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Multi-mode Motion Reliability Analysis for Cross Trajectory Tracking

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Abstract. In order to solve the problem of fuzzy trajectory tracking in the traditional multi-mode motion reliability analysis method, a multi-mode motion reliability optimization analysis method for cross trajectory tracking is proposed. Firstly, the instantaneous reliability model of motion accuracy and the time-varying reliability model of motion accuracy are constructed, and the multi-mode kinematic analysis for cross trajectory tracking is realized. According to the reliability analysis model, the trajectory tracking motion mode is determined, and the risk assessment coefficient of motion is obtained by using the first-order reliability algorithm for different motion modes. The instantaneous motion and the reliability of time-varying motionare calculated respectively, and the comprehensive reliability analysis results of multi-mode motion are output. By setting up a comparative experiment, the reliability analysis results of multi-mode motion were obtained. The results show that the multi-mode motion reliability analysis method for cross trajectory tracking has higher reliability comprehensive calculation value, higher reliability analysis accuracy and higher reliability risk assessment accuracy.

Keywords: Cross track, Trajectory tracking, Multimodal, Motion, Reliability analysis

1 Introduction

Multi-mode motion usually refers to a variety of motion modes such as stationary, walking, running, jumping, and rolling of a robot. During the movement, the robot receives different program control and will execute different movement modes, and there will also be multi-mode movement conversion. Therefore, it is necessary to ensure the reliability of the various motion modes of the robot and the transition between the motion modes to ensure the normal movement of the robot [1]

The object of reliability analysis is the comprehensive parameters with the failure of the robot as the main research object. Reliability research in the United States began in World War II. After a long period of research, there have been relatively complete reliability analysis methods based on fuzzy number arithmetic operations. This reliability analysis method has been applied to various foreign projects and has achieved certain application results. In the 1960s, China gradually raised the issue of reliability in terms of telecommunications and electronic computers. With the promotion of society, China strengthened its research on reliability analysis methods. China follows the development model of “lock-up-control-upgrade” to carry out further reliability analysis and research [2]. Reliability mainly refers to the ability or possibility of a product to perform a task without failure within a certain period of time or under fixed conditions, and it is a probability problem. Motion reliability is closely related to time, so when performing quantitative analysis of motion reliability, its time characteristics need to be sufficient. The longer the use time, the lower the reliability. And different product parameters and sport modes have varying degrees of reliability.

Literature [3] proposed the reliability analysis and optimization method of hip joint motion accuracy of bionic tree-climbing robot. After giving the parameters of the mechanism, based on the established mathematical model of the error, the motion reliability of the hip joint mechanism was obtained using

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Monte Carlo method. It further analyzes the influence of different error factors on the reliability of the mechanism, and the influence of the same error factor on the reliability of the movement in different directions of the mechanism, and analyzes the relationship between the mechanism reliability and the input parameters of the mechanism in this example. Literature [4] proposed a method of dynamic reliability evaluation of evidence in the framework of intuitionistic fuzzy and its application. The basic probability assignment function was transformed into an intuitionistic fuzzy set. The similarity between functions was calculated by using the similarity between fuzzy sets. Based on the concept of evidence support, the relationship between evidence support and reliability is analyzed to obtain relative and absolute reliability of evidence. Literature [5] proposed a time-varying reliability analysis method for robot motion, and based on kinematics analysis, a position error model of the robot's end effector reference point was established. Based on the robot pose error model, the point (static) reliability, time-varying (interval) reliability model of the end effector position accuracy, and the system reliability model of robot motion are proposed. Finally, an envelope method is presented to realize the efficient and high-precision solution of the above reliability model, and the effectiveness of the proposed model and solution method is verified by using a Stanford robot as an example.

In the above method, the trajectory tracking is blurred. In order to obtain more accurate reliability analysis results, a multi-modal motion reliability analysis method for cross trajectory tracking is proposed. Based on the robot cross trajectory for reliability analysis, the reliability of the motion mode of the cross trajectory tracking task is calculated and analyzed. It aims to improve the reliability of the comprehensive calculation results and provide a basis for a comprehensive and intuitive reflection of the overall movement of the mechanism.

