

## Research Article

# Multiobjective Optimization Design of Truss Antenna

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During the design and manufacturing process of the truss antenna, the surface accuracy of the truss antenna is inherently affected by tolerance. An appropriate optimal design of the truss antenna structure is important to improve surface accuracy. In order to receive the optimal design of the truss structure, this paper adopts the multiobjective optimization algorithm based on an approximate model to optimize the tolerance model with random error. Firstly, considering the influence of the processing and assembly errors of the members on the surface accuracy of the structure, the equilibrium state equation of the truss is established by the principle of minimum potential energy. Then, the relationship between the tolerance and the surface accuracy is obtained by the Monte Carlo method. For improving the computing efficiency of the Monte Carlo method, an approximate model of the truss antenna unit is established, where the rod length tolerance is set as the design variable, and the truss surface accuracy and processing cost are set as the objective functions. Finally, tolerance optimization is carried out by using the multiobjective genetic algorithm. The results indicate that the Pareto solution is obtained with an error less than 10%. Moreover, a set of solutions of the tolerance are obtained which can meet different antenna design requirements. And the results show that the influence of the web rod is significantly greater than that of the bottom rod on the surface accuracy of the structure.

## 1. Introduction

With the development of aerospace technology, the truss antenna has been successfully used in many aerospace missions due to its high storage ratio, high stiffness, and good deployment stability [1–3], for example, the “Mir” space station, the HJ-1-C satellite, and the Beidou navigation satellite. The truss antenna is composed of several essential truss elements, such as tetrahedron [4], quadrangular pyramid [5], hexagonal prism [6], and hexagonal pyramid [7]. Since the truss element is directly connected to the reflective surface, the surface accuracy is closely related to the truss accuracy. Due to the large number of truss rods, the cumulative error caused by the processing and assembly error has a significant impact on the accuracy. Many scholars have conducted in-depth research on the influence of processing and assembly error, especially random errors, on the surface accuracy of the truss based on the traditional empirical method and

analogy method [8–11]. And the Monte Carlo method is also widely used for random error analysis on the surface accuracy analysis [12–16].

Sun et al. [17] analyzed the influence of the cable net manufacturing error and other factors on surface accuracy and used the Monte Carlo method to calculate the variable range of surface accuracy. Forouraghi [18] introduced a new method based on GAs, which addresses both the worst-case tolerance analysis of mechanical assemblies and robust design. Yang et al. [19] established the precision analysis model of the planar four-closed-loop deployment mechanism, which reflects the relationship between the deformation of the mechanism and the deviation of the single rod. Lin et al. [20] employed the Monte Carlo method to simulate the machining error and the multi-closed-loop mechanism clearance and analyzed the deployment error of the antenna module, without optimizing tolerances further. Deng et al. [21] employed the back propagation neural

network algorithm to establish the prediction model of the truss antenna which can analyze the truss surface accuracy, repeatability, and critical node error. Wu et al. [16] derived the sensitivity relationship between node coordinate deviation, cable force deviation, and cable length error for Astro-Mesh reflectors, which is utilized to carry out the Monte Carlo simulations quickly. The method can predict the worst surface accuracy as precisely as the traditional method but with less time consumption. Singh et al. [22] optimized the cost-tolerance design of mechanical components based on the genetic algorithm and verified two example problems with interrelated dimensional chains. Sanz et al. [23] proposed a kind of Lagrange multiplier method to optimize the total manufacturing cost bearing in mind the cost functions based on the process and summarized several cost-tolerance relation models to get comparable results. Koziel and Ogurtsov [24] and Easum et al. [25] applied the multiobjective optimization method to antenna design, which improved the efficiency of the overall optimization analysis and opened up new ideas. Li et al. [26] built a flatness-oriented model for the Highly Stowed Deployable Antenna (HSDA), and Monte Carlo simulations are implemented to obtain the sensitivity for the parameters. Yuan et al. [27–30] put forward the concept of direct root mean square (DRMS) to describe the performance of antenna reflectors and carried out the related analysis on the large deployable mesh reflectors.

