Lightweight Design of Palletizing Manipulator Based on Structural Performance Influence Analysis

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Abstract. In order to better coordinate the structural performance with lightweight goal, multi-stage lightweight strategy based on structural performance influence analysis is proposed. The framework of knowledge-guided lightweight design with multiple behavior routes was constructed firstly. Some behavior routes, such as initial structural design, lightweight optimization combined with structural performance influence analysis and knowledge-guided lightweight optimization, were designed in this section. Secondly, the decomposition of decision task and the multi-stage lightweight decision based on structural performance influence knowledge were discussed. Finally, the palletizing manipulator with parallelogram leveling mechanism was taken as an example to apply proposed strategy. Comparing with the initial optimization model in the first stage, the total weight of the components after multi-stage lightweight has been reduced by 23.37%, but the maximum stress of total manipulator only increased by 10.3Mpa, which shows the significant effect of lightweight.

Keywords: Palletizing manipulator; Multi-stage lightweight design; Multiple behavior routes; Multiple working conditions; Influence analysis.

1. Introduction
Palletizing manipulator is an important equipment in automatic production, which is mainly used for grasping and stacking of materials. In palletizing operation, it is expected to have sufficient strength and stiffness under the loading condition, but also have the light and flexible structure to reduce energy consumption. To meet these expectations for palletizing manipulator, many researches have been made on structural performance analysis and optimization. In some studies, the size optimization of the arm and the topology optimization of the linkage have been carried out to reduce the weight without affecting the strength and stiffness of the structure[1][2]. However, the more design features, variables, working conditions, and performance constraints considered, the more complex the lightweight becomes[3]. Additive manufacturing technology can reduce the difficulty of manufacturing for the complex structure[4][5], but the complexity of the design process caused by the increase of structural features also needs to be solved urgently. Due to the intricate relationships among parameters, structural performance and lightweight goals, it is necessary to seek a breakthrough in design process to improve the lightweight efficiency and effectiveness. Therefore, a multi-stage lightweight strategy based on structural performance influence analysis is discussed in this paper.

2. The Framework of Knowledge-guided Lightweight Design with Multiple Behavior Routes
In order to realize the lightweight design with the guidance of structural performance influence analysis, a framework of knowledge-guided lightweight design is constructed and shown in figure 1, which includes nine behavior modules, thirteen behavior channels and a knowledge base. This framework is
especially suitable for the lightweight design of part family with different sizes and similar structures, because some knowledge can be reused. On the basis of this framework, multiple behavior routes are easy to be combined, some of which are shown in table 1.

| Basic features of model | Additional features | Parameters intervals of features |
|-------------------------|--------------------|---------------------------------|
| FEM analysis            | Structural evaluation | Knowledge acquisition |
| Force analysis          | Optimization       | Design behavior response |

**Figure 1.** The framework of lightweight design behaviors.

**Table 1.** The behavior routes of lightweight design.

| No. | Task                                      | Behavior route |
|-----|-------------------------------------------|----------------|
| 1   | Initial structural design                  | Route1 Initial structural design |
| 2   | Lightweight optimization combined with structural performance influence analysis | Route2 Lightweight optimization combined with structural performance influence analysis |
| 3   | Knowledge-guided lightweight optimization | Route3 Knowledge-guided lightweight optimization |

The main task of route 1 is to design and optimize the initial palletizing manipulator according with the requirements of structural performance under working conditions. Firstly, the basic features of model as well as the intervals of structure parameters are determined in the design module. Secondly, the 3D parametric model established by Creo to generate the solid samples in the modeling module. Thirdly, by using Creo and ANSYS, every 3D sample is realized force analysis and finite element analysis respectively. After evaluating the structural performance of samples, the elites are chose from samples. If meet the requirements, the initial design is completed. Otherwise, the behaviors whether to reselect the basic features, adjust parameter intervals or change the class of model are determined by the lightweight decision module. After that, according the response of behaviors, the route returns to the design module to update the design behaviors.

Route 2 is used for combining knowledge acquisition with optimization by executing the influence analysis module, knowledge acquisition module and optimization module in the cycle. The influences of structural parameters on the structural performance and the weight of model are analysed by Spearman correlation analysis, and then the relative influence is calculated. After that, the knowledge acquisition module is used for evaluate the adjustment priority for every structural parameter. The detail method of acquiring the structural performance influence knowledge had been illustrated in our past work[6]. When getting the response of design behaviors by lightweight decision, one branch is to update the optimization variables as well as their parameter ranges, or adding additional features by channel 10. The other branch is to execute some searching behaviors, such as competition and elites saving, generating new individuals and so on, to acquire the new samples under the guidance of the structural performance influence knowledge. Transforming these new samples to 3D models, the optimization enter into the next cycle.