2 Design of Multi-modal Motion Reliability Analysis Method

To analyze the motion reliability of the cross trajectory tracking task, the first step is to analyze the mathematical relationship between the end positioning accuracy and the motion reliability during the robot's cross trajectory tracking process. Therefore, a multi-modal kinematics analysis model of the robot during the tracking process is first constructed [6]. Under the analysis model, the motion mode on the tracking trajectory is determined, and then through the related calculation and analysis algorithms, the reliability analysis of multi-mode motion is realized, and the reliability analysis result is obtained.

2.1 Building a Model for Multimodal Kinematics Analysis

An analysis model of multi-mode motion reliability is constructed from three aspects: instantaneous motion accuracy, time-varying motion accuracy, and reliability error. It is necessary to fully consider the errors that may occur during the manufacturing and movement of the robot, and perform reliability modeling, error analysis and reliability evaluation on the robot.

Instantaneous Motion Accuracy Reliability Model. In general, the cross trajectory of a robot performing a tracking task is a continuous curve, and the speed and acceleration are kept as stable and continuous as possible to reduce the unnecessary motor load during the robot's movement [7-8]. Under continuous conditions, the motion reliability can be discretized, and a trajectory point on the tracking cross trajectory is i; and the envelope space formed by the trajectory point is Ω_i. Then the probability of meeting the task requirements at the trajectory point can be calculated by formula (1).

$$R = \Pr\left\{X_i^A(\Theta) - X_i^N(\Theta) \in \Omega_i\right\} \tag{1}$$

where, $X_i^A(\Theta)$ means the actual position of the robot end at the cross track point i, $X_i^N(\Theta)$ is the ideal place, and Θ is the parameter that affects the robot's terminal place. By solving the probability density function $p(x)$, multi-mode motion reliability can be obtained for cross trajectory tracking tasks.

Time-varying Reliability Model of Motion Accuracy. Assume that the robot adds a cross trajectory in a certain area, and the probability that the robot falls within a given error limit range in the specified interval is the time-varying reliability of the mechanism in the movement interval. Time-varying reliability of motion accuracy. It is shown in Fig. 1.

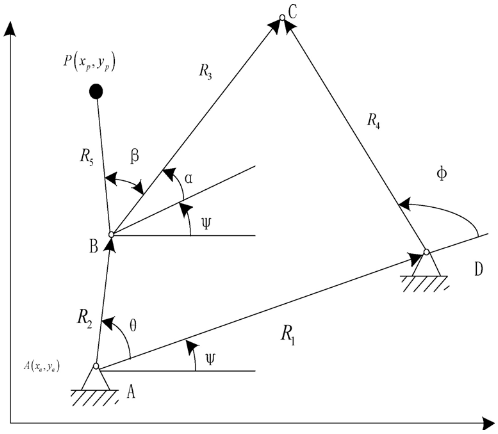


Fig. 1. Schematic diagram of time-varying reliability model of motion

This reliability model can reflect the accuracy with which a robot tracks a trajectory. In the schematic diagram of the time-varying reliability model, AB and BC are the initial planned routes, AD represents the newly added tracking trajectory route, and the structural parameter vector $R = [R_1, R_2, R_3, R_4]$, and each size structure meets the normal distribution law. From the distance tube between the four-bar mechanism of the robot in Fig. 1, based on the motion analysis of the four-bar mechanism of the model, a relationship model between input and output is established:

$$F = \begin{cases} R_1 \cos\phi + R_2 \cos\theta - R_3 \cos(\alpha + \varphi) - R_4 \\ R_1 \sin\phi + R_2 \sin\theta - R_3 \sin(\alpha + \varphi) \end{cases} \quad \textbf{(2)}$$

where, R_1, R_1, R_1 and R_1 means the length of different links. θ means the angle of crank AB relative to frame AD, α means the rotation angle of connecting rod BC, and φ means the angle between the frame AD and the x axis of the coordinate system. From the above analysis, relevant quantities can be substituted into related formulas, and the motion reliability of the tracking task robot affected by the basic size error can be obtained.

The gap error of the motion pair of the tracking task robot is mainly caused by manufacturing and unreasonable assembly and long-term wear and tear. It is shown in Fig. 2.

