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Optimal Analysis of Performance Improvement Strategy for Mechanical System Assembly Process Based on Fault Tree Model

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ABSTRACT The assembly quality of the mechanical product has a significant effect on its performance. The assembly process of the mechanical product is analyzed and optimized in this paper, then the goal of the product performance improvement is achieved by using the minimum cost. Firstly, decomposing the structure of the mechanical system by the ''Function-Motion-Action'' (FMA) decomposition method and the meta-actions are obtained. Then, the reason of the mechanical system performance failure is analyzed at the meta-action level and a modular fault tree model is established. Secondly, all BEs and MCSs that leading to the mechanical system performance failure are obtained through FTA, and an optimization model that considering mechanical system assembly performance index and cost is established combining cost-failure rate function relationship. Finally, using the optimization algorithm to solve the problem, and the optimal performance improvement strategy under a given performance index is obtained. The proposed method is used to optimize and analyze the performance improvement strategy of the assembly process of the computer numerical control (CNC) machine tool turntable system to obtain the optimal performance improvement strategy. The goal of improving the assembly quality of mechanical products can be achieved at the lowest cost by the optimal strategy. The method can effectively guide the production process of the mechanical product, save the produce cost and improve the assembly quality.

INDEX TERMS Meta-action, performance optimization, fault tree analysis, assembly process optimization, optimization algorithm.

I. INTRODUCTION

With the structure of mechanical system becoming more and more complex, the robustness of product performance has attracted. The performance of mechanical system is affected by many factors, including tolerance design, manufacturing accuracy of parts, assembly quality of product, working environment and human factors. In order to improve the performance of the mechanical product, a lot of research work have been done on the product tolerance design process. Zhang *et al.* [1] established a robust tolerance design method model that considering the relationship between performance, cost, design parameter and tolerance, and realized the optimal design of tolerance. Cheng *et al.* [2] proposed a new robust analysis method based on axiomatic design principle, which select the best design scheme by establishing the evaluation mechanism of the design scheme. Sun *et al.* [3] studied the effect of joint clearance and parameter uncertainty on the motion accuracy of mechanical systems, and proposed a multi-objective robust optimization method to reduce the effect. Huang *et al.* [4] proposed a structural tolerance design method of joint clearance generation function, which achieved the minimum total assembly cost and the best performance by determining the tolerance of the optimal design parameter. Yuan *et al.* [5] established a design reliability model considering manufacturing cost, quality loss and optimal tolerance allocation of assembly to achieve the optimal tolerance design under the lowest manufacturing cost and quality loss.

The effects of uncertain factors on the performance of mechanical system are reduced by implementing optimum design measures for tolerance robustness. However, the

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performance of the mechanical product needs to be guaranteed by the assembly process, and the quality in practical production and assembly process will have a significant effect on the function and performance of the product [6]–[9]. Therefore, some scholars have studied the assembly process of mechanical product to improve the quality of assembly process and achieve the goal of performance robustness and reliability. Andolfatto *et al.* [10] studied the problem of assembly process selection and geometric tolerance allocation of parts, and proposed a new method of computer aided assembly process planning to achieve the goal of minimizing assembly cost and maximizing product quality. Shao *et al.* [11] established a data-driven model of collaborative manufacturing system that considering geometric and physical properties, and carried out multi-objective optimization to the improved machine settings. He and Liu *et al.* [12] proposed a risk-oriented health assessment method and predictive maintenance strategy for assembly system to manage the health of the assembly system. Yin *et al.* [13] combined Rackwitz Fiessler analysis method with surrogate method to analyze and optimize the assembly process of landing gear, which improved the quality of product assembly and reduced the cost. He *et al.* [14] proposed a risk-oriented assembly quality analysis method that considering the impact of assembly changes on product reliability decline and accident risk, and the method could ensure the product assembly quality by identifying the risk source in the assembly process, necessary quality control measures and quality improvement activities. In view of the potential risks caused by the increasing complexity of manufacturing systems, Han *et al.* [15] proposed a task reliability-driven health assessment method. Li *et al.* [16] ensured the quality of product assembly process by identifying and controlling the key quality factors of assembly process under multi-source uncertainty. Liu *et al.* [17] proposed a reliability evaluation method which combines the process performance and product quality of hybrid assembly system, which generated more value on the premise that the system status and product quality are guaranteed. Although many research papers have studied assembly quality, cost and reliability, few studies focused on product performance improvement and cost optimization in assembly process.

