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Development of a navigation performance evaluation system

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Dear editor,

Owing to little exploration experience and great technical difficulty of deep space exploration autonomous navigation, the corresponding navigation performance evaluation system is seldom perfected [1]. Therefore, the establishment of an effective method to evaluate the navigation systems for deep space exploration has become a hot topic in the aerospace field [2, 3]. Navigation particle filtering is a key to achieve a high accuracy autonomous navigation [4]. Concerning navigation performance evaluation, high accuracy and high real-time performance of the autonomous-navigation filtering algorithm are required [5]. Generally, the development and evaluation of autonomous-navigation systems are always conducted simultaneously. The function and performance of the navigation systems can be evaluated to check whether they meet the design requirements [6]; moreover, the future working status of the systems can be monitored after deploying the evaluation to provide a basis for improving or enhancing the performance in subsequent developments of the systems. In view of the above, this study proposes a navigation performance evaluation system and different evaluation methods for the evaluation indicators. Our evaluation system comprises a network connection module, evaluation calculation module, and curve display module, which can receive navigation filter data, evaluate the navigation system performance indicators through the evaluation methods, and display the generated assessment results using a visual interface, respectively. A block diagram of the navigation performance evaluation system is shown in Figure 1(a).

Network connection module. The main function of this module is to establish a network connection with the data sender. Here, both transmission control protocol (TCP) and user datagram protocol (UDP) are provided, which allows users to set the format of sending and receiving data. The users can send or receive the data after setting the corresponding listening port and IP address. After successful connection, users can receive the navigation-filter data. The TCP and UDP communication objects can be created using the QTcpSocket and QUdpSocket classes, whose main responsibility is in sending and receiving data. The flow chart of the network connection module is shown in Figure 1(b).

Evaluation calculation module. We design a set of evaluation indicators such as accuracy, real-time performance, continuity, and availability to assess the performance of the navigation system.

(1) Accuracy. Accuracy is one of the most important indicators used in evaluating the performance of navigation systems. It mainly depicts the degree of difference between the real position and the calculated real-time position of the de-

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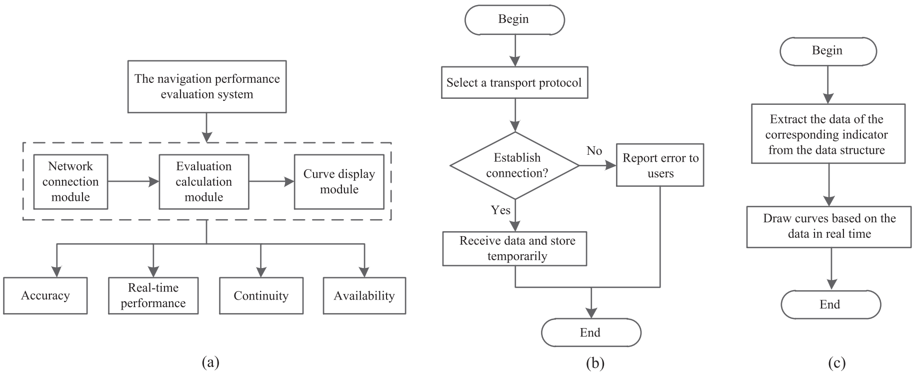

Figure 1 (a) A block diagram of the navigation performance evaluation system; (b) flow chart of the network connection module; and (c) flow chart of the curve display module.

tector by the autonomous-navigation system. Because of the complexity and unpredictability of the deep space environment, it is common for measuring instruments as well as random noise to cause systematic errors. The dispersion of the error is not fixed; thus, it is necessary to perform modeling analysis from the navigation principle and the navigation process standpoints. Sensors are used to acquire the observation information as the detector traverses, and the particle filter is subsequently estimated by combining the orbital dynamic models. Errors may occur at any stage during the autonomous navigation, which causes accuracy degradation. Thus, we adopt a forward mean square error to calculate the accuracy using the following equation:

$$R(k) = \sqrt{\frac{1}{k}\sum_{i=1}^{k}\Delta_i^2}, \tag{1}$$

where Δ_i represents the error at the i-th moment in the experiment. The forward mean square error uses all the data from the beginning to the present and accumulates the error of each data point.

