Evaluating LIMU System Quality with Interval Evidence and Input Uncertainty

Xiangyi Zhou[1], Zhijie Zhou[1*], Xiaoxia Han[1], Zhichao Ming[1] and Yanshan Bian[2]
[1] High-Tech Institute of Xi'an
Xi'an, 710025, China
[e-mail: zhouzj04@tsinghua.org.cn]
[2] Key Laboratory for Fault Diagnosis and Maintenance of Spacecraft in Orbit
Xi'an 710043, China
[e-mail: bys02201@163.com]
[*]Corresponding author: Zhijie Zhou

Received July 31, 2023; revised September 14, 2023; accepted October 19, 2023; published November 30, 2023

Abstract

The laser inertial measurement unit is a precision device widely used in rocket navigation system and other equipment, and its quality is directly related to navigation accuracy. In the quality evaluation of laser inertial measurement unit, there is inevitably uncertainty in the index input information. First, the input numerical information is in interval form. Second, the index input grade and the quality evaluation result grade are given according to different national standards. So, it is a key step to transform the interval information input by the index into the data form consistent with the evaluation result grade. In the case of uncertain input, this paper puts forward a method based on probability distribution to solve the problem of asymmetry between the reference grade given by the index and the evaluation result grade when evaluating the quality of laser inertial measurement unit. By mapping the numerical relationship between the designated reference level and the evaluation reference level of the index information under different distributions, the index evidence symmetrical with the evaluation reference level is given. After the uncertain input information is transformed into evidence of interval degree distribution by this method, the information fusion of interval degree distribution evidence is carried out by interval evidential reasoning algorithm, and the evaluation result is obtained by projection covariance matrix adaptive evolution strategy optimization. Taking a five-meter redundant laser inertial measurement unit as an example, the applicability and effectiveness of this method are verified.

Keywords: Interval evidential reasoning, laser inertial measurement unit, probability distribution, uncertain input.

http://doi.org/10.3837/tiis.2023.11.003 **ISSN : 1976-7277**

1. Introduction

At present, the development of inertial technology is becoming more and more mature, and it is applied to many industries, such as oil drilling, oil exploration, geodesy, large passenger aircraft, marine survey, geophysical survey and meteorological detection [1]. Inertia technology originated from classical theory, and after continuous development, it integrates the most advanced achievements of modern science and technology, including automatic control, precision measurement, modern physics, precision technology, electronic technology, microelectronics, computer and so on. Nowadays, the level of inertial technology has become one of the important symbols to measure the military strength and scientific and technological level of a country [2].

Inertial navigation is a precise navigation technology with high precision, strong autonomy, safety and reliability, which is not affected by external interference. Through real-time navigation calculation, it outputs navigation information such as attitude angle, speed and position, and provides precise control attitude reference for the carrier. It is widely used in navigation, aviation and aerospace technology [3]. Inertial group is the core component of navigation system, and its accuracy, stability and reliability are directly related to the strike accuracy of weapon system [4]. Among many inertial navigation systems, the strapdown inertial navigation system composed of laser gyro and quartz flexible accelerometer has attracted much attention because of its high precision, good reliability, fast response, small size and light weight [5]. The research on the quality evaluation of laser inertial measurement unit (LIMU) has become an important link in the use of LIMU.

Generally, the inertial instrument of the LIMU consists of three laser gyroscopes and three quartz flexible accelerometers, while the multi-meter redundant LIMU consists of multiple laser gyroscopes and accelerometers. Laser gyro is an optical gyro, which is based on Sagnac effect principle and is a device for measuring angular velocity by laser technology [6]. The cavity of laser gyro is made of highly stable materials, which ensures the high stability of gyro scale factor. The internal circuit of quartz flexible pendulum accelerometer is designed with a force feedback loop. When the flexible pendulum is sensitive to the acceleration deviation, it quickly balances due to the feedback force, thus obtaining the apparent acceleration information. As the temperature variation coefficient of quartz material constituting the pendulum assembly is small, the output of accelerometer is less affected by temperature, and the scale factor error level can be greatly reduced [7]. According to Newton's mechanics theory, when the acceleration of the carrier is known, the velocity and position information can be obtained by solving the physical motion equation [8]. The attitude information is determined by the angular velocity information, and the precise positioning of the carrier is completed together. Therefore, the performance of gyroscope and accelerometer directly affects the navigation accuracy of strapdown inertial navigation system. Considering that the secondary installation error caused by disassembly test will reduce the use accuracy, Wang Kun et al. calibrated the main error coefficient which has a great influence on the missile firing accuracy and is not stable, and the other stable error coefficients were determined by previous test data, thus evaluating the performance of the LIMU [9]. Chen et al. put forward to establish a comprehensive evaluation model by using time series principal component analysis, and evaluate the stability of the inertial measurement unit by combining the historical information and previous test data of inertial measurement unit [10].

Generally speaking, the quality evaluation of LIMU includes two aspects, one is the test calibration error, and the other is the management of resume information. Test calibration error is accomplished by test equipment, test method (calibration method) and software realization

[11]. Resume information management gives a performance evaluation grade by comparing the management requirements of national military standards. Both are indispensable and complement each other. The former is quantitative information, which directly reflects the performance of the LIMU, but there are some invisible features that cannot be characterized [12]. The latter is qualitative information with clear physical meaning, which can reflect the invisible characteristics that cannot be characterized by the LIMU test information, but there are certain uncertainties at the same time [13]. For example, appearance is one of equipment quality inspection. Because there is no actual test data, the evaluation of appearance is mainly based on the judgment of professional operation trumpeters and management personnel when carrying out maintenance tests, and the criteria are excellent (90-100), good (75-89), fair (65-75), qualified (65-60) and poor (< 60). The uncertainty of this index is that the numerical value represented by the index grade is in the form of interval, and the uncertainty brought by interval is obviously higher than the uncertainty of numerical value in information fusion. And the given grade of the national military standard is inconsistent with the quality evaluation grade, in GBJ 4312, the quality grade of weapons and equipment is divided into four grades: "New, Available, Degraded and Scrapped" [14, 15]. There is obviously an asymmetric hierarchical relationship between them, so it is impossible to directly fuse the information of indicators. It is necessary to establish the relationship between them to transform and fuse the information and get the evaluation results.

Interval evidential reasoning (IER) is an information fusion method, which has great advantages in dealing with uncertain information [16]. On the basis of evidence reasoning, IER considers the necessity of evidence non-standardization in the reasoning process, and expresses the evaluation trust of each evaluation index at different evaluation levels with interval belief, which has stronger ability to deal with uncertain information [17]. This method mainly unifies the trust identification framework of qualitative and quantitative attribute evaluation information in interval form, integrates interval uncertain evaluation information step by step, solves the fusion problem of interval uncertain evaluation information, obtains the trust degree of each scheme at each evaluation level, and uses utility theory to calculate the maximum, minimum and average utility values of each scheme to complete the ranking of the schemes [18]. Liu et al. used IER to update the threshold of data crossing evaluation level [19]. Aiming at the interval assignment problem, the interval efficiency matrix is set to calculate the best matching scheme between ships and routes, Xu et al. adopts the analytical algorithm of route allocation based on IER, which makes up for the deficiency of the simulation algorithm of uncertain route allocation [20]. Chen et al. obtained the performance evaluation results by distinguishing the interference of single evidence and two evidences, and proposed a robustness measure based on interval similarity, and optimized the reference value in the IER evaluation model. The proposed method was applied to a certain electric servo mechanism for performance evaluation and verification [21].

In order to solve the problem of asymmetry between the reference level given by the index and the evaluation result level in LIMU evaluation, this paper proposes a conversion method based on probability distribution to solve the asymmetry relationship [22]. Firstly, according to the index characteristics and factory information, the given index information is degraded to the original probability distribution, and the uncertain input information is converted into the form of interval evidence distribution. Then, the IER algorithm is used to fuse the input information, so as to get the evaluation results [23]. The main innovations are as follows: (1) When constructing the equipment performance evaluation index system, various kinds of information are fully considered, and the resume information is innovatively added to the index system, and the current national and industry standards are taken as the basis of reference values, and the expert knowledge is integrated into the evaluation process, so that the evaluation results have stronger practical significance; (2) The information is transformed by probability distribution, which clearly preserves the physical meaning of the index information and makes the evaluation results more interpretable; (3) Using IER for information fusion broadens the application scope of the method and further enhances the interpretability of the evaluation results.