The Monte Carlo method is widely used for the analysis and calculation of tolerances in the above studies. However, due to the high time consumption and low efficiency of the Monte Carlo method, it is difficult to build an efficient optimization model, making it challenging to optimize further and analyze the tolerance design. To improve the accuracy of the reflective surface of the truss antenna, it is necessary to carry out an overall optimization design for the tolerance of the truss rods to reduce the influence of random errors on the accuracy.

This paper calculates the equilibrium position based on the minimum potential energy principle for a tetrahedral truss antenna class, considering the customarily distributed errors. The surface accuracy distribution probability of the structure within the tolerance range is obtained by the Monte Carlo method, and an explicit model based on the radial basis function (RBF) approximation model is constructed to replace the calculation process of the Monte Carlo method. Finally, combined with the genetic algorithm to optimize its objective value, the Pareto solution set is obtained.

## 2. Truss Antenna Analysis

As shown in Figure 1, a type of truss antenna structure is composed of a plurality of tetrahedral elements, and each element contains four disc chucks, three base rods, and three web rods.

The truss rod deforms slightly due to tolerance-induced strains under ideal size assembly. Since the disc chuck size is small, it can be approximated as a rigid body. Due to the rods connected by the disc chuck and the included angle between the rods being fixed by the disc chuck, it is consid-

ered that the included angle remains unchanged. In the analysis, rod bending and compression deformation in the balance state should be fully considered.

**2.1. Rod Model.** Figure 2 shows the diagram of the deformation of the connection between the truss antenna rod and the disc chuck. As the disc chuck is connected with 6 bottom rods and 3 web rods, the geometric center of the disc chuck is the stitching point with the metal mesh surface. Connect the points to get a simple model of the disc chuck, which is a rigid body with 9 connection points and 1 center point.

In the local coordinate system, the rod has compression deformation and bending deformation, without considering torsional deformation. Due to the force on both ends of the rod, the bending deformation of the rod can be approximated as a bending model with one end fixed and the other free. At the same time, in order to meet the assembly requirements, it is assumed that the rod is suitable for the ideal rod length, resulting in axial deformations, and the deformation is the tolerance value. Under this initial deformation, the rod has the initial axial strain energy. When the member system is in equilibrium, the strain energy of the rod is expressed as

$$U = U_t + U_b. \quad (1)$$

The tensile and compressive strain energy is given by

$$U_t = \frac{1}{2} F \Delta l = \frac{F \Delta x}{2} = \frac{EA \Delta x^2}{2l}. \quad (2)$$

And the bending strain energy can be computed by

$$U_b = \frac{1}{2} M \theta = \frac{EI}{2l} \int_0^l \left( \frac{\pi \Delta z}{2l} \sin \left( \frac{\pi x}{2l} \right) \right)^2 dx = \frac{(\pi \Delta z)^2 EI}{16l^2}, \quad (3)$$

where  $E$  is the elastic modulus and  $A$  is the cross-sectional area of the rod.  $I$  is the moment of inertia of the cross-section while  $l$  is the length of the rod.  $F$  and  $M$  are the force and the bending moment of the rod, respectively, while  $y$  is the bending curve derivative of the rod, that is, the end bend angle.  $\Delta x$ ,  $\Delta z$  are the deformation of the rod end in the  $X$  and  $Z$  directions in the local coordinate system, respectively. Therefore, the matrix representation of strain energy is as follows:

$$U = \begin{bmatrix} \frac{EA}{2} & \frac{\pi^2 EI}{16} \end{bmatrix} \cdot \begin{bmatrix} \frac{\Delta x^2}{l} \\ \frac{\Delta z^2}{l^2} \end{bmatrix}. \quad (4)$$

**2.2. Overall Model of the Truss.** For the truss structure shown in Figure 3, a constraint equation needs to be established.