(2) Real-time performance. Real-time performance refers to the time it takes for a navigation algorithm to perform an operation cycle [7]. Real-time performance has two vital considerations: The first consideration concerns how complex the navigation algorithm is. To find the best design based on ensuring optimum accuracy, we must evaluate the detector's attitude, velocity, and position as quickly as possible to ensure that it can be corrected before large deviations occur while simultaneously considering other factors such as power consumption, volume, and weight of the detector hardware when designing the actual navigation systems; if we ignore the latter, the overall navigation system design may become unreasonable and impractical. The second consideration concerns how long it takes the navigation system to navigate to a new state after suffering external random disturbances. In this case, we use the running time consumed by the filtering algorithm as the evaluation criterion.

(3) Continuity. Continuity of an autonomous-navigation system indicates the ability of the system to continuously provide normal navigation and location services throughout the voyage of the detector without unintended interruptions. It comprises two aspects: spatial signal continuity and service continuity. The spatial signal continuity indicates the ability of the detector to continuously receive the observed signal from the sensor without signal interruption caused by external factors. Service continuity refers to the ability of the navigation systems to continuously provide with navigation and positioning services to the detector after the observed signal of the target object is accepted by the navigation systems. An important source of navigation system errors is the discontinuity of spatial signals. Navigation systems work continuously; if the observed signal is not continuous, the navigation system errors will be not corrected as time accumulates. If the service continuity of the autonomous-navigation systems is degraded, it will also cause errors in the flight control systems and reduce the control performance of the detector.

The number of continuous points can be obtained using the following error calculation equation:

$$\hat{e}(k) = \|e(k) - e(k-1)\|, \tag{2}$$

where $\hat{e}$ shows the error in estimating adjacent sampling points, $e(k)$ is the estimated value at time k, and $\|\cdot\|$ is a 2-norm. If $\hat{e}$ is less than a specific threshold, the point at time k is continuous. The continuity can be expressed using the following equation:

$$L = \frac{C}{T-1}, \tag{3}$$

where L is the continuity, C is the number of continuous point, and T is the total number of sampling points.

(4) Availability. Availability is a usage-oriented indicator for the detector of an autonomous-navigation system; it indicates the available proportion of system performance. This indicator includes service availability and spatial availability. Service availability refers to the percentage of time that the systems can provide effective navigation and positioning services to the detectors during the period in which the systems perform tasks. Its core idea is to set a threshold. When the positioning error of the detector at the current moment is less than this threshold, it implies that the sampling point is available; otherwise, the point is not available. Finally, the availability of the navigation systems can be calculated using the ratio of the number of sampling points available in the entire navigation process to the total number of sampling points. Spatial availability is the ability of navigation systems to measure accurate observation information through the use of sensors. Navigation satellites are subject to inaccurate navigation reference information due to numerous internal causes or deep space environments, which may also result in a decrease in usability.

For service availability, we would analyze the availability of its accuracy. Availability can be expressed using the following equation:

$$K = \frac{A}{T}, \tag{4}$$

where K denotes the availability, A represents the number of available points, and T is the total number of sampling points.

Curve display module. The main function of this module is to display in real-time the corresponding sampling point data obtained from the evaluation data in the storage structure, calculated by the evaluation calculation module. The functional flow chart of this curve display module is shown in Figure 1(c). The evaluation system was implemented in the Qt Creator development environment, which uses Qwt plugin for curve drawing.

The main interface contains buttons for network connection, evaluation calculation, and curve display. Herein, we discuss the display function of the evaluation system and enter the navigation evaluation interface by clicking the “Evaluation Calculation” button. In this interface, we can select four different evaluation indicators to display different curvilinear interfaces. For different evaluation indicators, different data types (position or velocity data), as well as different filtering algorithms, we use different color curves to display the differences easily. Taking the accuracy assessment as an example, we can enter the accuracy evaluation display interface by clicking the “Accuracy” radio button. Then, one or more filtering algorithms can be selected and the position or velocity is also selected. When the selection is completed, the corresponding accuracy evaluation result curve is displayed on the curve display area of the current interface. Likewise, the assessment interfaces of availability and continuity are also implemented.

Conclusion and future work. This study proposed an autonomous-navigation performance evaluation system and a set of basic evaluation indicators including accuracy, real-time performance, continuity, and availability. In addition, we analyzed the function and meaning of each index in the navigation system. Our future work would focus on perfecting the evaluation and display functions of the evaluation system.

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