A Design Method of Steering Gear Transmission Mechanism Based on Multi-objective Particle Swarm Optimization

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Abstract. Transmission device is a requisite part of the design of steering gear structure, the design process mainly aimed at transmission accuracy and structural stress characteristics and other objectives to optimize. In the traditional ways, the single objective optimization method does not have practical application value. Multi-objective optimization algorithm can be effectively applied to the structural design of steering gear by relying on its efficient and accurate search performance and convenient implementation method. In this paper, a new multi-level and multi-objective particle swarm optimization algorithm (MLMOPSO) is proposed, which adds boundary conditions to the hierarchical design model and performs multi-objective particle swarm optimization. The simulation results represent that compared with the traditional optimization algorithm, MLMOPSO has better optimization effect on linkage mechanism optimization. The optimization results have higher reference value in actual design and can be effectively applied to other engineering optimization problems, with strong robustness and generalization.

Keywords: Transmission device · Spatial Linkage · Multi-objective optimization · Particle swarm optimization

1 Introduction

The design of the electrical servo transmission mechanism includes the transmission accuracy and the structural stress characteristics and other objectives [1, 2]. The traditional optimization method is to use the weighting method, the constraint method or the goal programming method to transform it into a single-objective optimization problem [3], and use the mature single-objective optimization technology to optimize. Nevertheless, the single-objective optimization method requires sufficient preference information as the premise, and usually only obtain the global maximum or minimum solution, which does not have practical significance. This traditional design method not only has a large amount of calculation and workload, but also has low design efficiency, and the optimal value of the design scheme is difficult to evaluate.

Swarm intelligence algorithm is widely used in solving various engineering problems by virtue of its simple implementation method, efficient convergence speed and accurate global search performance [4]. As a leader in swarm intelligence algorithms, PSO has

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made remarkable achievements in engineering applications [5], such as engineering electromagnetics [6], structural design [7] and mechanical research [8].

Aiming at the target analysis in the design of steering gear transmission mechanism, this paper proposes a multi-level and multi-object particle swarm optimization algorithm—MLMOPSO. This method decomposes the objective function of the transmission mechanism from multiple objective functions to a single objective, and calculates the weight of each objective, and re-performs multi-objective search according to the weight. Compared with the traditional optimization method, MLMOPSO has a more reasonable and optimized structure, more convenient way of target definition, and can accurately based on the specific needs of engineers to search the optimal solution, thus reducing the transmission system of the traditional design in the process of time and resource depletion.

2 Problem Description

2.1 Spatial Linkage Model Analysis

Kinematics Analysis. As the basic component of the electrical servo transmission mechanism, the Spatial Linkage mechanism consists of two rotating pairs and two spherical pairs [9]. The rotating pair can rotate around the rotating shaft [10]. The space coordinate system is selected as shown in Fig. 1. The original moving rod QA is transmitted through the space link to realize the deflection of the follower rod OB angle.

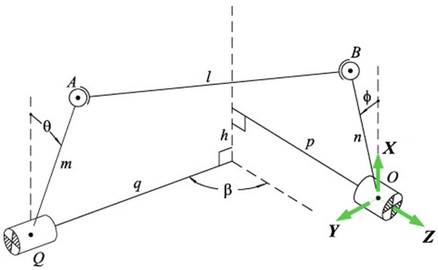


Fig. 1. RSSR Spatial Linkage structure

A and B point coordinates are obtained through coordinate transformation. The coordinates expressed by the method establish a mathematical equation based on the constraint of the length of the connecting rod AB, and obtain the functional relationship between the input angle and the output angle, and establish a functional relationship between the length of each rod and the output angle, which provides a basis for subsequent optimization design. The time-varying coordinates of the two points A and B are expressed as:

$$\begin{bmatrix} x^{(B)} \\ y^{(B)} \\ z^{(B)} \end{bmatrix} = \begin{bmatrix} m \cos\theta \\ m \sin\theta \\ q \end{bmatrix} \tag{1}$$

$$\begin{bmatrix} x^{(C)} \\ y^{(C)} \\ z^{(C)} \end{bmatrix} = \begin{bmatrix} -h + n\,cos\phi \\ n\,cos\,\beta\,sin\,\phi + p\,sin\,\beta \\ -n\,sin\,\beta\,sin\,\phi + p\,cos\,\beta \end{bmatrix} \tag{2}$$