There are two types of geometric constraints, one is the angle constraint between the end of the rod and the disc chuck, and the other is the distance constraint of the connection point. In order to ensure the geometric constraints between the rod and the connecting feet of the disc chuck,

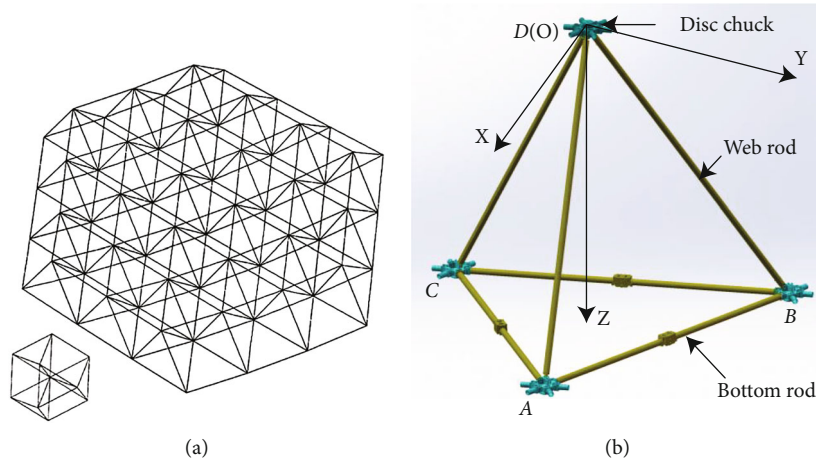


FIGURE 1: Antenna truss diagram: (a) truss antenna; (b) tetrahedral element.

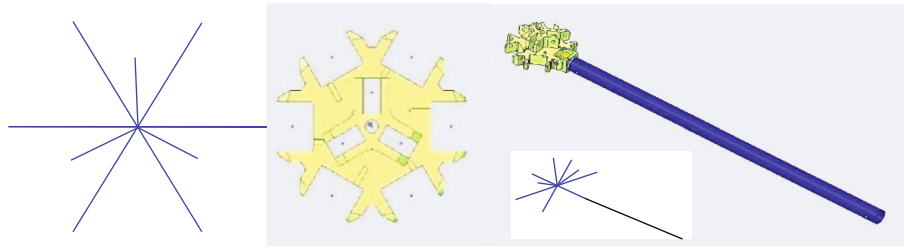


FIGURE 2: Rod deformation and disc chuck.

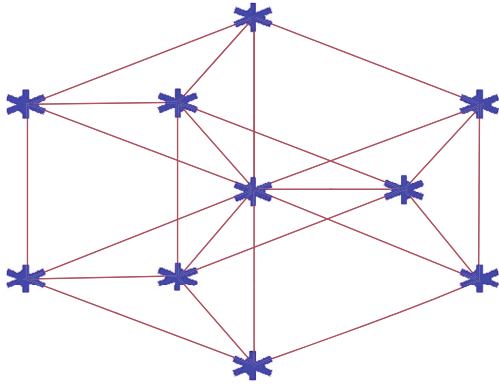


FIGURE 3: Rod deformation diagram.

there is a vector perpendicular relationship between the end normal of the bending rod and the direct line of the connecting feet of the disc chuck. The constraints are as follows:

$$\begin{aligned} g_1 &= i \cdot fx, \\ g_2 &= \|N - L\|, \end{aligned} \quad (5)$$

where  $i$  is the direction vector of the disc chuck connecting foot pointing to the geometric center of the disc chuck,  $fx$  is the normal vector of the end of the rod,  $\|N - L\|$  is the distance between the disc chuck connecting foot and the end point of the member,  $N$  is the coordinate of the disc chuck connecting foot, and  $L$  is the end coordinate of the member.

Hence, the construction of the mechanical model of the truss has been completed, and the equilibrium state can be obtained by solving the minimum value of the energy expression of the truss system.

**2.3. Surface Accuracy Solution.** According to the mechanical model of the truss antenna established above, we can solve the equilibrium position of the disc chuck. Since the reflection net is directly connected to the disc chuck, the position change of the disc chuck is used to measure the accuracy of the reflector, and the root mean square (RMS) of the disc chuck displacement in the normal direction of the reflector is used as the surface accuracy. Therefore, the expression is as follows:

$$\text{RMS} = \sqrt{\frac{1}{n} \sum_{i=1}^n \Delta_i^2}, \quad (6)$$

where  $\Delta$  is the radial deviation between the actual position of the disc chuck node and the ideal position and  $n$  is the number of disc chucks that constitute the reflective surface. By solving Equation (4), the obtained result is substituted into Equation (6) to solve the accuracy. Thus, the calculation of the surface accuracy of any tolerance value is completed. Considering the uncertainty of the actual length of the rod, the surface accuracy distribution model of the antenna under the tolerance is further constructed by the Monte Carlo method.