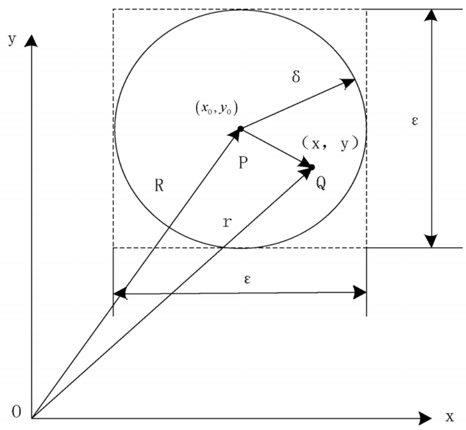


Fig. 2. Schematic diagram of time-varying reliability error area of motion

According to Fig. 2 Error diagram, the unit circle represents the desired output point, (x, y) means the actual input point, and the vector radius between the two Δr is the reliability error vector. P means the sleeve hole center, Q means the pin center, and the length of the rod OP is R. R represents the radius of motion under ideal conditions. Taking into account factors such as the manufacturing, unreasonable assembly, and long-term wear of the tracking task robot, a certain motion pair clearance error will occur.

The center of the sleeve hole P is transferred to the pin center of the Q, therefore, O represents the effective link length, which is set as r.

For the component, through sampling, it is found that the length R to the point O is the pin center Q, and it is randomly distributed within the erroneous circle with the diameter Δr, i.e., the distribution of (x, y) is the standard normal distribution, therefore:

$$E(x) = E(y) = 0 \quad \textbf{(3)}$$

where, x and y means the horizontal and vertical coordinates of time-varying reliability error area, and then the time-varying reliability model of the trajectory mechanism can be defined as:

$$R(x_0, y_0) = \eta \Pr\left\{\left(\left|g_1(X,\theta)\right| \le \varepsilon\right) \cap \left(\left|g_2(X,\theta)\right| \le \varepsilon\right), \forall \theta \in [x_0, y_0]\right\} \quad \textbf{(4)}$$

where, ε is the allowable error limit, and x_0 are y_0 the start and end positions of the robot's cross-tracking trajectory.

2.2 Determine Trajectory and Track Motion Patterns

The basic modes of the robot on the cross-tracking trajectory include walking, running, stationary, and jumping. In the process of multi-mode motion reliability analysis, specific analysis is required for each motion mode. Therefore, it is necessary to determine the trajectory tracking motion mode in the multi-modal kinematics analysis model. First measure its speed. If the speed measurement calculation result is zero, it is determined that the current motion mode of the robot is the stationary mode; If the result is not zero, the acceleration of the robot needs to be calculated. If the speed is greater than 3m / s and the acceleration is greater than zero, the current mode is the running mode, otherwise it is determined to be the walking mode. In addition, the distance between the robot and the ground needs to be calculated. When the distance from the ground exceeds 20% of its own height, it is determined as a jumping mode.

Considering the problem of cross-track tracking, it can be known that in the process of tracking a moving target, it is not exactly a linear movement, and there will be a movement change tracking. In order to simplify the calculation, this paper takes the angle of intersection as a research example to analyze the problem of tracking the robot's movement direction, especially in the instantaneous reliability analysis, the intersection of steering is used as the instantaneous motion.

2.3 Risk Assessment of Joint Probabilistic Motion

It can be seen from the constructed reliability model expression that multi-mode motion reliability has non-linear characteristics. There is a movement change. Therefore, the first-order reliability algorithm is used to solve the motion risk coefficient [9-10]. Assume that the corresponding rotation angle of the robot at each cross-tracking point is R. i = [1, 2, …, m], where m is the discrete number of cross track points. Firstly, the tracking cross trajectory variable is transformed into a standard normal space expression, and the transformation method is shown in formula (5).