The rest of this article is organized as follows. In the second section, the quality evaluation problem based on IER considering uncertain input is sorted out and described, and the method to solve the problem is put forward in the third section. In the fourth section, the feasibility of the solution proposed in this paper is verified by experimental analysis of case data. The conclusion of this paper is shown in section 5.

2. Problem Formulation

When evaluating the quality of LIMU, due to the management and design requirements, it is inevitable to use standards to classify the grades. However, due to the disunity and uncertainty of standards, the grade uncertainty and numerical uncertainty of reference grades lead to inaccurate evaluation [24]. Numerical certainty refers to the deterministic probability corresponding to each level, which usually occurs in deterministic events. For example, under a specific model, when the product life obeys Gaussian distribution, the remaining life can be obtained through the model after the service time is determined [25].

When the numerical value is uncertain, the probability corresponding to each grade is in the form of interval. This situation usually appears in the resume information that someone participates in and manages artificially. As an example, the appearance is one of the equipment quality inspections. Because there is no actual inspection data, the evaluation of the appearance is mainly based on the judgment of professional operation trumpeters and management personnel during the maintenance test, and the criteria are excellent (90-100), good (75-89), fair (65-75), qualified (65-60) and poor (< 60). The uncertainty of this index is that the numerical value represented by the index grade is in the form of interval, and the uncertainty brought by interval is obviously higher than the uncertainty of numerical value in information fusion. The above examples also have uncertain grades, that is, the given grade of the national military standard is inconsistent with the quality evaluation grade. In National Military Standards of People's Republic of China (PRC) 4312, the quality grade of weapons and equipment is divided into four grades: New, Available, Degraded and Scrapped [14, 15]. The definitions of the two grades are defined in detail in the national military standard, which has formed a mature application in equipment management. In the quality evaluation system of LIMU, the standard of grade classification also adopts the national military standard to improve the credibility of the quality evaluation results.

Based on this, under the premise of not destroying the existing equipment management system, how to evaluate the quality under the condition of uncertain input has become a challenge at present.

Evidence, weight and reliability are the three elements of evidence reasoning. $(u_1,\cdots,u_i,\cdots,u_L)$ represents the input information. Turn the input into evidence, in the form of $\{(K_1,k_1),\cdots,(K_{M_i},k_{M_i})\}$, Which K_{M_i} represents the reference grade of the index i, M_i represents the number of reference levels of the index i,with the degree level k_{M_i} representing the reference grade of the index i. $(\omega_1,\cdots,\omega_i,\cdots,\omega_L)$ represents the relative importance of the corresponding evidence; $(r_1, \cdots, r_i, \cdots, r_L)$ represents the reliability of the evidence source relative to the results. The transformed evidence is fused by IER.

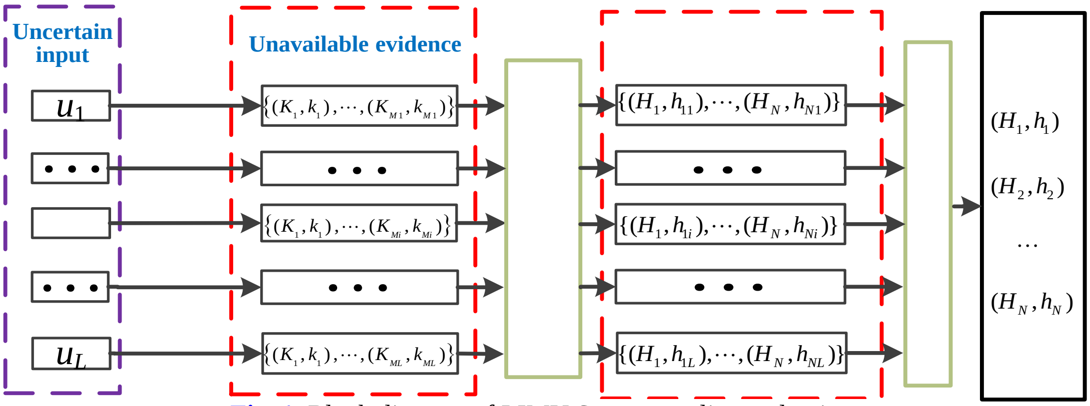

Fig. 1. Block diagram of LIMU System quality evaluating

In the evaluation process of evidence reasoning, the following problems are faced:

Problem 1 Transformation relation with uncertain grade. Usually, in the case of human participation in the rating, the rating division is uniform. In other words, subjectively speaking, every time scale is the same, every grade scale is the same, and every interval scale is the same. In the sense of probability distribution, the distribution form of this information is uniform distribution. However, LIMU is composed of many components, and the life of electronic components mostly obeys Gaussian distribution, so the life trend of LIMU is inconsistent in time scale. It is necessary to solve the relationship between index grade and evaluation grade by mathematical method. Then how to solve the corresponding relationship between index grade and evaluation grade under uncertain input is the first problem facing this paper.

Problem 2 Interval information with numerical uncertainty. After determining the corresponding relationship between index grade and evaluation grade, the conversion problem of uncertain input information is solved. The structure of the transformed information is consistent with the evaluation result, but the transformed information is still uncertain, which is determined by the nature of information. Then, how to use IER to effectively fuse uncertain interval information and make the results credible and reliable is the second problem this paper faces.

3. Quality Evaluation Method Based on IER under Input Uncertainty

According to the above questions, this paper adopts the method based on probability distribution to solve the information conversion of the asymmetry between index grade and evaluation grade. Based on the index characteristics and factory information, the given index information is reduced to the original probability distribution, and the uncertain input information is converted into the form of interval evidence distribution. Then, the uncertain information is fused by IER method.

3.1 Interval Belief Structure Transformation Based on Probability Distribution

Li proposed a conversion method based on conversion matrix, which solved the conversion of reference grade under the condition of grade asymmetry [22]. This method relies on expert knowledge, but it cannot be embedded in the current knowledge system, that is, standard documents. In practical application, in relevant documents or standards, the definition of reference grade of resume information is often qualitative. For example, when evaluating the equipment appearance, the qualified standard is "the coating is corroded and peeled off, but it does not affect the use". It is difficult for the equipment operator to directly give the belief level under the "qualified" standard, but he can give the interval range of the basic belief level of this reference level, such as "the qualified belief level is 0.5 to 0.8". Then, how to fuse the uncertain index information under these belief intervals to get the evaluation results is a problem we have to solve.

Take "Normal, Abnormal" as an example, when it is converted into "New, Available, Degraded and Scrapped", the reference grade is $\{(K_1,k_1),(K_2,k_2)\}$, $k_1+k_2=1$. The evaluation level is 4, respectively $\{(H_1,h_1),(H_2,h_2),(H_3,h_3),(H_4,h_4)\}$. As shown in the **Fig. 2**, the two are uniformly distributed during conversion, and the starting and ending points are 0-1. The belief level of the evaluation grade K_1 is $l_1=1-x$, and the belief level of the evaluation grade K_2 is $l_2=x$. $\delta_1,\delta_2,\delta_3,\delta_4$ is the interval boundary value or critical value of H_1,H_2,H_3,H_4 in this probability distribution.

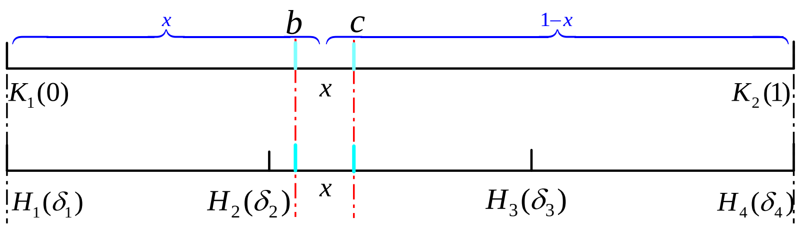

Fig. 2. Schematic diagram of grade transformation based on uniform distribution

When x is uncertain, that is $x\in[b,c]$, x falls in the interval (H_2,H_3), and the interval reference grade and result grade are based on the rules to obtain the following expression [26]:

$$\begin{Bmatrix}(K_1,[1-b,1-c])\\(K_2,[a,b])\end{Bmatrix}\Leftrightarrow\begin{Bmatrix}(H_1,[0,0]);\\(H_2,[\frac{\delta_3-c}{\delta_3-\delta_2},\frac{\delta_3-b}{\delta_3-\delta_2}]);\\(H_3,[\frac{b-\delta_2}{\delta_3-\delta_2},\frac{c-\delta_2}{\delta_3-\delta_2}])\\(H_4,[0,0])\end{Bmatrix} \tag{1}$$

In $(K_1,[1-b,1-c])$, K_1 is the grade of the index, $1-b$ is the lower limit of the grade, and $1-c$ is the upper limit of the grade.

