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PRECISION ANALYSIS AND INDEX DISTRIBUTION SYSTEM DESIGN OF AVIONICS SYSTEM BASED ON BP NEURAL NETWORK

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Abstract

For the urgent need of quantitative analysis and evaluation of avionics system performance indexes in the multi-platform cooperative engagement environment, this paper presents the precision analysis and index optimization distribution algorithm of avionics system based on BP neural network, and verifies its scientific nature and effectiveness by a case. The scheme of this paper can provide reference and basis for avionics system indexes design, and play a significant role in aircraft finalizing and practical application.

Keywords: Avionics System, BP Neural Network, Precision Analysis, Index Distribution

1. Introduction

It is an important link of the general project approachment of weapon and equipment to carry out quantitative analysis and calculation of the tactical and technical indexes of the weapons and equipment, as well as accurately assessing equipment capability requirements. Traditionally, the tactical and technical indexes can be easily captured through the analogy of equipment. However, with the development of systematic operations, the aviation weapon and equipment platform often cooperates with multiple platforms to perform combat missions. The variety of battlefield environment, the diversity of mission organization, and the diversity of available resources all determine the increasing difficulty of requirements demonstration of the aviation weapon and equipment. As a result, the analysis of the tactical and technical indexes is becoming more important.

In the actual operational use of aircraft, due to the complexity of the battlefield environment, attack conditions and target movement, the avionics system performance is affected by many factors. Therefore, it has a great impact on the weapon hit precision. Analysis of the effect and influence degree of these factors on the avionics system is important to improve the avionics system performance. When the avionics system is operating normally, various error sources do not act on the avionics system alone. Multiple error sources often exist simultaneously and there is a strong interaction coupling effect when it occurs. Therefore, when multiple error sources are simultaneously applied to the system, the impact on the system overall precision will be different from the impact when each error source apply alone. And this difference will be more significant when the system is more complex and there are more error sources [1]. Therefore, this paper achieves the optimal distribution of the avionics system precision, based on the cognition of the system precision to the sensitivity of each error source, through analyzing the influence of the main error source and the interaction between error sources on the avionics system precision.

2. Precision Sensitivity Analysis of Avionics System

2.1 Problem Description and Definition of Precision Sensitivity of Avionics System

The sensitivity of avionics system precision is defined as the influence degree on the avionics system precision of each error source when it varies within the range of possible values. The magnitude of the influence degree is called the sensitivity coefficient of each error source. The larger the sensitivity coefficient is, the greater the influence of the different error source value on the system precision will be [2,3]. According to the influence methods of the input index on the output, the sensitivity coefficient can be divided into main effect, full effect, second-order interaction effect and higher-order interaction effect. This paper mainly studies the main effect of each error source on system precision. The core purpose of the precision analysis of avionics system is to obtain the sensitivity coefficient of each error source by analyzing them. In practice, through mainly considering the property with a large sensitivity coefficient and removing the error source with small sensitivity coefficient according to experience, the complexity of the system and the workload of data analysis and processing can be greatly reduced, and the precision of the system can be greatly improved. At the same time, the sensitivity coefficient of each error source can be used to solve the corresponding problem.

2.2 Headers and Footers Main Error Source and Precision Evaluation Index of Avionics System

The precision index of avionics system in this paper mainly refers to the hit probability and the killing probability, and the main factors affecting the killing probability of the avionics system weapons are the errors caused by various detections or measurements of airborne sensors [4]. Therefore, the error sources studied in this paper mainly include: sensors (radar, infrared, laser detection error), inertial navigation (measurement error), atmospheric (measurement error), and environmental error (weather conditions). Environmental errors cannot be artificially controlled, so they are taken as fixed values, and other errors are all superimposed on the standard value as white noise.

3. Back-propagation Neural Network

3.1 Basic Concepts

The Artificial Neural Networks (ANN) system emerged after the 1940s. It is made up of many neurons with adjustable connection weights, having the features of massive parallel processing, distributed information storage, and good self-organizing and self-learning capabilities [5].

