Optimal selection of a modular robot system for automatic polishing and deburring

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Abstract. Aimed at a six-DOF modular robot system for automatic polishing and deburring, the optimal selection of mechanism parameters were completed in order to explore the flexibility impact of upper arm and forearm length to the end of manipulator. Firstly, the robot system is introduced; Secondly, three indicators including condition number index、Structural Length Index and Global Conditioning Index were employed as optimization indicator for mechanism parameters of manipulator, and orthogonal experiment was designed based on the Grey Taguchi Method; Thirdly, Grey Relational Analysis method was conducted to process experiment results and grey relational grade for each group was solved, and variance analysis method was used to analyze the influence of each mechanism parameters on performance indexes; Lastly, variation curve between grey relational grade and mechanism parameters was drawn, and optimized mechanism parameters were derived. It was found that although overall dimension of manipulator was slightly decreased by comparing the original and optimized manipulator length, but the performance indexes were improved. The results not only verified the correctness of proposed optimization method, but also laid a foundation for subsequent research on dynamic performance of modular robot system.

Introduction

A robot with two modular arms can finish polishing and deburring coordinated operation. Modular arms can change to different configurations to adopt to different environment[1].The mechanism parameters of the manipulator not only have a great influence on the size of the working space, but also affect the flexible performance distribution. Therefore, in the design phase of the manipulator, it is very important to determine the optimal mechanism parameters of the manipulator to meet the requirements of the flexible performance of the manipulator. Kinematics flexibility of manipulator is a key research content in robot kinematics. Many researchers at home and abroad have done some researches on it, and proposed many flexibility index [2-6].

This paper takes the modular arm of the service robot as the research object. In order to meet the requirements of the experiment, a degree of freedom is added to the original five degree of freedom manipulator, and the length of the arm and the arm of the manipulator are unequal. The related research shows that when the size of the arm and the arm of the arm is equal, the flexibility of the end is the maximum. In order to research the influence of the size of the arm and arm on its terminal flexibility, the structural parameters of the manipulator are optimized based on the flexible performance index.

Kinematics analysis of manipulator

Fig.1 simply shows that a polishing and deburring mobile robot with two arms is polishing a tap. In this paper, A modular arm which is equipped on a mobile robot is shown in Fig.2. Kinematics model and Jacobian of this arm can be found in reference[7].

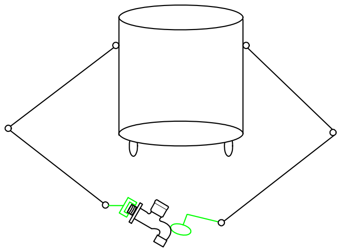


Fig. 1 Construct process of the modular manipulator

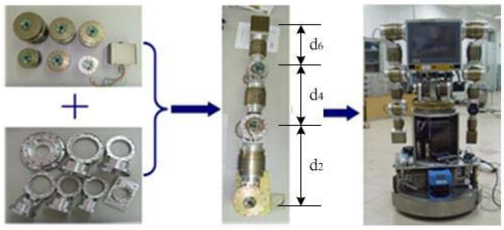


Fig. 2 Model of modular manipulator

The coefficient of variation and performance index of local and global

Condition number index. The relation between the condition number and the Jacobian singular value[8] is:

$$\kappa(\boldsymbol{J}) = \frac{\sigma_{\max}(\boldsymbol{J})}{\sigma_{\min}(\boldsymbol{J})} \qquad (1)$$

where $\sigma_{\max}(\boldsymbol{J})$ and $\sigma_{\min}(\boldsymbol{J})$ the maximum and minimum singular values of the Jacobian matrix. In order to resolve the problems of the condition number of Jacobian matrix, calculate the definition of Euclidean norm condition number, as follow:

$$\kappa(\boldsymbol{J}) = \sqrt{tr(\boldsymbol{JNJ}^T)tr(\boldsymbol{J}^{-1}\boldsymbol{NJ}^{-T})} \qquad (2)$$

$$\boldsymbol{N} = \frac{1}{n}\boldsymbol{I}_{n\times n} \qquad (3)$$

where $tr()$ is the matrix trace, n is the dimensions of the matrix and $\boldsymbol{I}$ is identity matrix.