Analyzing and optimizing the mechanical product to achieve low cost and high reliability, but only the function of the product can be guaranteed. However, the performance of the mechanical product is equally important in the actual production process. For example, in the working process of computer numerical control (CNC) machine tool, it is necessary to ensure that it can work normally and complete the prescribed function, but also to ensure that the precision of the product processed meets the requirement, so the former is the function of it and the latter is the performance. Consequently, the Fault Tree Analysis (FTA) method is used to analyze the performance failure of mechanical product in this paper to find out the reasons that lead to the instability of the product performance in assembly process. Then, determines the failure rate, improvement measures and cost of the basic event(BE) that lead to the performance failure based on historical data and optimize the assembly process of product by using the optimization algorithm. Finally, the performance improvement strategy with minimal cost is found. This paper is organized as follows: Section II proposes a modular fault tree modeling method based on the ''Function-Motion-Action'' (FMA) decomposition method, and an optimization method of mechanical product performance improvement strategy that considering cost minimization is proposed in Section III. The effectiveness of the proposed method is verified by practical engineering example in Section IV. Finally, a conclusion is summarized in Section V.

II. STRUCTURAL DECOMPOSITION AND FAULT TREE MODELING

A. ''FMA'' DECOMPOEITION METHOD

In order to analyze the reasons of the performance failure of the mechanical system, it is necessary to decompose the structure of mechanical system firstly. Zhang and Ran *et al.* [18]–[21] proposed a structural decomposition method of FMA. Compared with the traditional decomposition method for the mechanical structure, the FMA method decomposes the mechanical system into several series connected meta-actions. The performance of the product is realized by the performance of each meta-action unit and the connection between meta-actions, and the assembly quality of a single part has a direct impact only on the meta-action unit in which it is located. Therefore, decomposing the structure of the mechanical system by FMA decomposition method and analyzing of the reasons of mechanical system performance failure at meta-action level. By this way, the modular analysis of mechanical structure is realized, which reduces the difficulty and complexity of the analysis [21]. The detailed process of the FMA decomposition method is shown in Fig. 1.

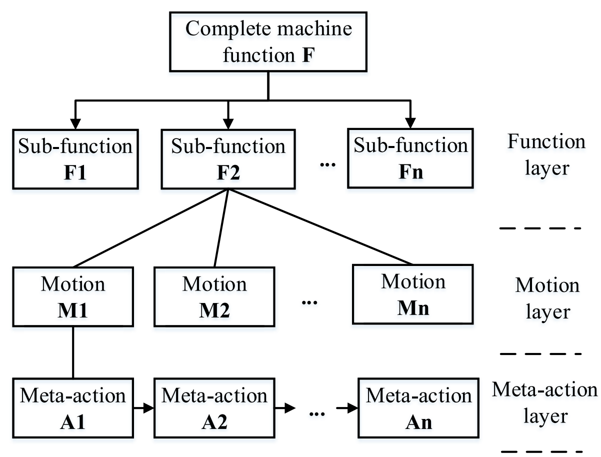

FIGURE 1. FMA decomposition method.

B. FAULT TREE ANALYSIS

Fault tree is a special inverted logic causality diagram, which was developed by Bell Telegraph Telephone Laboratory in 1962, and it has become a powerful tool in the study of system reliability, security and risk [22].

Fault tree takes an undesirable product failure or catastrophic dangerous event, namely top event (TE), as the object of analysis to find all basic events (BE) that will lead to the occurrence of the TE by strict hierarchical fault causal logic analyzing from top to bottom. Between the TE and the BE are the intermediate events (IE). Finally, the logical relationship among TE, IE and BE is connected by logic gates ("AND gate" or "OR gate"), and the logical block diagram is drawn to form the FTA model [23], [24].

In the logic structure of the fault tree, TE is connected with all BEs ($X_i, i = 1, 2, \ldots, N$) through logic gates and IEs, where X_i represents the $i-th$ BE and N represents the number of BE. P_i denotes the failure rate of the X_i and P^{TE} denotes the failure rate of the TE. Thus, when all logic gates in the fault tree are "AND gate" or "OR gate", the failure rate of the TE is:

$$P^{TE} = \begin{cases} \prod_{i=1}^{N} P_i & for\ \ AND\ \ gate \\ 1 - \prod_{i=1}^{N} (1 - P_i) & for\ or\ gate \end{cases} \tag{1}$$

FTA is to qualitatively find out the possible causes of the TE and find the Minimum Cut Sets (MCS) which are minimal, necessary and sufficient conditions for the occurrence of the TE. Using binary decision graph to analyze the fault tree and determine all MCS, M_i, ($i = 1, 2, \ldots, N_k$) denotes the $i - th$ MCS, where N_k is the number of the MCS [25], [26]. Hence, the failure rate of the TE can be calculated as follows:

$$P^{TE} = 1 - \prod_{i=1}^{N_k} \{1 - P(M_i)\} \tag{2}$$

where $P(M_i)$ denotes the failure rate of the M_i. MCS is a combination of BE, which can be expressed as:

$$M_i = \{X_1, X_2, X_3, \ldots X_m\} \tag{3}$$

where $X_i \in (X_1, X_2, \ldots, X_N)$, $1 \le m \le N$. m is not only the number of BEs in M_i but the order of it, then the maximum order of MCS is N and the minimum is 1.

