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A REDUNDANT ADAPTIVE NAVIGATION METHOD BASED ON DYNAMIC PERFORMANCE EVALUATION FOR AEROSPACE VEHICLE

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Abstract

The aerospace vehicle (ASV) is a new type of vehicle which can not only cruise in the atmosphere at hypersonic speed, but also orbit beyond the atmosphere. The multi-task and multi-mode characteristics of ASV put forward new requirements for the flexibility, reliability and stability of its navigation system. In order to ensure the reliability of the navigation system in the long flight process, based on the traditional decentralized filtering, this paper constructs the integrated navigation database, selects the optimal integrated navigation method by the real-time performance evaluation index, and constructs a redundant adaptive navigation method based on the dynamic performance evaluation. In this paper, the simulation results show that the performance evaluation index can track the accuracy of the integrated navigation in real time and make it possible for the adaptive navigation system to flexibly select the appropriate integrated navigation scheme. In the flight process of ASV, the adaptive navigation system can select the optimal integrated navigation scheme under the current situation according to the real-time task requirements, and effectively improve the overall accuracy of the navigation system.

Keywords: Multi-information Fusion, Adaptive, Redundant Navigation Database, Actual Navigation Performance Evaluation, Aerospace Vehicle

1. Introduction

The aerospace vehicle integrates the advantages of aviation technology and space technology, and has been attached great importance to by various military powers for its great strategic military application value. The aerospace vehicle is a new reusable vehicle that integrates aircraft, spacecraft and carrier. Its power device is composed of air-breathing engine and rocket jet engine[1]. It can not only make hypersonic cruise flight in the atmosphere, but also enter orbit through the atmosphere. With the current one-time use carrier rocket, the spacecraft and part of the repeated use of the space shuttle, compared it is repeating usability, launch the operation cost, maintainability, turnaround time and flexible mobility has a revolutionary change, is the future into space and control space, ensure that the core competence of the space superiority key pillars, is also a premise to carry out large-scale space development, It has broad application prospect[2].

In the 1980s, there was a boom in the development of space aircraft in the world. The United States, the United Kingdom, France, Germany, the former Soviet Union, Japan, India and other countries put forward various plans and schemes for space aircraft. However, due to the limitations of the level of aerospace technology and funding at that time, these plans and schemes did not come true. Since the 1990s, the world's aerospace powers have shifted their focus to the research and technical verification of aerospace vehicles in advance. In 2010, the successful launch of the US X-37B orbital test vehicle has promoted the development of aerospace vehicles in many countries around the world. At present, Russia is the world leader in hypersonic technology and has launched the Multi-Purpose Space System (MAKS) program, which has entered the flight verification stage of aerospace vehicles. The UK has also made solid progress in the development of the Skylon aerospace vehicle project, which is scheduled to fly in the next few years[3]. Germany is also cooperating with other countries in the research and development of "Sanger" space aircraft[4]; Japan has mastered key technologies such as ignition, thrust measurement, fuel regulation and engine cooling; India's defence ministry has also launched a small reusable aerospace vehicle programme. By contrast, the United States is a leader in the development of aerospace vehicles. The X-37B has successfully conducted five launch and landing tests, and is expected to be further developed in the future as research continues to deepen and technology advances[5].

The characteristics of multi-task and multi-operation mode of aerospace vehicle require flexibility, reliability and stability of navigation system. In order to ensure the reliability of the long-duration flight navigation system of aerospace vehicle, the different cooperation of multiple integrated navigation systems can provide accurate navigation information continuously in the whole flight process of aerospace vehicle in the case of failure and abnormality of some navigation systems. In order to ensure the reliability of the navigation system during the whole flight several redundant navigation sensors can be used to form the redundant multi-source fault tolerant integrated navigation system. This, in turn, brings the need for a new navigation system. Different flight stages have different flight environments, at the same time, the demand for the output precision of the navigation system is also different. Therefore, it is necessary to have a navigation system that can be applied to the whole flight, which can make use of onboard redundant navigation sensors to achieve optimal information matching and processing in different flight stages, so as to obtain high reliability and precision navigation results.

The optimal fusion of navigation sensors with redundant configuration can be realized by information fusion method. At present, the information fusion methods of navigation system can be divided into two categories: centralized filtering and decentralized filtering. Because the redundancy potential of centralized filtering multi-sensor integrated navigation system can not always be fully utilized decentralized filtering has been paid more and more attention. Decentralized filtering divides the state estimation problem of a high-order system into several local state estimation problems of subsystems, and obtains the global state estimation of the system according to certain criteria.

2. Adaptive Navigation Scheme for ASV

2.1 Analysis of ASV Navigation System

The flight process of aerospace vehicle can be divided into ascent, in-orbit, re-entry and landing stages. In different stages of flight environment is different, the accuracy and performance of the navigation system also have different requirements. In order to meet the mission requirements of aerospace vehicles, the navigation system must have high precision and adaptive characteristics. On this basis, this paper presents an adaptive navigation scheme based on dynamic performance evaluation. The flight stage of the aerospace vehicle and its performance requirements for the navigation system are shown in Figure 1.

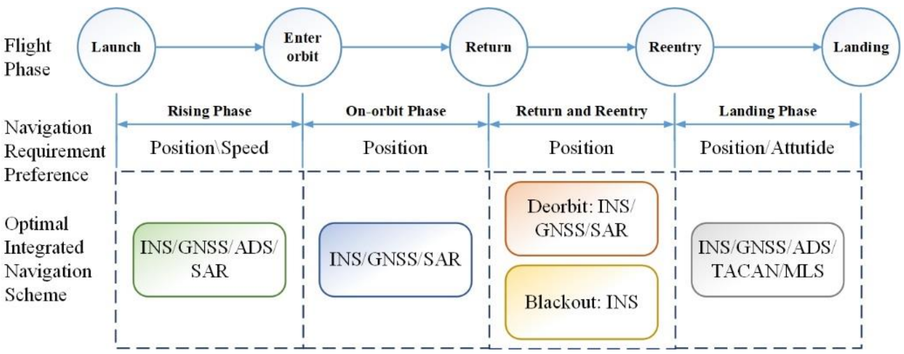


Figure 1 - Schematic diagram of priority of navigation information fusion at each stage of ASV

As can be seen from Figure 1, in the ascent stage, there is a higher demand for navigation position and velocity information; in the orbit and reentry stage, there is a higher demand for navigation position information; while in the landing stage, there is a high demand for navigation position and attitude information. Combine with the aerospace vehicle task environment, this paper designs the navigation system configuration scheme as shown in Figure 1.

