A topology optimization method of robot lightweight design based on the finite element model of assembly and its applications

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Abstract
Topology optimization is a widely used lightweight design method for structural design of the collaborative robot. In this article, a topology optimization method for the robot lightweight design is proposed based on finite element analysis of the assembly so as to get the minimized weight and to avoid the stress analysis distortion phenomenon compared to the conventional topology optimization method by adding equivalent confining forces at the analyzed part's boundary. For this method, the stress and deformation of the robot's parts are calculated based on the finite element analysis of the assembly model. Then, the structure of the parts is redesigned with the goal of minimized mass and the constraint of maximum displacement of the robot's end by topology optimization. The proposed method has the advantages of a better lightweight effect compared with the conventional one, which is demonstrated by a simple two-linkage robot lightweight design. Finally, the method is applied on a 5 degree of freedom upper-limb exoskeleton robot for lightweight design. Results show that there is a 10.4% reduction of the mass compared with the conventional method.

Keywords
Topology optimization, lightweight design, boundary constraints, equivalent confining stress, robot assembly model

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Introduction

Nowadays, the robot is not only worked in structured and known industrial environment but also in unstructured and unknown one, like medical care, service fields, and so on.\(^1\) The collaborative robots, which interact with human being directly during work, have been developed and widely used in all kinds of conditions because the reduced mass and inertia of the robot can cause less harm to human beings when they are collided.\(^2\) For this reason, lightweight design becomes a key point in developing a collaborative robot. And researchers often take two methods for robot lightweight design, one is to use the new type of lightweight materials and another is to optimize part structure.\(^3,4\) Due to the high cost and difficulty in manufacturing of the lightweight material,\(^5\) most lightweight designers prefer taking the structural topology optimization method.\(^6,7\) Moreover, structural topology optimization is an ideal design method in the preliminary design stage to get the desired structure of the part because it is to seek the suitable material distribution within the optimized area\(^8,9\) rather than modify the existing part structure.\(^10\) And it is a popular optimal design method that has been widely used in the fields of aerospace, automobile, robot, and so on.\(^11,12\)

As the topology optimization applied in the fields of robot design, the conventional approach is to build the finite element model (FEM) of the part to be optimized first, then to modify the part structure by the topology optimization algorithm with the constraints of the equivalent confining stress at the analyzed part boundary. We define this conventional method as boundary equivalent confining stress-based topology optimization (BECS-TO) method for simplicity in this article. Based on this method, Huang and Zhang\(^9\) redesigned the L-shape arm of Motorman-HP20 robot to reduce the mass and the maximum displacement of the robot with the rated load. Albers and Ottnad\(^13,14\) achieved the lightweight design goal of the ARMAR III humanoid robot by this method. Cong et al.\(^15\) optimized the arms of the silicon transfer robot arm to reduce the weight and improve the stiffness of the system. Ye et al.\(^3\) used this method in the lightweight design of the humanoid robot and reduced the quality of its frame by 50.15\% without changing its stiffness and vibration performance with the extended battery life. In fact, the internal stress distribution and deformation of the part with this method are not equal to the actual ones according to Saint-Venant’s principle.\(^16\) And the differences could affect the effectiveness of the lightweight design. However, if the structure topology optimization of the part is based on the robot assembly model with the finite element analysis (FEA), the deviation of the part’s internal stress distribution and deformation can be avoided compared with the BECS-TO method.

And we define this as boundary actual confining stress-based topology optimization (BACS-TO) method, correspondingly. However, the advantages of the BACS-TO method used for robot structure topology optimization have not yet been reported to the best of our knowledge.

In this article, the advantages of the BACS-TO method compared with BECS-TO are demonstrated by a simple two-linkage robot lightweight design first. Then, the design steps of the BECS-TO method are proposed for the lightweight design
of the robot. Finally, this method is used on a 5 degrees of freedom (DOF) upper-limb exoskeleton robot and the results are compared with the BECS-TO method.

**Contrastive analysis of BECS-TO and BACS-TO methods on structure optimization**

**The introduction of FEA and topology optimization**

As the two methods of BECS-TO and BACS-TO are based on FEA and topology optimization, we introduce the basic rationales of FEA and topology optimization before applications.