C. MODULAR FAULT TREE MODELING

Decomposing the structure of the mechanical system by FMA method, and FTA is carried out at the level of meta-action to realize modular fault tree modeling. Modular fault tree only reconstructs modules and not only does not change the original structure of the fault tree but also does not introduce BE of other tree [26]. Then, the modular fault tree for the performance failure of mechanical system is established, as is shown in Fig.2. The sub- fault tree model is utilized to analyze the performance failure of the meta-action unit and the whole machine, which improves the efficiency of the fault tree modeling and analysis.

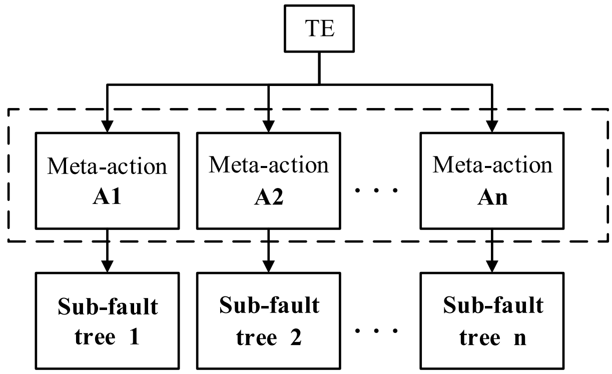

FIGURE 2. Modular FTA.

III. PERFORMANCE OPTIMIZATION ANALYSIS

A. COST-FAILURE RATE ANALYSIS

All BE and MCS are obtained by FTA. The BE is improved to reduce the failure rate by analyzing the failure mechanism, then the performance of the whole system is improved. However, the cost of improvement and the impact on the performance of the whole system are different due to the different character of each BE, so the goal of the whole system improvement can be achieved by improving a limited number of BE.

Selecting the appropriate BE to improve the performance of the whole system, thus there has a variety of selection strategies, E_j denotes the $j - th$ improvement strategy:

$$E_j = \{X_1, X_2, \cdots X_i, \cdots, X_D\}, \quad D \le N \tag{4}$$

where D denotes the number of BE. C_i is the cost of X_i that included in the improvement strategy E_j, and C_i relates to the failure rate of X_i and is a function of the failure rate P_i [27]:

$$C_i = f_i(P_i), \quad (i = 1, 2, \ldots, DD \le N) \tag{5}$$

P_i denotes the failure rate of X_i and f_i denotes the "cost-failure rate" function of X_i. Then, the total cost of the improved strategy E_j is:

$$C_J^T = \sum_{i=1}^{D} C_i, \quad D \le N \tag{6}$$

Thus, we can obtain the total failure rate P_j^{TE} and total cost C_j^T of the improvement strategy E_j, they are the functions of the failure rate of BE, that is:

$$\begin{cases} C_J^T = F_1(P_1, P_2, \ldots, P_n) \\ P_J^{TE} = F_2(P_1, P_2, \ldots, P_n) \end{cases} \tag{7}$$

B. ESTABLISHMENT AND SOLUTION OF OPTIMAL MODEL

According to analyze the modular fault tree and the relationship between the cost and failure rate in the process of assembly of mechanical system, the optimization model of cost-failure rate for assembly process of mechanical system is established as follows:

$$\begin{aligned} \min \quad & C_J^T = F_1(P_1, P_2, \ldots, P_n) \\ s.t. \quad & P_J^{ET} = F_2(P_1, P_2, \ldots, P_n) \\ & P_i^L < P_i < P_i^U, \quad i = 1, 2, \ldots, n \end{aligned} \tag{8}$$

where P_i^L and P_i^U denote the endpoint values of cost-failure rate function of BE, respectively. The important meaning of formula (8) is: "given a failure probability of the TE, find the appropriate improvement strategy that make the total cost minimum". Now the failure rate of BE is interval value, and the failure rate interval of the whole system can be calculated [28]:

$$P_{\min}^{ET} \le P^{ET} \le P_{\max}^{ET} \tag{9}$$

Formula (8) is a typical single objective optimization problem. Many swarm intelligence optimization algorithms can solve this problem, such as genetic algorithm(GA), ant colony optimization(ACO) algorithm, immune algorithm(IA), particle swarm optimization(PSO) algorithm and so on [29]–[35].

C. COMPUTATIONAL PROCEDURE

To sum up, the flow chart of the proposed method in this paper is shown in Fig. 3:

Step 1: Determining the performance improvement and optimization problem for the assembly process of the mechanical system.

Step 2: Decomposing the structure of the mechanical system by FMA method and the meta-actions are obtained.

Step 3: Analyzing the reason of the mechanical system performance failure at the meta-action level and a modular fault tree model is established.