2.2 Models of Redundant Navigation Systems for ASV

Before analyzing the adaptive navigation scheme of aerospace vehicle, it is necessary to configure the navigation subsystems of aerospace vehicle, such as inertial navigation system (INS), global navigation satellite system (GNSS), starlight navigation system (SAR), atmospheric data system (ADS), tactical air navigation system (TACAN) and microwave landing system (MLS), and establish the corresponding model.

1) Inertial Navigation System

The inertial navigation system obtains high precision angular acceleration and acceleration through gyroscope and accelerometer, and obtains position information and velocity information through dead reckonings. However, the errors of its position, speed and attitude accumulated over the working time and showed a divergent trend. Therefore, this paper takes the inertial navigation system as the core, supplemented by other navigation systems to form an integrated navigation system.

The state matrix $X(t)$ is defined as strapdown inertial navigation system error. Combine with the error equation of basic navigation parameters of the strapdown inertial navigation system and the error equation of inertial instrument, the state equation of the inertial/multi-sensor integrated navigation system can be obtained as follows:

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

Where, $F(t)$ represents the one-step state transition matrix of the state equation of the inertial/satellite integrated navigation system; $G(t)$ represents the system white noise error matrix of the state equation of the inertial/satellite integrated navigation system; $W(t)$ is the system error white noise vector of the state equation of inertial/satellite integrated navigation system, and the system state vector is defined as[6]:

$$\begin{aligned} X=[&\phi_n \quad \phi_\mathrm{e} \quad \phi_\mathrm{d} \quad \delta V_n \quad \delta V_e \quad \delta V_d \quad \delta L \quad \delta\lambda \quad \delta h \\ &\varepsilon_{bx} \quad \varepsilon_{by} \quad \varepsilon_{bz} \quad \varepsilon_{rx} \quad \varepsilon_{ry} \quad \varepsilon_{rz} \quad \nabla_{rx} \quad \nabla_{ry} \quad \nabla_{rz}]^T \end{aligned} \tag{2}$$

Where ϕ_e,ϕ_n,ϕ_u is the error Angle of three-way digital platform; $\delta v_e,\delta v_n,\delta v_d$ is the three-direction velocity error; $\delta L,\delta\lambda,\delta h$ is the error of latitude, longitude and altitude; $\varepsilon_{bx},\varepsilon_{by},\varepsilon_{bz}$ and $\varepsilon_{rx},\varepsilon_{ry},\varepsilon_{rz}$ are the three-way gyro constant drift error and the three-way first-order Markov drift error respectively; $\nabla_{rx},\nabla_{ry},\nabla_{rz}$ is the zero deviation of the three-way accelerometer.

2) Global Navigation Satellite System

GNSS is a general term for all operating Satellite Navigation Systems, including the U.S. 's GPS, Russia's Glonass and China's Beidou Navigation System[7]. GNSS provides high precision navigation parameter information for the carrier by means of Doppler ranging or time ranging[8].

In this paper, GNSS provides the position (longitude, latitude, height), speed (north, east, ground) and attitude (roll Angle, pitch Angle, heading Angle under geographical system) of the carrier, and INS/GNSS adopts the combination of position, speed and attitude.

The measurement vector of INS/GNSS subsystem is defined as:

$$Z_{GNSS}(t)=\begin{bmatrix} \gamma_{INS}-\gamma_{GNSS} \\ \theta_{INS}-\theta_{GNSS} \\ \psi_{INS}-\psi_{GNSS} \\ v_{nINS}-v_{nGNSS} \\ v_{eINS}-v_{eGNSS} \\ v_{dINS}-v_{dGNSS} \\ (L_{INS}-L_{GNSS})R_n \\ (\lambda_{INS}-\lambda_{GNSS})R_e\cos L \\ h_{INS}-h_{GNSS} \end{bmatrix}=\begin{bmatrix} \delta\gamma+O_{\gamma GNSS} \\ \delta\theta+O_{\theta GNSS} \\ \delta\psi+O_{\psi GNSS} \\ \delta v_n+M_{nGNSS} \\ \delta v_e+M_{eGNSS} \\ \delta v_d+M_{dGNSS} \\ R_n\delta L+N_{LGNSS} \\ R_e\cos L\delta\lambda+N_{\lambda GNSS} \\ \delta h+N_{hGNSS} \end{bmatrix}=\begin{bmatrix} H_{aGNSS}(t) \\ H_{vGNSS}(t) \\ H_{pGNSS}(t) \end{bmatrix}X(t)+N_{GNSS}(t) \tag{3}$$

Where, $O_\gamma, O_\theta, O_\psi$ is the attitude error of the auxiliary navigation system, M_n, M_e, M_d is the speed error of the auxiliary navigation system, and N_L, N_λ, N_h is the position error of the auxiliary navigation system.