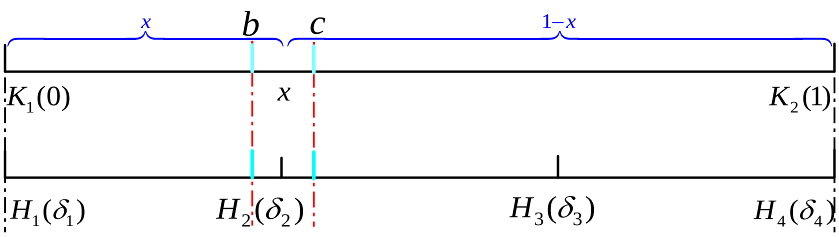

Fig. 3. Schematic diagram of level-crossing conversion based on uniform distribution

After the conversion, the information gets the level of the information and the upper and lower limits of the level.

When the interval crosses the evaluation level,

$$\begin{Bmatrix} (K_1,[1-b,1-c]) \\ (K_2,[a,b]) \end{Bmatrix} \Leftrightarrow \begin{Bmatrix} (H_1,[0,\frac{\delta_2-b}{\delta_2-\delta_1}]); \\ (H_2,[\frac{b}{\delta_2-\delta_1},\frac{c-\delta_2}{\delta_3-\delta_2}]); or (H_2,[\frac{c-\delta_2}{\delta_3-\delta_2},\frac{b}{\delta_2-\delta_1}]) \\ (H_3,[0,\frac{c-\delta_2}{\delta_3-\delta_2}]) \\ (H_4,[0,0]) \end{Bmatrix} \quad (2)$$

More generally, when x is uncertain, $x \in [b,c]$, $[k^-_{M_i,1}, k^+_{M_i,1}]$ represents the interval belief of the index reference level [26], and the $i-th$ index reference level $\{(K_1,k_1),\cdots,(K_{M_i},k_{M_i})\}$, $k_1+\cdots+k_{M_i}=1$ is transformed into the evaluation level $\{(H_1,h_1),\cdots,(H_N,h_N)\}$, $h_1+\cdots+h_N=1$. In $H=\{(H_1,h_1),\cdots,(H_N,h_N)\}$, belief not $h_1,\cdots h_N$ is an independent belief structure, and $h_{1,i}\in[h^-_{1,i},h^+_{1,i}],\cdots h_{N,i}\in[h^-_{N,i},h^+_{N,i}]$, they satisfy the normalization condition, namely $\sum_{s=1}^{n} h_{s,i}=1$.

$$\begin{Bmatrix} (K_1,[k^-_{1,i},k^+_{,i}]) \\ \cdots \\ (K_{M_i},[k^-_{M_i,i},k^+_{M_i,i}]) \end{Bmatrix} \Leftrightarrow \begin{Bmatrix} (H_1,[h^-_{1,i},h^+_{1,i}]); \\ (H_2,[h^-_{2,i},h^+_{2,i}]); \\ \cdots \\ (H_N,[h^-_{N,i},h^+_{N,i}]) \end{Bmatrix} \quad (3)$$

In a certain probability distribution, its density function is $f(x)$, $F(x)=\int f(x)dx$. $\mu_1,\cdots,\mu_{M_i}$ is the interval $\mu_1,\cdots,\mu_{M_i}$ boundary value or critical value, and $\delta_1,\cdots,\delta_N$ is the interval $H_1,\cdots,H_N$ boundary value or critical value. The interval reference grade and evaluation grade get the above expression.

When the interval where x is located does not cross the grade, and when the uncertain reference grade interval (H_j,H_{j+1}) exists, the interval belief transformed equation is as follows:

$$h^-_{j,i}=\frac{f(\delta_{j+1})-c}{f(\delta_{j+1})-f(\delta_j)}, h^+_{j,i}=\frac{f(\delta_{j+1})-b}{f(\delta_{j+1})-f(\delta_j)} \quad (4)$$

$$h^-_{j+1,i}=\frac{b-f(\delta_{j+1})}{f(\delta_{j+1})-f(\delta_j)}, h^+_{j+1,i}=\frac{c-f(\delta_{j+1})}{f(\delta_{j+1})-f(\delta_j)} \quad (5)$$

$$h^-_{1,i}=h^+_{1,i}=\cdots=h^-_{j-1,i}=h^+_{j-1,i}=h^-_{j+2,i}=h^+_{j+2,i}=\cdots=h^-_{N,i}=h^+_{N,i}=0 \quad (6)$$

When the interval where x is located crosses the evaluation level H_j, the belief conversion equation of the interval is as follows:

$$h^-_{j-1,i}=0, h^+_{j-1,i}=\frac{f(\delta_j)-b}{f(\delta_j)-f(\delta_{j-1})} \quad (7)$$

$$h_{j,i}^{-}=\min\left(\frac{b-f(\delta_{j-1})}{f(\delta_{j})-f(\delta_{j-1})},\frac{f(\delta_{j+1})-c}{f(\delta_{j+1})-f(\delta_{j})}\right),h_{j,i}^{+}=\max\left(\frac{b-f(\delta_{j-1})}{f(\delta_{j})-f(\delta_{j-1})},\frac{f(\delta_{j+1})-c}{f(\delta_{j+1})-f(\delta_{j})}\right) \quad (8)$$

$$h_{j+1,i}^{-}=0,h_{j+1,i}^{+}=\frac{c-f(\delta_{j})}{f(\delta_{j+1})-f(\delta_{j})} \quad (9)$$

$$h_{1,i}^{-}=h_{1,i}^{+}=\cdots=h_{j-2,i}^{-}=h_{j-2,i}^{+}=h_{j+2,i}^{-}=h_{j+2,i}^{+}=\cdots=h_{N,i}^{-}=h_{N,i}^{+}=0 \quad (10)$$

$$A=\begin{array}{c} \\ \\ \\ \\ \end{array}\overset{\qquad\qquad\qquad j \qquad\qquad\qquad\qquad j+1}{\begin{bmatrix} 0 & & 0 & 0 & & 0 \\ & & \cdots & \cdots & & \\ 0 & \cdots & a_{j} & a_{j+1} & \cdots & 0 \\ 0 & \cdots & \dfrac{\dfrac{F(\delta_{j+1})-x}{F(\delta_{j+1})-F(\delta_{j})}-a_{j}x}{1-x} & \dfrac{\dfrac{x-F(\delta_{j})}{F(\delta_{j+1})-F(\delta_{j})}-a_{j+1}x}{1-x} & \cdots & 0 \\ & & \cdots & \cdots & & \\ 0 & & 0 & 0 & & 0 \end{bmatrix}}\begin{array}{l} \\ \\ q \\ q+1 \\ \\ \\ \end{array} \quad (11)$$

When x is determined, $k_{M_i,1}^{-}=k_{M_i,1}^{+}$, the interval degenerates into a numerical value, and the index information $\mu_q \le x \le \mu_{q+1}$, $q=1,2,\cdots,M_i$, when $\delta_j \le x \le \delta_{j+1}$, $j=1,2,\cdots,N$, and x fall in the interval (H_j,H_{j+1}) , the evaluation grade density function is $f(x)$, $F(x)=\int f(x)dx$. Substitute into the above equation to get the transformation matrix A ,which has been proved by Zhou [22].

3.2 Quality Evaluation Based on IER

IER method expresses the evaluation trust of each evaluation index at different evaluation levels with belief in interval form, which has stronger ability to deal with uncertain information [27]. This method is mainly to unify the trust identification framework of qualitative and quantitative attribute evaluation information in interval form, and gradually integrate interval uncertain evaluation information to solve the fusion problem of interval uncertain evaluation information [28].