Step 4: Obtaining all BE and MCS that leading to the mechanical system performance failure through FTA, and establishing an optimization model that considering mechanical system assembly performance index and cost.

Step 5: Using optimization algorithm to solve the problem and the optimal performance improvement strategy under a given performance index is obtained.

Step 6: Outputting the optimal strategy.

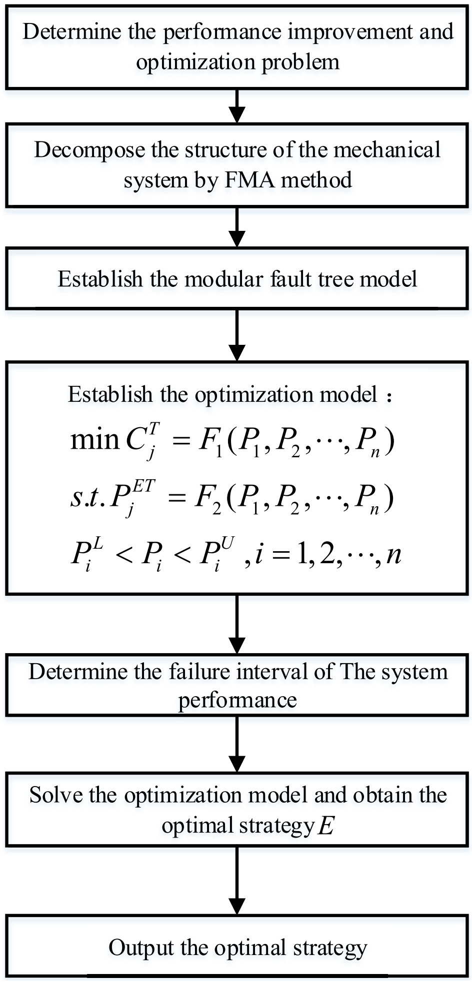

FIGURE 3. The flowchart of the proposed approach.

IV. ENGINEERING EXAMPLE

The motion performance of the turntable system for CNC machine tool affects the processing accuracy of parts directly and the assembly process of turntable system has a significant effect on its performance. Through analysis of the after-sales service records of the turntable system manufacturer in recent years, the failures of the turntable system are mainly focused on the performance failures such as abnormal noise, vibration, unstable rotation, unstable positioning accuracy, and functional failures such as unable to rotate, oil leakage and braking failure. The reasons of the performance failure for the turntable system include: unstable output power of the motor, control system problem, quality reason of the parts, assembly quality reason, wrong operation of users and abnormal wear of parts etc. Through analysis of the customer service records, 70% of the performance failures are caused by the quality of assembly process. Therefore, this paper only research on the performance improvement and optimization of the turntable system assembly process without considering unstable output power of the motor, control system problem, quality reason of parts, wrong operation of users and abnormal wear of parts etc.

The structure diagram of the turntable system for CNC machine tool is shown in Fig. 4, the mechanical part is mainly composed of box, motor gear, middle gear, worm, worm gear and worktable etc. The working process of the turntable system is as follows: firstly, the motor shaft output torque to drive the motor gear to rotate; secondly, the middle gear and the motor gear mesh to drive the worm to rotate; thirdly, the worm and the worm gear mesh to drive the worm gear to rotate; finally, the rotary motion of the worktable is realized because it is fixed together with the worm gear.

A. FMA DECOMPOSITION

Through analysis the composition of the structure of the turntable system for CNC machine tool, combining with its