The specific meanings of related parameters are shown in Table 1:

Table 1. Parameter meaning

Parameter	Meaning
m	Length of the original rod QA
l	Length of the rod AB
n	Length of the follower rod OB
h	The length between the original rod and the driven rod
β	The angle between the original rod and the follower rod
p	Slave rod to shaft length
q	Length of the original rod to the shaft
θ	Input angle
ϕ	Output angle

Kinetic Analysis. In the specific analysis process, ignore the influence of the gravity of the rudder surface, assuming that the rudder surface is subjected to a constant torque of 32500 N.m. The force analysis of the follower is shown in Fig. 2. According to the stress balance condition (force balance and moment balance).

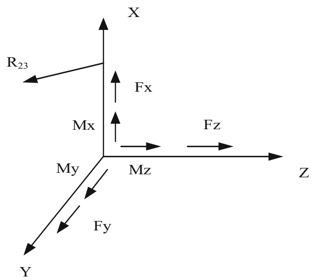


Fig. 2. Force analysis of follower

Among them:

$$\begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & -n \\ 0 & n & 0 \end{bmatrix} \begin{pmatrix} R_{23x} \\ R_{23y} \\ R_{23z} \end{pmatrix} + \begin{pmatrix} M_x \\ M_y \\ M_3 \end{pmatrix} = \begin{pmatrix} 0 \\ 0 \\ 0 \end{pmatrix} \tag{3}$$

$$\begin{pmatrix} R_{23x} \\ R_{23y} \\ R_{23z} \end{pmatrix} + \begin{pmatrix} F_{O3x} \\ F_{O3y} \\ F_{O3z} \end{pmatrix} = \begin{pmatrix} 0 \\ 0 \\ 0 \end{pmatrix} \tag{4}$$

2.2 Optimization Function Construction

The rod length is used as the design variable for subsequent optimization design:

$$\mathrm{X} = \left(\mathrm{x}_1\ \mathrm{x}_2\ \mathrm{x}_3\right) \tag{5}$$

Among them: x_1 the length of the tripod rod, x_2 the length of the base rod, and x_3 the length of the connecting rod. The optimization target mainly includes two aspects. One is the angle of deflection of the rudder surface is maximized when the screw nut has a fixed displacement, the highest space utilization, another optimization goal is good force characteristic during the operation of the electrical servo, which is expressed by the function relationship:

$$\begin{aligned} &\min f_1(x) = -\max(\theta_{rudder\_surface}) \\ &\min f_2(x) = -\max(F) \end{aligned} \tag{6}$$

This project defines the design requirements of the rods length:

$$lb < X < ub \tag{7}$$

3 Objective Function Solving

3.1 Single Objective Optimization

Based on the design mode of actual transmission structure, an improved PSO algorithm—boundary analysis particle swarm optimization (BDAPSO) is adopted in this paper. In practical engineering design, the boundary value is often a local extreme point, models based on boundary values or analysis of boundary conditions (or first derivatives of boundary functions) are often of practical significance [11]. As a classical black box test method, the boundary value analysis method can be used as a critical condition in the actual optimization process to improve the efficiency of the algorithm.