Since there is no attitude error in the system state variable, the attitude error Angle needs to be transformed into the strapdown inertial navigation mathematical platform error Angle. The transformation relationship is as follows:

$$\begin{bmatrix} \delta\gamma \\ \delta\theta \\ \delta\psi \end{bmatrix} = \frac{-1}{\cos\theta}\begin{bmatrix} \cos\psi & \sin\psi & 0 \\ -\sin\psi\cos\theta & \cos\psi\cos\theta & 0 \\ \cos\psi\sin\theta & \sin\psi\sin\theta & \cos\theta \end{bmatrix}\begin{bmatrix} \phi_N \\ \phi_E \\ \phi_D \end{bmatrix} = A_{3\times3}\begin{bmatrix} \phi_N \\ \phi_E \\ \phi_D \end{bmatrix} \tag{4}$$

Then, the observation matrix of the measurement equation in Equation (2) is:

$$H_{aGNSS}(t)_{3\times18} = \begin{bmatrix} A_{3\times3} & 0_{3\times3} & 0_{3\times3} & 0_{3\times9} \end{bmatrix}_{3\times18} \tag{5}$$

$$H_{vGNSS}(t)_{3\times18} = \begin{bmatrix} 0_{3\times3} & diag\begin{bmatrix} 1 & 1 & 1 \end{bmatrix} & 0_{3\times3} & 0_{3\times9} \end{bmatrix}_{3\times18} \tag{6}$$

$$H_{pGNSS}(t)_{3\times18} = \begin{bmatrix} 0_{3\times3} & 0_{3\times3} & diag\begin{bmatrix} R_n & R_e\cos L & 1 \end{bmatrix} & 0_{3\times9} \end{bmatrix}_{3\times18} \tag{7}$$

3) Starlight Navigation System

Starlight navigation is based on the inertial reference frame, which uses astrometric instruments to obtain the celestial body's position and height relative to the measurement point, and then works out the navigation information. Commonly used star navigation instruments include star tracker, astronomical compass and sextant, etc[9]. However, due to the impact of astronomical observation factors such as clouds, it is unable to provide navigation information throughout the mission, which is often used to assist other navigation systems.

In this paper, the position (longitude, latitude, height) and attitude (roll Angle, pitch Angle, heading Angle) of the carrier are provided by SAR, and INS/SAR combination adopts the combination of position and attitude.

The measurement vector of INS/SAR subsystem is defined as:

$$Z_{SAR}(t) = \begin{bmatrix} \gamma_{INS} - \gamma_{SAR} \\ \theta_{INS} - \theta_{SAR} \\ \psi_{INS} - \psi_{SAR} \\ (L_{INS} - L_{SAR})R_n \\ (\lambda_{INS} - \lambda_{SAR})R_e\cos L \\ h_{INS} - h_{SAR} \end{bmatrix} = \begin{bmatrix} \delta\gamma + O_{\gamma SAR} \\ \delta\theta + O_{\theta SAR} \\ \delta\psi + O_{\psi SAR} \\ R_n\delta L + N_{LSAR} \\ R_e\cos L\delta\lambda + N_{\lambda SAR} \\ \delta h + N_{hSAR} \end{bmatrix} = \begin{bmatrix} H_{aSAR}(t) \\ H_{pSAR}(t) \end{bmatrix} X(t) + N_{SAR}(t) \tag{8}$$

Where:

$$H_{aSAR}(t)_{3\times18} = \begin{bmatrix} A_{3\times3} & 0_{3\times3} & 0_{3\times3} & 0_{3\times9} \end{bmatrix}_{3\times18} \tag{9}$$

$$H_{pSAR}(t)_{3\times18} = \begin{bmatrix} 0_{3\times3} & 0_{3\times3} & diag\begin{bmatrix} R_n & R_e\cos L & 1 \end{bmatrix} & 0_{3\times9} \end{bmatrix}_{3\times18} \tag{10}$$

4) Atmospheric Data System

Atmospheric data system is a kind of system which provides comprehensive and high precision atmospheric data information. As a common recorded navigation system, ADS can provide altitude, speed and other navigation information for flight information only by itself under all-weather conditions without radiating any information outward[10]. However, the working condition of ADS is affected by the acquisition of atmospheric data and information, so it cannot be used at hypersonic velocity and outside the atmosphere.

In this paper, the ADS provides the height and velocity of the carrier (northward, eastward and groundward), and the INS/ADS combination adopts the combination of height and velocity.

The measurement vector of INS/ADS subsystem is defined as:

$$Z_{ADS}(t)=\begin{bmatrix} v_{nINS}-v_{nADS} \\ v_{eINS}-v_{eADS} \\ v_{dINS}-v_{dADS} \\ h_{INS}-h_{ADS} \end{bmatrix}=\begin{bmatrix} \delta v_n+M_{nADS} \\ \delta v_e+M_{eADS} \\ \delta v_d+M_{dADS} \\ \delta h+N_{hADS} \end{bmatrix}=\begin{bmatrix} H_{vADS}(t) \\ H_{hADS}(t) \end{bmatrix}X(t)+N_{ADS}(t) \tag{11}$$

Where:

$$H_{vADS}(t)_{3\times18}=\begin{bmatrix}0_{3\times3} & diag\begin{bmatrix}1 & 1 & 1\end{bmatrix} & 0_{3\times3} & 0_{3\times9}\end{bmatrix}_{3\times18} \tag{12}$$

$$H_{hADS}(t)_{1\times18}=\begin{bmatrix}0_{1\times6} & \begin{bmatrix}0 & 0 & 1\end{bmatrix} & 0_{1\times9}\end{bmatrix}_{1\times18} \tag{13}$$

5) Tactical Air Navigation System

The radio navigation system is a kind of navigation system which can measure the distance and Angle by receiving the radio signals set by the electronic equipment on the moving body, and calculate the corresponding navigation parameters on this basis, so as to determine the position of the moving body[11]. The system can be used all day and all day, but the available distance is limited by the radio transmission power and the antenna.

The position (longitude, latitude and height) of the carrier provided by TACAN in this paper, and INS/TACAN combination adopts the way of position combination.