$$U_i = \phi\left(F_{R_i}(R_i)\right) \quad \textbf{(5)}$$

where, μ_{L_i} means the accumulative distribution function of R_i. The size variable of the tracking trajectory follows a normal distribution, so formula (6) can be transformed into:

$$U_i = \phi^{-1}\left[\phi\left(\frac{L_i - \mu_{L_i}}{\sigma_{L_i}}\right)\right] = \frac{L_i - \mu_{L_i}}{\sigma_{L_i}} \quad \textbf{(6)}$$

where, μ_{L_i} is the expected value of the size variable L_i, and σ_{L_i} is the standard error of the size variable L_i. The first order reliability algorithm will linearize the state limit function at u^*, and the formula to get the solution is as follows:

$$s.t. f(u) = \min \left\| u^{*} \right\| \sigma \tag{7}$$

where, $f(u)$ is the mode limit function in standard normal space. Assume that the rotation angle of the robot at each cross-tracking trajectory point is φ_i, and the value of i is $1,2,...,m$ in which m is the discrete number of trajectory points. For each motion mode, the robot tracks the trajectory in a specified expected operating interval, and its motion risk coefficient can be expressed as:

$$\chi_j = \int_{-\varepsilon}^{\varepsilon} \frac{1}{(2\pi)^m \left|\sum\right|} \exp\left(-\frac{(z-U_i)\sum^{-1}(z-U_i)^T}{f(u)} \right) dz \tag{8}$$

where, μ_z is the average value of g_j, and $\sum$ is the covariance between the various elements of vector z. It can be seen that the time-varying risk of robot multi-mode motion needs to be based on the calculation of the mean and mutual covariance of motion errors [11]. The value of the reliability risk assessment obtained is lower than 1, and it is judged that the movement of the mode is reliable, otherwise it is judged that the movement is risky [12].

2.4 Calculate the Reliability of Multi-mode Motion

Time-varying reliability. Assume that the variables of each mode obey the normal distribution in the time-varying reliability model, the formula (8) can be solved with a second-order high-precision [13], and the corresponding failure probability can be obtained at the same time. The calculation process of the reliability of each time-varying component mode. It is shown in Fig. 3.

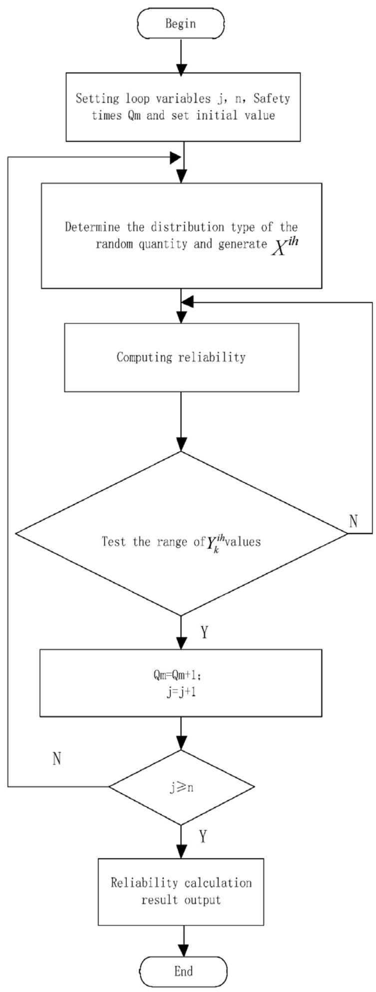


Fig. 3. Multi-modal motion reliability calculation process

Fig. 3 shows that the reliability of each time-varying component in the multi-mode motion is calculated. First, a variable for the control loop needs to be set as time-varying motion variable and this variable is set to be represented by j in this calculation process. Set the number of sampling times for multi-mode exercise to n, take a larger initial value in the exercise sequence, and set the safe number in this mode to Q_m, and the remaining original value is set to 0. Then a series of initial values are input into the cyclic algorithm for a specific calculation process, and an m-dimensional random vector is generated from the distribution type of the random variable [14]. The random vector is X^{ih}. Calculate the value of Y_k^{ih} according to the mapping and normal distribution. Test the range of the value of Y_k^{ih}. If it is within χ_j, the value of Q_m+1 is set to Q_m and output the specific numeral value of Y_k^{ih}. Otherwise, re-judgment is performed until the results of the risk assessment are met [15-16]. Finally, the sizes of j and n are checked, and under the condition of multiple modes of motion, the results of the time-varying component motion reliability calculation for j not less than n are output.