**The basic rationale of FEA.** FEA is an effective numerical analysis method for static and dynamic analysis of a mechanical structure. When FEA is carried out, finite element mesh generation is the first step for analysis, and the mesh is connected to each other by nodes; then, the element stiffness matrices $K^e$ can be calculated from equation (1), after which, the equilibrium equation (2) is established after the element stiffness matrices are integrated into the total stiffness matrix $K$. Then, the fixation constraint is determined to calculate the displacement of each element node, which has two types. One is to set the displacement of a node in a certain direction with number 0 and the other is to set the displacement of a node $n$ in a certain direction with a constant value. Finally, the stress and strain of each element can be calculated by equation (3)

\[ F^e = K^e \cdot \Phi^e \]  
\[ F = K \cdot \Phi \]

where $F^e$ is the element node force density matrix, $K^e$ is the element stiffness matrixes, and $\Phi^e$ is the element node displacement vector

\[ \sigma = D \cdot B \cdot \Phi^e \]

where $\epsilon$ is the strain component at any point in the element, $\sigma$ is the stress component at any point in the element, $D$ is the elastic matrix, and $B$ is the element geometric matrix.

**The basic rationale of topology optimization.** As we know, the topology optimization for the structure lightweight design is also based on FEA, which is used as the constraint of the optimization method with the objective of the minimized mass of the structure. Here, the solid isotropic material with penalization (SIMP) method\(^{17}\) is used to build the mathematical model of topology optimization shown in equation (4)
Find \[ \rho = \{\rho_1, \rho_2, \ldots, \rho_N\}^T \in \mathbb{R}^N \]

\[
\begin{align*}
\text{Min } M &= \sum_{i=1}^{N} \rho_i v_i \\
\text{s.t.} \quad & g(\rho) \leq 0 \\
& K \cdot \Phi = F
\end{align*}
\] (4)

where \( \rho_i \) represents the relative density of the \( i \)th mesh, which is the design variable; \( N \) represents the total number of mesh; \( M \) represents the total mass of the structure; \( v_i \) represents the volume of the \( i \)th mesh; \( g(\rho) \) represents the constraint function, which can be displacement, stress, and so on; and \( \rho_{\text{min}} \) represents the minimum relative density.

Thus, the main difference between BECS-TO and BACS-TO is the fixation condition of the boundary condition. The fixation constraint of the BECS-TO is to set the displacement to 0, while the BACS-TO is to set the displacement to a constant value, which will lead to the difference of the loads’ distribution. So the results of the optimization based on BECS-TO and BACS-TO are different.

In this article, the lightweight design process of FEA and topology optimization is carried out by the software ANSYS Workbench (ANSYS, USA) to avoid complex equations.

**Differences of FEA results based on BECS-TO and BACS-TO methods**

In order to further verify the difference between the methods of BECS-TO and BACS-TO, a simple two-linkage robot model is introduced for lightweight design. The model consists of two equal-section beams, which are named as Part 1 and Part 2, respectively, as shown in Figure 1(a). Part 2 is the one to be optimized. The length \( L_2 \) of Part 2 is variable for explaining the difference, and the length \( L_1 \) of Part 1 is constant, and the length of the robot is \( L_3 \). \( W \) and \( H \) are the width and height of the section, respectively, which are also constant. A vertical load \( F_1 \) is set to the right surface of Part 2, and the left boundary of Part 1 is fixed. As the method of BECS-TO is applied to the optimization of Part 2, the equivalent confining forces fix the left boundary of Part 2 to establish its FEM, as shown in Figure 1(b). The stress distribution and deformation of Part 2 are obtained by FEA. However, with the method of BACS-TO, the FEM of the assembly is established to analyze the stress distribution and deformation of Part 2, which connects to Part 1. And the actual boundary condition of the model is shown in Figure 1(c). Then, the different results of lightweight robot design by BECS-TO and BACS-TO are calculated on a simple two-linkage robot.

The length of the robot \( L_3 \) and the value of \( L_1 \) and \( L_2 \) are listed in Table 1. The width and height of the equal-section rods are 20 and 50 mm, respectively. The material of

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Part 1 and Part 2 is aero metal (7075-T6; density = $2.81 \times 10^3$ kg/mm$^3$, Young’s modulus = 72 GPa, and Poisson’s ratio = 0.33). The load $F_1$ is set as 5 kg.

Figure 2 illustrates the stress distribution of Part 2 when the value of $L_2$ is 150 mm based on two kinds of FEM. It shows that compared with the result of FEA based on BACS-TO, the maximum stress of Part 2’s left surface based on BECS-TO is larger and the minimum stress is smaller.