BP (Back Propagation) neural network is a concept proposed by scientists led by Rumelhart and McClelland in 1986. As a multilayer feedforward neural network trained according to the error back propagation algorithm, it is the most widely used neural network which is also called error back propagation algorithm. The BP neural network algorithm can theoretically approximate an arbitrary function. It has strong nonlinear mapping ability with its basic structure consisting of nonlinear changing units. Moreover, the number of middle layers of the network, the number of processing units of each layer, and the learning coefficient of the network can be changed according to specific conditions, making the BP neural network great flexibility. Therefore, it has wide application prospects in many fields such as optimization, signal processing and pattern recognition, intelligent control, fault diagnosis and so on.

3.2 Fundamental Principles

A typical BP neural network consists of three layers, that is, the input layer, the hidden layer, and the output layer [6]. Its topology is shown in Figure 1. The learning process of BP neural network consists of two parts, namely the information forward propagation process and the error back propagation. When the information is forward propagating, the input samples are passed in from the input layer, processed by the hidden layer, and passed to the output layer. If the actual output of the output layer is in error with the expected output, and the error is greater than the target error, the network enters the error back propagation phase. At this stage, the main operation is to correct the weight of each neuron. The two processes of the information forward propagation and the error back propagation are repeated all the time until the end of the network training. Then the error between the actual and the expected output will be less than the target error [7,8].

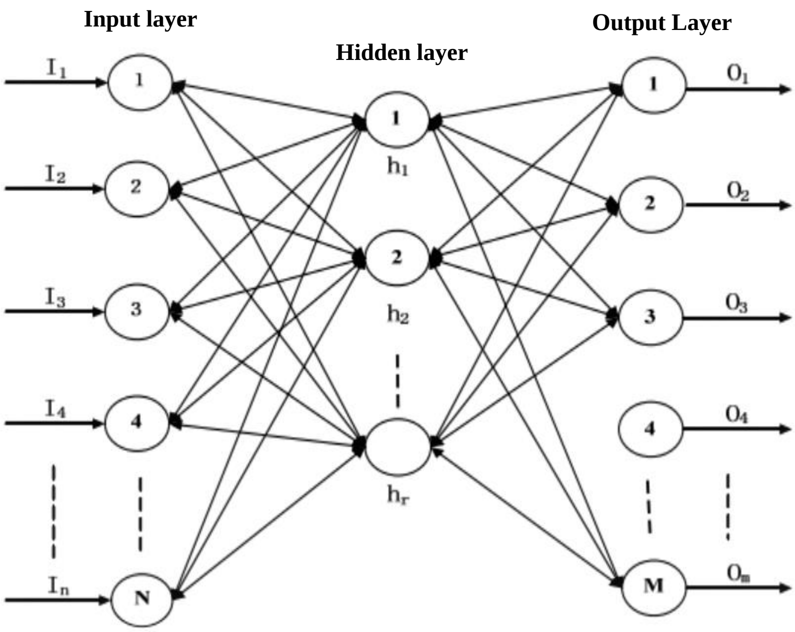


Figure 1 – Three-layer BP neural network topology

The learning rate of the neural network has a great influence on the convergence speed, which directly affects the time and precision of the training. With large learning rate, the iterative process will oscillate and diverge, which may make the system unstable. The smaller learning rate will make the training time longer and the convergence speed slower. However, the error of the network can be guaranteed by small learning rate to slip to the minimum error value without jumping out of the valley of the error surface. Therefore, the choice of learning rate is also crucial.

4. Design of Precision Analysis and Index System for Avionics System Based on BP Neural Network

4.1 Overall Design

The overall scheme of the aircraft avionics system precision analysis and index distribution system is shown in Figure 2. It mainly includes operational simulation, precision analysis, sensitivity analysis and index optimal distribution. The system performs operational simulation according to the loaded task scenario, and orderly performs avionics system precision analysis, local sensitivity analysis, global sensitivity analysis and precision optimal distribution according to the simulation results. The system error distribution scheme is verified through simulation to check whether the distribution result satisfies the system precision requirements. Final scheme meeting the demand is the required design scheme with the index optimization of avionics system.