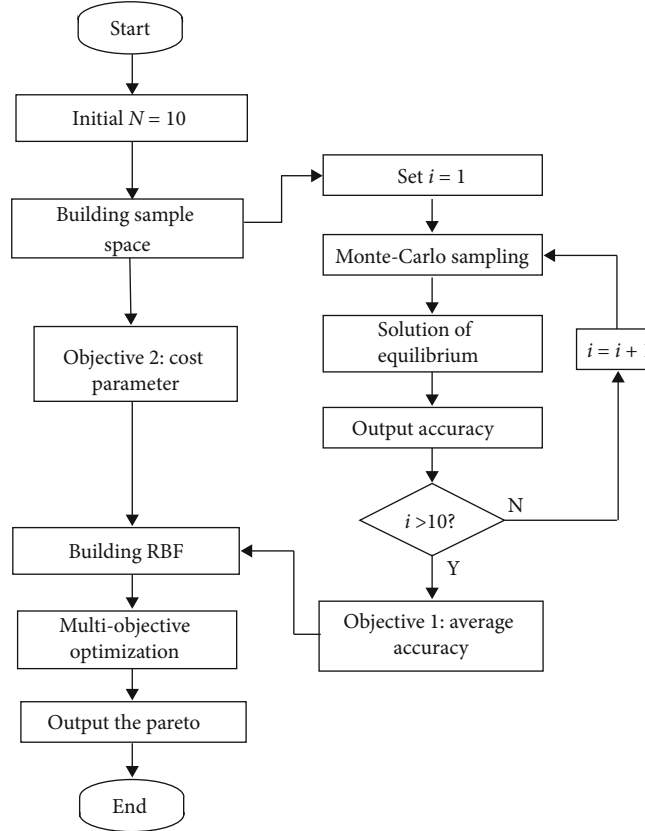


FIGURE 4: Calculation flow chart of the optimal design.

### 3. Optimization Model

The multiobjective optimization problem (MOP) consists of multiple objective functions that have constraints and contradict each other. Because there is no unified measurement standard between those objectives, it is challenging to assign weights. In recent years, intelligent algorithms have been commonly used to solve such problems. This paper employs a multiobjective genetic algorithm to solve the problem.

**3.1. Design Variable.** As shown in Figure 1, the members of the truss include two types of web rods and bottom rods. Tolerance ranges are set for two types, assuming that their tolerance ranges are symmetrically distributed. Referring to the actual processing experience, in general, the tolerances are symmetrically distributed in both directions and do not exceed 0.4 mm. The bottom rod tolerance value and the web rod tolerance value need to be set as design variable 1 and design variable 2, respectively, as shown in the following formula:

$$x_1 \in [0, 0.4] x_2 \in [0, 0.4]. \quad (7)$$

These variables are in millimeters.

**3.2. Objective Function.** The surface accuracy and cost are set as the optimization objective. Since the surface accuracy is affected by random errors, which lead to the floated accuracy, the average accuracy value is taken as objective 1. This

value is calculated by the Monte Carlo method. The smaller the average value, the higher the antenna accuracy. Considering that the size of the rods obeys the normal distribution within the tolerance range, the standard deviation is set to one-third of the tolerance value, and the mean value is 0. The normal distribution parameter is  $(0, x/3)$ , where  $x$  is the tolerance value. Objective 1 is expressed as follows:

$$f_1 = 100 \times \text{ave}(\text{RMS}), \quad (8)$$

where  $\text{ave}(\text{RMS})$  means to calculate the average value of the RMS from the Monte Carlo result.

The cost of the product is affected by different processing personnel and different processing techniques. In order to obtain a more accurate cost-tolerance model, it is necessary to obtain the relevant parameters to fit the actual statistical sample data. Scholars [31, 32] have proposed a variety of fitting methods based on different elementary functions. Currently, the commonly used fitting model curves include the exponential model and negative square model. In this paper, the relationship between processing cost and tolerance is fitted with a negative square model. Considering the confidentiality and uncertainty of the specific cost value, and to simplify the calculation, the relevant parameters in the model are set to 1. The total processing cost  $cb$  is expressed as follows:

$$cb = (a(X_i)^{-2} + b), \quad (9)$$

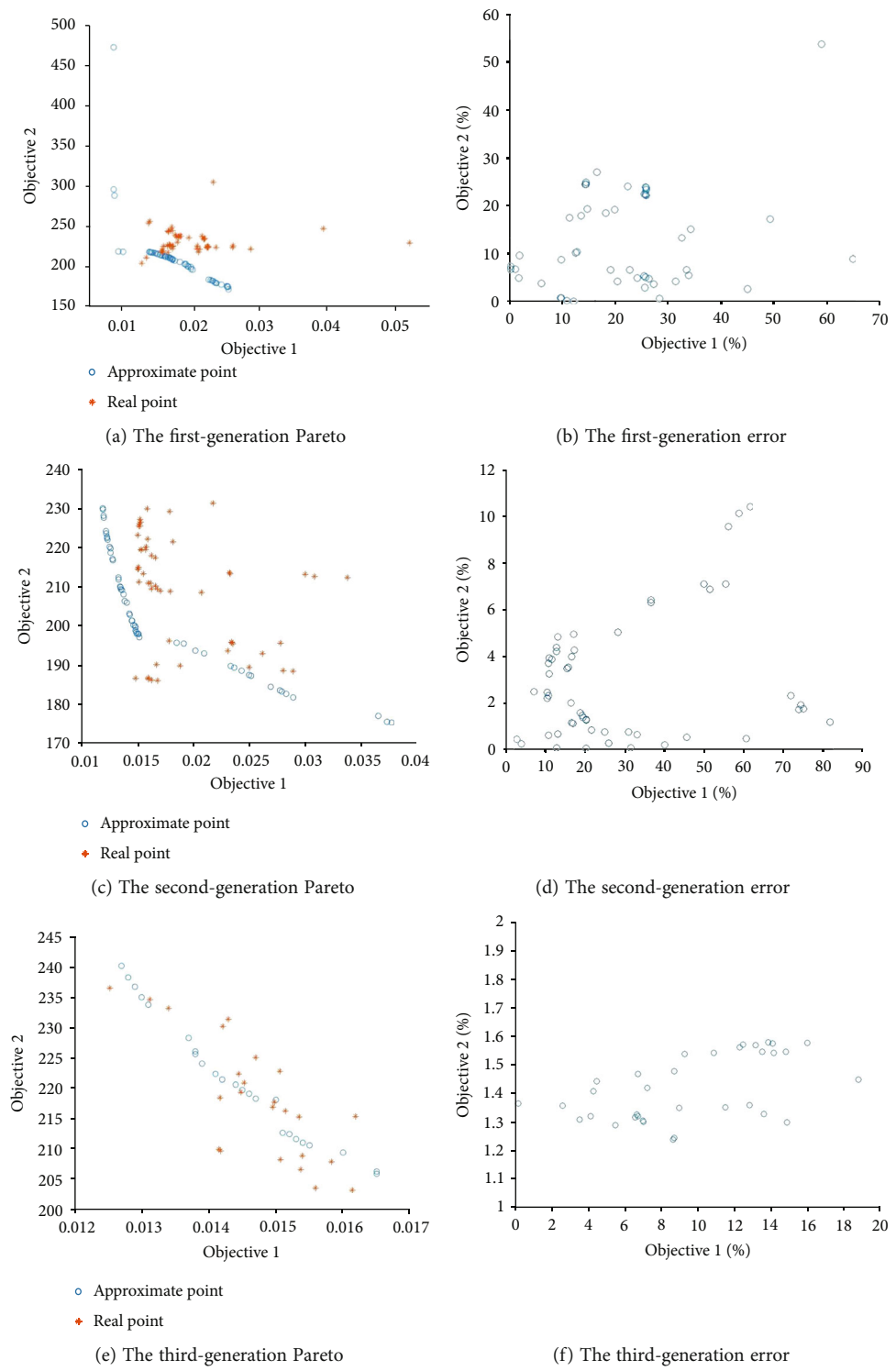


FIGURE 5: Continued.