Suppose $\Theta=\{\theta_1,\theta_2,\cdots,\theta_N\}$ is the frame of discernment, $P(\Theta)=\{\varnothing,\{\theta_1\}\}$ is the n proposition, $n=1,2,\cdots N$. Without loss of generality, given a piece of evidence e_i, it can be described as the following belief distribution form:

$$e_i=\{(\theta,h_{\theta,i}),\forall\theta\subseteq\Theta;i=1,2,\cdots,L;\sum_{\theta\subseteq\Theta}h_{\theta,i}=1\} \quad (12)$$

Among them, $(\theta,h_{\theta,i})$ is the focal point of evidence e_i if and only if $h_{\theta,i}>0$, which means that e_i supports the proposition θ with a belief of $h_{\theta,i}$. Weighted reliability distribution method considering reliability in evidence reasoning rules. The interval probability quality is obtained by the following equation:

$$m_{n,i}=[m_{n,i}^{-},m_{n,i}^{+}]=[\tilde{\omega}_i h_{n,i}^{-},\tilde{\omega}_i h_{n,i}^{+}] \quad (13)$$

What is not assigned to any evaluation level at present is the probability quality $m_{P,i}$ of the framework, which can be divided into two parts, in which $\bar{m}_{P,i}$ is caused by the relative importance of indicators, and $\tilde{m}_{P,i}$ is caused by the incompleteness of indicators in the evaluation system.

$$\bar{m}_{P,i} = \bar{m}_i(P) = (1-\tilde{\omega}_i)\cdot\sum_{n=1}^{N} h_n \tag{14}$$

$$\tilde{m}_{P,i} = [\tilde{m}^-_{P,i}, \tilde{m}^+_{P,i}] = [\tilde{\omega}_i h^-_{P,i}, \tilde{\omega}_i h^+_{P,i}] \tag{15}$$

$$\tilde{\omega}_i = \omega_i / (1+\omega_i - r_i) \tag{16}$$

$$\sum_{n=1}^{N} m_{n,i} + \bar{m}_{P,i} + \tilde{m}_{P,i} = 1 \tag{17}$$

Evidence weight ω_i and evidence reliability r_i are key parameters to describe the characteristics of evidence [29]. The main difference between them is that the weight of evidence reflects the preference of decision makers for evidence and is used to describe the subjective characteristics of evidence, that is, subjective uncertainty; The reliability of evidence reflects the ability of evidence sources to accurately express real evidence, which is used to describe the objective characteristics of evidence, that is, objective uncertainty [30]. When $\omega_i = r_i$, the rule of evidential reasoning degenerates into evidential reasoning algorithm.

Fusion of interval probability quality into probability distribution of combined intervals:

$$m_n = k\left[\prod_{i=1}^{L}(m_{n,i} + \bar{m}_{P,i} + \tilde{m}_{P,i}) - \prod_{i=1}^{L}(\bar{m}_{P,i} + \tilde{m}_{P,i})\right] \tag{18}$$

$$\tilde{m}_{P,i} = k\left[\prod_{i=1}^{L}(\bar{m}_{P,i} + \tilde{m}_{P,i}) - \prod_{i=1}^{L}\bar{m}_{P,i}\right] \tag{19}$$

$$\bar{m}_{P,i} = k\left[\prod_{i=1}^{L}\bar{m}_{P,i}\right] \tag{20}$$

$$k = \left[\sum_{n=1}^{N}\prod_{i=1}^{L}(m_{n,i} + \bar{m}_{P,i} + \tilde{m}_{P,i}) - (N-1)\prod_{i=1}^{L}(\bar{m}_{P,i} + \tilde{m}_{P,i})\right]^{-1} \tag{21}$$

When using IER to evaluate equipment quality, remember that the evaluation reference grade of an index is $K_i = \{(K_1, k_1), \cdots, (K_{M_i}, k_{M_i})\}$, and in the quality evaluation framework, an index system of equipment quality evaluation is constructed by L indexes, in which the reference grade of the $i-th$ index is M_i; L pieces of evidence representing the formation of L indexes. $R = (r_1, \cdots, r_L)^T$ represents the reliability of the index, w represents the weight of the index, and e; R represents the evaluation grade of n quality evaluation results.

Because the interval structure is complete, $h^-_{P,i} = h^+_{P,i}$, exactly $\tilde{m}^-_{P,i} = \tilde{m}^+_{P,i} = 0$.

$$m_n = k\left[\prod_{i=1}^{L}(m_{n,i} + \bar{m}_{P,i}) - \prod_{i=1}^{L}\bar{m}_{P,i}\right] \tag{22}$$

$$\tilde{m}_{P,i} = 0 \tag{23}$$

$$\bar{m}_{P,i} = k\left[\prod_{i=1}^{L}\bar{m}_{P,i}\right] \tag{24}$$

$$k = \left[\sum_{n=1}^{N}\prod_{i=1}^{L}(m_{n,i} + \bar{m}_{P,i}) - (N-1)\prod_{i=1}^{L}(\bar{m}_{P,i})\right]^{-1} \tag{25}$$

The weight ϖ_i is weighted by experts, and the reliability r_i is calculated by the conversion loss factor based on probability distribution.

In the interval belief transformation, the transformation method based on probability distribution will transform the input information into the belief distribution form of evidence. Equipment input information is within the validity period, and the probability distribution is obtained based on product testing [31]. This kind of test intensity is higher than the use conditions, and the probation period is longer [32].

$$r_i = r_{i,1} \cdot r_{i,2} \tag{26}$$

$$r_{i,2} = \min\left(\frac{\Phi(\mu_{M_i}) - \Phi(\mu_1)}{F(\delta_N) - F(\delta_1)}, \frac{F(\delta_N) - F(\delta_1)}{\Phi(\mu_{M_i}) - \Phi(\mu_1)}\right) \tag{27}$$

Due to the inconsistency of time scales, there is a certain information loss in the conversion process, and the reliability reduction caused by the inherent characteristics of information sources is represented by $r_{i,2}$, and the reliability reduction caused by the inherent characteristics of information sources is represented by $r_{i,1}$. Together, they constitute the evidence reliability r_i of the index. μ_1, μ_{M_i} is the endpoint value of index reference grade, and its density function is $\varphi(x)$, $\Phi(x) = \int \varphi(x)dx$. δ_1, δ_N is the endpoint value of evaluation grade, and its density function is $f(x)$, $F(x) = \int f(x)dx$.

So as to obtain a fusion result.

$$e_{(L)} = \{(H_n, [h_n^-, h_n^+]), \forall n = 1, \cdots, N; 0 \le \sum_{n=1}^{N} h_n^- \le 1\} \tag{28}$$

Finally, by implementing the following nonlinear optimization model, the overall interval belief is obtained:

$$Max / Min \quad h_n = m_n / (1 - \bar{m}_P) \tag{29}$$

$$s.t. \quad m_{n,i}^- \le m_{n,i} \le m_{n,i}^+ \tag{30}$$

$$\bar{m}_{P,i} = 1 - \tilde{\varpi}_i \tag{31}$$

$$\sum_{n=1}^{N} m_{n,i} + \bar{m}_{P,i} = 1 \tag{32}$$

The IER model is optimized by the projection covariance matrix adaptive evolution strategy (P-CMA-ES) to solve the overall belief.

$$e_{(L)} = \{(H_n, h_n), \forall n = 1, \cdots, N\} \tag{33}$$

3.3 Quality Evaluation Steps of LIMU Based on IER Considering Input Uncertainty

Based on the above conclusions, we can get the general steps of LIMU quality evaluation based on IER under uncertain input, as follow in Fig. 4:

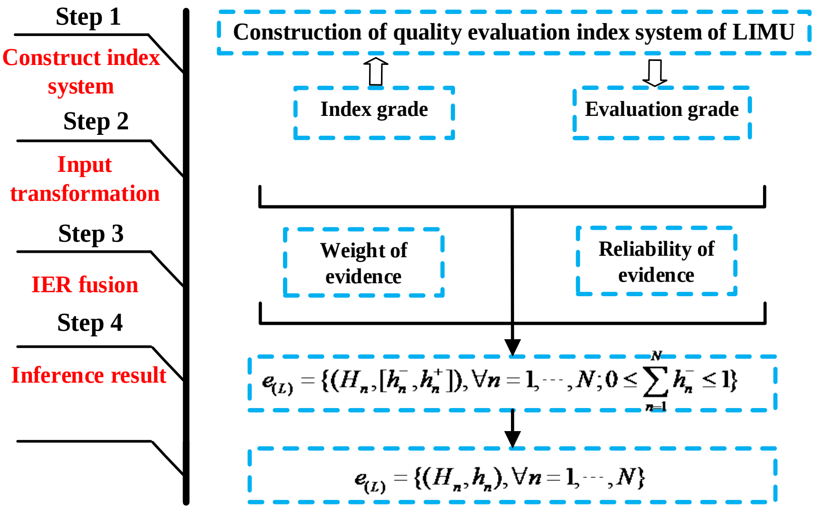

Fig. 4. Flow chart of LIMU quality evaluation based on IER under input uncertainty

4. Case Analysis

LIMU is the mainstream of high-performance inertial instruments in the world at present. Since the 1960s, laser inertial navigation technology has gradually developed. Inertial sensitive elements are directly installed on the carrier, and the electronically navigation platform is replaced by a mathematical platform, which has become an important development direction of inertial navigation technology. In 1970s, inertial navigation technology and computer technology have made great progress. The continuous progress of electronic technology, modern control theory and computer technology created favorable conditions for the development of strapdown inertial technology. The appearance of Global Positioning System (GPS) promoted the development of integrated guidance of inertial navigation and GPS. The application of the proposed evaluation method in engineering practice is illustrated by taking the five-meter redundant LIMU as an example to verify the effectiveness of the proposed method [33].