The FEA results of Part 2 based on BECS-TO and BACS-TO are shown in Figure 3 and Table 2. The $\sigma_{\text{max}1}$ and $\sigma_{\text{min}1}$ denote the maximum and minimum stress of Part 2’s left surface analyzed by the method of BECS-TO, respectively, and the $\sigma_{\text{max}2}$ and $\sigma_{\text{min}2}$ denote the same one by that of BACS-TO. Figure 3 and Table 2 demonstrate that the maximum stress $\sigma_{\text{max}1}$ of Part 2’s left boundary calculated by BECS-TO is larger than $\sigma_{\text{max}2}$ by BACS-TO. Moreover, the change span of the minimum stress $\sigma_{\text{min}1}$ at the left surface of Part 2 calculated by BECS-TO is larger than $\sigma_{\text{min}2}$ by BACS-TO.

**Figure 1.** Model of the two-linkage robot and the boundary conditions: (a) model of two-linkage robot, (b) the equivalent boundary conditions, and (c) the actual boundary conditions.

**Table 1.** The size parameter of the two-linkage robot.

| No. | 1  | 2  | 3  | 4  | 5  | 6  | 7  | 8  |
|-----|----|----|----|----|----|----|----|----|
| $L_1$ (mm) | 400 | 400 | 400 | 400 | 400 | 400 | 400 | 400 |
| $L_2$ (mm) | 50  | 100 | 150 | 200 | 250 | 300 | 350 | 400 |
| $L_3$ (mm) | 450 | 500 | 550 | 600 | 650 | 700 | 750 | 800 |
The topology optimization of Part 2 is conducted after the FEA based on the FEM of the part and assembly, respectively. And the objective is to minimize the mass of the structure. In addition, the end displacement of the robot under the rated load is used as the design constraint. As we cannot find any related literature that discusses how to set the displacement constraint of the robot, a commercial collaborative robot was measured with its rated load for design reference. The result is 3 mm with the arm span of 820 mm of the robot.

**Table 2.** The maximum value of stress at Part 2’s contact boundary based on BECS-TO and BACS-TO.

| No. | 1    | 2    | 3    | 4    | 5    | 6    | 7    | 8    |
|-----|------|------|------|------|------|------|------|------|
| $\sigma_{\text{max}}$ (MPa) | 1.818 | 2.894 | 4.222 | 5.572 | 6.935 | 8.301 | 10.296 | 11.782 |
| $\sigma_{\text{max}}$ (MPa) | 0.872 | 1.719 | 2.580 | 3.450 | 4.360 | 5.245 | 6.145 | 7.048 |
| $\sigma_{\text{min}}$ (MPa) | 0.145 | 0.037 | 0.018 | 0.131 | 0.245 | 0.360 | 0.479 | 0.596 |
| $\sigma_{\text{min}}$ (MPa) | 0.357 | 0.360 | 0.364 | 0.367 | 0.397 | 0.401 | 0.415 | 0.419 |

BECS-TO: boundary equivalent confining stress-based topology optimization; BACS-TO: boundary actual confining stress-based topology optimization.

**Topology optimization and its results of the part based on BECS-TO and BACS-TO method**

The topology optimization of Part 2 is conducted after the FEA based on the FEM of the part and assembly, respectively. And the objective is to minimize the mass of the structure. In addition, the end displacement of the robot under the rated load is used as the design constraint. As we cannot find any related literature that discusses how to set the displacement constraint of the robot, a commercial collaborative robot was measured with its rated load for design reference. The result is 3 mm with the arm span of 820 mm of the robot.
Then, we can calculate all displacements with different lengths of $L_2$ in Table 1 according to the mechanics of materials\textsuperscript{18} as in equation (5)

$$\Delta s = \frac{F l^3}{3EI}$$

where $\Delta s$ is the end displacement of the cantilever beam, $F$ is the end load, $l$ is the length of the cantilever beam, $E$ is Young’s modulus, and $I$ is the moment of inertia. Therefore, the ratio relationship between the maximum end displacement of the reference robot and the end displacement constraint for topology optimization is derived by equation (6)

$$\frac{\Delta s_1}{\Delta S} = \frac{F_2}{F_3} \left(\frac{l_1}{L}\right)^3$$

where $l_1$ is the length of the model used for FEA, $L$ is the arm span of the reference robot arm, $F_2$ is the load applied to the end of the model, and $F_3$ is the rated load of the reference robot. During the optimization of the two-linkage robot, the value of $F_2$ is 5 kg. $\Delta S$ is the maximum end displacement of the reference robot and $\Delta s_1$ is the end displacement constraint of Part 2 for the topology optimization. Therefore, the end displacement constraint for the topology optimization of Part 2 based on different methods can be calculated by equation (2), as listed in Table 3.

