2017 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)
September 24–28, 2017, Vancouver, BC, Canada

Design and development of a soft gripper with topology optimization*

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***Abstract*— Soft robots, primarily made out of intrinsically soft materials, have flourished greatly in the past decade due to their advantages such as flexibility and adaptability over rigid-bodied robots. A rich repertoire of soft robots designed from intuitive or biomimetic approaches have been developed to provide new solutions for robots. However, these design approaches are limited by the designers' experience and inspiration, and a systematic design methodology for soft robots is still missing. We tackle this issue by mathematically recasting the design problem under the framework of topology optimization problem. To demonstrate the effectiveness of the proposed methodology, in this paper, we develop a pneumatically actuated soft gripper consisting of three fingers, each finger is able to undergo a free travel bending and deliver a grasping force. Hence, each gripper finger is designed as a continuum compliant mechanism to achieve its maximal bending deformation. The proposed soft gripper with complex shape is directly fabricated through 3D printing technology. Experimental results show that the deflected soft finger is able to achieve a 41° free travel bending and generate 0.68N blocked force upon 0.11MPa actuation pressure. This work represents an important step towards the goal of designing soft robots automatically.**

I. Introduction

Stemming from robotics, soft robotics is used to underline the shift from robots with rigid linkages and joints to soft continuum structures that are inherently compliant and exhibit large strains in normal operations [1]. Soft robots are primarily composed of soft materials with comparable elastic modulus of biological tissue and organs, which enable them to undergo continuous deformation and produce desired locomotion [2]. Benefitting from their intrinsically low stiffness property, soft robots show advantages especially in interacting with natural unstructured environments and safely serving human beings [2][3]. A rich repertoire of soft devices with smart actuators and sensors have demonstrated soft robots are capable of fulfilling tasks including quadrupedal locomotion [4], peristaltic locomotion [5], rolling [6], jumping [7] and grasping [8][9].

Current dominant design approaches for soft robots come primarily from biomimetic and intuitive perspectives. The former is physiologically or morphologically mimicking various living organism [10], from earthworm and caterpillar [5][6], octopus [11][12] to human finger [13][14] and hand [15]. The intuitive designs are often made on an ad hoc basis and undergo a trial-and-error process, which to a large extent depend on the designers' experience and inspiration [3][16]. Some examples of intuitive designs include the pneumatic networks (PneuNets) composed devices [4], fiber reinforced designs [8] and particle jamming devices [9]. Even though it usually turns out that the biomimetic and intuitive designs are effectual, the design process is empirical and time-consuming, showing limited potential applications on creating novel soft devices. The modeling and designing of soft robots are in need of a systematic approach to automatically create conceptual soft devices [3][17]. Lipson *et al.* tried to adopt evolutionary algorithms to automatically design soft robots, where a set of deformable cantilever beams were designed and tested, but no practical applications was clarified [19][20]. In this paper, we take a topology optimization based new approach to design a soft gripper, as shown in Fig. 1.

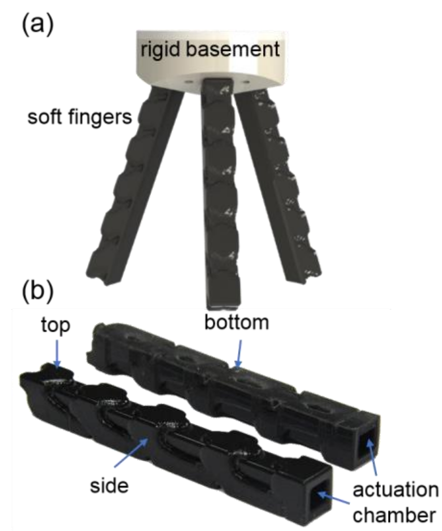

Fig. 1 (a) Prototype of a three-fingered soft gripper and (b) two 3D printed samples of optimized soft gripper finger

In our proposed method, the gripper structure design problem is recast as a topology optimization problem, and the goal is to find a suitable shape in the admissible design space so that the objective function can reach a minimum. This optimization problem is solved by the solid isotropic material with penalization method (SIMP), where densities of the

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discretized elements are taken as design variables [21]-[24]. Comparing with the intuitive and biomimetic approaches, where a soft robot is designed from an initial shape guess and prescribed constraints, the optimization approach is able to release these artificial constraints, and mathematically search the optimal design in a larger design space, resulting in better designs than existing ones can be expected.