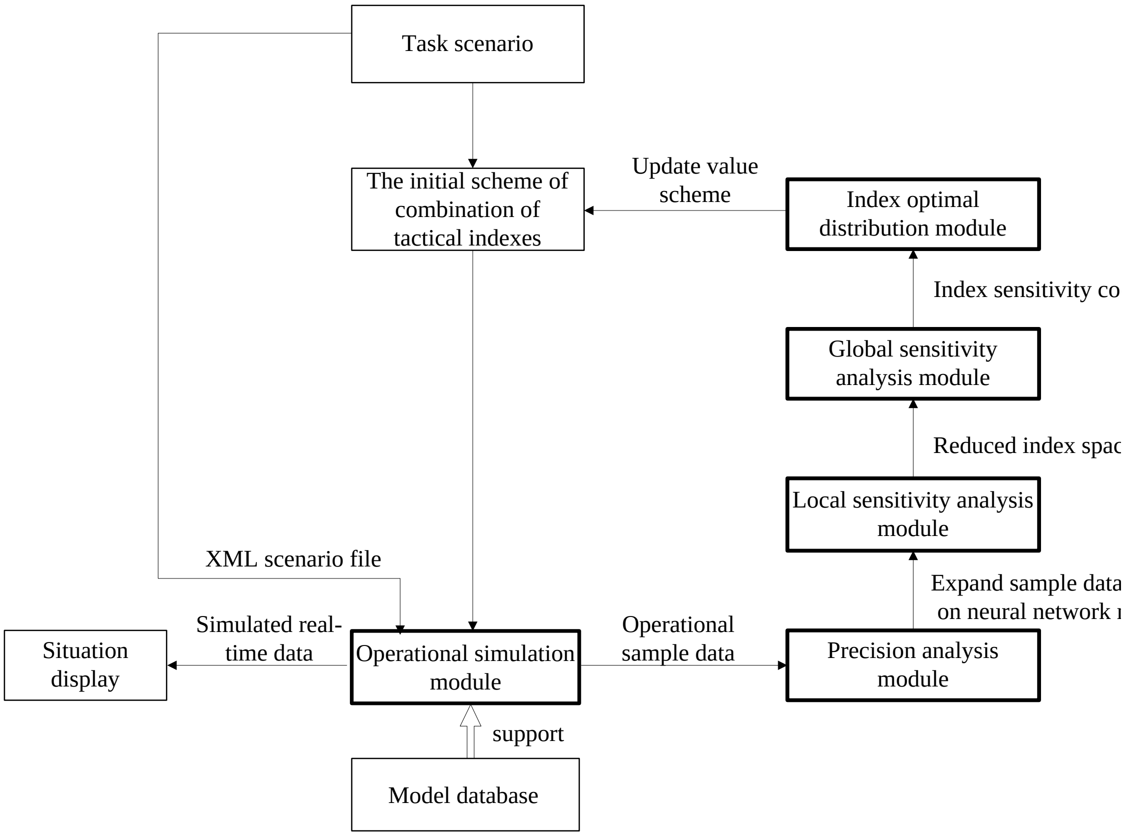


Figure 2 –System overall design

4.2 Design of Key Modules

4.2.1 Precision analysis of avionics system based on BP network

The avionics system precision analysis module takes the index value of each error source as the input, and obtains the sample precision value (Missile miss distance De /Kill probability P_{kill} /Circular probability error CEP) through simulation calculation. In theory, the Monte Carlo method can be used to obtain the precision value corresponding to any input combination, thus providing sufficient sample data for sensitivity analysis. However, since the combat simulation process is time-consuming, the time cost of the Monte Carlo method is unacceptable with the increasing simulation number of times. Based on the above reasons, this paper uses BP neural network to fit the precision analysis agent model, and then carries out the precision evaluation based on the agent model. The precision analysis model of the avionics system using a single hidden layer BP network is shown in Figure 3.