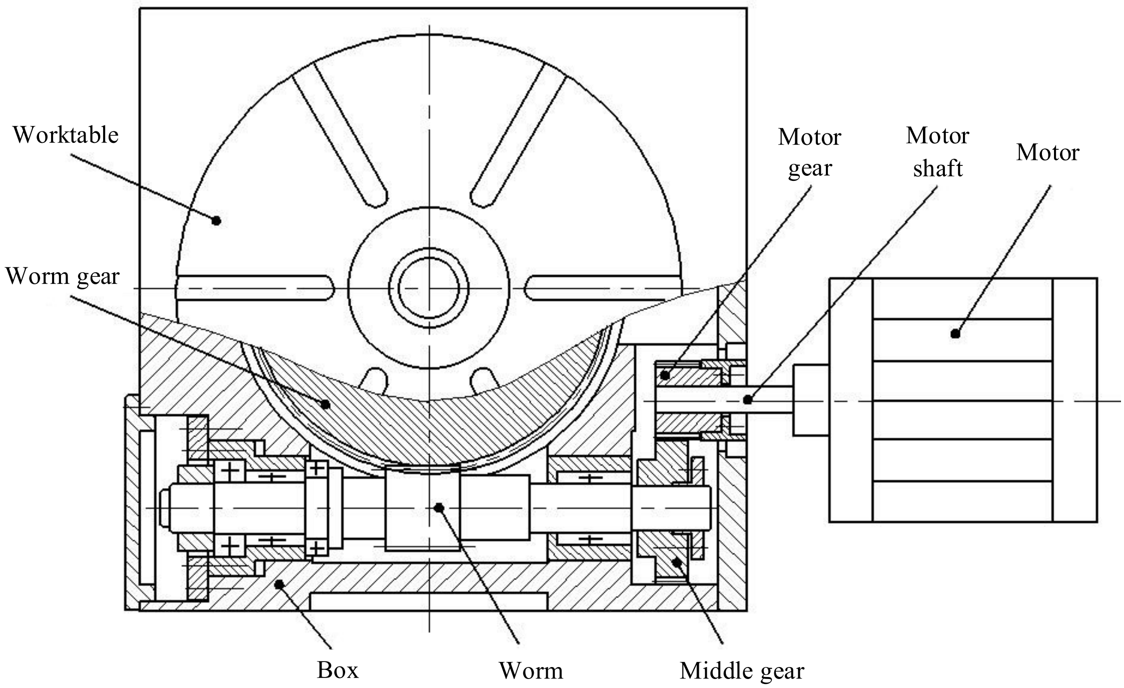

FIGURE 4. Structural diagram of turntable system.

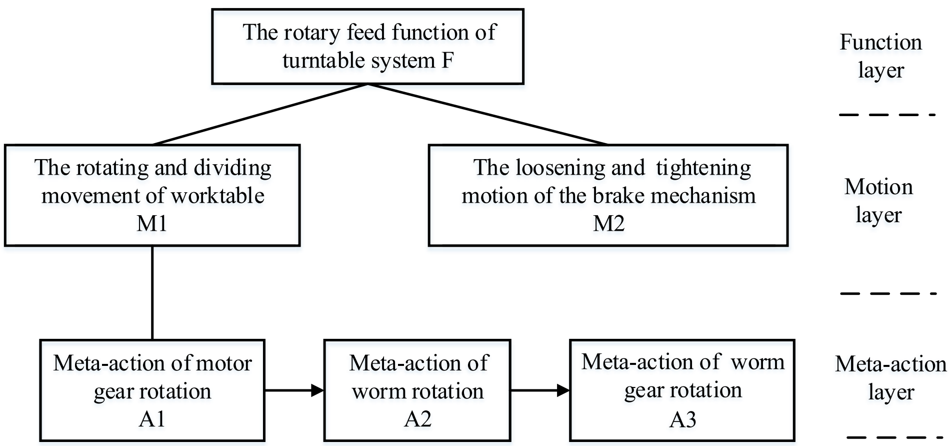

FIGURE 5. FMA decomposition of the turntable system.

main functions in the actual working process and the way to realize, the turntable system is divided into functional layer, motion layer and meta-action layer by FMA method which is shown in Fig.5.

(1) Function layer: the main function of the turntable system is to realize the rotary feed movement accurately and stably in the working process of CNC machine tool. Then, function layer is the rotary feed function of the turntable system (F).

(2) Motion layer: The main motion of the turntable system is the rotating and dividing movement of the worktable (M1) and the loosening and tightening motion of the brake mechanism (M2). The assembly of the mechanical system is only studied in this paper, but brake mechanism is mainly controlled by hydraulic and electronic control system, so only the rotating and dividing movement of the worktable (M1) is studied.

(3) Meta-action layer: The worktable performs continuous or dividing feed motion, and it was decomposed into three meta-actions: motor gear rotation (A1), worm rotation (A2) and worm gear rotation (A3).

B. MODULAR FAULT TREE MODELING

Establishing the modular FTA model of performance failure for the turntable system by analyzing the enterprise after-sales service data and the assembly process technology of