Based on the analysis above, the structure topology optimization of Part 2 is conducted by the ANSYS topology optimization modules. Figure 4 demonstrates the optimization result of the Part 2 based on the BECS-TO and BACS-TO, respectively, when the value of $L_2$ is 150 mm. Then, the structure of optimized Part 2 is modified for its machinability, as shown in Figure 5. The mass, maximum stress,
and end displacement of redesigned Part 2 are shown in Table 4. Here, \( m_1 \) and \( m_2 \) are the mass of the Part 2 optimized by BECS-TO and BACS-TO, respectively, besides, \( \sigma_1 \) and \( s_1 \) and \( \sigma_2 \) and \( s_2 \) are the maximum stress and end displacement of the robot based on these two methods, respectively. As shown in Figure 6, the mass of Part 2, \( m_2 \), is obviously lighter than \( m_1 \) with the constraints of end displacement and allowable stress. But the end displacement and maximum stress are increased.

### Application of the BACS-TO method

**Design steps of BACS-TO method**

When the method of BACS-TO is applied to the lightweight design of the robot, the steps are shown as follows:

1. Build the FEM of the robot’s assembly including material setting, mesh generating, and boundary conditions adding (loads and constraints) for the model.
Figure 5. The modified structure of Part 2 when the value of $L_2$ is 150 mm: (a) BECS-TO and (b) BACS-TO.

Table 4. The results of optimization.

| No. | 1    | 2    | 3    | 4    | 5    | 6    | 7    | 8    |
|-----|------|------|------|------|------|------|------|------|
| 1   | 0.141| 0.281| 0.422| 0.562| 0.703| 0.843| 0.984| 1.124|
| 2   | 0.061| 0.130| 0.239| 0.260| 0.330| 0.393| 0.422| 0.486|
| 3   | 0.024| 0.050| 0.091| 0.130| 0.222| 0.242| 0.367| 0.417|
| 4   | 7.936| 8.867| 9.748|10.663|11.641|12.570|13.971|25.692|
| 5   | 47.90 |14.964|15.413|18.816|20.011|27.633|21.579|26.058|
| 6   | 0.296 |0.400 |0.539 |0.703 |0.900 |1.131 |1.407 |1.730 |
| 7   | 0.330 |0.430 |0.580 |0.800 |1.110 |1.250 |1.429 |2.105 |

$m_1$, $\sigma_1$, and $s_1$ represent the results of optimization based on BECS-TO method and $m_1$, $\sigma_1$, and $s_1$ represent the results based on BACS-TO method.

Figure 6. The comparison of non-optimized and optimized Part 2 by two methods, $m$ is the mass of non-optimized Part 2, $m_1$ and $m_2$ are the mass of Part 2 optimized by BECS-TO and BACS-TO methods, respectively.
2. Set the results of FEA to be displayed (stress, strain, deformation, etc.) based on needs.
3. Choose the design and non-design domain. Commonly, the non-design domain is the connection features of the parts (a hole, groove, etc.), which are used for the assembly of the optimized parts.
4. Define the design variable of topology optimization (i.e. relative density of element) and set minimized mass as the objective and the maximum end displacement as the constraint.

Before optimization, the model of the robot shall be simplified to reduce calculating time as follows:

1. The parts with little influence on the optimization results, such as functional parts and non-load-bearing parts, should be ignored.
2. The features with little impacts on the accuracy of analysis should be removed such as chamfers, bosses, recesses, flanges, rule, and so on.

**The application of BACS-TO method on the lightweight design of a 5 DOF upper-limb exoskeleton robot**

A 5 DOF upper-limb exoskeleton robot is shown in Figure 7, which is designed for upper-limb rehabilitation training for patients with the maximum load capacity of 5 kg and end displacements of 3 mm, where the displacement is determined taking the commercial robot and human being’s actual situations into account. When optimizing, the robot is set in its horizontal pose, because all joints of the robot would bear the biggest static load in this condition. At the same time, the maximum acceleration of Joint 2 and Joint 4 is set to 60 and 120°/s², respectively, according to Nef et al.¹⁹ Then, the topology optimization is according to the steps mentioned above.

After doing FEA of the robot, the support of Joint 1, Joint 2, and Joint 4 (J₁, J₂, and J₄) and the linkages between Joint 1 and Joint 2, Joint 2 and Joint 3, and Joint

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**Figure 7.** The three-dimensional model of the 5 DOF upper-limb exoskeleton robot.
4 and Joint 5 (J1-2, J2-3, and J4-5) are chosen to be optimized, because simulation results show that the stress of those parts are far less than the allowable stress of the material, and the changes in their structure have a greater impact on the mass of the robot. Before optimization, the non-design domain of them must be set to follow the rule mentioned above to guarantee the assembly of the parts. The non-design domain of J1 that shall be optimized with the method of BACS-TO is circled in Figure 8.