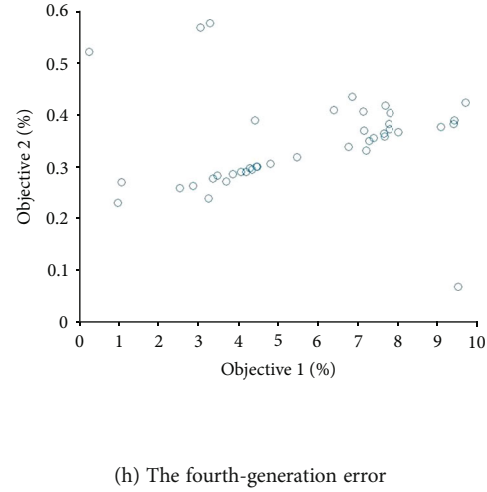
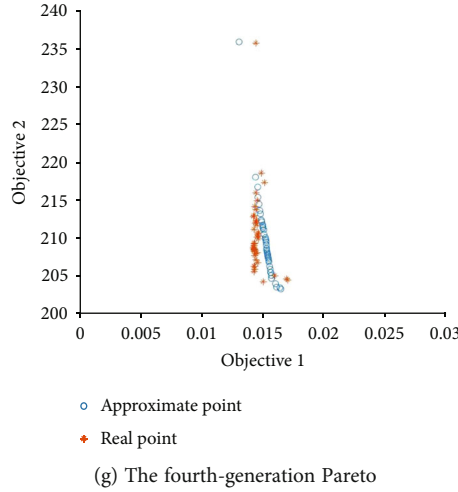


FIGURE 5: Pareto result.

where  $b$  is the fixed cost during machining, which is not affected by changes in business volume during a certain period of time.  $a$  is the cost variation coefficient caused by the tolerance change of the machined part, and  $X$  is the rod tolerance. In order to improve the computational efficiency of the objective, an approximate model is constructed for the above objectives. The approximate model is a method to complete the construction of an explicit function model based on the mapping relationship of the implicit function. The radial basis function approximation model is selected, and its expression is as follows:

$$\tilde{f}(X) = \sum_{i=1}^N h_i(\|X - X_i\|)w_i, \quad (10)$$

where  $N$  is the number of overall sample points,  $i = 1, 2, \dots, N$ ,  $X_i$  is the sample point matrix,  $\tilde{f}(X)$  is the approximation value corresponding to  $X$ ,  $h_i(\|X - X_i\|)$  is the kernel function, and  $w_i$  is the linear weighting coefficient.

**3.3. Optimization Model.** Considering the above factors, the optimization model of the truss structure can be described as

$$\begin{aligned} &\text{Minimize} \quad \left\{ \tilde{f}_1(\mathbf{X}_1, \mathbf{X}_2), \tilde{f}_2(\mathbf{X}_1, \mathbf{X}_2) \right\} \\ &\text{subjected to} \quad 0 \leq \mathbf{X}_1 \leq 0.4, 0 \leq \mathbf{X}_2 \leq 0.4 \end{aligned} \quad (11)$$

$\tilde{f}_1(\mathbf{X}_1, \mathbf{X}_2), \tilde{f}_2(\mathbf{X}_1, \mathbf{X}_2)$  is an approximation of the real function.  $\mathbf{X}_1, \mathbf{X}_2$  is the design variable. The process of the optimization algorithm is shown in Figure 4.

## 4. Optimization Results

**4.1. Initial Settings.** To simplify the calculation of the antenna truss, the length of the rod is set as 500 mm, and the total samples of the approximate model are set to 20. First, in the feasible domain of the design variables, the sample is obtained by the optimal Latin hypercube sampling method. Then, the calculation of the objective value is com-

pleted by the Monte Carlo method for each sample point. Finally, the initial construction of the optimization model is completed.

**4.2. Analysis of Optimization Results.** The multiobjective optimization genetic algorithm is set 600 times, and the model accuracy is further improved through the interpolation method. The results obtained by each generation of interpolation are shown in Figures 5(a), 5(c), 5(e), and 5(g). At the same time, the approximate value of the Pareto solution is compared with the real value. The error is shown in Figures 5(b), 5(d), 5(f), and 5(h). The interpolation method is used to update each generation, and the interpolation is four times in total.