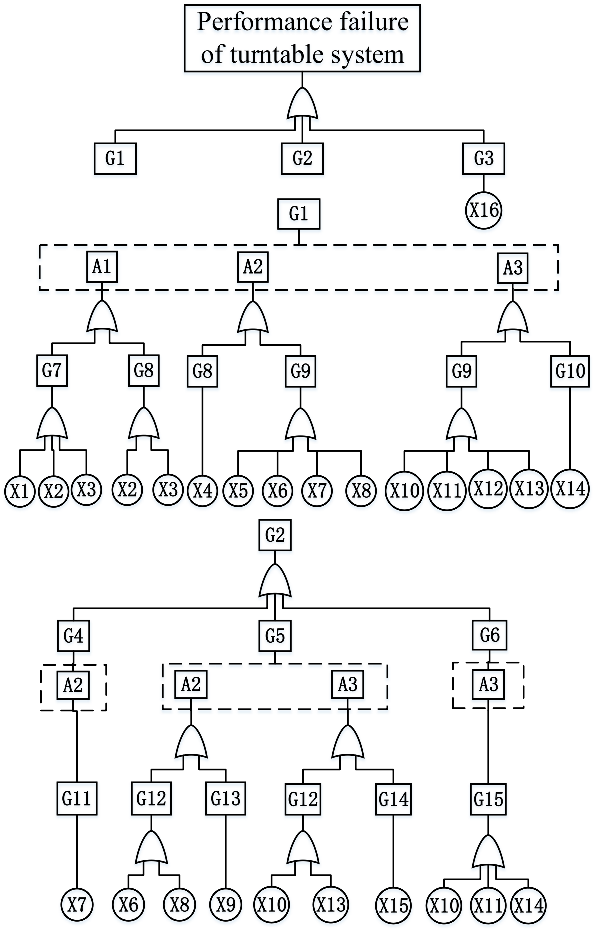

FIGURE 6. **The modular FTA model for turntable system.**

the production. The modular FTA model of the performance failure for the turntable system is shown in Fig. 6, and the meaning of symbol in the fault tree is shown in Table 1.

C. ESTABLISH THE OPTIMIZE MODEL

Above all, 16 BE and 16 MCS are obtained by the modular FTA of the performance failure for the turntable system. Table 2 shows the failure rate of each BE in the assembly process of the turntable system, the failure rate after improving and the cost of the improvement. Both the failure rate and the cost information come from data collection of the production process, after-sales service and the judgment of relevant technicians who based on their experience. The cost unit is in USD in the data that have been used.

According to the modeling method in Section III and the cost-failure rate information of BE, the optimization model of the assembly process performance of the turntable system is established as follows:

$$\begin{aligned} \min \quad & C^T = \sum_{i=1}^{16} C_i * S_i \\ s.t. \quad & P^{ET} = 1 - \prod_{i=1}^{16} \left\{ 1 - \left[P_i^L * (1 - S_i) + P_i^U * S_i \right] \right\} \\ & P_i = P_i^L or P_i^U, i = 1, 2, \ldots 16; S_i = 0 or 1 \end{aligned} \tag{10}$$

In the optimization problem, only two endpoint values of the cost-failure rate function are analyzed for each BE, so the failure rate and cost of BE include two cases. C^T denotes the minimum cost and P^{ET} denotes the performance failure rate of the turntable system. When $S_i = 1$, means improving X_i, the failure rate is P_i^U and the cost is C_i; if $S_i = 0$, means there is no improvement about X_i, the failure rate is P_i^L and the cost is zero.

D. SOLVE THE OPTIMIZATION MODEL

GA and PSO algorithm are stochastic search and optimization technology, which can quickly and accurately search the global optimal solution of a single objective and multi-objective especially when the constraint function is non-differentiable or discontinuous [29], [30], and they are very suitable for solving the optimization problem of Formula 10. GA has excellent global optimization ability but it converges slowly compared with PSO algorithm. However, the PSO algorithm is easily trapped in the local optimum and appeared premature convergence, which results in inaccurate of the optimization result. GA-PSO algorithm combines the advantages of the above two algorithms, which not only enhances the ability of searching for globally optimal, but also improving the convergence rate [35]. Then, the computational performance of the above algorithms is compared. When the target interval of the performance failure rate of the turntable system is [6.5%, 7.5%], the GA and GA-PSO algorithm are used to solve the optimization problem respectively. The convergence process of the two algorithms is shown in Fig. 7, and the optimization results are shown in Table 3.

As is shown in Fig. 7, the performance of the GA-PSO algorithm is obviously better than that of GA. The optimization results of the two algorithms are listed in Table 3 ("•" means improving BE, "∘" means there is no improvement about BE). The results of the two optimization algorithms are the same, but the number of generations of GA-PSO algorithm is significantly less than that of GA, which has excellent global optimization ability and fast convergence speed.

The performance failure rate for the turntable system is divided into 13 intervals, and the GA-PSO algorithm is used to optimize the solution of formula (10). The optimal performance improvement strategy and the failure rate value of this problem are obtained in each failure rate interval, and the strategy has the minimum cost for the improvement. Then, the optimization results are shown in Table 4.

E. RESAULTS AND DISCUSSIONS

As is shown in Table 4, the optimal performance improvement strategy in each failure rate interval can be achieved by using the optimization model, and the performance failure value and cost of the strategy are also obtained. For example, when the target interval of the performance failure rate of turntable system is [6.0%,6.5%], the performance improvement strategy is [• • • • ∘ • • • ∘ • ∘ ∘ ∘ ∘ ∘∘],

TABLE 1. The meaning of symbol in the fault tree.