Instantaneous Reliability. Considering the randomness of the motion mode state, the movement coordinates of the robot at each moment $p\left(x_p, y_p\right)$ is also random. The turning angle at the intersection is selected as the instantaneous motion for analysis. Set $\left(x^*, y^*\right)$ as the expected output track point coordinates [17]. The multi-mode motion error of the robot in the x and y directions is expressed by formula (9).

$$\begin{cases} g_x\left(X,\theta\right) = x_p - x^* \\ g_y\left(X,\theta\right) = y_p - y^* \end{cases} \tag{9}$$

Thus, the instant reliability of the robot at the angle θ.

$$R\left(\theta\right) = \Pr\left\{\left(\left|g_x\left(X,\theta\right)\right| \le \varepsilon\right) \cap \left(\left|g_y\left(X,\theta\right)\right| \le \varepsilon\right)\right\} \tag{10}$$

where, ε means allowable error limit, $g_x\left(X,\theta\right)$ and $g_y\left(X,\theta\right)$ means the kinematic errors of the robot at the x and y directions.

The instantaneous reliability analysis algorithm is used to solve the data required in the reliability calculation formula, and the corresponding failure risk probability value is calculated [18-20].

Comprehensive Reliability. By comprehensively calculating the reliability of each mode component of multi-mode motion in cross trajectory tracking, and the instantaneous reliability calculation result of transition between modes, the comprehensive reliability of multi-mode motion in cross trajectory tracking can be obtained. The multi-mode input motion and output motion satisfy the condition of formula (11).

$$F\left(M,N,q\right) = 0 \tag{11}$$

where, M set is the input motion, N set is the output motion, and q is the effective structural parameter vector in the case of random error. On the premise of satisfying the above formula conditions, the final calculation result of comprehensive reliability can be obtained by formula (12).

$$R_z = \chi_j \left(\frac{\delta - \sum_{i=1}^{n} FR_m}{\sqrt{\sum_{i=1,j=1}^{n} FR_m}} \right) R\left(\theta\right) \tag{12}$$

where, δ means the attitude error vector, R_m means the effective structural length, F means the input and output relationship model, and χ_j means adjacent joint change matrix.

Make a frequency histogram based on multiple sampling values and enter statistical data into formula (12). Finally, based on the obtained distribution function, the average value of the comprehensive reliability of multi-mode motion in cross trajectory tracking is calculated, which is the result of reliability analysis. When the value of the result is lower than 1, it is determined that the multi-mode motion is reliable, otherwise it is determined that the motion is at risk.

3 Experimental Analysis and Results

3.1 Experimental Enviroment and Dataset

In order to verify the effectiveness of the multi-modal motion analysis method in cross trajectory tracking, experiments were performed to compare the reliability analysis and optimization method of hip joint motion accuracy of the bionic tree-climbing robot proposed in Literature [3], and the intuitions proposed in Literature [4] The dynamic reliability assessment and application of evidence in the fuzzy framework, and the method of robot time-varying reliability analysis proposed in Literature [5]. The experimental data set is from the **iResearch** data. It is shown in Table 1.

Table 1. Experimental environment

Item	Parameter range
Structural parameters of the robot	$\beta = -19.78^{\circ}$
Installation parameters	$x_a = 6.0mm$ $y_a = 14mm$ $\varphi = 22^{\circ}$

The length and size distribution are shown in Table 2.

Table 2. Rod length and size distribution

Size variable	Mean μ/mm	Standard deviationσ/mm	Distribution
R_1	84.69	0.05	Normality
R_2	23.98	0.05	Normality
R_3	88.0	0.05	Normality
R_4	65.49	0.05	Normality
R_5	39.12	0.05	Normality

In Table 2, R1-R5 indicates the rod length of the different links of the tracking robot. Defining the rod length and size distribution can provide a more complete experimental environment for trajectory tracking, and avoid external factors from interfering with the experimental results.