4.1 Construction of Quality Evaluation Index System of LIMU

Before the quality evaluation, the index system is constructed according to the test points and structural characteristics of the five-meter redundant LIMU.

Based on the optical principle, laser gyro has no errors related to gravitational acceleration and cross-coupling effect compared with mechanical gyro, but laser gyro itself has also produced some new error sources [34]. It mainly includes the following four aspects: 1) Zero bias error; 2) Scale factor error; 3) Error of gyro self-locking effect; 4) gyro random drift error. The bias parameter is not only one of the important error parameters of LIMU, but also an important index to measure the accuracy level of laser gyro [35], and its stability has a great influence on the accuracy of inertial navigation [36].

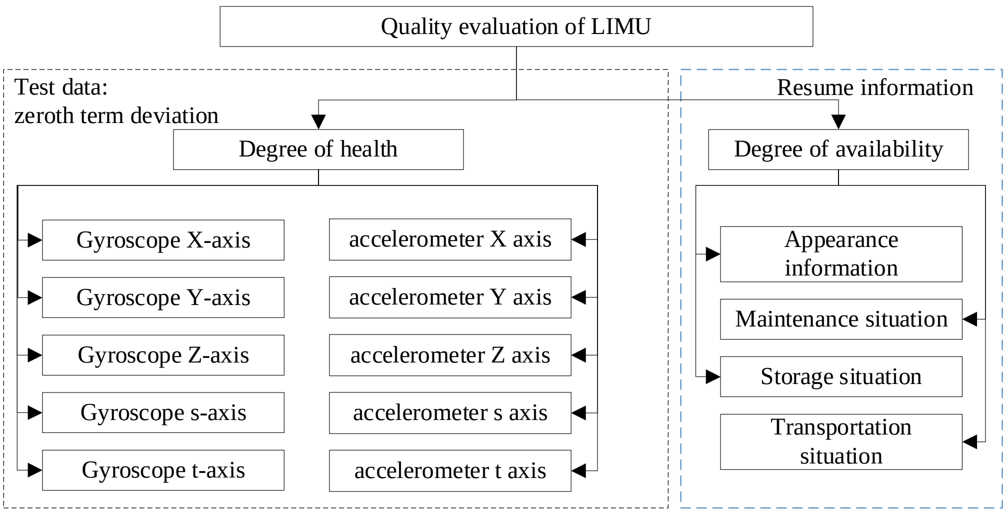

Fig. 5. Quality evaluation index system of laser inertial navigation unit

Construction of quality evaluation index system of LIMU. Based on the optical principle, laser gyro has no errors related to gravitational acceleration and cross-coupling effect compared with mechanical gyro, but laser gyro itself has also produced some new error sources [34].

Due to the limitation of test equipment and test time, combined with the comparison of LIMU error precision, this paper selects the zero-order term deviation as the health index from the test angle, and selects the appearance, maintenance, storage and transportation as the usability index from the perspective of resume management [37]. Construct a five-meter redundant LIMU quality evaluation index system as shown in Fig. 5 above.

4.2 Interval Belief Structure Transformation Based on Probability Distribution

According to the established index system, sort out the data. In the actual operation process, because the appearance has no actual test data, the evaluation of the appearance is mainly based on professional operators and managers to judge the appearance during the annual inspection of the laser inertial group [38].

Table 1. Criteria for judging appearance information grade

Grade	Grade description	Belief interval
A	The paint surface is intact, the appearance is intact and the logo is complete and clear.	0.9-1
B	The coating is slightly peeled off locally, corroded in spots, slightly scratched, with complete marks and slightly damaged appearance, which does not affect the use.	0.75-0.89
C	The coating partially falls off, the marks are incomplete, and the appearance is slightly damaged, which does not affect the use of equipment.	0.6-0.75
D	The corrosion is obvious, the coating falls off in a large area, the scratch is deep and long, and the mark is incomplete, which affects the use.	0-0.6

The grade description and its corresponding score interval is the basis for the use managers to evaluate the grade. If the rating is given as Table 1, the belief interval of the index is 0.75-0.89.

The maintenance situation is divided into three levels according to the degree of failure: minor repair, medium repair and major repair [39]. Establish a model based on maintenance times and level:

$$y = \frac{A_2 - (\alpha_1 \cdot x_1 + \alpha_2 \cdot x_2 + \alpha_3 \cdot x_3)}{A_2 - A_1} \tag{34}$$

In the equation, α_1, α_2, α_3 are the failure coefficients corresponding to minor repair, medium repair and major repair respectively; x_1, x_2, x_3 is the number of minor repairs, medium repairs and major repairs; A_1 is the maximum or theoretical limit of its maintenance conversion value; A_2 is the minimum value of its maintenance conversion.

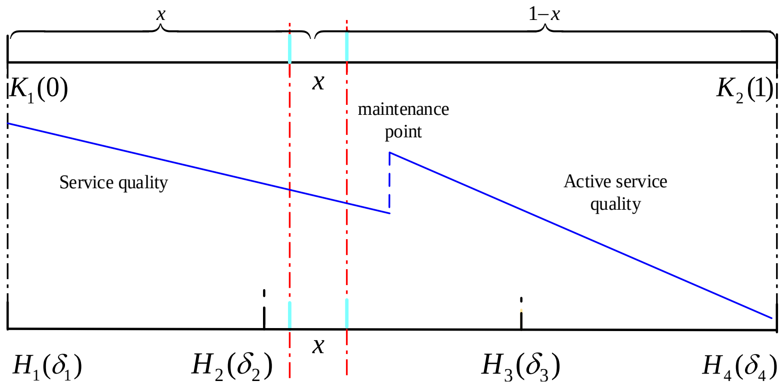

Fig. 6. Schematic diagram of grade conversion based on piecewise function distribution

In the maintenance point, the quality of the parts is improved after maintenance, but it will not reach the optimal state, and the speed of natural damage is faster than that before maintenance, that is, the function value of the maintenance point is lower than that of the initial point, and the slope after maintenance point is higher than that before maintenance point. At the maintenance point, the quality of the parts is improved after maintenance, but it will not reach the optimal state, and the speed of natural damage is faster than that before maintenance, that is, the function value of the maintenance point is lower than that of the initial point, and the slope after maintenance point is higher than that before maintenance point.

In this model, between two repairs, because the maintenance time is simplified to a time point, the uncertainty of time leads to the uncertainty of maintenance quality, which leads to the uncertainty of the input index of maintenance situation, making the maintenance situation an interval input.

As described above, electronic components all describe the probability of their state according to Gaussian distribution as shown in **Fig. 7**, the deviation information of gyroscopes (D_{0x} , D_{0y} , D_{0z} , D_{0s} , D_{0t}) and accelerometers (K_{ax0} , K_{ay0} , K_{az0} , K_{as0} , K_{at0}). In a set of data, there are maximum and minimum deviations from the theoretical values. If the maximum and minimum deviations are equal, the interval information will degenerate into numerical information, and the upper bound of the interval will be equal to the next interval.

According to Liu's research, transportation information obeys uniform distribution.

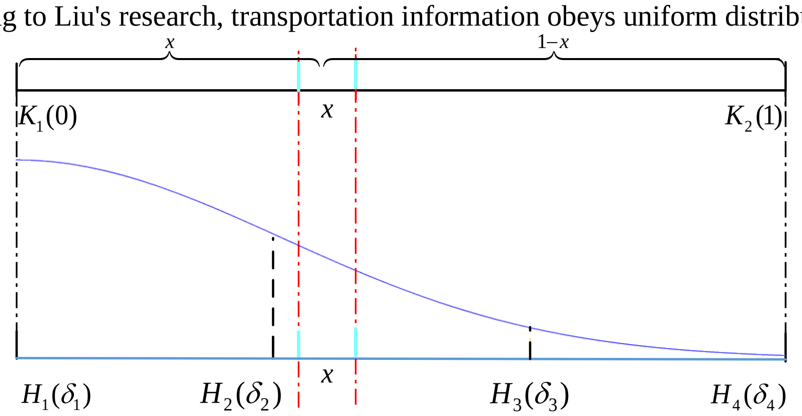

Fig. 7. Schematic diagram of grade conversion based on Gaussian distribution

The storage condition is determined by the validity period and the storage time. The required storage environment of laser inertial assembly, including storage temperature, storage humidity, etc., will shorten the storage period if the storage environment is not up to standard.