SLI index. SLI index is used to evaluate the structural efficiency of the manipulator. The SLI index is defined as the ratio of the manipulator length sum to the cube root of the workspace volume. It is not related to the configuration of the manipulator, and the calculation formula is as follows:

$$Q = \frac{L}{\sqrt[3]{V}} \qquad (4)$$

$$L = \sum_{i=1}^{n}(a_{i-1} + d_{i-1}) \qquad (5)$$

where V is the volume of reachable workspace; L is the length sum of the robot manipulator; a_{i-1} is the link length; d_{i-1} is the joint offset.

The Monte Carlo method [9] is used to get the point cloud of the workspace and the volume of the reachable workspace is calculated by the number of grids containing the space point.

GCI index. The GCI index is a global performance index based on the Jacobian matrix condition, which is not related to the manipulator configuration. GCI indicators[5] is defined as follows:

$$\eta = \frac{A}{B} \in (0,1) \qquad (6)$$

$$A = \int_W \left(\frac{1}{\kappa}\right) dW \qquad (7)$$

$$B = \int_W dW \quad (8)$$

where η denote GCI, that is the distribution of the condition number of the Jacobian matrix over the entire manipulator workspace, and W is a specific point of the manipulator workspace. B is the workspace volumeand κ is the conditionnumber at a specific point of the robot manipulator workspace. The GCI ranges from

$$0 < \eta < 1. \quad (9)$$

The working space of the manipulator is not easily represented in Cartesian space, which is expressed in the joint space ,as follows:

$$A = \int_R (\frac{1}{\kappa})|\Delta| d\theta_n \cdots d\theta_2 d\theta_1 \quad (10)$$

$$B = \int_R |\Delta| d\theta_n \, L \, d\theta_2 d\theta_1 \quad (11)$$

where R is the manipulator workspace in joint space and Δ is the determinant of the Jacobian matrix.

Due to the fact that there is still a six-fold integral in the upper integral, the exact solution of the integral is not easy to solve and the calculation process is complicated. In this paper, the discrete equation [10] is used to calculate and analyze, as follows:

$$\eta = \frac{1}{n_{WS}} \sum_{j=1}^{n_{WS}} \frac{1}{\kappa} \quad (12)$$

where n_{WS} is number of nodes in the manipulator workspace.

It can be seen from Eq. (6) that when the GCI value is close to 1, the manipulator has better GCI performance. Conversely, the GCI performance is poor.

Coefficient of variation of condition number. The coefficient of variation is a statistical indicator in statistics, which is mainly used to measure the dispersion degree of probability distribution data. The calculation formula is

$$c_V = \frac{\sigma}{\mu} \quad (13)$$

where c_V is the coefficient ofvariation, σ is the standard deviation and μ is the average value.

Eq. (13) shows that the coefficient of variation is the standard deviation of mean. It can be used to compare and analyze data with different mean and standard deviation.

Experiment design and experiment results processing

In the process of optimizing the parameters of the mechanism, different values are taken for the parameters of the different mechanism. Then the combinations are arranged and the optimal parameters of the mechanism are obtained. The computational process is very complex and time-consuming, so it is necessary to design a suitable experiment for the problem of the above optimization process. In this paper, the orthogonal test of the [11] is designed and the parameters of the manipulator mechanism are optimized.

Orthogonal experiment design and experiment results. Orthogonal experiment design is a method of arranging experiment and analyzing experiment results by orthogonal table. In this paper, the variables are designed with three link lengths（d_2, d_4, d_6）. The three factors and five levels orthogonal experiment were analyzed and the experiment was arranged according to the orthogonal table. Due to the possible influence of the size of the motor, reducer and connecting piece of the mechanical arm, it is necessary to ensure that the movement of the mechanical body is not interfered and the maximum load of the motor is not exceeded. The current mechanism parameters of the manipulator are designed to be five levels of gradual change. The highest level is 1.5 times that of the lowest level, and the five level data of the link length is shown in Table 1.