3.2 The Experimental Index

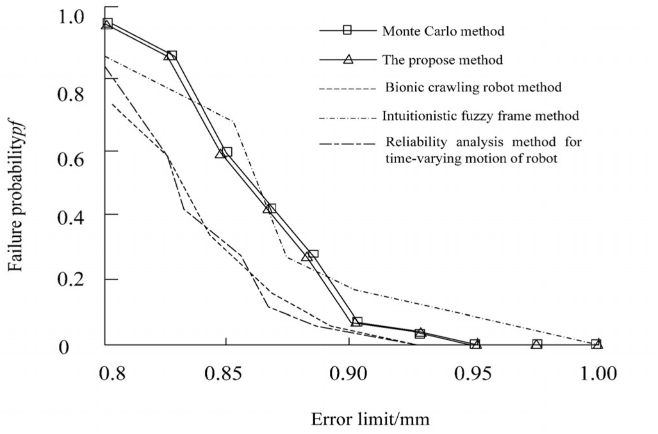
(1) Time-varying failure probability. From the comprehensive reliability, the curve of the robot's time-varying failure probability in the x and y directions as a function of the error limit is obtained.

(2) Reliability analysis accuracy. According to the comprehensive reliability result calculated by formula (12), the accuracy of the test analysis is performed.

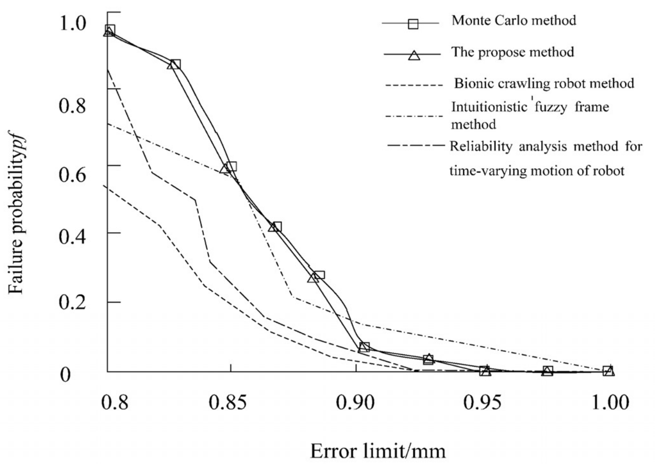
(3) Reliability risk assessment accuracy, when the reliability assessment accuracy value is less than 1, it is determined that the multi-mode motion is reliable; otherwise, it is determined that there is a risk in the motion, and the reliability risk evaluation efficiency is analyzed.

3.3 The Experimental Rusults

The formula (11) is used to calculate the time-varying failure probability of the robot under different application methods, and compared with the Monte Carlo simulation results. The Monte Carlo method is also called random sampling or statistical test method. Monte Carlo method can simulate the actual physical process realistically, so the problem solving is in line with reality. This method is compared with this and other methods to clearly observe the differences between different methods and actual results. Specific experimental test results are shown in Figure4.



(a) Time-varying failure probability of the trajectory robot in the x-direction



(b) Time-varying failure probability of the track robot in the y-direction

Fig. 4. Comparison results of time-varying failure probability of trajectory robot

In Fig. 4, the time-varying failure probability of the robot obtained by the multi-modal motion analysis method in cross trajectory tracking has a good agreement with Monte Carlo simulation results. The time-varying failure reliability analysis method of the bionic crawling robot and the robot has a low degree of agreement between the time-varying failure probability and the Monte Carlo simulation results. The degree is relatively good, but it is significantly lower than this method. The main reason is that the method in this paper analyzes the basic patterns on the cross-tracking trajectory, including walking, running, stationary, and jumping, so that the multi-mode input motion is distinguished and the reliability calculation value is improved. A curve about the accuracy of the analysis.

It can be seen from the Fig. 5 that the accuracy of the multi-modal motion analysis method in cross trajectory tracking is up to about 98%. The average accuracy is about 70%. After statistics and calculations, the average accuracy rate of the bionic crawler robot in multi-mode motion reliability analysis is about 45%. The accuracy is 25% lower than that of this method. The average accuracy rate of the intuitionistic fuzzy frame method and the robot’s time-varying motion reliability analysis method are 31% and 48%, respectively. They are 39% and 22% lower than the proposed methods. It can be seen that the reliability analysis proposed method designed is more stable than that in literature. The main reason is that this paper uses a first-order reliability algorithm to solve the motion risk coefficient, which satisfies the requirements of reliability calculation to a large extent, and ensures the accuracy of comprehensive reliability analysis.