At present, the shortening of the validity period is difficult to quantify, and the uncertainty caused by it also leads to the uncertainty of the storage situation, which makes the storage situation an interval input.

Because the standards of various types of LIMU are not uniform, the following is the result of five tables of redundant LIMU input information, as shown in the Table 2 below. Among them, the data information of gyroscope and accelerometer has been given according to the standard criterion after preprocessing. Taking K_{ax0} as an example, 0.2-0.25 means that the maximum degree of data deviation is 0.25 and the minimum is 0.2 in 3δ.

Table 2. Overview of five-meter redundant LIMU input information

Index	input data	Index	input data
D_{0x}	0.12-0.15	K_{ax0}	0.19-0.25
D_{0y}	0.29-0.33	K_{ay0}	0.16-0.19
D_{0z}	0.11-0.17	K_{az0}	0.2-0.23
D_{0s}	0.32-0.36	K_{as0}	0.09-0.1
D_{0t}	0.15-0.2	K_{at0}	0.05-0.08
Appearance information	Quality grade（B 0.75-0.89 ）		
Maintenance situation	5 minor repairs, 1 medium repair and 0 major repairs.		
Storage situation	1054 hours in working, 7-8 hours in non-working environment.		
Transport situation	The highway is 9,000 kilometers, the railway is 500 kilometers.		

According to the description of quality status grades, such as GJB 4386 <Requirements and Methods for Quality Evaluation of Weapon Equipment Maintenance>, the reference values of evaluation results are as follows:

Table 3. Description and setting of equipment performance quality grade

Grade	Grade description	Reference value of evaluation result δ
H_1	Delivered by the manufacturer, not tested by the user, the storage life conforms to the regulations, and the supporting facilities are complete, which can meet the task requirements.	0
H_2	It has been put into use, its technical performance meets the requirements, its quality is normal, and it can meet the task requirements. Meet the above requirements after minor repairs.	0.2
H_3	It needs to be overhauled and repaired in order to meet the task requirements, and it can be repaired and has repair value.	0.7
H_4	Reach the specified service life, and have no service life extension, repair and use value or fail to meet the service life requirements but have no repair or use value. And those that exceed the storage life and seriously affect the safety of use and storage.	1

After the equipment is distributed, it is in a new product for a short time and then degenerates into a usable state; Similarly, the equipment will soon be retired after reaching the condition to be repaired, and it will reach the state to be scrapped, $\Theta = \{H_1, H_2, H_3, H_4\}$, New H_1, Available H_2, Degraded H_3, Scrapped H_4.

The index information and its distribution, as well as the reference grade setting of the evaluation results, are determined and substituted into the known model, and the evidence shown in the following **Table 4** is obtained through the transformation based on probability distribution.

Table 4. Evidence Form of Five-meter of Redundant LIMU Indicators

Index	**Reference of** H_1	**Reference of** H_2	**Reference of** H_3	**Reference of** H_4
D_{0x} (deg/h)	[0.2478,0.3974]	[0.6026,0.7522]	[0,0]	[0,0]
D_{0y} (deg/h)	[0,0]	[0.7201,0.8052]	[0.1948,0.2799]	[0,0]
D_{0z} (deg/h)	[0.1484,0.4474]	[0.5526,0.8516]	[0,0]	[0,0]
D_{0s} (deg/h)	[0,0]	[0.6570,0.7413]	[0.2587,0.3430]	[0,0]
D_{0t} (deg/h)	[0,0.2478]	[0.7522,1]	[0,0]	[0,0]
K_{ax0} /g	[0,0.0494]	[0.8912,0.9506]	[0,0.1088]	[0,0]
K_{ay0} /g	[0.0494,0.1981]	[0.8019,0.9506]	[0,0]	[0,0]
K_{az0} /g	[0,0]	[0.9346,1]	[0,0.0654]	[0,0]
K_{as0} /g	[0.4975,0.5476]	[0.4524,0.5025]	[0,0]	[0,0]
K_{at0} /g	[0.5978,0.7484]	[0.2516,0.4022]	[0,0]	[0,0]
Appearance information	[0.75,0.89]	[0.11,0.25]	[0,0]	[0,0]
Maintenance situation	[0.8457,0.8408]	[0.1543,0.1592]	[0,0]	[0,0]
Storage situation	[0.8939,0.8949]	[0.1051,0.1061]	[0,0]	[0,0]
Transport situation	[0.9333,0.9333]	[0.0667,0.0667]	[0,0]	[0,0]

Taking K_{ax0} whose belief interval crosses grades as an example, it is known that x obeys Gaussian distribution, and the evaluation grade density function is $f(x)=\frac{1}{\sqrt{2\pi\sigma}}\cdot e^{-\frac{x^2}{2\sigma^2}}$, $\Phi(x)=\int_0^x \frac{1}{\sqrt{2\pi\sigma}}\cdot e^{-\frac{x^2}{2\sigma^2}}dx$.

$$X(Min): h_1=\frac{\Phi(0.2)-\Phi(0.19)}{\Phi(0.2)-\Phi(0)}=0.0494 \qquad h_2=\frac{\Phi(0.19)-\Phi(0)}{\Phi(0.2)-\Phi(0)}=0.9506 \tag{35}$$

$$X(Max): h_2=\frac{\Phi(0.7)-\Phi(0.25)}{\Phi(0.7)-\Phi(0.2)}=0.8912 \qquad h_3=\frac{\Phi(0.25)-\Phi(0.2)}{\Phi(0.7)-\Phi(0.2)}=0.1088 \tag{36}$$

From Equation (1)-(10), the belief distribution intervals of all indicators as shown in the following **Fig. 8** can be obtained.

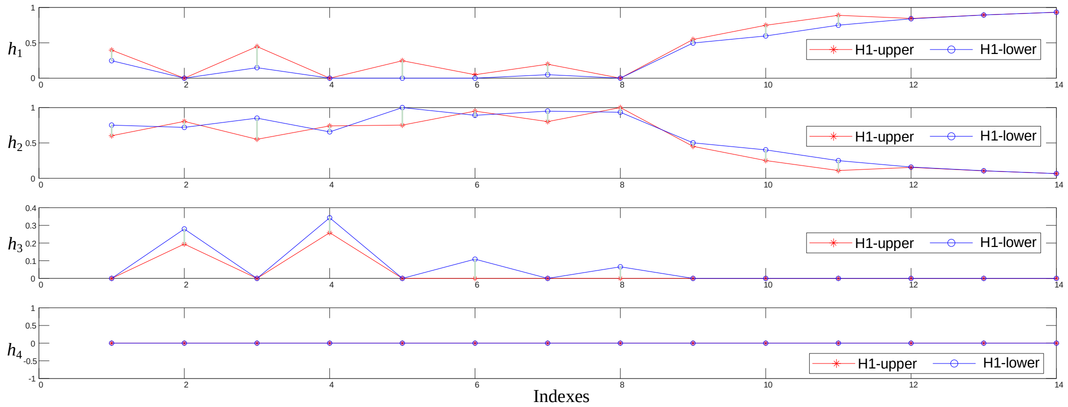

Fig. 8. Belief distribution of LIMU index information converted into evidence

In evidence, weight is the relative importance compared with other evidence, and reliability is the inherent characteristic of evidence as a correct judgment of results. In this case, the weight is obtained through expert empowerment [40]. $r_{i,2}$ in $r_i = r_{i,1} \cdot r_{i,2}$ can be obtained by the transformation of uniform distribution and Gaussian distribution. Suppose that,

$$\varpi = [0.8\ 0.8\ 0.8\ 0.7\ 0.7\ 0.8\ 0.8\ 0.8\ 0.7\ 0.7\ 0.6\ 0.6\ 0.6\ 0.6] \tag{37}$$

Combined with Equation (27) ,

$$r = [0.55\ 0.55\ 0.55\ 0.48\ 0.48\ 0.55\ 0.55\ 0.55\ 0.48\ 0.48\ 0.6\ \ 0.87\ 0.58\ 0.62] \tag{38}$$

4.3 Evaluation of IMU Quality State Based on Interval Evidence Reasoning

The evaluation results are obtained according to the quality evaluation steps of LIMU based on IER in the case of grade asymmetry.