Route 3 is to realize knowledge-guided lightweight optimization. Since the structural performance influence knowledge is relatively stable within a certain range, the influence analysis does not need to be performed in every cycle. In this route, the influence analysis module and knowledge acquisition module are not executed, but the knowledge is directly obtained from the knowledge base. Furthermore, the optimal route after the lightweight decision module is the same as route 2.

3. Multi-stage Lightweight Decision Based on Structural Performance Influence Knowledge

Due to the large number of components, features, structural parameters and working conditions, the lightweight design for overall palletizing manipulator is a hard work. Considering the differences of
influence on lightweight, it is worthwhile to break down the task. The complex decision task is described by a decomposition tree, which shown in figure 2. According to this decision tree, it is easy to divide the process of lightweight into several stages with their models recombined adaptively. That is, you only need to change the decision behaviors to make the lightweight model in every stage changed flexibly.

**Figure 2.** The decomposition tree of decision task.

In this paper, according to the classification of features, the dangerous conditions for every component and the structural performance influence knowledge, there are five stages in the lightweight task. In the first stage, the basic features of main components for palletizing manipulator are taken as the objects, and the structural performance characteristics under dangerous conditions are considered. The hierarchical optimization of structural parameters with regions adjustment is carried out under the guidance of the adjustment priority. In the second stage, the additional features of the main components are designed and optimized. In the third and fourth stages, the lightweight of the basic and additional features for the secondary components are carried out respectively. In the fifth stage, the local features are optimized and the result of lightweight with best comprehensive structural performance is identified.

4. Application

4.1. The Task of Lightweight Optimization

The palletizing manipulator with parallelogram leveling mechanism is taken as an example in this paper. The basic model of this manipulator, which composed of the rear arm, driving link, drag link, first parallel link, forearm, triangle joint, second parallel link, and end gripper, is shown in figure 3.

**Figure 3.** The basic model of palletizing manipulator.

In this example, there are seven components of the palletizing manipulator taken as the lightening objects. According to the working process, four extreme positions of palletizing manipulator are considered in the structural performance analysis, which are the highest, the lowest, the nearest and the farthest. On this basis, the lightweight optimization is carried out by taking the minimum weight of palletizing manipulator as objective function and the maximum stress less than the allowable value under four working conditions as structural performance constraints. The optimization model is as follows:

$$\min W = \sum_{i=1}^{N} W_i$$  

(1)
\[ \begin{align*}
&\begin{cases}
    x_{ij\min} \leq x_{ij} \leq x_{ij\max} & i = 1,2,\ldots,N; \quad j = 1,2,\ldots,J_j \\
    \sigma_{i\max} \leq [\sigma_i] & \sigma_{i\max} = \max \{\sigma_{1\max}, \sigma_{2\max}, \sigma_{3\max}, \sigma_{4\max}\}
\end{cases} \\
\end{align*} \tag{2} \]

Where \( N \) is the number of components; \( W \) is the total weight of palletizing manipulator; \( W_i \) is the weight of the \( i \)th component, which depend not only on the size of features, but also on the basic features and additional features of the model decided in different stages of optimization. All of variables are the positive integer in this paper. \( x_{ij} \) is the \( j \)th variable of the \( i \)th component; \( J_i \) is the number of variables for the \( i \)th component considered in optimization; \( x_{ij\max} \) and \( x_{ij\min} \) are the maximum and minimum values for \( x_{ij} \) respectively. Variables as well as their interval constraints are determined under the guidance of influence knowledge. \( \sigma_{i\max} \) is the maximum stress under four working conditions; \( [\sigma_i] \) is allowable value of stress for the \( i \)th component.

### 4.2. Multi-stage Lightweight Design Based on Structural Performance Influence Analysis

#### 4.2.1. The first stage lightweight design for main components.

As the main load-bearing components for palletizing manipulator, the rear arm and the forearm are designed in the first stage. By analysing under four typical working conditions, it is found that the highest working condition is the most dangerous condition for both components. Considering the efficiency and effectiveness for analysing many samples, the adaptive meshing method is adopted in the cycle and tens of thousands of finite elements are formed in each sample. Through the loop execution of route 1, the features of components and the intervals of parameters are determined. The rear arm contains 13 structural parameters, and the forearm contains 15 structural parameters. Because the influence knowledge may vary with parameter intervals, the route 2 and route 3 execute alternately in this stage.