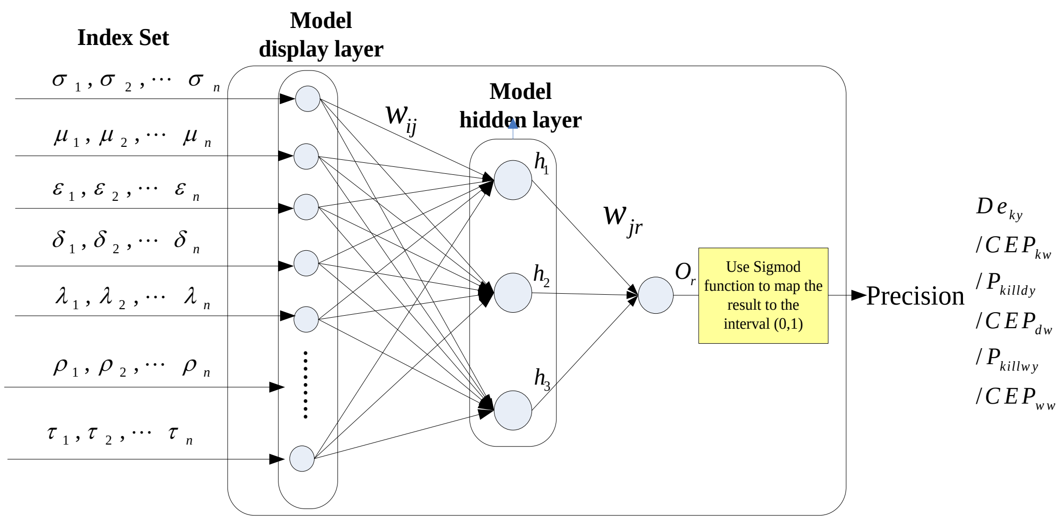


Figure 3 –Avionics system precision analysis model

Using the basic idea of the BP neural network model, each error source index is used as the input layer. Let *M* represent the number of input layer nodes; *Q* represents the number of hidden layer nodes, *L* represents the number of output layer nodes; b_j represents the value of the j-th neuron in the hidden layer; w_{ij} represents the connection weight between the nodes in the input layer and the hidden layer; w_{jr} represents the connection weight between the nodes in the hidden layer and the output layer; Assume that the input of the nodes in the hidden layer or the output layer is the weighted sum of the output of the previous layer nodes. It is important to determine the value of *M*, *Q*, and *L* in this model. The analysis process is as follows:

- Determine the number *M* of input neurons. According to the task scenario, the number of major error sources that have a significant impact on the avionics system is selected as the number of input neurons;
- Determine the number *L* of output neurons. The precision analysis model is essentially a function learning network. The output is a comprehensive index of system precision. The output has only one measure value in the interval (0, 1), which is one-dimensional, so the number of output neurons is one;
- Determine the number *Q* of hidden layer neurons. The selection of the number of hidden layer nodes is very complicated. If the number of nodes is too small, the fault tolerance is poor, and the ability to identify untrained samples is low; Too many nodes will increase the convergence time and reduce the generalization ability. At present, the more common method is trial and error by test, that is, training the network with different hidden nodes by using the same sample set until the weight value no longer changes the stable position, and then, according to the minimum test error, determining the number of neurons in the hidden layer of the network. M represents the number of input layer nodes, L represents the number of output layer nodes, and a is a constant in the interval of (0, 10). Since the hidden layer has three nodes that already satisfy the function structure, a is taken as 0, so the number of hidden layers is 3.