As shown in the following **Fig. 9**, the evidence distribution is concentrated in three grades H_1, H_2, H_3, namely, "New, Available and Degraded ", which is consistent with the current use status of the LIMU. The " Available " status value of the H_2 grade is large and the probability is high. In the H_1 grade, the maximum span is 0.9333; In grade H_2, the maximum span is 0.8839; **In grade** H_3, the maximum span is 0.3430.

Table 5. Reasoning results of LIMU based on IER

Index	**Reference of** H_1	**Reference of** H_2	**Reference of** H_3	**Reference of** H_4
Evaluation results	[0.0234,0.1642]	[0.8356,0.9763]	[0.0002,0.0003]	[0,0]

As can be seen from the reasoning results, the value of "comparable goods" in grade H_2 is the largest, indicating that the probability of being in "comparable goods" in the habitual group is the highest, up to 0.9763.

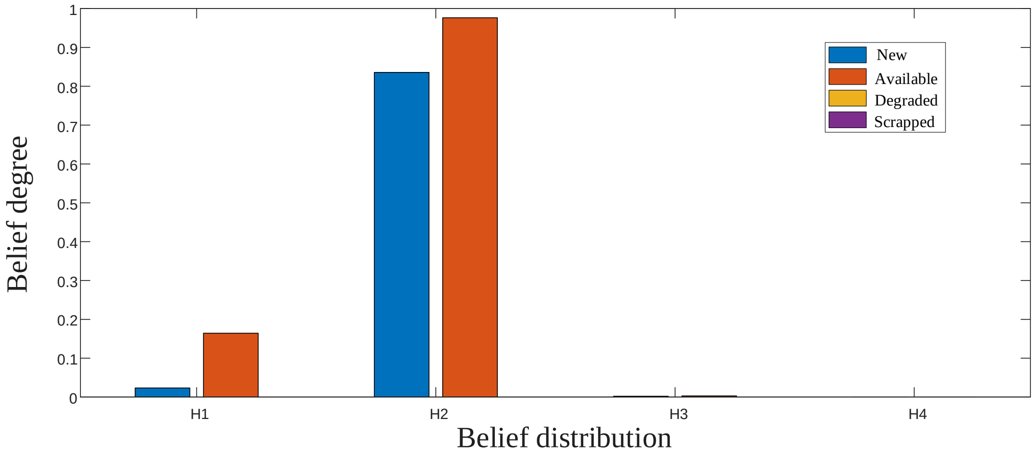

Fig. 9. Belief distribution of results based on IER in LIMU

The reasoning results in **Table 5** above show that in Grade H_1, the interval length is 0.1408; In the H_2 grade, the interval length is 0.1407; In the H_3 grade, the interval length is 0.0001, which greatly reduces the uncertainty of the results. It means that the input uncertainty is improved under the framework of IER, and the generated results will reduce the input uncertainty. In **Fig. 9**, the probability of H_2 grade is much greater than that of H_1 grade, and the results are more concentrated, while the relatively concentrated evaluation results are more conducive to decision makers to make decisions that are more integrated and more in line with the equipment quality status, especially task decisions adapted to emergency situations.

$\{(H_1, 0.0938), (H_2, 0.9059), (H_3, 2.5E-4), (H_4, 0)\}$ is the optimization result with. Because the interval span of IER reasoning results is small and the numerical value is concentrated, the optimization effect is not obvious, but the P-CMA-ES algorithm is indispensable as a supplement to IER.

5. Conclusion

In the evaluation of LIMU under uncertain input, this paper puts forward a conversion method based on probability distribution to convert the index reference grade into evidence consistent with the evaluation grade, aiming at the grade asymmetry caused by the inconsistency between the evaluation grade in the standard specification and the reference grade in the index discrimination. In the case of uncertain input, the uncertainty is expressed by the interval degree distribution, and the generated evidence is fused through the IER algorithm, and the final evaluation results are obtained through P-CMA-ES optimization. Taking the redundant LIMU as an example, under the uncertain input, the length of the degree result interval is greatly reduced, the distribution is more concentrated, the decision efficiency is greatly improved, and the applicability and effectiveness of the method are verified.

The article emphasizes the importance of a comprehensive evaluation model that considers both quantitative and qualitative aspects, including industry standards and expert knowledge. An innovative method based on probability distribution to address the asymmetry between reference grades and evaluation results in the article. The method's use of interval evidence reasoning algorithms for information fusion adds depth to its innovative approach.

This method can not only solve the current difficulties faced by the quality evaluation of LIMU, but also be extended to the quality evaluation of general equipment to form a systematic capability evaluation system, which provides solid technical support for overall task planning and decision-making.

References

[1] C. X. Zhang, M. X. Ling, S. X. Zhang, "Research on attitude algorithm of strapdown inertial navigation system," *Journal of Inertial Technology of China*, vol. 7, no. 1, pp. 13-16, 1999.
[2] S. Q. Zhou, "Development of New Inertia Technology," *Aeronautical Missiles*, vol. 6, pp. 70-77, 2001.
[3] K. D. Wang, Q.T. Gu, "Optimization of dither amplitude and frequency of RLG," in *Proc. of 2002 IEEE Position Location and Navigation Symposium (IEEE Cat. No.02CH37284)*, pp. 277-282, 2002. Article (CrossRef Link)
[4] J. J. Zhang, J. B. Jiang, Z. Li, "Research on digital jitter frequency offset technology of ring laser gyro," *Journal of Missile and Guidance*, vol. 29, no. 6, pp. 63-66, 2009. Article (CrossRef Link)
[5] Z. Chen, *Principle of strapdown inertial navigation system*, Beijing, China: Aerospace Press, 1986.
[6] G. M. Drona, Y. B. Itzhak, "Unified approach to inertial navigation system error modeling," *Journal of Guidance Control Dynamics*, vol. 15, no. 3, p. 648, 1992. Article (CrossRef Link)
[7] Z. Xiong, J. Y. Liu, X. Y. Lin, Q. H. Zeng, "Error compensation technology of inertial devices in laser gyro strapdown inertial navigation system," *Journal of Shanghai Jiao Tong University*, vol. 37, no. 11, pp. 1795-1799, 2003. Article (CrossRef Link)
[8] L. Bai, Y. Y. Qin, F. Wu, "Research on on-board calibration technology of SINS," *Journal of Northwestern Polytechnical University*, vol. 28, no. 3, pp. 369-374, 2010.
[9] K. Wang, B. H. Xu, F. J. Meng, "Failure mode analysis and performance evaluation method of laser strapdown inertial navigation unit," *Aviation precision manufacturing technology*, vol. 56, no. 6, pp. 11-14, 2020. Article (CrossRef Link)
[10] J. C. Chen, Z. C. Zhen, J. H. Xu, Y. F. Gao, "Strapdown IMU stability assessment based on time series principal component analysis," *Modern Defense Technology*, vol. 44, no. 6, pp. 142-147, 2016. Article (CrossRef Link)
[11] W. S. Che, J. H. OH, "Development of force-balance accelerometer with high accuracy for precision motion measurement," *Measurement science & technology*, vol. 7, no. 7, pp. 1001-1011, 1996. Article (CrossRef Link)
[12] R. Zhuang, D. F. Jiang, Y. Wang, "An approach to optimize building area ratios scheme of urban complex in different climatic conditions based on comprehensive energy performance evaluation," *Applied Energy*, vol. 329, pp.1-29, 2023. Article (CrossRef Link)
[13] R. H. Mu, X. Q. Zeng, "A Review of Deep Learning Research," *KSII Transactions on Internet and Information Systems*, vol. 13, no. 4, pp. 1738-1764, 2019. Article (CrossRef Link)
[14] Environmental Test of Electrical and Electronic Products, GB/T 2423-1997, 1997.
[15] General Technical Conditions for Quality Classification and Grading, GJB 4312-2002, 2002.
[16] S. W. Tang, Z. J. Zhou, X. X. Han, Y. Cao, P. Y. Ning, et al, "A New Evidential Reasoning Rule Considering Interval Uncertainty and Perturbation," *IEEE Transactions on Cybernetics*, vol. 5, no. 53, pp. 3021-3034, 2023. Article (CrossRef Link)
[17] D. L. Xu, J. B. Yang, Y. M. Wang, "The evidential reasoning approach for multi-attribute decision analysis under interval uncertainty," *European Journal of Operational Research*, vol. 174, no. 3, pp. 1914-1943, 2006. Article (CrossRef Link)
[18] J. B. Yang, M. G. Singh, "An evidential reasoning approach for multiple- attribute decision making with uncertainty," *IEEE Transactions on Systems Man Cybernetics-Systems*, vol. 24, no. 1, pp. 1-18, 1994. Article (CrossRef Link)
[19] Z. J. Zhou, T. Y. Liu, G. Y. Hu, S. Z. Li, G. L. Li, et al, "A fault detection method based on data reliability and interval evidence reasoning," *Acta automatics sinical*, vol. 46, no. 12, pp. 2628-2637, 2020. Article (CrossRef Link)