	Symbol	Description	Symbol	Description
Meta-action	A1	Performance failure of motor gear rotation	A3	Performance failure of worm gear rotation
	A2	Performance failure of worm rotation	-	-
	G1	Abnormal vibration and noise of turntable	G9	Large clearance between worm and worm gear
	G2	Unstable rotation of the worktable	G10	Interference between worktable and box
	G3	Inaccurate of worktable reset	G11	Axial vibration of the worm
	G4	Vibrating of the worktable	G12	Small clearance between worm and worm gear
IE	G5	Creeping rotation of the worktable	G13	Worm rotation is inflexible
	G6	Worktable run-out error beyond the standard	G14	Worm gear rotation is inflexible
	G7	Interference between motor gear and box	G15	Installing accuracy of worktable beyond the standard
	G8	Large clearance between motor gear and middle gear	-	-
	X1	Unreasonable pre-tightening of motor gear	X9	Excessive pre-tightening force of worm bearing
	X2	Inaccurate positioning of the motor	X10	Unreasonable grinding of the worm gear adjusting disc
	X3	Pre-tightening of motor gear tensioning sleeve is not in place	X11	Installing accuracy of worm gear bearing beyond the standard
	X4	Pre-tightening of middle gear tensioning sleeve is not in place	X12	Preload of the worm gear is not up to standard
BE	X5	The concentricity of worm bearing beyond the standard	X13	Unreasonable of assembly clearance between the worm gear and worm
	X6	Unreasonable grinding of the worm adjusting disc	X14	Pre-tightening force for worktable installation not up to standard
	X7	Insufficient axial preloading of worm	X15	Excessive pre-tightening force of worm gear bearing
	X8	Worm bearing positioning beyond the standard	X16	Installation position deviation of the zero-touch-block

TABLE 2. The cost-failure rate information of be.

BE	P_i^L (%)	P_i^U (%)	Cost (10^3)	BE	P_i^L (%)	P_i^U (%)	Cost (10^3)
X1	0.8403	0.4215	0.42	X9	0.3514	0.1757	0.83
X2	1.6531	0.5510	0.76	X10	1.3861	0.4560	1.30
X3	0.8329	0.4165	0.35	X11	0.3528	0.1764	1.50
X4	0.7589	0.3795	0.46	X12	0.2316	0.1158	0.60
X5	0.6829	0.3415	0.80	X13	0.5165	0.2583	1.10
X6	1.2639	0.4213	1.20	X14	0.6536	0.3268	0.73
X7	0.6546	0.3273	0.65	X15	0.3277	0.1639	0.92
X8	0.5102	0.2551	0.72	X16	0.2643	0.1322	0.21

TABLE 3. The optimization results of the two algorithms.

Algorithm	Optimal performance improvement strategy																Cost (10^3)	Number of generations
	X1	X2	X3	X4	X5	X6	X7	X8	X9	X10	X11	X12	X13	X14	X15	X16		
GA	●	●	●	●	○	○	●	○	○	●	○	○	○	○	○	○	3.94	175
GA-PSO	●	●	●	●	○	○	●	○	○	●	○	○	○	○	○	○	3.94	92

it means the performance improvement goal can be achieved by improving $X1$, $X2$, $X3$, $X4$, $X6$, $X7$, $X8$ and $X10$ in the assembly process, at this time the failure rate is 6.40% and the cost is 5.86×10^3 USD. When the target interval of the performance failure rate for turntable system is [9.0%, 9.5%], the performance improvement strategy is [○ ● ● ○○ ○ ○ ○ ○ ○○ ○ ○ ○ ○ ○], it means the performance improvement goal can be achieved by only improving the $X2$ and $X3$ in the assembly process, at this time the failure rate is 9.33% and the cost is 1.11×10^3 USD.

TABLE 4. Optimization results.

Failure rate interval (%)	P^{ET} (%)	Optimal performance improvement strategy																Cost (10^3)
		X1	X2	X3	X4	X5	X6	X7	X8	X9	X10	X11	X12	X13	X14	X15	X16	
[4.5, 5.0]	4.97	●	●	●	●	●	●	●	●	●	●	○	●	●	●	●	●	11.05
[5.0, 5.5]	5.48	●	●	●	●	●	●	●	●	●	●	○	○	○	●	○	●	8.43
[5.5, 6.0]	5.97	●	●	●	●	○	●	●	●	○	●	○	○	○	●	○	●	6.80
[6.0, 6.5]	6.40	●	●	●	●	○	●	●	●	○	●	○	○	○	○	○	○	5.86
[6.5,7.0]	6.95	●	●	●	●	○	●	○	○	○	●	○	○	○	○	○	○	4.49
[7.0,7.5]	7.43	●	●	●	●	○	○	●	○	○	●	○	○	○	○	○	○	3.94
[7.5,8.0]	7.97	●	●	●	○	○	○	○	○	○	●	○	○	○	○	○	●	3.04
[8.0,8.5]	8.48	●	●	●	●	○	○	○	○	○	○	○	○	○	○	○	●	2.20
[8.5,9.0]	8.95	●	●	●	○	○	○	○	○	○	○	○	○	○	○	○	○	1.53
[9.0,9.5]	9.33	○	●	●	○	○	○	○	○	○	○	○	○	○	○	○	○	1.11
[9.5,10.0]	9.71	○	●	○	○	○	○	○	○	○	○	○	○	○	○	○	○	0.76
[10.0,10.5]	10.34	○	○	●	○	○	○	○	○	○	○	○	○	○	○	○	○	0.35
[10.5,11.0]	10.71	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	0.00