Figures 5(a), 5(c), 5(e), and 5(g) are the distribution diagrams of the Pareto, and the horizontal axis is objective 1. Its value indicates the size of the average error, that is, the antenna surface accuracy. The vertical axis is objective 2, and its value indicates the level of the tolerance of the rod, that is, the cost of processing. Figures 5(b), 5(d), 5(f), and 5(h) are the percentage error between the approximate value and the real value, where the horizontal axis is the error of objective 1, and the vertical axis is the error of objective 2. Finally, we calculated the relationship between objective and tolerance, with accuracy and cost as the objective. In the overall truss antenna, the surface accuracy is usually between 1 mm and 3 mm. Since only one antenna unit is analyzed in this paper, the accuracy is relatively high. The above results are updated between generations by interpolation, and the points inserted in each generation are listed in Table 1.

Table 1 and Figure 5 show that the accuracy of the optimization results is improved by 2 interpolations effectively, and the final error is within 10%, of which the error of objective 2 is within 1%, which meets the initial design requirements. Figure 5(g) shows that the approximate point fits well with the real point, which can reflect the mathematical relationship between the variable and the objective. Therefore, it can obtain several sets of design points. Due to the



TABLE 1: Interpolation points.

No.	Design variable		Objective	
1	0.3546	0.2795	0.0153	258.4548
2	0.3756	0.3283	0.0148	213.8136
3	0.3367	0.3314	0.0209	238.2558
4	0.3367	0.3280	0.0195	239.9791
5	0.3375	0.3283	0.0194	239.1903
6	0.3981	0.3649	0.0168	186.2326
7	0.4000	0.3085	0.0338	212.3154
8	0.3687	0.3272	0.0142	218.3945

TABLE 2: Optimization results.

No.	×1 bottom rod tolerance	×2 web rod tolerance	f1 average precision	f2 cost
1	0.3870	0.3375	0.01613	203.15525
2	0.3672	0.3272	0.01448	219.31574
3	0.3794	0.3341	0.01540	208.85426
4	0.3680	0.3199	0.01506	222.69887
5	0.3558	0.3097	0.01253	236.36700

large number of obtained solutions, some points are selected and listed in Table 2.

Table 2 shows that if attention is paid to the high precision of the antenna regardless of the cost, the second set of design data can be selected, which has a high average accuracy of 0.01448 mm. If more emphasis is placed on cost, the first and third sets of design data can be selected, on the basis of sacrificing certain accuracy. If the accuracy and cost are considered comprehensively, there are several other sets of design data for selection, which can be further discussed according to other design requirements to meet different needs.

From the relationship between design variables and accuracy, one can conclude that the value of the web rod tolerance is often smaller than the bottom rod tolerance. In other words, the web rod tolerance has a more critical impact on the surface accuracy, so it is necessary to pay more attention to the web rod during manufacturing.

## 5. Conclusion

This paper analyzes the influence of uncertainty on the surface accuracy caused by the processing and assembly error in the space deployable antenna structure. First, the mechanical model is established based on the principle of minimum potential energy, and the precision distribution of its equilibrium state is solved by the Monte Carlo method. Then, a mathematical model between tolerance and accuracy is constructed by the radial basis function approximation model, which effectively saves the computational cost. Finally, a multiobjective optimization model is established, and the multiobjective genetic optimization algorithm is adopted to optimize and solve multiple sets of Pareto solu-

tions that meet different production requirements. The conclusion is as follows:

- (1) Under the premise of the processing and assembly error set in this paper, when the tolerances of the bottom rod and the web rod are designed as ( $\pm 0.3558$  mm,  $\pm 0.3097$  mm), they have the best average accuracy value of 0.01253 mm, which can be considered the minimum accuracy of the structure
- (2) From the relationship between design variables and accuracy, it can be concluded that the value of the web rod tolerance is often smaller than the bottom rod tolerance. That is, the influence of the web rod tolerance on the accuracy is more critical. Hence, more attention needs to be paid to the web rod accuracy during designing
- (3) The calculation process of the accuracy probability distribution based on the Monte Carlo method is simplified by the radial basis function approximation model. As a result, through the multiobjective genetic optimization method and the local interpolation method, a solution set with an average error of less than 10% is obtained, which provides a more efficient and comprehensive design scheme for the antenna tolerance design

## Data Availability

The raw/processed data required to reproduce these findings cannot be shared at this time as the data also forms part of an ongoing study.

## Conflicts of Interest

The authors declare that they have no conflicts of interest.

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