Table 1 Five levels parameter of link size

Link number	Level 1 (m)	Level 2 (m)	Level 3 (m)	Level 4 (m)	Level 5 (m)
Link 1	0.2624	0.2952	0.328	0.3608	0.3936
Link 2	0.2212	0.2489	0.2765	0.3042	0.3318
Link 3	0.2690	0.3026	0.3362	0.3698	0.4034

Grey correlation analysis of experiment results. In this paper, grey relational analysis method [12] is used to process and analyze the experiment results.For convenience of analysis, must be to data processing of the above indexes calculated value.Firstly, the index values in Table 3 are normalized. Secondly, the gray relational coefficient is calculated according to the processed data, and the relationship between the real data and the ideal value is obtained. Finally, the gray relational coefficient is calculated according to grey relational coefficient. However, the larger the index value of the above three indexes is, the smaller the value of the index is, so it needs to be calculated separately. First of all, for the GCI index, the greater the value is, the better the value is. And the normalization is made by using the Eq. (14). For the SLI index and the discrete coefficient of the condition number, the smaller the value is, the better. The Eq. (15) is used for normalization, in which $x_0(k)=1$, i.e., the ideal value is 1.The final result shown in Table 4.

$$x_i(k)=\frac{y_i(k)-\min y_i(k)}{\max y_i(k)-\min y_i(k)} \quad (14)$$

$$x_i(k)=\frac{\max y_i(k)-y_i(k)}{\max y_i(k)-\min y_i(k)} \quad (15)$$

where $x_i(k)$ is the value of normalization; $y_i(k)$ is the value of i th-experiment; $\min y_i(k)$ and $\max y_i(k)$ are the lower and upper limits of value in k th-experiment, respectively.

Secondly, the grey relational coefficient of each index is calculated. The grey relational coefficient reflects the relative difference between the data after processing and the ideal value. The calculation is given by Eqs. (16) and(17), and the calculation results are shown in Table 4.

$$\zeta_i(k)=\frac{\Delta_{\min}+\zeta*\Delta_{\max}}{\Delta_{0i}(k)+\zeta*\Delta_{\max}} \quad (16)$$

$$\Delta_{0i}=\left|x_0(k)-x_i(k)\right| \quad (17)$$

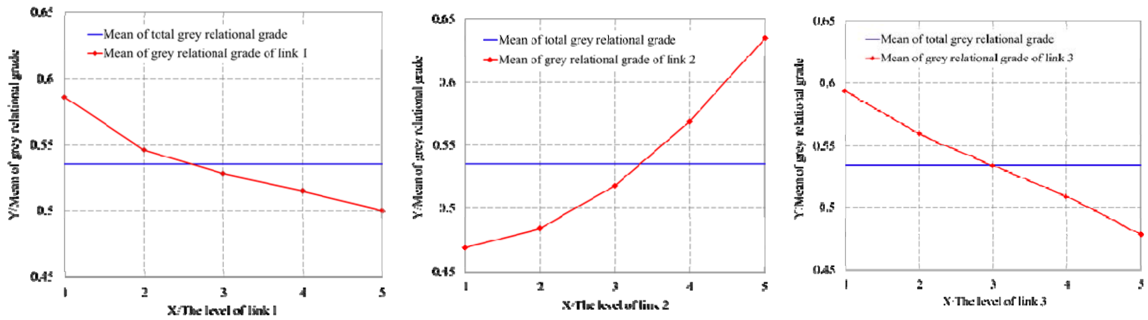
where ζ is the distinguishing coefficient, and the smaller the value of ζ, the better the resolution.(in which $\zeta=0.5$). Finally, the grey relational degree of each group experiment was calculated and sorted. The correlation degree refers to the approximate degree of the experimental results of each group and the ideal result, which is calculated by Eq. (18).

$$\gamma_i=\frac{1}{n}\sum_{k=1}^{n}\zeta_i(k) \quad (18)$$

where γ_i is the grey relational grade in i th-experiment, n is the number of performance index.