The measurement vector of INS/TACAN subsystem is defined as:

$$Z_{TACAN}(t)=\begin{bmatrix} (L_{INS}-L_{TACAN})R_n \\ (\lambda_{INS}-\lambda_{TACAN})R_e\cos L \\ h_{INS}-h_{TACAN} \end{bmatrix}=\begin{bmatrix} R_n\delta L+N_{LTACAN} \\ R_e\cos L\delta\lambda+N_{\lambda TACAN} \\ \delta h+N_{hTACAN} \end{bmatrix}=H_{pTACAN}(t)X(t)+N_{TACAN}(t) \tag{14}$$

$$H_{pTACAN}(t)_{3\times18}=\begin{bmatrix}0_{3\times3} & 0_{3\times3} & diag\begin{bmatrix}R_n & R_e\cos L & 1\end{bmatrix} & 0_{3\times9}\end{bmatrix}_{3\times18} \tag{15}$$

6) Microwave Landing System

The microwave landing system is to use the microwave receiver equipped by the aircraft, combined with the known landing site and other parameters, through the heading guidance, glide guidance data, solve the geometric relationship between the carrier and the landing site, so as to guide the pilot to control the aircraft into the landing site[12]. The system can provide high precision relative position information, but it can only be applied to the area near the landing site.

In this paper, MLS provides position (longitude, latitude and height) and attitude (roll Angle, pitch Angle and heading Angle under geographical system) of the carrier, and INS/MLS combination adopts the way of position and attitude combination.

The measurement vector of INS/MLS subsystem is defined as:

$$Z_{MLS}(t)=\begin{bmatrix} \gamma_{INS}-\gamma_{MLS} \\ \theta_{INS}-\theta_{MLS} \\ \psi_{INS}-\psi_{MLS} \\ (L_{INS}-L_{MLS})R_n \\ (\lambda_{INS}-\lambda_{MLS})R_e\cos L \\ h_{INS}-h_{MLS} \end{bmatrix}=\begin{bmatrix} \delta\gamma+O_{\gamma MLS} \\ \delta\theta+O_{\theta MLS} \\ \delta\psi+O_{\psi MLS} \\ R_n\delta L+N_{LMLS} \\ R_e\cos L\delta\lambda+N_{\lambda MLS} \\ \delta h+N_{hMLS} \end{bmatrix}=\begin{bmatrix} H_{aMLS}(t) \\ H_{pMLS}(t) \end{bmatrix}X(t)+N_{MLS}(t) \tag{16}$$

Where:

$$H_{aMLS}(t)_{3\times18} = \begin{bmatrix} A_{3\times3} & 0_{3\times3} & 0_{3\times3} & 0_{3\times9} \end{bmatrix}_{3\times18} \tag{17}$$

$$H_{pMLS}(t)_{3\times18} = \begin{bmatrix} 0_{3\times3} & 0_{3\times3} & diag\begin{bmatrix} R_n & R_e\cos L & 1 \end{bmatrix} & 0_{3\times9} \end{bmatrix}_{3\times18} \tag{18}$$

3. Redundant Adaptive Airborne Navigation Method based on Dynamic Performance Evaluation

3.1 Information Fusion Scheme for Adaptive Navigation System

In this paper, based on the traditional decentralized filtering algorithm with two parallel structures, all possible combinations of sub-filters are listed according to the sub-filters formed by navigation sensors selected by space and space aircraft, and a complete integrated navigation scheme database is formed. Combined with the navigation system redundancy configuration scheme, a number of integrated navigation scheme databases are formed. Based on the integrated navigation scheme database, according to the current task environment, through the evaluation of the dynamic performance of the navigation system, the appropriate integrated navigation scheme can be provided for the navigation system more flexibly. The structural block diagram of the adaptive integrated navigation system proposed in this paper is shown in Figure 2 below.

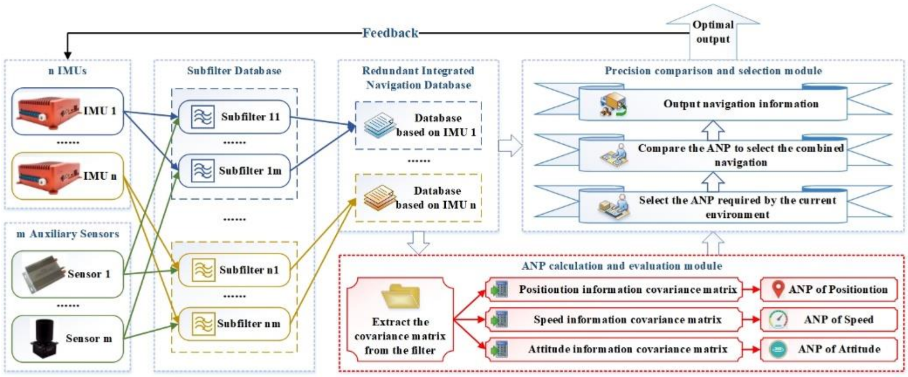


Figure 2 - Block diagram of adaptive integrated navigation

3.2 Dynamic Evaluation Algorithm of Performance Index of Subsystems

The task of navigation is to provide the 6-DOF navigation parameters of the moving carrier, namely the 3-D position and 3-D Angle, which determine the spatial position and state of an object. Most of the existing decentralized filters adopt relatively fixed parallel hierarchical structure and switching mode, and their information fusion mode cannot adapt to the characteristics of large range and multiple flight modes of aerospace vehicles. For example, when a group of sub-filters that simply output high-precision attitude information are added into the overall solution, the position accuracy of the navigation output cannot be improved, and even the original position accuracy will be affected. In the whole flight mission process of the aerospace vehicle, the priority requirements for position information and attitude information are different at different stages. The information priority of each task stage is shown in Figure 1.

In traditional integrated navigation, all navigation sensors are combined to obtain all navigation information with optimal overall accuracy. In order to better play to the characteristics of all kinds of navigation sensor, need to study for space complex multi-stage, change under the environment of running multiple information fusion adaptive integrated navigation method, based on the redundant navigation sensor information dynamic matching real-time optimal combination, for the current environment of reliability and accuracy of the optimal navigation information. In this paper, the navigation precision of the information with high priority in different stages is calculated and compared, and the navigation scheme with the highest information precision is selected from the integrated navigation database to obtain the optimal navigation results with the required information.