The stress distributions of the robot are shown in Figure 9. Simultaneously, the BECS-TO method used in Ye et al.\textsuperscript{3} is applied to optimize the same components of the robot. The optimized results of the two methods on the robot’s parts are shown in Figure 10.

**Results**

The optimized parts in Figure 10 are modified by the 3D modeling software for its machinability after topology optimizing, as shown in Figure 11, which demonstrates that the structure of the same component optimized based on the BECS-TO and BACS-TO methods has a little difference. In order to compare the
differences between the two methods, the FEA on the optimized parts with its assembly model is used again. And the mass and maximum stress of the optimized parts are listed in Table 5. The analysis result of the optimized robot is listed in Table 6.

**Figure 10.** The optimization result of the parts based on the BECS-TO and BACS-TO methods. The parts from left to right are J1, J2, J4, J1-2, J2-3, and J4-5: (a) BECS-TO and (b) BACS-TO.

**Figure 11.** The modified model based on the result of optimization: (a) BECS-TO and (b) BACS-TO.
The data in Table 5 demonstrate that the mass of each part optimized by BACS-TO is less than the one achieved by BECS-TO. According to Table 6, the total mass of the optimized parts based on BACS-TO is reduced by 10.4% compared with the one based on BECS-TO.

In general, the lightweight design of the upper-limb exoskeleton robot, based on the proposed method, can increase the effectiveness of lightweight design compared with the conventional one. Finally, the exoskeleton robot prototype with the parts optimized by BACS-TO was completed, as shown in Figure 12.

### Conclusion and future work

Lightweight design is a key point to the collaborative robot development. In this article, we proposed a topology optimization method based on robot assembly models with FEA. Its effectiveness of lightweight is demonstrated by the lightweight design of a simple two-linkage robot and a 5 DOF upper-limb exoskeleton robot, whose results are compared with the ones based on the widely used conventional method of BECS-TO.

However, compared with the optimization results based on the BECS-TO method, the end displacement and maximum stress of robot based on the method of BACS-TO are larger. During the lightweight design of the upper-limb exoskeleton robot based on the BACS-TO method, the end displacement of the robot and

### Table 5. The mass and maximum stress of the optimized parts.

| Parts         | J1  | J2  | J4  | J1-2 | J2-3 | J4-5 |
|---------------|-----|-----|-----|------|------|------|
| Initial mass (kg) | m₀  | 1.647 | 0.881 | 0.487 | 0.810 | 0.260 | 0.395 |
| Optimized mass (kg) | a   | 0.957 | 0.595 | 0.444 | 0.563 | 0.16  | 0.104 |
|               | b   | 0.853 | 0.553 | 0.431 | 0.46  | 0.128 | 0.102 |
| Max-stress (MPa)   | a   | 38.232 | 50.873 | 17.128 | 8.6247 | 8.9607 | 17.29 |
|               | b   | 30.441 | 87.489 | 12.071 | 14.318 | 9.6984 | 10.831 |

a represents the results based BECS-TO method and b represents the results based on BACS-TO method.

### Table 6. The total mass of optimized parts and the FEA result of the optimized robot.

|                          | a     | b     | Rangeability (%) |
|--------------------------|-------|-------|------------------|
| Total mass of optimized parts (kg) | 2.823 | 2.527 | -10.4            |
| Max-stress (MPa)         | 243.61 | 328.03 | 34.65            |
| End displacement (mm)    | 2.139 | 2.769 | 29.45            |

a represents the results based BECS-TO method and b represents the results based on BACS-TO method. Rangeability is the change percentage of the value obtained based on BACS-TO method compared to the value obtained based on BECS-TO method.
the maximum stress are increased by 29.45% and 34.65%, respectively, compared with the results based on BECS-TO. Actually, when the allowable stress and end displacement constraint are met, mass is the key factor that influences the safety of collaborative robot.

It has been proved in this article that the proposed method is an effective lightweight design method for multi-DOFs robot. Theoretically, it is a useful optimal method of structure with multi-DOFs mechanism. Besides this, size optimization\cite{20} is also a useful optimal method for robot structure when the shape and topology of the part are designed. In the future, based on the proposed topology optimization in the article, size optimization will be applied on the lightweight design of the robot to obtain more reasonable structure. Moreover, more design variables (relative density, geometric parameters, etc.) and constraints (fatigue and working conditions, etc.) shall be considered to make a powerful optimization tool set for robot lightweight design in the future.

**Declaration of conflicting interests**

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*Figure 12. The prototype of 5 DOF upper-limb exoskeleton robot.*
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