Soft robots generate their mobility through deformation of a continuum flexible body, therefore the techniques for modeling the kinematics and dynamics of conventional hard material composed robots become inapplicable. Currently, online or offline finite element method (FEM) is a widely accepted method in modeling and analyzing the soft robots [17][18]. On designing the optimal soft gripper, the topology optimization is implemented iteratively. In each iteration loop, the current structure is modelled and analyzed with FEM method. Hence, the proposed design methodology integrated modeling and design together.

The optimized structure with complex shape can hardly be fabricated through conventional soft robots manufacturing technique, say molding and casting. With the favor of 3D printing technology, soft robots with complex geometry can be easily fabricated and integrated as a monolithic body [7][12]. Here, a PolyJet 3D printer (Objet Connex 260) is used to fabricate the soft gripper. Sequentially, the soft gripper is characterized by testing its free travel trajectory and blocked force through experiments. This soft gripper proposed with topology optimization and fabricated through 3D printing technique represents an important step towards the framework of developing soft robots automatically. Specially, the proposed design methodology can be freely extended to more types of soft robots with multiple functionalities, by mathematically formulating the desired configuration as the optimization objective and constraints.

II. METHODOLOGY

From a structure perspective, a soft gripper finger is able to convert longitudinal and radial deformation into bending when it is asymmetric in terms of geometry, material distribution or boundary and loading conditions. The soft gripper consists of three soft fingers, a rigid basement, fixture parts and some pneumatic accessories (Fig. 1a), where the fingers are periodically distributed along the basement circumference. Since all the three fingers are identical, we simplify the problem of designing a soft gripper to a single gripper finger which can be modelled as a cantilever beam. As a typical compliant mechanism, the gripper finger is designed to maximize its bending deformation.

A. Design Requirements

To simplify the computational complexity and guarantee the space for pneumatic actuation, the soft finger is initialized as a hollow cuboid entity with a cuboid actuation tube in the center (Fig. 2a), whose length is L, width is w and wall thickness is t. The dimensions of the gripper can be customized according to the application requirements. In this paper, we set them consistent with a typical human finger, $L = 128mm, w = 16mm$. The loading and boundary conditions of the gripper finger are shown in Fig. 2b, where the finger is clamped at the support end and subject to uniform pressure on the intra-surface.

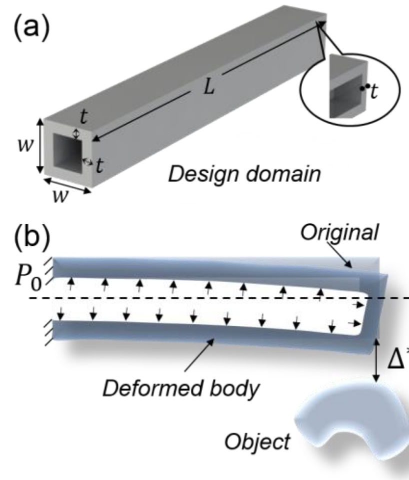

Fig. 2 Prototype of soft gripper finger. (a) Dimensional parameters. (b) Boundary and loading conditions.

To finish a grasping task, the fingertip is required to travel a distance of Δ^*, and then interact with the object (Fig. 2b). To overcome the gravity of the lifted object and lift it up, the interaction force needs to be greater than F. We introduce an artificial spring with stiffness of $k_e = F/\Delta^*$, connected to the fingertip to integrate these two requirements, i.e. the free travel Δ^* and interaction force F. In this manner, the grasping process is descried mathematically, and the design objective is simplified to maximize the output displacement at the fingertip.

B. Optimization problem definition

In material construction perspective, a complex shaped part can be viewed as a discretized regular-shaped reference domain whose composed elements can be either solid or void. Hence, the soft gripper finger structural design problem is actually a material redistribution issue. Here, the widely used SIMP method is adopted to solve this problem, where the material distribution is described by density design variables $\boldsymbol{\rho}$ that evaluated between 0 (void) and 1 (solid material) at each discretized element within the design domain [21][22]. By determining the values of $\boldsymbol{\rho}$, the optimal soft gripper structure will be obtained.