In this paper, Actual Navigation Performance (ANP) was selected as the dynamic Performance evaluation index to calculate the current Navigation accuracy and integrity of the carrier. According to the actual navigation performance theory, the position, velocity and attitude covariances are obtained through decentralized estimation of sub-filters by using multivariate Gaussian characteristics. Then, the evaluation model from the covariance matrix to the actual navigation performance indexes is established to obtain the corresponding dynamic performance evaluation indexes. The calculation is as follows:

3.2.1 ANP Calculation Method for Position Information

According to multivariate Gaussian characteristics, the covariance matrix of the position can be obtained by using the covariance matrix of the sub-filter, which is defined as follows[13]:

$$E_{pos} = \begin{bmatrix} \delta\varphi & \delta\lambda \end{bmatrix} \tag{19}$$

$$P_{pos} = \mathrm{cov}\left[E_{pos} \right] = \begin{bmatrix} \sigma_{\varphi}^2 & \sigma_{\varphi\lambda}^2 \\ \sigma_{\lambda\varphi}^2 & \sigma_{\lambda}^2 \end{bmatrix} \tag{20}$$

The position estimation error of the integrated navigation system includes longitude error and latitude error in the horizontal plane, which is non-horizontal error, and it needs to be transformed into linear error in the horizontal plane through coordinate transformation (x, y):

$$\begin{cases} x = \delta\lambda \cdot R\cos\varphi \\ y = \delta\varphi \cdot R \end{cases} \tag{21}$$

On this basis, the covariance of the position error is obtained from the covariance matrix, which can be used to determine the long and short semi-axes of the ellipse.

$$e_{pos} = \begin{bmatrix} x & y \end{bmatrix} \tag{22}$$

$$p_{pos} = \begin{bmatrix} \sigma_x^2 & \sigma_{xy}^2 \\ \sigma_{yx}^2 & \sigma_y^2 \end{bmatrix} = R^2 \begin{bmatrix} \cos^2\varphi\sigma_{\lambda}^2 & \cos^2\varphi\sigma_{\varphi\lambda}^2 \\ \cos^2\varphi\sigma_{\lambda\varphi}^2 & \sigma_{\varphi}^2 \end{bmatrix} \tag{23}$$

Construct probability ellipse and calculate eigenvalues:

$$p_{pos} = A\Lambda A^{-1} \tag{24}$$

Where, A is the eigenvector of the eigenvalue λ_i corresponding to matrix p_{pos}, then the long and short semi-axes of the ellipse are:

$$axis_{\mathrm{major}} = \max\left(\sqrt{\lambda_1}, \sqrt{\lambda_2}\right) \tag{25}$$

$$axis_{\mathrm{minor}} = \min\left(\sqrt{\lambda_1}, \sqrt{\lambda_2}\right) \tag{26}$$

Calculate the ANP of position information:

$$ANP_{posi} = k \cdot axis_{\mathrm{major}} \tag{27}$$

$$k = \frac{(2.4477 - 1.9625)}{axis_{\mathrm{major}} / axis_{\mathrm{minor}}} + 1.9625 \tag{28}$$

3.2.2 ANP Calculation Method for Attitude Information

The covariance matrix of the attitude is obtained by using the covariance matrix of the sub-filter, which is defined as follows:

$$E_{atti} = \begin{bmatrix} \delta\varphi_E & \delta\varphi_N & \delta\varphi_U \end{bmatrix} \tag{29}$$

$$p_{atti} = \mathrm{cov}\left[E_{atti}\right] = \begin{bmatrix} \sigma_{\varphi_E}^2 & \sigma_{\varphi_E\varphi_N}^2 & \sigma_{\varphi_E\varphi_U}^2 \\ \sigma_{\varphi_N\varphi_E}^2 & \sigma_{\varphi_N}^2 & \sigma_{\varphi_N\varphi_U}^2 \\ \sigma_{\varphi_U\varphi_E}^2 & \sigma_{\varphi_U\varphi_N}^2 & \sigma_{\varphi_U}^2 \end{bmatrix} \tag{30}$$

Calculate the long and short half axes of the probability ellipse:

$$p_{atti} = A\Lambda A^{-1} \tag{31}$$

Where, A is the eigenvector of the eigenvalue λ_i corresponding to matrix p_{pos}, then the long and short semi-axes of the ellipse are:

$$axis_{\text{major}} = \max\left(\sqrt{\lambda_1}, \sqrt{\lambda_2}, \sqrt{\lambda_3}\right) \tag{32}$$

$$axis_{\text{minor}} = \min\left(\sqrt{\lambda_1}, \sqrt{\lambda_2}, \sqrt{\lambda_3}\right) \tag{33}$$

Calculate the ANP of attitude information:

$$ANP_{atti} = k \cdot axis_{\text{major}} \tag{34}$$

$$k = \frac{(2.4477 - 1.9625)}{axis_{\text{major}} / axis_{\text{minor}}} + 1.9625 \tag{35}$$

3.2.3 ANP Calculation Method for Velocity Information

The covariance matrix of the velocity is obtained by using the covariance matrix of the sub-filter, which is defined as follows:

$$E_v = \left[\delta v_E \quad \delta v_N \quad \delta v_U\right] \tag{36}$$

$$p_v = \mathrm{cov}\left[E_v\right] = \begin{bmatrix} \sigma_{v_E}^2 & \sigma_{v_E v_N}^2 & \sigma_{v_E v_U}^2 \\ \sigma_{v_N v_E}^2 & \sigma_{v_N}^2 & \sigma_{v_N v_U}^2 \\ \sigma_{v_U v_E}^2 & \sigma_{v_U v_N}^2 & \sigma_{v_U}^2 \end{bmatrix} \tag{37}$$