By influence analysis, the sensitive factors for rear arm mainly include thickness of plates, the distance of side plates, distance from the arc plate to the hole and the external circle of the holes. The stress nephograms of excellent rear arm acquired by route 1 is shown in figure 4, and that of the best rear arm in first stage is shown in figure 5. Comparing the weight of the model, the rear arm in figure 4 is 67.72kg, while that in figure 5 is 55.85kg. It is illustrated that the weight has been reduced by 17.53% after the first stage of lightening, but the maximum stress only increases by 8.71Mpa and less than the allowable value of 145Mpa. It is also found that the dangerous positions mainly appear in the bigger reamed hole and the edge of side plates near the bigger reamed hole. when the weight difficult to be lightened by optimizing the structural parameters of basic features, it is necessary to enter the next stage.

Similarly, the first-stage lightweight of forearm is carried out, and the stress nephograms of forearms are shown in figure 6 and figure 7. By influence analysis, it is found that the maximum stress of the forearm always occurs near the hole connected with the rear arm, and the geometrical parameters of the side plates have significant influence on the maximum stress and the weight. Figure 6 also shows that the maximum stress is 81.16Mpa, while that in figure 7 is 112.65Mpa. Comparing to figure 6, although the stress increased, the weight of model has been reduced from 59.77kg to 44.82kg.
4.2.2. The second stage lightweight design for main components. The second stage mainly focuses on the design and optimization of additional features for the main components based on the lightweight results of the first stage. According to the stress distribution, the geometric shape, size and position distribution of additional features are determined to remove the material from the model. Stress nephogram of the best components in this stage are shown in figure 8 and figure 9 respectively. Figure 8 illustrates that the maximum stress of the best rear arm is 144.09Mpa. Comparing to figure 5, the weight of the rear arm has been reduced from 55.85kg to 49.14kg by removing local material from the side plates. Similarly, the weight of the forearm has been reduced from 44.82kg to 40.29kg, but the maximum stress only increases by 1.57Mpa.

4.2.3. The third stage and the fourth stage lightweight design for the secondary components. In the third and the fourth stages, the lightweight of the secondary components are carried out. The dangerous condition of secondary components may be different from that of main components, so it is also necessary to execute route 1 and optimize the basic characteristics firstly. Among these components, the driving link and triangle joint are considered to remove material in the fourth stage. Stress nephogram of the excellent drive link and triangle joint are shown in figure 10 and figure 11 respectively.

4.2.4. The final result of lightweight for palletizing manipulator. In the fifth stage, the local features are adjusted. It is more important that when the change of values for some features make the increase ratio of maximum stress in component much more than the reduction ratio of weight, the behavior is no longer wise. In addition, for the slender parts, the allowable stress is often set less than that of the main
component. After multi-stage optimization, the final results of palletizing manipulator under four typical working conditions are shown in table 2. Comparing with the initial optimization model in the first stage, the total weight of the final components has been reduced from 188.14kg to 144.17kg. It is indicated that the total weight reduced by 23.37%, but the maximum stress of total mechanism only increased by 10.3Mpa.

| Name               | Stress under four typical condition (MPa) | Weight (kg) |
|--------------------|------------------------------------------|-------------|
| rear arm           | 143.83 (highest), 81.28 (farthest), 28.91 (nearest), 9.64 (lowest) | 49.14       |
| driving link       | 45.30 (highest), 78.62 (farthest), 60.31 (nearest), 69.08 (lowest) | 12.00       |
| drag link          | 23.56 (highest), 33.12 (farthest), 31.54 (nearest), 15.15 (lowest) | 18.00       |
| first parallel link| 44.20 (highest), 47.10 (farthest), 114.95 (nearest), 47.10 (lowest) | 5.89        |
| forearm            | 114.22 (highest), 60.63 (farthest), 69.82 (nearest), 47.53 (lowest) | 40.29       |
| triangle joint     | 62.12 (highest), 10.11 (farthest), 20.72 (nearest), 10.53 (lowest) | 9.89        |
| second parallel link| 119.70 (highest), 21.86 (farthest), 25.56 (nearest), 26.93 (lowest) | 8.96        |

5. Conclusion
For complex mechanism, optimizing all of components at the same time is a hard work. By taking the multi-stage lightweight design for palletizing manipulator as example, the conclusions are as follows:

- The structural performance evaluation and influence analysis are very important in the process of lightweight design. It is found that some influences closely relate to basic features of model as well as their parametric modeling schemes. The reproduction and change of geometric features in the basic models are more convenient by behavior decomposition.
- The multi-stage lightweight strategy is benefit to simplify the design task. Actually, behavior decomposition improves the flexibility of combining more behavior schemes, which also facilitates the increase and decrease of behaviors.
- In contrast, when the value of parameter changes within a certain range, the influence of parameter on structural performance and lightweight are relatively stable. Therefore, the methods of knowledge expression and utilization in lightweight design will be further studied in the future to improve the reusability of knowledge in similar structures.

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