Optimization result analysis

According to the correlation degree data, the average correlation degree of each institution parameter is calculated. the corresponding change curve is drawn, as shown in Fig.6, the total mean value is 0.5349.



(a) (b) (c)

Fig. 6 Grey relational grade curve of links

（a）Mean of grey relational grade curve of link 1 （b）Mean of grey relational grade curve of link 2

（c）Mean of grey relational grade curve of link 3

The optimized structure parameters should choose average correlation peak corresponds to the link length. Fig.6 shows that the level 1 of the link 1, the level 5 of link 2and the level 1 of link 3 have the largest of mean of grey relational grade in the corresponding. Table 2 shows that a comparison of mechanism parameters between initial and after optimization. The optimization indexes of the manipulator before and after optimization are shown in Table 2.

Table 2 Comparison of link size before and after optimization

	Before optimization （m）	After optimization （m）
Link 1	0.3280	0.2624
Link 2	0.2765	0.3318
Link 3	0.3362	0.2690
Length of the arm	0.9407	0.8632

Table 3 Comparison each optimizing indexes of manipulator before and after optimization

Index	Before optimization	After optimization	Percentage of promotion (%)
Cv	94.6895	94.5554	1.40
SLI	0.6856	0.6742	1.66
GCI	0.0280	0.0293	4.64

Table 2 and 3 show that the total length of manipulatoris reduced after optimization. But the discrete coefficient of the condition number and SLI and GCI index were improved by 1.40%, 1.66% and 4.64% respectively. This shows that the optimized manipulator mechanism parameters can make the manipulator have a better performance index compared with the original. In order to analyze the influence of each parameter on the optimization index and the order of its primary and secondary, the experiment results are analyzed by variance. And the results are shown in Table 4.

Table 4 Variance analysis results

Parameter	Bias squares	DOF	Standard deviation	F value	Squaresum proportion
Link 1	0.0394	4	0.0099	58.7040	25.32%
Link 2	0.0921	4	0.0230	137.2161	59.19%
Link 3	0.0221	4	0.0055	32.8637	14.2%
Error	0.0020	12	[ ]	[ ]	1.29%
Sum total	0.1556	24	[ ]	[ ]	100%

Table 4 shows that, the three factors' value of the link 2 are the largest.This indicates that link 2 has the greatest influence on the flexible performance indicators of the manipulator, and the link 1 is second.

Summary

Aimed at six-DOF modular manipulator for automatic polishing and deburring, the optimization of mechanism parameters were completed in order to explore the flexibility impact of upper arm and forearm size on the end of manipulator. Firstly, the robot system is introduced. Secondly, the optimizing indicators of manipulator system parameters with three indexes: condition number index、Structural Length Index and Global Conditioning Index. And orthogonal experiment was designed based on the Grey Taguchi Method. Finally, Grey Relational Analysis method and the Grey Incidence Analysis method were conducted to process experiment results, and get the optimized structure parameters.The results can be obtained from the experiment results: the size of link 1 and 3 has reduced after optimization, but the link 2 has increased and the total length of the arm is slightly reduced. The coefficient of variation and the SLI and GCI indexes are increased by 1.4%, 1.66% and 4.64% respectively after the optimization.According to the results of variance analysis,the link 2 has the greatest influence on the flexible performance index of the manipulator, and the link 1 is second. As a result, the trend of the size to equal length of the arm and the small arm, its flexibility improved than before. The effect of link 2 on flexibility is also consistent with the principle of "multi-move small arms and little move arms" during movement. The experiment results verify the feasibility of the scheme in this paper. This paper provides a theoretical basis for the design of the manipulator and lays the foundation for the study of the dynamic performance of the manipulator and the optimization of dynamic parameters.

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