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Real-time total system error estimation: Modeling and application in required navigation performance

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Abstract In required navigation performance (RNP), total system error (TSE) is estimated to provide a timely warning in the presence of an excessive error. In this paper, by analyzing the underlying formation mechanism, the TSE estimation is modeled as the estimation fusion of a fixed bias and a Gaussian random variable. To address the challenge of high computational load induced by the accurate numerical method, two efficient methods are proposed for real-time application, which are called the circle tangent ellipse method (CTEM) and the line tangent ellipse method (LTEM), respectively. Compared with the accurate numerical method and the traditional scalar quantity summation method (SQSM), the computational load and accuracy of these four methods are extensively analyzed. The theoretical and experimental results both show that the computing time of the LTEM is approximately equal to that of the SQSM, while it is only about 1/30 and 1/6 of that of the numerical method and the CTEM. Moreover, the estimation result of the LTEM is parallel with that of the numerical method, but is more accurate than those of the SQSM and the CTEM. It is illustrated that the LTEM is quite appropriate for real-time TSE estimation in RNP application.

1. Introduction

With the development of the next generation air transportation system (NextGen), performance based navigation (PBN) is required to implement in the next few years by the International Civil Aviation Organization (ICAO).[1] Required navigation performance (RNP) is a core component of PBN, which plays an important role in guaranteeing flight efficiency and safety.[2]

RNP defines a total of four performance parameters: accuracy, integrity, continuity and availability. Integrity is especially important for aviation safety, which indicates the ability of a timely alert to a user in the presence of a system failure or an excessive error.[3–6] For RNP operation, total system error (TSE) is estimated to compare with the navigation specification to judge whether an aircraft satisfies the RNP requirement or not. Since the true position is unknown, TSE obeys a certain probability distribution during a flight. Consequently, real-time TSE should be estimated to compare with the threshold to provide a timely warning when TSE exceeds

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the bounds. It may cause false alarms if the estimation is conservative. Otherwise, it may cause missed warnings, which is hazardous to flight safety. Moreover, TSE estimation methods should be efficient to meet the real-time requirement.

Currently, the existing TSE estimation methods include the root sum square method (RSSM) and the scalar quantity summation method (SQSM). The RSSM obtains the distribution of TSE as a Gaussian with a standard deviation equal to the root sum square of the standard deviations of flight technical error (FTE) and navigation system error (NSE).[7,8] As the distributional property of TSE cannot accurately reflect the true TSE of a current moment, it may be unsuitable for real-time application. The SQSM regards FTE and NSE as scalar quantities and sums them to estimate TSE.[9] Nevertheless, the method does not distinguish the lateral and longitudinal components of TSE, which may lead to conservative results when the true FTE and NSE are in different directions.

In the works above, TSE is estimated as a simple sum of FTE and NSE, while the formation mechanism of TSE is rarely discussed. The goal of TSE estimation is to compute a statistical bound of TSE so as to guarantee that the probability of the true TSE exceeding the said number is smaller than the performance requirement. A similar concept is the protection level (PL), which has been widely used in NSE to describe a bound of the horizon/vertical positioning error linked to the integrity risk. In this paper, research on an accurate and real-time TSE estimation method for RNP application is presented.

2. TSE estimation model

In this section, the properties of FTE and NSE are analyzed to obtain the formation mechanism of TSE. Then, the TSE estimation is modeled as the estimation fusion of a fixed bias and a Gaussian random variable.