Calculate the long and short half axes of the probability ellipse:

$$p_{atti} = A\Lambda A^{-1} \tag{38}$$

Where, A is the eigenvector of the eigenvalue λ_i corresponding to matrix p_{pos}, then the long and short semi-axes of the ellipse are:

$$axis_{\text{major}} = \max\left(\sqrt{\lambda_1}, \sqrt{\lambda_2}, \sqrt{\lambda_3}\right) \tag{39}$$

$$axis_{\text{minor}} = \min\left(\sqrt{\lambda_1}, \sqrt{\lambda_2}, \sqrt{\lambda_3}\right) \tag{40}$$

Calculate the ANP of velocity information:

$$ANP_{atti} = k \cdot axis_{\text{major}} \tag{41}$$

$$k = \frac{(2.4477 - 1.9625)}{axis_{\text{major}} / axis_{\text{minor}}} + 1.9625 \tag{42}$$

3.3 Adaptive Navigation based on Dynamic Performance Evaluation of Redundant Subsystems

As shown in Figure 2, this paper takes n sets of INS as the core component of the navigation system and forms A sub-filter by combining with other m sets of auxiliary navigation systems in the way of standard Kalman filter respectively, in which the sub-filter composed of the $No.i$ INS and the $No.j$ auxiliary navigation is denoted as $Sf_{i,j}$. The sub-filter adopts closed-loop Kalman filter, and its expression is as follows[14]:

The one-step prediction equation of the state:

$$\hat{X}_{k|k-1} = \Phi_{k,k-1}\hat{X}_{k-1|k-1} \tag{43}$$

The estimation equation of the state:

$$\hat{X}_{k|k} = \hat{X}_{k|k-1} + K_k\left(Z_k - H_k\hat{X}_{k|k-1}\right) \tag{44}$$

The gain equation of the filter:

$$K_k = P_{k|k-1}H_k^T\left(H_kP_{k|k-1}H_k^T + R_k\right)^{-1} \tag{45}$$

The mean square error equation of one step prediction:

$$P_{k|k-1} = \Phi_{k,k-1}P_{k-1}\Phi_{k,k-1}^T + \Gamma_{k-1}Q_{k-1}\Gamma_{k-1}^T \tag{46}$$

The mean square error equation of the estimation:

$$P_{k|k} = \left(I - K_kH_k\right)P_{k|k-1}\left(I - K_kH_k\right)^T + K_kR_kK_k^T \tag{47}$$

Where, Z_k and H_k are respectively the quantity direction finding quantity and measurement matrix at the moment k as described in Section 2.2 of this paper; $\hat{X}_{k|k-1}$ is the one-step prediction value of system state; $\hat{X}_{k|k}$ is the estimated value of the system state at the current moment; K_k is the filtering gain matrix at the current moment of the system; $P_{k|k-1}$ is the covariance matrix of one-step prediction error estimation of system state; $P_{k|k}$ is the covariance matrix of system state error estimation; $\Phi_{k,k-1}$ is the one-step transfer matrix of the system; Q_{k-1} is the system state noise matrix; R_k is the measurement noise matrix. Then the state estimate and state error estimate covariance matrix are denoted as the error matrix $X_{i,j}$ and covariance matrix $P_{i,j}$ of the sub-filter $Sf_{i,j}$, respectively.

Sub-filters composed of the same INS form a filter database together, then a total of n sub-filter databases are formed. Where, the $No.i$ sub-filter database is denoted as follows:

$$Db_{sf,i} = \left\{Sf_{i,1} \quad \cdots \quad Sf_{i,k} \quad \cdots\right\}, k = 1,\cdots,m \tag{48}$$

Then a combined navigation scheme database centered on the i $No.i$ INS is established with the sub-filters in database $Db_{sf,i}$, denoted as $Db_{IN,i}$.

$$Db_{IN,i} = \left\{IN_{i,1} \quad \cdots \quad IN_{i,l} \quad \cdots\right\}, l = 1,\cdots,2^m - 1 \tag{49}$$

The error matrix $X_{i,j}$ and covariance matrix $P_{i,j}$ of each combination mode in the database are extracted, and the dynamic performance evaluation indexes of its position, speed and attitude are calculated by using the algorithm in Section 3.2 above. As shown in Figure 3, before modifying INS_i, the required performance evaluation indicators are selected for calculation according to the current task requirements, and the integrated navigation scheme with the smallest ANP value is selected for modifying INS_i. Before the output of the adaptive navigation system, INS_i with the smallest current ANP value is selected as the optimal output of the adaptive navigation system by comparing the dynamic performance index of INS_i with redundant configuration.

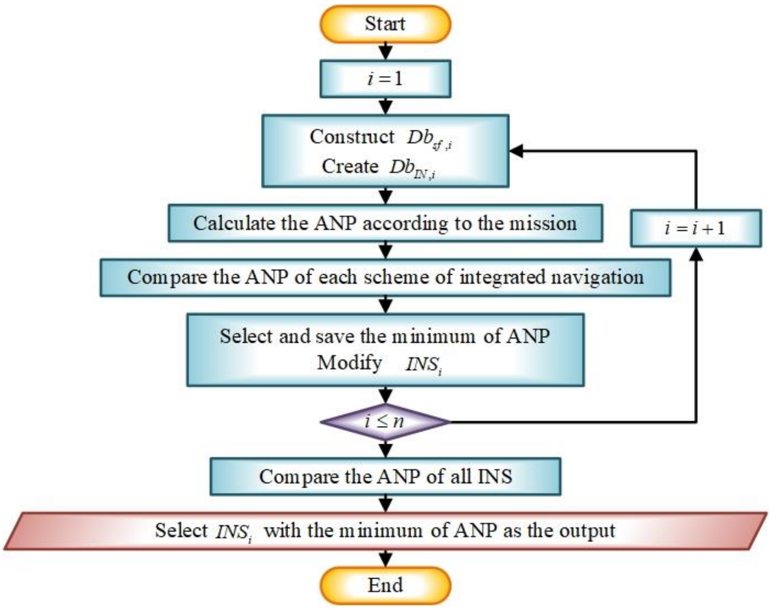


Figure 3 - Flow chart of adaptive navigation system

4. Simulation and Analysis

To test the dynamic performance evaluation indicators in the practical application of the navigation task, this section will combine space flight path, according to this paper, section 2, the adaptive navigation system, navigation system of inertial navigation redundancy configuration simulation, validation navigation method in this paper is compared with traditional method, the extraction of the optimal output performance advantages.