3.2 Multi-level and Multi-object Particle Swarm Optimization

Multilevel optimization lack powerful global search capabilities, in order to solve this problem, a new MLMOPSO algorithm is proposed by placing multi-objective optimization on the top of multi-level structure. MLMOPSO's approach is as follows: after establishing the unified function of the optimization model, it is divided into multiple objective functions, then BDAPSO optimization was carried out for them respectively, and their optimal values were obtained and put into archives. Meanwhile, the optimal

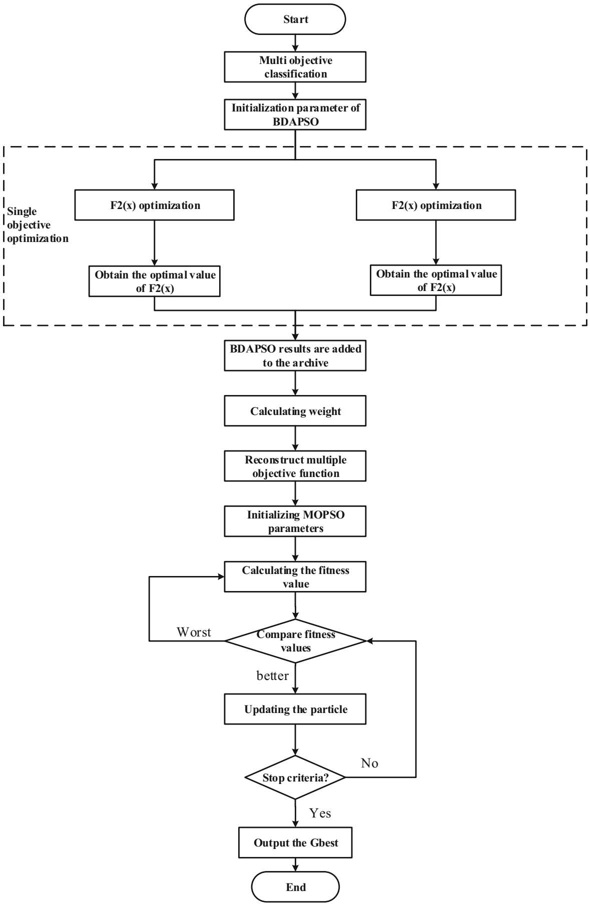


Fig. 3. The flowchart of MLMOPSO

value change rate of each objective function was differentiated, and it was defined as the target weight, which was linearly processed with the preset weight of the engineer. Finally, the above feedback information was collected for multi-objective particle swarm optimization. The flow chart of MLMOPSO is described in Fig. 3.

In the process of MOPSO particle update, this paper refers to the AG-MOPSO method in reference [12], but improves the adaptive mesh density estimation algorithm, and adds the true value of particle boundary when calculating the boundary of target space in the t-round particle evolution. Then the distance of grid space in the algorithm is calculated as follows:

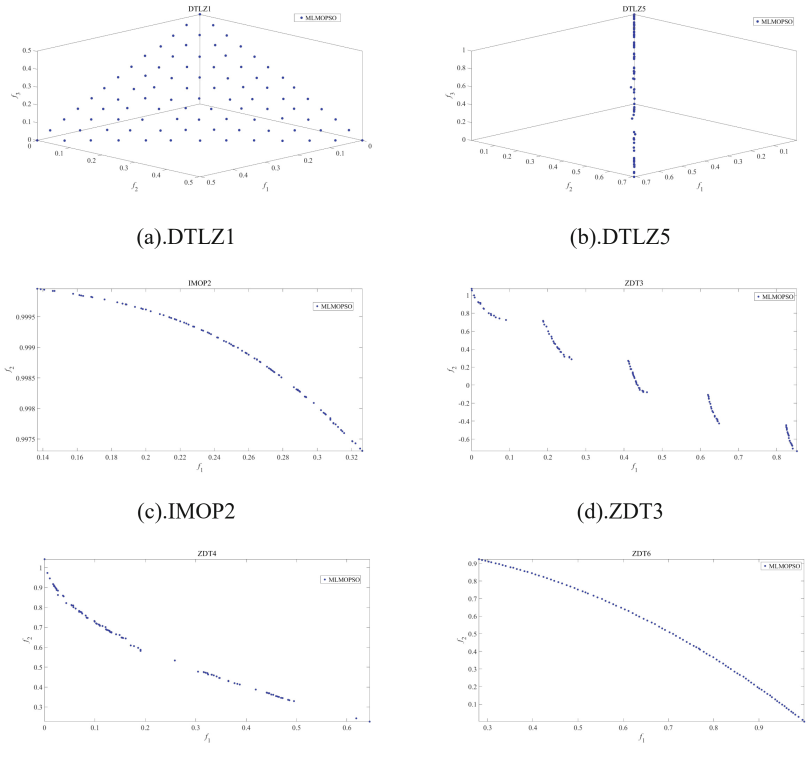
$$\Delta F_i{}' = \frac{\left|\max F'_i - trueF_i\right| - \left|\min F'_i - trueF_i\right|}{M} \tag{8}$$