TSE is defined as the deviation of a flight true position away from the desired path, which mainly consists of path definition error (PDE), FTE and NSE, as shown in Fig. 1. On the assumption that PDE is negligible, TSE is the integration of FTE and NSE.[10]

To estimate TSE accurately, it is essential to know the properties of the two main components, i.e., FTE and NSE. Recently, FTE has been investigated,[11] and can be obtained from a flight management system (FMS) timely and accurately.[12,13] NSE varies with navigation modes. With the development of global navigation satellite system (GNSS), the GNSS-based navigation mode is becoming an inevitable trend in the future. Consequently, the GNSS-based real-time TSE estimation is researched in this section, which can be easily extended to other navigation modes. The NSE of the GNSS mode obeys a Gaussian distribution, whose covariance matrix is decided by the geometrical configuration and the pseudorange errors.[14]

In this paper, real data of RNP during an approach phase are utilized to valid the properties of FTE and NSE. As shown in Fig. 2(a), the figure shows that the difference between FTE and FMS observations is less than 0.05 m. With FMS observations, FTE can be obtained as a bias error at each sample time. The Gaussian assumption is simple and convenient for calculation, which has been widely used to describe the GNSS navigation error. As shown in Fig. 2(b), the normal quantile–quantile (Q–Q) plot of NSE indicates that NSE is close to a Gaussian distribution, although it does not strictly obey the distribution as imperfect data. Consequently, the problem of real-time TSE estimation can be transformed into the estimation fusing of a bias error and a Gaussian random variable.

The NSE of GNSS positioning obeys Gaussian distribution $N(\mathbf{0}, \boldsymbol{\Sigma})$, where $\boldsymbol{\Sigma}$ is the covariance matrix of the distribution. $\boldsymbol{\Sigma}$ with N_s visual satellites can be obtained as: $\boldsymbol{\Sigma} = \sigma_p^2(\boldsymbol{H}^T \boldsymbol{H})^{-1}$, where σ_p is the standard deviation of pseudorange errors and $\boldsymbol{H} \in \mathbf{R}^{Ns\times 4}$ is the observation matrix. As matrix $\boldsymbol{H}$ is calculated by the N_s directions from the receiver to the visual satellites, it is usually called the geometrical configuration matrix. To obtain the parameters of the Gaussian distribution of NSE, the geometrical configuration and the pseudorange errors should be applied.

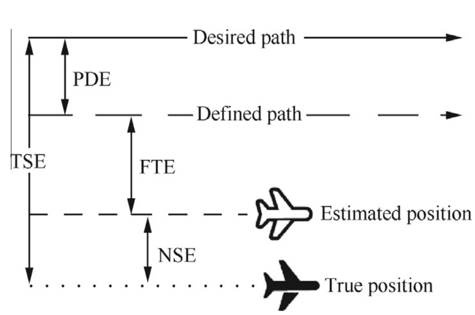

Fig. 1 Composition of TSE.

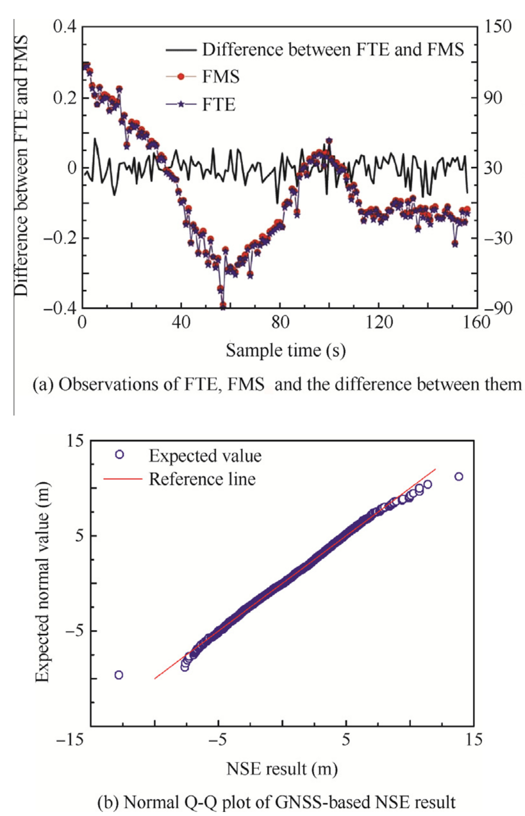

Fig. 2 Properties of FTE and NSE with real data of one approach phase.