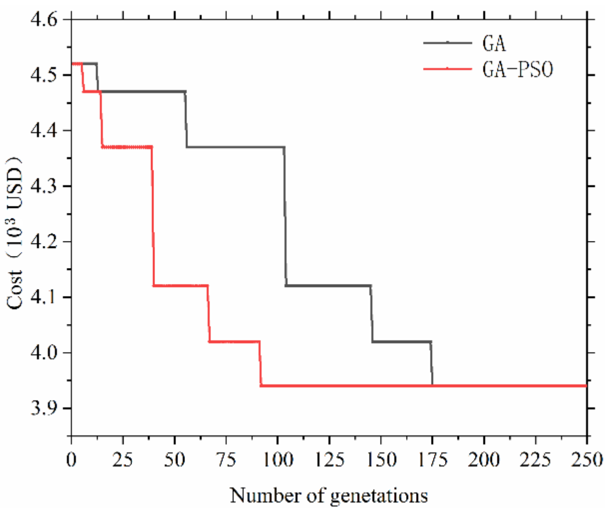

FIGURE 7. Convergence process of the two algorithms.

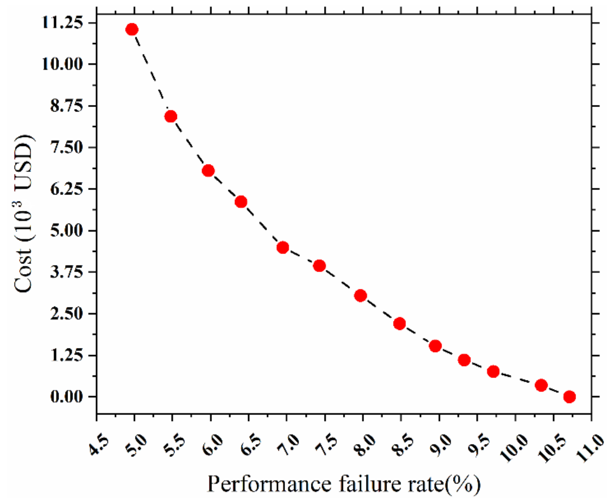

FIGURE 8. The relationship between cost and performance failure rate.

The relationship between the performance improvement cost and the performance failure rate of the turntable system is illustrated in Fig.8. Therefore, the optimal performance improvement strategy can always be found in each failure rate interval to ensure that the performance indicators meet the requirement while minimizing the cost. With the number of performance failure rate intervals increasing, the relationship between the performance improvement cost and the performance failure rate will agree with the dotted line. Hence, in the actual assembly process of the mechanical system, the optimization method that proposed in this paper is used to achieve the goal of the assembly quality of the mechanical product with the least cost and realizing the optimal allocation of enterprise resources.

V. CONCLUSION

In this paper, an optimization analysis method of the performance improvement strategy for the mechanical system assembly process that based on FTA is proposed. Firstly, decomposing the structure of the mechanical system by the FMA decomposition method and the meta-actions are obtained. Then, the reason of the performance failure for mechanical system is analyzed at the meta-action level and a modular fault tree model is established. The meta-action act as the smallest unit of FTA, which accords with the produced mechanism of the mechanical product failure and improves the efficiency and accuracy of the FTA. All BE and MCS that leading to the performance failure of the mechanical system are obtained through FTA. And an optimization model that considering the mechanical product assembly performance index and cost is established combining cost-failure rate relationship. Using optimization algorithm to solve the problem, and the optimal performance improvement strategy under a given performance index is obtained. The effectiveness of the proposed method is illustrated by the turntable system of CNC machine tool. However, the example in this paper only considers the endpoint value for the cost-failure rate function, the cost-failure rate function relationship also can be discrete or continuous.

The proposed method has guiding significance for the production process of the mechanical product, which can achieve the performance improvement goal at minimum cost and conducive to the optimal allocation of resources. In the process of solving the optimization model, the GA-PSO algorithm that with higher computational efficiency is used by comparing the performance of GA and GA-PSO algorithm. In the future, other state-of-the-art algorithms will be used to further improve the efficiency and accuracy of optimization analysis. However, only the assembly process is studied in this paper, the control system and parts wear also have important effects on its performance. Later, these factors will be further studied to improve the performance of the mechanical product.

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