of Electrical and Information Engineering, Hunan University, Hunan 410012, China

Received 23 February 2017; received in revised form 10 October 2017; accepted 20 October 2017
Available online 13 November 2017

Abstract

The current terrain aided navigation system has a shortcoming that it depends on terrain feature, so we need to select the terrain matching area and plan the flight path according to the flight mission in advance. In this paper, we present a real-time airborne terrain aided inertial navigation system. The system can plan and select the matching area online according to the heading angle and estimated position errors during aircraft flight, and adopt the appropriate terrain-aided navigation algorithm for different terrain areas and flight conditions. So it can ensure the positioning accuracy and improve the ability of carrier to maneuver at the same time. In order to verify the performance of the system, a flight simulation experiment and a real flight test are carried out, and we conduct a research on the performance of matching area planning and real-time positioning. The tests results show that the system can improve the ability of carrier to maneuver and the performance of real-time positioning. In addition, the system has a higher positioning accuracy and reliability than traditional TERCOM and SITAN methods. The position error is less than 50 m in acquisition mode and less than 18 m in tracking mode with the terrain elevation map of 25 m-resolution.

Keywords: Terrain-aided navigation; Inertial navigation; Matching area selection; Robust terrain matching algorithm

1. Introduction

Nowadays, navigation is closely related to various aspects of our lives, while some techniques have some shortcomings, even Global Navigation Satellites System (GNSS) with problems, such as atmospheric delays, code bias and multi-path (Wei et al., 2013; Najibi and Jin, 2013; Jin et al., 2009, 2011, 2016; Jin and Najibi, 2014). Because terrain aided navigation (TAN) have the advantages of independence, high navigation accuracy, concealment and all-weather work (Sineglazov, 2014), it has received widely attention and research and has been successfully applied in cruise missiles, aircraft and ships (Zhao and Yan, 2013).

The principle of TAN is to take terrain elevation data under the measured trajectory and the stored digital terrain elevation model as the input information and adopt the matching algorithms to achieve the purpose of positioning. Therefore, TAN algorithms have a great effect on the real-time performance and accuracy of positioning. The well-developed approaches of TAN are roughly classified into two different types at present. One is the terrain contour matching (TERCOM) algorithm based on correlation operation (Jianchun et al., 2007; Kim and Sukkarieh,

* Corresponding author at: Science and Technology on Aircraft Control Laboratory, Beihang University, Beijing 100191, China.
E-mail addresses: zhangqieqie@buaa.edu.cn (Q.Q. Zhang), flylong@buaa.edu.cn (L. Zhao).

https://doi.org/10.1016/j.asr.2017.10.038
0273-1177/

2004; Lee et al., 2012; Zhao, 2011; Zhao et al., 2015). The other is the Sandia Inertial Terrain-Aided Navigation (SITAN) algorithm based on Extended Kalman Filtering (EKF) (Eroglu and Yilmaz, 2014; Li et al., 2011; Teixeira et al., 2012). The TERCOM algorithm can achieve fast localization in the condition of large initial position error, however the real-time performance is poor and the aircraft cannot be maneuvered when positioning is performed. SITAN has the ability of continuous real-time positioning in maneuvering flight, but it has a higher false fix probability in the case of large initial position error or intensive terrain gradient variance. On the basis of the two algorithms, a number of better performance matching algorithms have been developed in recent years (Copp and Subbarao, 2015; Johnson et al., 2015; Yoo and Chan, 2015; Yun and Chan, 2014). A TERCOM method based on three-stage logic judgment is proposed by Zhao (2012), which can reduce the false fix probability of tradition TERCOM algorithm. The terrain-aided navigation based on the constrained particle swarm optimization algorithm is proposed by Murangira and Musso (2013), it can reduce the complexity of the algorithm and improve the positioning accuracy. The Heli/SITAN algorithm is proposed by Hollowell (1990), which adopt single state kalman filter to achieve reliable position estimation under the condition of large initial position error. It can reduce the false fix probability of SITAN algorithm. On the basis of SITAN, BUAA Inertial Terrain-Aided Navigation (BITAN) algorithm is proposed by Chen (1992) and the improved BITAN II algorithm is proposed by Pei et al. (1996), which has a higher positioning accuracy and the circular error probability (CEP) can reach 39.5 m with the terrain elevation map resolution of 100 m. TERPROM terrain reference navigation system combine the SITAN system with TERCOM system to make the system more robust (Cowie et al., 2008). Zhao (2012) and Cheng et al. (2016) proposed robust algorithms can efficiently restrain the filter diverging caused by incorrect mathematics model and greatly improve the accuracy of parameter estimation. The development of TAN algorithms provides a powerful support for the development and application of terrain-aided navigation system.

However, the positioning accuracy and real-time performance of terrain-aided navigation system are not only related to the terrain matching algorithm, but also affected by terrain features. In the mountainous and hilly areas where the terrain features are obvious, it has higher location accuracy. But it is not suitable to perform the matching positioning in areas where the terrain features are not obvious in the plain or sea level. Therefore, in the implementation of terrain matching algorithm, we need to select the appropriate terrain matching area. For the selection of terrain matching area, Song et al. (2016) proposed the criterion of terrain matching region selection based on terrain feature parameter, and given the logical judgment function of selecting matching area. On the basis of fuzzy decision, Wang et al. (2017) proposed a method based on Vague set fuzzy reasoning to select the terrain matching area. Due to the limitation of matching algorithm and terrain features, the application of the terrain-aided navigation system in the present time needs to plan the flight route according to mission and select the matching area, which limits the maneuverability and the real-time positioning performance of the carrier. Aimed at this drawback, a real-time airborne terrain-aided navigation system is proposed in this paper, which can plan and select the matching area online according to the heading angle and estimated position errors during carrier flight and adopt the appropriate terrain-aided navigation algorithm for different terrain areas and flight conditions, so that the carrier has higher maneuverability and real-time positioning capability. In this paper, we proposed a online system of matching area planning and adaptability analysis, and presented a robust terrain aided inertial navigation algorithm and positioning reliability assessment method.

A brief overview of real-time terrain aided inertial navigation system is presented below. A description of the proposed matching area planning model, adaptability analysis method of terrain matching area and robust terrain aided navigation algorithm is then given. System tests and analysis are then introduced. And finally some conclusions are given.

2. System overview

The structure diagram of the real-time terrain aided inertial navigation system is shown in Fig. 1. The system is mainly composed of the inertial navigation system (INS) and terrain aided navigation system (TANS). The working principle of the system is that terrain matching area planning and selection system first plan matching area according to the current latitude λ, longitude L, heading angle ψ, east and north estimated position error σ_E and σ_N obtained from the inertial navigation system. Then analyze the adaptability of the matching area according to adaptability analysis method of terrain matching area. If the matching area is suitable for terrain matching, then the system execute TAN algorithm based on terrain altitude ht below carrier and matching area elevation database to obtain the optimal estimation of the navigation error state as the correction information of the inertial navigation system. Where ht is calculated by the difference between barometric altimeter data h and radar altimeter data hr, and navigation error state include position error $\Delta\lambda$, ΔL and Δh and velocity error Δv.

The system introduced a real-time terrain matching area planning and selection module on the basis of traditional TANS (Lu et al., 2014), which can realize automatic planning of terrain matching area, analyze the adaptability of the matching area and provide the decision for executing suitable TAN algorithm.

The aim of matching area planning is to plan and select suitable area from the digital terrain elevation database (DTED) as the terrain matching area of the current stage