[20] Y. S. Xu, "A ship routing method based on the evidence reasoning approach using interval belief degreesChinese Full Text," *Journal of Shandong University of Technology (Natural Science Edition)*, vol. 28, no. 2, pp. 62-69, 2014.
Article (CrossRef Link)

[21] L. Y. Chen, Z. J. Zhou, X. X. Han, C. C. Zhang, P. Y. Ning, "A robust performance evaluation method based on interval evidential reasoning approach under uncertainty," *ISA transactions*, vol. 139, pp. 448-462, 2023. Article (CrossRef Link)

[22] Z. G. Li, Z. J. Zhou, J. Wang, W. He, X. Y. Zhou, "Health assessment of complex system based on evidential reasoning rule with transformation matrix," *Machines*, vol. 10, no. 4, pp. 250, 2022.
Article (CrossRef Link)

[23] F. J. Zhao, Z. J. Zhou, C. H. Hu, L. L. Chang, Z. G. Zhuo, et al, "A new evidential reasoning-based method for online safety assessment of complex systems," *IEEE Transactions on systems, man, and cybernetics, systems*, 48, no. 6, pp. 954-966, 2018. Article (CrossRef Link)

[24] R. X. Duan, Y. N. Lin, L. F. Hu, "Reliability analysis for complex systems based on dynamic evidential network considering epistemic uncertainty," *Computer Modeling in Engineering & Sciences*, vol. 1, no. 113, pp. 17-34, 2017. Article (CrossRef Link)

[25] Y. Lee, I. Chang, S. Oh, Y. J. Nama, Y. Chae, et al, "Hierarchical Flow-Based Anomaly Detection Model for Motor Gearbox Defect Detection," *KSII Transactions on Internet and Information Systems*, vol. 17, no. 6, pp. 1516-1529, 2023. Article (CrossRef Link)

[26] J. B. Yang, P. Sen, "A general multi-level evaluation process for hybrid MADM with uncertainty," *IEEE transactions on systems, man, and cybernetics*, vol. 24, no. 10, pp. 1458-1473,1994.
Article (CrossRef Link)

[27] L. L. Gu, X. L. Geng, "Multi-attribute decision-making method based on interval evidence reasoning," *Journal of Shanghai University of Technology*, vol. 41, no. 3, 236-243, 2019. Article (CrossRef Link)

[28] L. Q. Jin, X. Fang, Y. Xu, "Interval multi-attribute decision-making method based on evidential reasoning and prospect theory," *Fuzzy System and Mathematics*, vol. 31, no. 6, pp. 124-131, 2017.

[29] H. Jo, S. Kim, D. Won, "Advanced Information Security Management Evaluation System," *KSII Transactions on Internet and Information Systems*, vol. 5, no. 6, pp. 1192-1213, 2011.
Article (CrossRef Link)

[30] L. M. Guo, Y. L. Luo, X. K. He, G. Y. Hu, Y. Dong, "A Method for Service Evaluation Based on Fuzzy Theory for Cloud Computing," *KSII Transactions on Internet and Information Systems*, vol. 11, no. 4, pp. 1820-1840, 2017. Article (CrossRef Link)

[31] S. Distefano, A. Puliafito, "Reliability and availability analysis of dependent–dynamic systems with DRBDs," *Reliability engineering & system safety*, vol. 94, no. 9, pp. 1381-1393, 2009.
Article (CrossRef Link)

[32] X. F. Huang, P. H. Jiang, M. C. Li, X. Zhao, "Applicable framework for evaluating urban vitality with multiple-source data, empirical research of the pearl river delta urban agglomeration using BPNN," *Land*, vol. 11, no. 11, pp. 1901-1911, 2022. Article (CrossRef Link)

[33] F. Yu, B. Xie, "Research on optimal configuration of 5-instrument redundancy strapdown inertial measurement unit," *Aviation Precision Manufacturing Technology*, vol. 51, no. 06, pp. 19-22, 2021.

[34] M. S. Grewal, V. D. Henderson, "Application of Kalman filtering to the calibration and alignment," in *Proc. of 29th IEEE Conference on Decision and Control*, vol.6, pp. 3325-3334, Honolulu, HI, USA, 1990. Article (CrossRef Link)

[35] Z. J. Zhou, P. Y. Ning, J. Wang, C. C. Zhang, Z. C. Feng, et al, "An evidential reasoning rule-based quality state assessment method of complex systems considering feature selection," *IEEE Transactions on Instrumentation and Measurement*, vol. 72, pp. 1-13, 2023. Article (CrossRef Link)

[36] R. Luo, P. Li, L. Y. Yu, "A calibration method for redundant IMU considering accelerometer asymmetric error," *Journal of Chinese Inertial Technology*, vol. 31, no. 02, pp. 114-120, 2023.
Article (CrossRef Link)

[37] G. F. Zhou, Z. Chen, R. Lv, H. F. Tu, S. Xu, "Virtual IMU and turntable attitude compensation for HITL simulation," *Systems Engineering and Electronics*, vol. 44, no. 04, pp. 1329-1335, 2022.
Article (CrossRef Link)

[38] M. M. Shan, H. Fu, "Digitization beyond tool rationality: research on the improvement path of governance efficiency of Chinese social organizations in annual inspection," *Decision science*, vol. 2, pp. 69-77, 2023.
[39] W. S. Li, J. H. Zhang, J. C. Li, "Development of virtual maintenance training system based on the linkage of installation and simulation," *Mechanical Management and Development*, vol. 38, no. 09, pp. 171-173, 2023. Article (CrossRef Link)
[40] S. W. Tang, Z. J. Zhou, C. H. Hu, F. J. Zhao, Y. Cao, "A new evidential reasoning rule-based safety assessment method with sensor reliability for complex systems," *IEEE Transactions on Cybernetics*, vol. 52, no. 5, pp. 4027-4038, 2022. Article (CrossRef Link)

Xiangyi Zhou: Xiang-Yi Zhou received the B.Eng. degree from the Rocket Force University of Engineering in 2018., China, in 2020. She is currently pursuing the M.Eng. degree in High-Tech Institute of Xi'an, China. Her research interests include evidential reasoning, performance evaluation, resume information and quality certification.

Zhijie Zhou: Zhi-Jie Zhou received the B.Eng. and M.Eng. degrees from the High-Tech Institute of Xi'an, Xi'an, China, in 2001 and 2004, respectively, and the Ph.D. degree from Tsinghua University, Beijing, China, in 2010, all in control science and management. He is currently an Associate Professor with the High-Tech Institute of Xi'an. In 2009, he was a Visiting Scholar with the University of Manchester, Manchester, U.K., for six months. He has published approximately 70 articles. His research interests include belief rule base, dynamic system modeling, hybrid quantitative and qualitative decision modeling, and fault prognosis and optimal maintenance of dynamic systems.

Xiaoxia Han: Associate Professor of Rocket Force University of Engineering, obtained a master's degree from Xi'an University of Architecture and Technology in 2004. Her main research interests are control theory and application, water supply and drainage technology, air conditioning and ventilation guarantee, health assessment, etc.

Zhichao Ming: Zhichao Ming received the B.Eng. degree in control science and management from Heilongjiang University, Harbin, China, in 2020, and the M.Eng. degree from the High-Tech Institute of Xi'an, Xi'an, China, in 2023, where she is currently pursuing the doctor's degree. Her research interests include belief rule base, information fusion, safety assessment, fault diagnosis and optimal maintenance of dynamic systems.

Yanshan Bian: Yanshan Bian received the Ph.D. degree from Space Engineering University, Beijing, China, in 2014, in communication and information. He is currently an electronic engineer with the High-Tech Institute of Xi'an. He has published approximately 30 articles. His research interests include VR, AI, and fault prognosis.