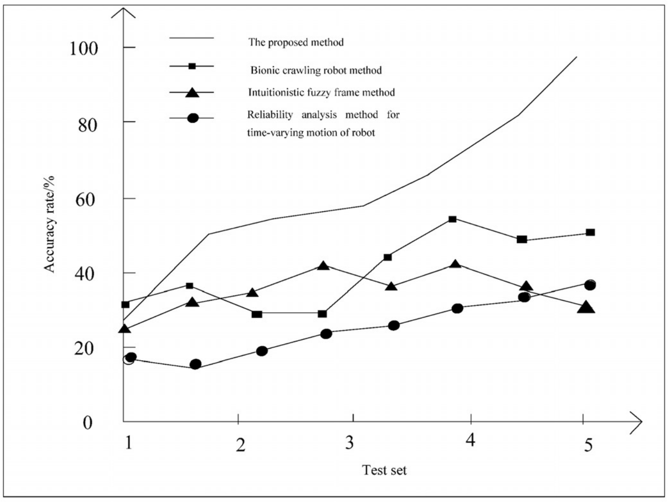


Fig. 5. Accuracy comparison curve

Matlab simulation experiment software is used to conduct experiments to obtain the reliability risk assessment accuracy of the robot. It is shown in Fig. 6.

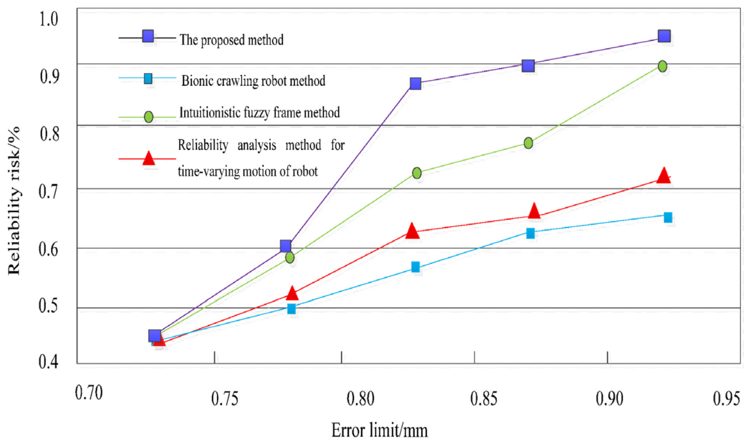


Fig. 6. Comparison of reliability risk assessment accuracy of different methods

Fig. 6 shows that the reliability risk assessment accuracy of the multi-modal motion analysis method in cross trajectory tracking reaches more than 95%. The reliability risk assessment of the bionic crawling robot, the intuitionistic fuzzy frame method, and the robot's time-varying motion reliability analysis method also tends to rise, but overall it is lower than the cross-trajectory tracking method, reaching 90%, 70%, and 68% respectively. According to the data analysis, the reliability risk assessment accuracy of other methods is far lower than that of this method, which verifies the excellent performance of this method. The main reason is that the method in this paper is based on the calculation of the mean and mutual covariance of the motion error, and performs trajectory tracking in a prescribed expected operating interval, which improves the effect of risk assessment.

4 Conclusions

This paper proposes a multi-modal motion reliability analysis method for cross trajectory tracking, builds a multi-modal kinematic analysis model, determines trajectory tracking motion modes, combines probabilistic motion risk assessment, and calculates multi-modal motion reliability. The designed multi-modal motion reliability analysis method is applied to it, and a good application effect is obtained. The reliability analysis model and solution algorithm proposed in this paper are suitable for the motion reliability analysis of the trajectory mechanism, and can reflect the overall motion of the mechanism in a comprehensive and intuitive way.

However, the multi-modal motion reliability analysis method only designs and analyzes the reliability of the four motion modes of the robot. In addition, the robot can also implement other motion modes such as rolling, sitting and lying. Therefore, in the future research, more motion modes need to be fully considered and the trajectory planning research of robots under uncertainty should be carried out.

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