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A new optimal structural boundary modification algorithm in the multi-objective topology optimization of microgripper

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ABSTRACT: In industries where manufacturing and assembly operations are to be carried out with a high degree of precision on a micro scale, precise control and movement of components on a micro scale are desperately needed. Integrated microgripper mechanisms are used for this purpose. In this paper, a compliant-based microgripper is designed using multi-objective topology optimization method and the final form of the mechanism is prepared for manufacturing using a new optimal structural boundary modification algorithm. Usually, the optimization faces some problems in the designing step of the structure topology, such as node to node joining rather than the correct joining of the elements, as well as staircase boundaries due to the analysis of the problem with the finite element method. To overcome these drawbacks, in this paper, the curve fitting method is used to minimize the sum of squared errors in the boundary profile of the structure; meanwhile, the optimized objective functions of the structure are improved and better results are obtained. Finally, the performance results of the microgripper are confirmed using the comparison between numerical simulations and empirical tests.

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1- Introduction

Microgripper is one of the tools for high-precision positioning of the micro specimens with minimal error. Various methods have been proposed by researchers for designing compliant mechanisms such as the mechanism synthesis method [1], and topology optimization [2, 3], Among these, topology optimization provides a logical, fast, and efficient approach. For example, in references [4, 5], a topology optimization method was used for extracting the conceptual design of the compliant microgripper mechanism. The extracted conceptual design was not appropriate for manufact=uring because the topology optimization methods use finite element, and so, the mentioned conceptual design should be reformed at its boundaries. In the studies in the field of preparing the microgripper mechanism for manufacturing by post-optimization techniques [6, 7], the effect of changes, which are applied to the mechanism, is ignored.

In the present paper, the existing problems in manufacturing the conceptual design are resolved through the use of a new optimal boundary modification algorithm so that the performance indicators and optimized objective functions of the structure will be improved. First, the microgripper's conceptual design is developed using the topology optimization method. Then, the new optimal boundary modification algorithm is applied to prepare the microgripper for manufacturing. After that, the microgripper manufacturing method and testing process will be expressed and finally, the numerical and empirical results will be compared.

2- Methodology

In this paper, the conceptual design of the mechanism is obtained from multi-objective topology optimization. To this end, the design domain of the mechanism, input and output forces, and the supports are considered as depicted in Fig. 1.

Fig. 1. Initial design domain

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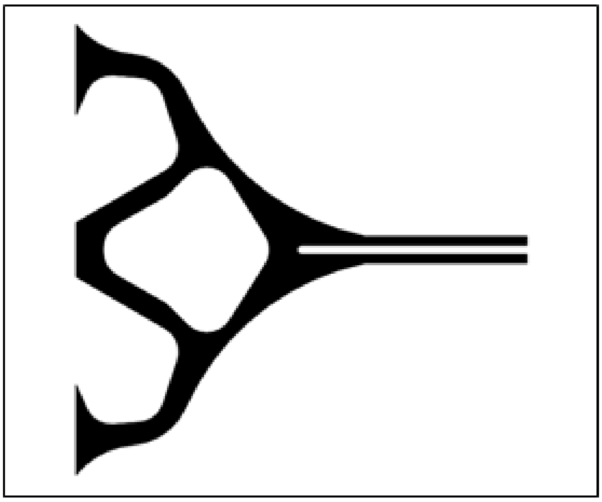

Fig. 2. The final design of the microgripper

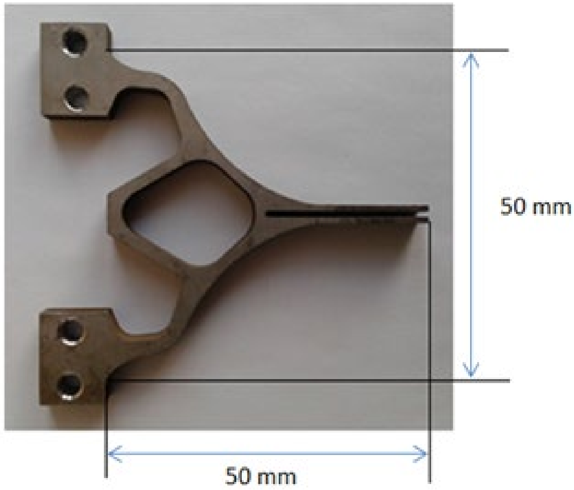

Fig. 3. The manufactured microgripper

The structure should be stiff enough to sustain external loads, so the strain energy of the structure should be reduced subsequently. Hence, the desired objective function is the minimization of the strain energy as well as minimization of the structure volume. For structural strain energy, we have [8]:

$$SE = \frac{1}{2}\{D\}^T [K]\{D\} \tag{1}$$

where, K is the general stiffness matrix and D is the node displacement vector resulted from f_{in} orce.

