Automatic synthesis of compliant forceps for robot-assisted minimally invasive surgery

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Abstract: In this paper, we present a novel method to automatically synthesize compliant forceps for robot-assisted minimally invasive surgery. Due to its monolithic structure and high dexterity, the compliant mechanism becomes an emerging solution to miniaturize surgical forceps for minimally invasive procedures. However, it is complicated and inefficient to use traditional rigid-joint-based kinematic method to synthesize compliant forceps. To cope with this problem, we have developed a topology optimization based synthesis method. A realized forceps was presented in the paper which illustrated the synthesis process and demonstrated the efficiency of the proposed method.

I. Introduction

Over the last decades, robot-assisted minimally invasive surgery (MIS) has greatly revolutionized the traditional surgical techniques and reduced the trauma of patients. Many research efforts have been carried out on the design of MIS forceps as it is an important tool for grasping, retracting and stabilizing tissues or organs in the surgery. Currently, most MIS forceps utilize rigid mechanical joints for realizing clamping movements (see Fig. 1a). The main limitations of the rigid-joint-based forceps are the complicated assembling process and the lack of haptic force feedback during the surgery [1]. To cope with these problems, compliant mechanisms (see Fig. 1b) are often used to replace the rigid joints, as their monolithic structure greatly simplifies the assembling and sterilization process. The flexible behavior of compliant mechanisms also enables controlled movements with haptic feedback.

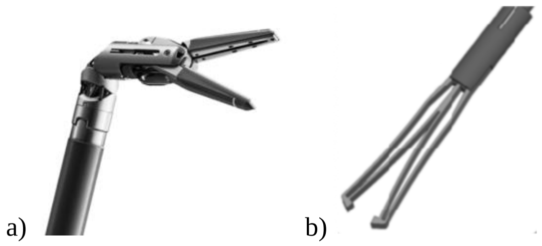


Figure 1: Rigid-joint-based and compliant MIS forceps: a) A rigid-joint-based forceps of the da Vinci surgical system [2], b) A compliant MIS forceps for robotic vitreoretinal surgery [3].

In the current state of art, pseudo-rigid-body-model (PRBM) method is always used to synthesize compliant mechanisms, in which the flexible parts are simplified as a combination of rigid bodies and torsional springs [1]. However, for designing micro forceps for MIS, where the detailed displacement and stress distribution should also be considered, the PRBM method reaches its limit. Therefore, advanced methods, which can accurately and efficiently synthesize compliant MIS forceps, are highly desirable.

II. Automatic synthesis method

The synthesis method in this paper is based on topology optimization techniques. The goal is to find an optimal void-solid (0-1) material distribution of a predefined 2D design domain which will allow to achieve the maximum displacement of the forceps tip with a given input load [4]. The workflow of the method is shown in Fig. 2. All algorithms are implemented in our design platform in Matlab, the Solid Geometry (SG) Library [5].

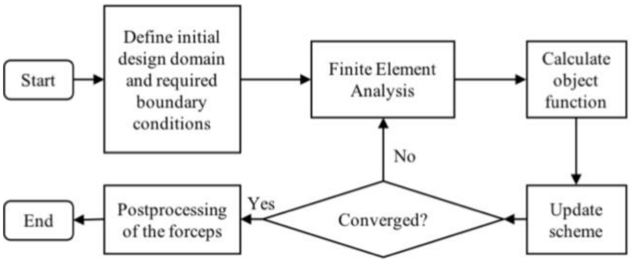


Figure 2: Workflow of the automatic synthesis method for MIS forceps, which is based on topology optimization.

The design process starts by constructing a design domain for the forceps. Since a compliant forceps is usually symmetric, only half of the design domain is considered in the optimization algorithm. Boundary conditions should be defined as loading cases for the MIS forceps, such as fixed parts and the tendon force of the cable. In the next step, the design domain will be discretized into small elements by the finite element method (FEM). A vector $\boldsymbol{\rho}$, which contains the density of all elements, is defined as design variables. The design problem can be formulated as:

$$\max_{\boldsymbol{\rho}} \quad u_{out}(\boldsymbol{\rho}) = \boldsymbol{L}^T\boldsymbol{U} \tag{1}$$

$$\text{subject to:} \quad \boldsymbol{K}\boldsymbol{U} = \boldsymbol{F} \tag{2}$$

$$V(\boldsymbol{\rho}) \leq \nu V_0 \tag{3}$$

where $\boldsymbol{U}$ is the displacement vector of all nodes. u_{out} in (1) is the displacement of the tip of the forceps, which should be maximized during the optimization process. The node of u_{out} can be addressed by the vector $\boldsymbol{L}$. $\boldsymbol{K}$ and $\boldsymbol{F}$ in (2) are the global stiffness matrix and load vector. Additionally, the volume of the synthesized forceps can be controlled by the volume fraction ν in (3), where V_0 and V are the volume of the initial design domain and the final design. $\boldsymbol{\rho}$ is iteratively modified by the following update scheme:

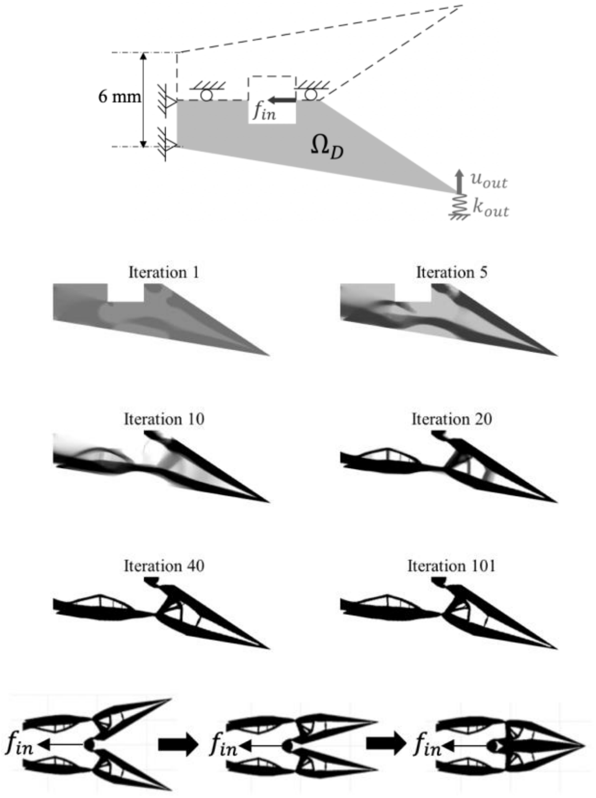
$$\rho^{new} = \begin{cases} \rho^{-} & if\ \rho \cdot B^{\eta} \leq \rho^{-} \\ \rho \cdot B^{\eta}, & if\ \rho^{+} > \rho \cdot B^{\eta} > \rho^{-} \\ \rho^{+} & if\ \rho \cdot B^{\eta} \geq \rho^{+} \end{cases} \tag{4}$$

$$B = \frac{-\frac{\partial u_{out}}{\partial \rho}}{\lambda \frac{\partial V}{\partial \rho}} \tag{5}$$

where ρ^{new} is the updated density. ρ^{-} and ρ^{-} are lower and upper limit of ρ^{new} in each iteration. B in (5) is a function of the sensitivity functions. Finally, when the optimization converges, the 2D boundary of the final topology can be extracted and extruded into 3D solids by using our SG Library. The realized design result can be directly 3D printed.

III. Design example

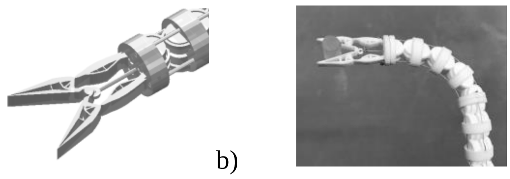
This section demonstrates the proposed automatic synthesis method with a design example. Fig. 3 presents the automatic synthesis process.



a) b). c)

Figure 3: Automatic synthesis of a compliant forceps for robot-assisted MIS: a) Schematic representation of the design problem, b) Evolution process of the density during some iterations, c) FEM-simulation of the realized forceps under load f_{in} showing the deformation.

Fig. 3a) shows the design problem of the example with prescribed boundary conditions. Ω_D is the design domain. The left side of the design domain is set to be fixed. f_{in} is the tendon force of the cable which is 1 N. k_{out} is a linear spring with a spring constant of $0.5\ \mathrm{kg/s^2}$ to imitate the elastic tissue which is to be clamped. Fig. 3b) shows the evolution process of the density $\boldsymbol{\rho}$ of the material in the design domain. The black area represents the final topology of the optimization process, which converges at the 101th iteration with 56.32 s. The calculations were carried out on a computer with an Intel Core i7 CPU at 2.9 GHz and 16GB of RAM. The FEM simulation result in Fig. 3c) demonstrated the clamping function of the synthesized forceps. Finally, the retracted 2D contour of the optimized forceps was extruded in 3D solid by our SG Library. The 3D forceps was then mounted to a tendon-driven soft robot structure as is shown in Fig. 4a). The entire robotic system was fabricated with selective laser sintering (SLS) with the material of polyamide PA2200 [6]. Fig. 4b) demonstrated the clamping function of the printed forceps by clamping a tissue-like elastic tube.



a) b)

Figure 4: Realized compliant MIS forceps in a robotic system: a) 3D surface model of the realized forceps which is mounted to a tendon-driven soft robot structure, b) SLS-printed prototype of the forceps which is clamping an elastic tube.

IV. Conclusion

In this paper, we presented a method for achieving automatic synthesis of compliant forceps for robot-assisted MIS. The method is based on topology optimization techniques. The automatic synthesis can be easily achieved by providing the position of the forceps tip, the initial design domain and boundary conditions of the design problems. A design example was presented to illustrate this procedure. FEM simulations and a clamping test of the 3D-printed prototype have also evaluated the performance of the realized compliant MIS forceps. In future work, we plan to develop this method to synthesize compliant forceps with specific functionalities to further improve the performance of robot-assisted MIS.

References

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