Among them, $\max F'_i$ and $\min F'_i$ represents the extreme value of the current particle on a single target, $trueF_i$ represents the real boundary value in the optimization equation, and M represents the number of groups.

4 Experiment and Analysis

4.1 Algorithm Analysis

In order to verify the performance of the multi-objective optimization algorithm proposed in this paper, MLMOPSO algorithm is used for multi-objective optimization experiment on the open test function, and the effect is shown in Fig. 4. It is tested on two three objective functions and four double objective functions, all are the search results after 20000 iterations, the parameter setting and test functions are the same as the reference [13] and [14].



(a).DTLZ1 (b).DTLZ5

(c).IMOP2 (d).ZDT3

(e).ZDT4 (f).ZDT6

Fig. 4. (a)–(f) The optimization result of MLMOPSO algorithm

It can be seen from Fig. 4. that MLMOPSO algorithm can search better results in the solution space for different multi-objective functions, and the results are accurate, consistent with the real Pareto front according to references [13] and [14], which proves that the multi-objective optimization performance of MLMOPSO algorithm is better.

4.2 Spatial Linkage Optimization

Boundary Analysis. This paper determines the particle boundary value according to the actual application requirements of the steering gear.

Table 2. The particle boundary (mm)

Length	Base	Transmission	Tripod
Upper	30	15	130
Lower	90	60	180

In the experiment, the overall size of single-objective algorithm is 35, the maximum number of iterations is 1000, and the particle boundary value of BDAPSO is shown in Table 2. The algorithm running environment is the same as above, the kinematics and kinetics of the mathematical model established in Sect. 4.1 are optimized.

BDAPSO algorithm was used to optimize the dynamic and kinematic models, and the comparison algorithm was GA and PSO, with an average of 50 experimental results. According to the actual engineering application requirements, the kinetic parameters of the three structures of the Spatial Linkage mechanism of the steering engine are shown in Table 3:

Table 3. The length parameter of the Kinetic (mm)

Parameter	BDAPSO	GA	PSO
Base	57.971 ± 8.102	63.863 ± 7.467	60.755 ± 8.324
Transmission	42.456 ± 6.651	35.830 ± 8.033	38.732 ± 6.921
Tripod	143.984 ± 7.527	131.203 ± 3.270	139.347 ± 4.550

Kinematics parameters are shown in Table 4:

Table 4. The length parameter of the Kinematics (mm)

Parameter	BDAPSO	GA	PSO
Base	63.506 ± 8.052	75.520 ± 3.295	70.583 ± 5.642
Transmission	37.371 ± 6.682	22.206 ± 3.972	30.775 ± 4.463
Tripod	152.736 ± 7.514	144.819 ± 5.267	149.551 ± 7.793

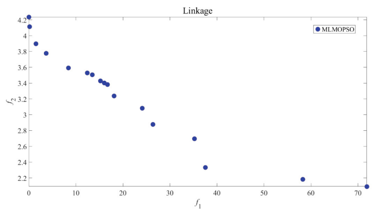
The results show that the optimized parameters of BDAPSO are significantly better than those of GA and PSO, and the probability of the boundary value in the optimized results is relatively large.