The BP neural network calculation can be used to obtain the functional relationship between the system precision （De_{ky}/CEP_{kw}/$P_{kill\,dy}$/CEP_{dw}/$P_{kill\,wy}$/CEP_{ww}） and the various input indexes （$(\sigma_1, \sigma_2, \cdots, \cdots)$/$(\mu_1, \mu_2, \cdots, \cdots)$/$(\varepsilon_1, \varepsilon_2, \cdots, \cdots)$/$(\delta_1, \delta_2, \cdots, \cdots)$/$(\lambda_1, \lambda_2, \cdots, \cdots)$/$(\rho_1, \rho_2, \cdots, \cdots)$/$(\tau_1, \tau_2, \cdots, \cdots)$）. For example, the relationship between the aircraft air-to-air combat mission (controlled weapons) precision index and the tactical index:

$$
\begin{aligned}
De_{ky} &= f_{ky}(\sigma_1, \sigma_2, \cdots, \cdots) \\
&= f(x_1, x_2, x_3, x_4, x_5, \cdots) \\
&= \left(1 + \exp\left(-\left(\sum_{j=1}^{3} w_{jr} \times \frac{1}{1 + \exp\left(-(\sum_{i=1}^{37} w_{ij} x_i + b_j)\right)} + b_r\right)\right)\right)^{-1}
\end{aligned}
\tag{1}
$$

In the above formula, the parameters w_{ij}, w_{jr} can be estimated by batch gradient descent and backpropagation algorithm.

4.2.2 Sensitivity analysis

The sensitivity analysis of the error source index aims at obtaining the qualitative and quantitative results of the influence degree of each error source index on the avionics system precision, through calculating by the sensitivity analysis algorithm based on the sample data. It provides basis for the precision optimal distribution. The error source sensitivity analysis algorithm mainly includes local sensitivity analysis algorithm and global sensitivity analysis algorithm.

(1) Local sensitivity analysis

The local sensitivity analysis module mainly analyzes the influence degree and range of the variation of the single error source index on the avionics system precision. Then it further selects the sensitivity index from many error source indexes and determines its sensitive interval, in order to reduce the sample space for carrying out the global sensitivity in the next step. The avionics system precision analysis model designed in this paper is a complex nonlinear system. Therefore, the entropy method is used to analyze the local sensitivity of the error source index of the avionics system precision. The main process of local sensitivity analysis is:

- Select the main error source alternative set of the avionics system. Select and discretize a certain index within a certain interval to make the sample set of the index, with fixing the value of other error source index;
- Select one sample point one by one, input it to the “system precision analysis model”, perform “system precision calculation”, and record the precision data. Perform precision calculation for all the indexes in the alternative set in order; Get the precision value x_{ij} corresponding to the n alternative error source index of all the m sample points;
- Perform the entropy method calculation, for example, calculate the entropy of the j-th error source evaluation index:

$$e_j = \frac{-1}{\ln n} \sum_{i=1}^{m} p_{ij} \ln p_{ij} \tag{2}$$

$p_{ij} = x'_{ij} / \sum_{i=1}^{m} x'_{ij}$ represents the weight of the i-th sample point under the j-th error source index. Calculate the sensitivity of the j-th error source index:

$$S_j = (1 - e_j) / \sum_{j=1}^{n} (1 - e_j) \tag{3}$$

The sensitivity ranking of each error source index is obtained, then select and obtain the sensitivity index and its sensitive interval, in order to reduce sample space for the global sensitivity analysis in the next step.

(2) Global sensitivity analysis

According to the nonlinear feature of the precision analysis model of the avionics system, this paper uses the Sobol analysis method to complete the global sensitivity analysis of the error source index. The global sensitivity analysis is based on the local sensitivity analysis of the error source index, which is mainly to combine the multi-dimensional analysis of the sensitivity index and to explore the influence degree of multiple indexes on the system precision.

The Sobol sensitivity analysis method is a Monte Carlo method based on variance. The basic idea is to analyze the influence of input on the output variance and evaluate the sensitivity of the single or multiple inputs interaction, by calculating the contribution of the single or multiple inputs to the output variance. Sensitivity index of the Sobol index method include the main effect index, the full effect index, and the interaction effect index. This paper focuses on the main effect index.