4.1 Simulation Conditions

According to the flight mission of aerospace vehicle, its flight process can be divided into ascent stage, in-orbit stage, re-entry stage and landing stage. Combined with the flight environment of each flight stage, the flight path of the aerospace vehicle was simulated, and the simulation time was 4500s.The three-dimensional track is shown in Figure 4.

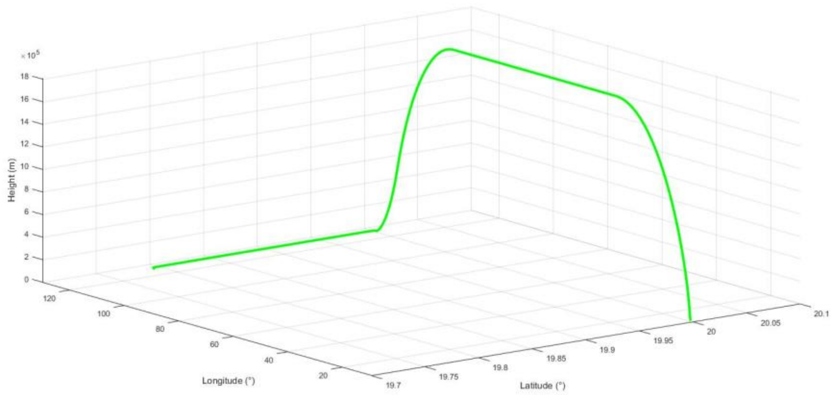


Figure 4 - 3D schematic diagram of flight path of aerospace vehicle

This simulation takes the inertial navigation system as the core component and the other navigation systems as the auxiliary navigation system to form a variety of integrated navigation modes and establish the integrated navigation scheme database.

The adaptive navigation system is equipped with two sets of inertial navigation systems, whose parameters are shown in Table 1 below.

Table 1 - INS parameters

Attribute	**Value**
Gyro drift error rate	0.1 °/hr
First order Markov correlation time of gyro drift error	3600s
Accelerator bias error	0.0001 ×g
First order Markov correlation time of accelerator bias error	1800s
Output cycle time	0.02s

The adaptive navigation system is additionally equipped with GNSS, SAR, ADS, TACAN and MLS. The parameters of the navigation subsystem are shown in Table 2 below.

Table 2 - Subsystem parameters of adaptive navigation system

Subsystem Type	**Output Information Type**	**Precision Value**	**Measuring Unit**	**Services Time(s)**
GNSS	Position	100	m	0-4500
	Velocity	0.4	m/s	
	Attitude	0.02	°	
SAR	Position	50	m	1200-2800
	Attitude	0.01	°	
ADS	Height	50	m	0-700
	Velocity	0.2	m/s	3300-4500
TACAN	Position	20	m	3500-4500
MLS	Position	10	m	4000-4500
	Attitude	0.01	°	

4.2 Analysis of Simulation Results

The adaptive navigation system based on dynamic performance evaluation method is simulated according to the above modeling of the flight path and navigation system of the aerospace vehicle. Figure 5 below shows the service time of each subsystem at each stage during the flight of the space vehicle.

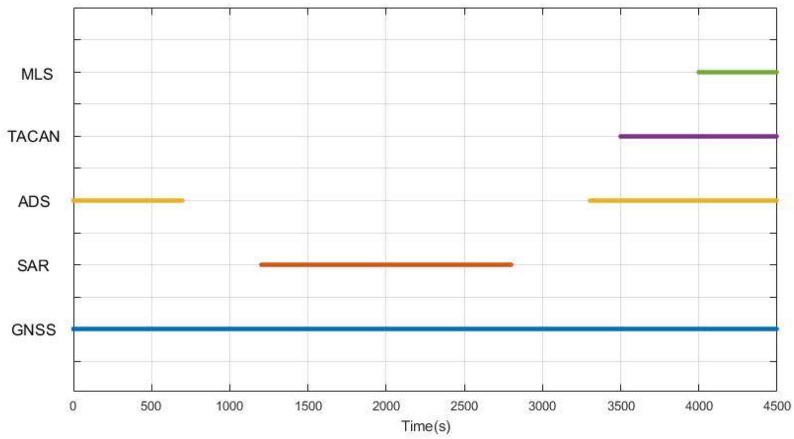
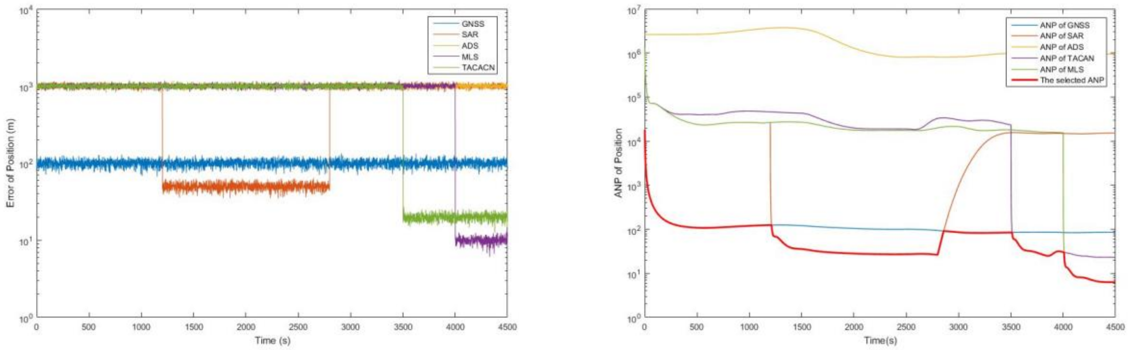