Results of Multi-objective Optimization. According to the comparison and feedback between BDAPSO optimization results and practical applications in the previous section, weight of objective function and particle boundary value were reconstructed, and multi-objective optimization of objective function was conducted by MLMOPSO. The weight calculation formula is as follows:

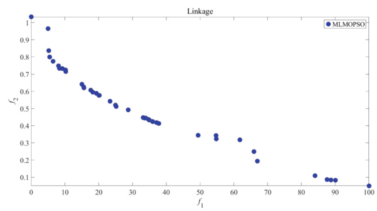
$$\omega_i = \frac{dF_i}{dlength} \tag{9}$$

Among them, F_i is the changing value of kinematics equation and dynamics equation of the objective function, length is the mean value of three parameters of the transmission mechanism.

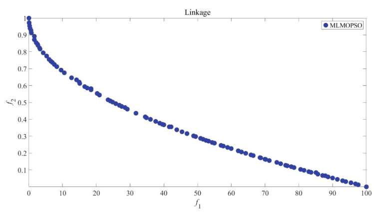
According to the optimization results, particle boundary parameters are updated as [40, 25, 160] to [90, 60, 180], and MLMOPSO parameters are set as follows: population number is set as 50, archive number is set as 50, and particle boundary value is placed in the archive in advance. The inertia weight is 0.9 → 0.1,C1 = C2 = 1.5. The algorithm running environment is the same as above. The multi-objective optimization of spatial linkage is carried out for 500, 2000, 5000, 10000 iterations respectively, take the results of 100 experiments and average them, the results are shown in Fig. 5.



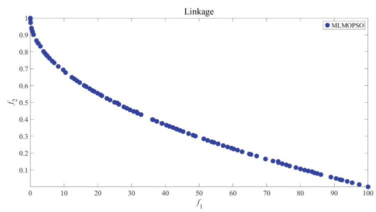
(a). Results of 500 iterations



(b). Results of 2000 iterations



(c). Results of 5000 iterations



(d). Results of 10000 iterations

Fig. 5. (a)–(d) Optimization results of MLMOPSO

The convergence curve is shown in Fig. 6.

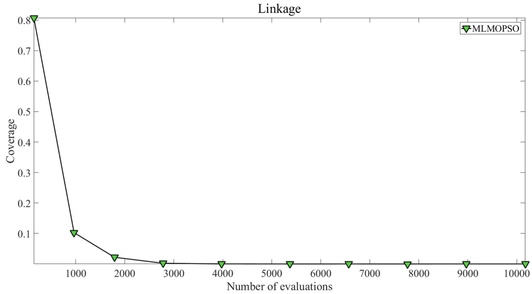


Fig. 6. Convergence curve of spatial linkage optimization

It can be seen from Fig. 5. that the algorithm proposed in this paper has good performance for the optimization of the spatial linkage structure. The search for the Pareto optimal set of two different optimization objectives can quickly converge, and it is also in line with the engineering in subsequent experiments. According to the actual requirements of the application, according to the convergence effect in Fig. 6, it can be clearly seen that the algorithm has reached convergence after 3000 iterations, which has the advantage of the algorithm in the application.

5 Conclusions

The design of linkage structure of steering gear is an optimization process. The traditional optimization method can't optimize the linkage structure at the same time and has no practical guidance effect. To solve this problem, this paper proposes a multi-level multi-objective particle swarm optimization method to optimize the linkage structure of the actuator. The weight of each optimization objective is analyzed through a single objective, and the multi-objective particle swarm optimization is used to search the optimal solution of multiple objectives. This paper takes the actual linkage mechanism as an example to verify the algorithm. The experimental results show that the algorithm can effectively search the optimal solution for the spatial linkage design of the steering gear, and has a guiding role for the actual engineering design.

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