Set the system precision model to

$$Y = F(X_1, X_2, \cdots, X_k) \tag{4}$$

In the formula, as the input, *Y* is the system precision, $X_1, X_2, \cdots, X_k$ is the main factor affecting the avionics system precision. The main effect index of X_i is defined as:

$$S_{X_i} = \frac{V_{x_i}(\mathrm{E}_{x_{\sim i}}(\mathrm{Y} \mid \mathrm{x}_i))}{V(Y)} \tag{5}$$

Among them, $V(Y) = E_{x_i}(V_{x_{-i}}(Y \mid \mathrm{x}_i)) + V_{x_i}(\mathrm{E}_{x_{-i}}(Y \mid \mathrm{x}_i))$, the main effect index reflects the contribution of the i-th factor X_i alone to the variance of the system precision *Y*. Its value is between 0 and 1. The sensitivity of each variable can be ranked according to the value size of the main effect index. The larger the main effect index is, the greater the influence of the variable change on the output will be.

4.2.3 Precision optimal distribution

Precision optimal distribution realizes the optimal distribution from the precision index to the error source index, based on the sensitivity analysis of the error source. Firstly, according to the results of the sensitivity analysis of the error source, each error source index is initially distributed within the boundary constraint conditions. And the satisfaction degree of the distribution scheme to the system precision requirements under the equipment applications of the combat scenario is verified. If the precision requirements are satisfied, then output the error distribution scheme; if not, the distribution scheme is appropriately adjusted and verified again until the precision requirements are met.

In the initial value distribution of each error source index, the following principles are applied:

The main effect values of each error source obtained by the global sensitivity analysis are: $S_{x_1} \cdots S_{x_n}$. First, the main effect values are normalized, that is, $\sigma_{x_i} = \frac{S_{x_i}}{\sum_{i=1}^{n} S_{x_i}}$. Assuming that the value intervals of each error source are $[\mathrm{a}_1, \mathrm{b}_1], \cdots [\mathrm{a}_n, \mathrm{b}_n]$, according to the value σ_x of the error source, the corresponding value can be : $\delta_{x_i} = a_i + (1 - \sigma_{x_i}) \times b_i$. Verify the satisfaction degree of the preliminary scheme to the system precision requirements. If the precision requirements are not met, the distribution scheme is repeatedly adjusted based on the previous one.

4.3 Simulation Case

This paper takes the air combat task of the single aircraft as an example, changes the aircraft detection mode, and uses the three different sensors, namely radar, infrared, and laser, for target detection, tracking, strike and evaluation. Different errors of the system were selected as the twelve error source indexes, and the hit probability was calculated by 300 times simulation, and the result was used as the sample data of the precision analysis. Then conduct the BP neural network for sensitivity analysis, carry out the sensitivity analysis of the error source, and use the precision allocation optimization algorithm to obtain the index distribution scheme. The sensor performance parameters and error source index allocation scheme are shown in table 1 and table 2,3,4. According to the error distribution scheme, the hit probability calculated after 10 simulations is respectively 77.24% (radar), 88.63% (infrared) and 81.90% (laser), all exceeding the set 75% hit probability. The comparison of the error source sensitivity of the three different detection methods using radar, infrared and laser are as shown in Table 5. It can be seen that the sensitivity intervals of different parameters are different, and the sensitivity intervals of different sensors are not the same either. Through sensitivity analysis, the error source which has a larger impact on the simulation can be observed, and in the practice this effect should be removed as much as possible.