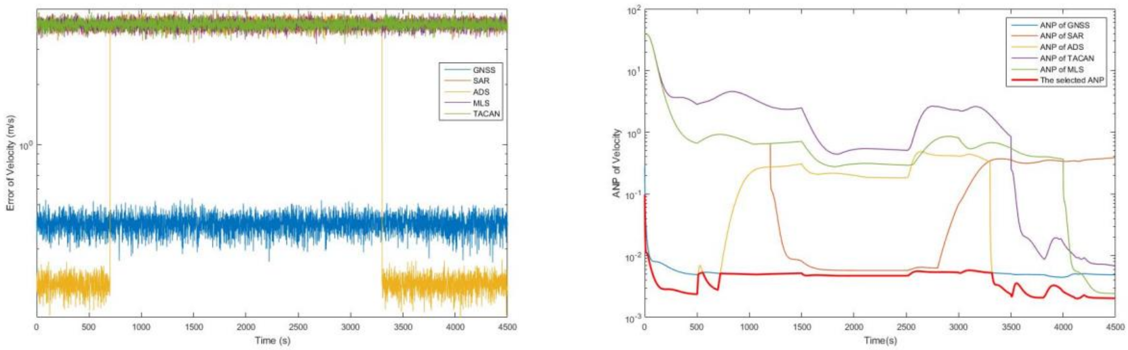
Figure 5 – Service time of the subsystems

Subgraph (a) of Figure 6, Figure 7 and Figure 8 respectively show the position, velocity and attitude error curves of each subsystem. Subgraph (b) shows the ANP of position, velocity, and attitude of each subsystem.



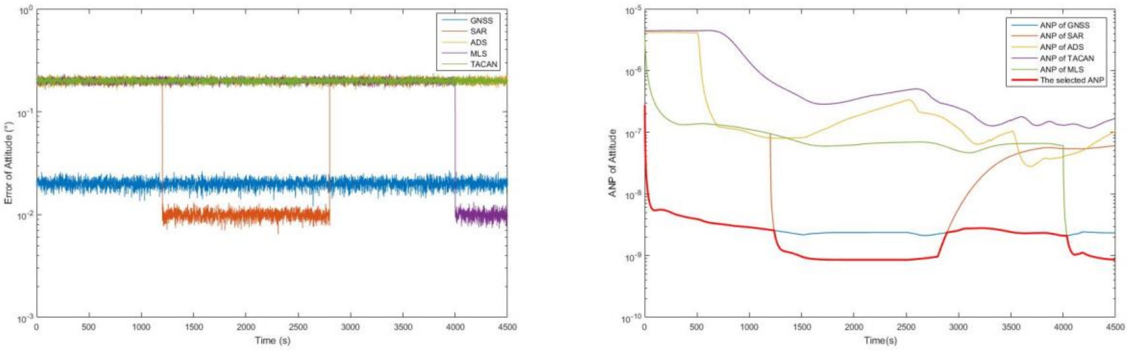
(a) (b)

Figure 6 - Error (a) and ANP (b) of the subsystems(Position)



(a) (b)

Figure 7 - Error (a) and ANP (b) of the subsystems(Velocity)



(a) (b)

Figure 8 - Error (a) and ANP (b) of the subsystems(Attitude)

According to the above curves, it can be seen that the dynamic performance evaluation index proposed in this paper can track the errors of integrated navigation well. Through comparison and selection in advance, a suitable integrated navigation scheme can be provided to modify the inertial navigation.

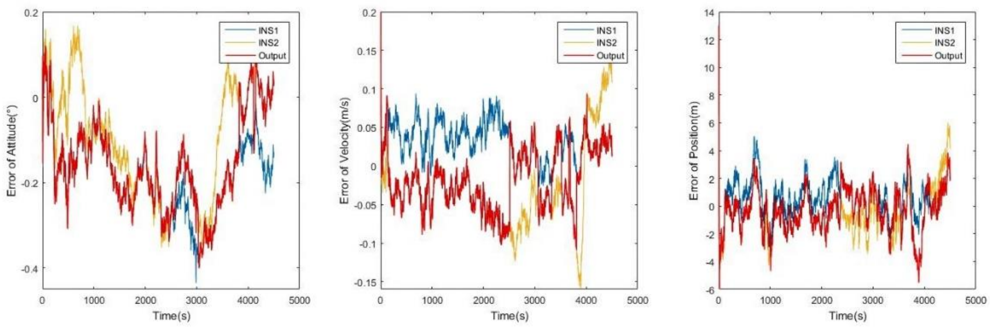


Figure 9 - Error of adaptive navigation system

Figure 9 is the error curve after selecting the optimal navigation output from the output of two sets of INS through dynamic performance evaluation. As can be seen from the above figure, through dynamic performance evaluation, the adaptive navigation system proposed in this paper can select the optimal output from the inertial navigation system with redundant configuration, effectively improving the overall navigation accuracy.

It can be seen from the simulation results in this section that the adaptive navigation method proposed in this paper can provide high-precision navigation information in the whole flight mission of aerospace vehicle.

5. Conclusions

To sum up, this paper studies the airborne redundant adaptive navigation method based on dynamic performance evaluation for aerospace vehicle. Based on the traditional two-level parallel decentralized filtering structure, the integrated navigation scheme database is formed to make the multi-information integrated navigation scheme more flexible. The optimal navigation scheme can also be selected in the navigation system with redundant navigation sensors. At the same time, aiming at the multi-information integrated navigation filtering algorithm, the performance calculation and prediction module are added to make the prediction of navigation scheme accuracy possible. By adding the precision contrast and selection module, the navigation scheme with higher navigation precision is selected from the multi-source information navigation scheme database, and the overall accuracy of the multi-information fusion integrated navigation system is improved.

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