In this article, the new structural boundary modification algorithm is used. For this purpose, the B-spline curve, which is calculated by minimizing the sum of squared errors, is fitted to the structure boundary. The innovation proposed in this article is that during the calculation of mentioned curve, the objective functions of the optimization problem are calculated as well; i.e. the sum of squared errors is minimized besides considering the objective functions values; otherwise, the structure may deviate from the optimum state after the boundary modification.

The B-spline curve is extracted from the following equation [9]:

$$x(u) = \sum_{j=0}^{n} B_i N_{i,k}(u) \tag{2}$$

where B_i s the i^{th} ontrol point $n+1$, the number of control points, and $N_{i,k}(u)$ s the basis function of the B-spline curve, which is defined as follows:

$$N_{i,k}(u) = \frac{(u - t_i)N_{i,k-1}(u)}{t_{i+k-1} - t_i} + \frac{(t_{i+k} - u)N_{i+1,k-1}(u)}{t_{i+k} - t_{i+1}} \tag{3}$$

and

$$N_{i,1}(u) = \begin{cases} 1 & if \quad t_i \le u \le t_{i+1} \\ 0 & otherwise \end{cases} \tag{4}$$

The sum of squared errors is calculated as follows:

$$f = \sum_{j=0}^{r} \left\| P_j - x(u_j) \right\|^2 \tag{5}$$

Therefore, considering Eqs. (3) and (6) we will see:

$$f = \sum_{z=0}^{r} \left\| P_z - \sum_{j=0}^{n} B_i N_{i,k}(u_j) \right\|^2 \tag{6}$$

The optimization of f ^{f} value is performed so that the values of the objective functions (strain energy and volume of the structure) are minimized in comparison to the original values. So the final form of the structure will be as shown in Fig. 2.

The microgripper is made from 316 Stainless Steel sheets (Fig. 3).

3- 3. Results and Discussion

By simulating the microgripper in the ANSYS WORKBENCH analysis software, the input and output displacements of the jaws can be obtained using finite element numerical solution and the results are plotted in Fig. 4. As can be seen in the diagram, there is a good match between the numerical and the experimental results, and the maximum error is equal to 7.76 %.

4- Conclusions

In this paper, an optimum conceptual design of the compliant mechanism of microgripper structure is obtained using a multi-objective topology optimization method. Due to the staircase boundaries, the manufacturing process of the microgripper encounters difficulty. Therefore, using a logical and systematic approach, the boundaries of the structure were corrected. To this end, the curve fitting method was used to minimize the sum of squared errors of the boundary profile and the optimized objective functions were improved. Then, the final structure obtained from optimization was constructed

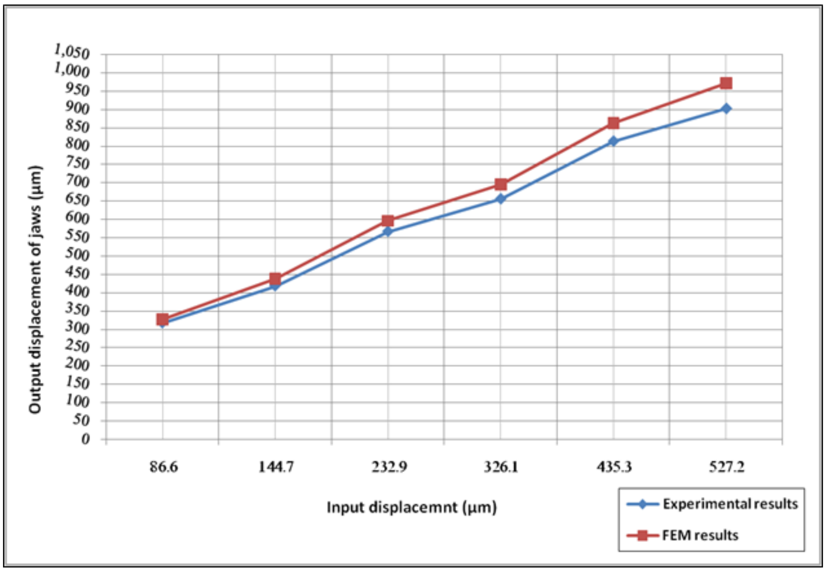

Fig. 4. Variation of the output displacement for the applied input displacement

from 316 stainless steel sheets and the EDM-Wire cut method and laboratory tests were performed on it. The results of the experiments show an appropriate consistency between the simulation results and the built structure

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