Table 1 – Performance comparison of three different sensors

Parameters / Sensors	Maximum detection distance (km)	Clockwise/ Anticlockwise Horizontal search angle (°)	Upper sight/ Lower sight search angle (°)	Maximum track distance (km)	Upper sight/ Lower sight track angle (°)	Maximum angular velocity of search and track target (rad/s)	Time from search to track (s)
Radar	30	-135/135	-45/45	20	30/-30	36	2
Infrared	13	-50/50	-45/45	13	30/-30	36	2
Laser	15	-180/180	-45/45	15	30/-30	36	2

Table 2 – Final assignment scheme of radar error sources index

Inertial navigation system				Air data system				Radar			
Position measuring error (X azimuth)	Position measuring error (Y azimuth)	Position measuring error (Z azimuth)	Speed measuring error (X azimuth)	Speed measuring error (Y azimuth)	Speed measuring error (Z azimuth)	Attitude error (Y)	Pitch error (P)	Altitude measuring error (H)	Detection distance error (D)	Detection azimuth error (Y)	Detection pitch error (P)
1.241	2.585	2.431	0.668	2.152	0.386	0.003	0.003	13.578	2.539	0.003	0.003

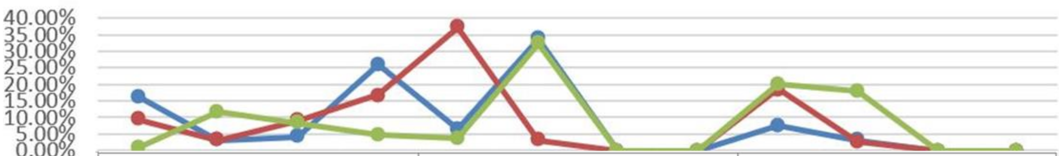
Table 3 – Final assignment scheme of infrared error sources index

Inertial navigation system				Air data system				Infrared			
Position measuring error (X azimuth)	Position measuring error (Y azimuth)	Position measuring error (Z azimuth)	Speed measuring error (X azimuth)	Speed measuring error (Y azimuth)	Speed measuring error (Z azimuth)	Attitude error (Y)	Pitch error (P)	Altitude measuring error (H)	Detection distance error (D)	Detection azimuth error (Y)	Detection pitch error (P)
1.106	2.189	1.146	0.474	0.03	2.149	0.003	0.003	2.607	2.27	0.003	0.003

Table 4 – Final assignment scheme of laser error sources index

Inertial navigation system				Air data system				Laser			
Position measuring error (X azimuth)	Position measuring error (Y azimuth)	Position measuring error (Z azimuth)	Speed measuring error (X azimuth)	Speed measuring error (Y azimuth)	Speed measuring error (Z azimuth)	Attitude error (Y)	Pitch error (P)	Altitude measuring error (H)	Detection distance error (D)	Detection azimuth error (Y)	Detection pitch error (P)
2.647	0.461	0.818	1.434	1.647	0.008	0.003	0.003	0.701	0.153	0.003	0.003

Table 5 – Sensivity comparison of the three detection methods



	Inertial navigation system				Air data system				Laser/Infrared/Laser			
	Position measuring error (X azimuth)	Position measuring error (Y azimuth)	Position measuring error (Z azimuth)	Speed measuring error (X azimuth)	Speed measuring error (Y azimuth)	Speed measuring error (Z azimuth)	Attitude error (Y)	Pitch error (P)	Altitude measuring error (H)	Detection distance error (D)	Detection azimuth error (Y)	Detection pitch error (P)
Series1	16.20%	2.90%	4.10%	26%	6%	33.70%	0.00%	0.00%	7.40%	3.20%	0.00%	0.00%
Series2	9.40%	3.10%	9.10%	16.90%	37.00%	3.20%	0.00%	0.00%	18.50%	2.70%	0.00%	0.00%
Series3	0.80%	11.70%	8.30%	4.80%	3.90%	32.40%	0.00%	0.00%	20.00%	18.00%	0.00%	0.00%

Series1 Series2 Series3

5. Brief Summary

Aiming at the problem of quantitative analysis and evaluation of avionics system performance index, this paper proposes a design scheme based on BP neural network of the precision analysis and index distribution system of the avionics system, and verifies the scientificity and availability of the method through simulation. The system designed by this paper can provide reference and basis for the index design of the avionics system, which is of great significance for aircraft finalizing and practical application.

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