The soft gripper structure design problem is formulated as a conventional compliant mechanism synthesis problem, which is to maximize the deflection of the fingertip u_{out} [23][24]. Since u_{out} is evaluated along the downward direction (Fig. 2b), the optimization model is described as:

$$\begin{gathered} \min_{\boldsymbol{\rho}} J = u_{out} \\ s.t.\ \boldsymbol{K}(\boldsymbol{\rho})\boldsymbol{U} = p_0\boldsymbol{n}_p + k_e\boldsymbol{l}_{\mathbf{u}_o}^{\boldsymbol{T}}\boldsymbol{U} \\ \sum_{e=1}^{N} v_e\rho_e \leq V^* \end{gathered} \tag{1}$$

where $\boldsymbol{K}(\boldsymbol{\rho})$ is the global stiffness matrix; $\boldsymbol{U}$ is the displacement field; $\boldsymbol{l}_{\boldsymbol{u}_o}$ is a vector indicates degree of freedom of the output node; p_0 denotes the actuation force on a unit area; $\boldsymbol{n}_p$ indicates the normal direction of the actuation pressure loaded intra-surface; v_e and ρ_e denote the elementwise volume and density, respectively; N is the number of discretized elements; and the volume constraint V^* is imposed to guarantee the convergence of this problem.

C. Modified SIMP approach

Following the scheme of the modified SIMP topology optimization method [21], the design domain is discretized by N finite elements, and each element is described by its density ρ_e, then the element Young's modulus is given by

$$E_e(\rho_e) = E_{min} + (E - E_{min})\rho_e^P, \quad \rho_e \in [0,1], e = 1,2,\dots,N \tag{1}$$

where E is the Young's modulus of the solid material. E_{min} is that of the void phase, to avoid singularity of the global stiffness matrix, it is typically taken as 10^{-3}. P is the penalization power, usually set as 3. In this regard, the elasticity matrix can be stated by

$$\boldsymbol{D_e} = E_e \boldsymbol{D_e^0}$$

$$\boldsymbol{D_e^0} = \begin{bmatrix} \lambda_e + 2G_e & \lambda_e & \lambda_e & 0 & 0 & 0 \\ \lambda_e & \lambda_e + 2G_e & \lambda_e & 0 & 0 & 0 \\ \lambda_e & \lambda_e & \lambda_e + 2G_e & 0 & 0 & 0 \\ 0 & 0 & 0 & G_e & 0 & 0 \\ 0 & 0 & 0 & 0 & G_e & 0 \\ 0 & 0 & 0 & 0 & 0 & G_e \end{bmatrix} \tag{2}$$

$$G_e = \frac{1}{2(1+\upsilon)}, \lambda_e = \frac{\upsilon}{(1+\upsilon)(1-2\upsilon)}, e = 1,2,\dots,N$$

where υ is Poisson's ratio. Using the FEM discretization, the element stiffness matrix $\boldsymbol{K}_e$ is calculated by,

$$\boldsymbol{K_e} = \boldsymbol{E_e K_e^0}, \quad \boldsymbol{K_e^0} = \int_{\Omega_e} \boldsymbol{B^T D_e{}^0 B}\, \mathrm{d}\Omega_e, e = 1,2,\dots,N \tag{3}$$

where Ω_e is the computational domain occupied by the e^{th} element, $\boldsymbol{B}$ is the strain-displacement matrix.

The optimization problem (1) is solved by the method of moving asymptotes (MMA) algorithm [25]. Sensitivity of the objective function J with respect to the design variables $\boldsymbol{\rho}$ can be calculated using the adjoint sensitivity method,

$$\frac{\partial J}{\partial \rho_e} = \boldsymbol{\lambda^T} \frac{\partial \boldsymbol{K(\rho)}}{\partial \rho_e} \boldsymbol{U} \tag{4}$$

where $\boldsymbol{\lambda}$ is the adjoint displacement field, obtained by solving the adjoint equation,

$$\boldsymbol{K\lambda} = -\boldsymbol{l_{u_o}} \tag{5}$$

The derivative of the global stiffness matrix with respect to the design variables is computed directly from Eq. (4) as

$$\frac{\partial \boldsymbol{K(\rho)}}{\partial \rho_e} = P\rho_e^{P-1}(E - E_{min})\boldsymbol{K_e^0} \tag{6}$$

III. Numerical Implementation and Results

A. Numerical Implementation

The SIMP topology optimization scheme is implemented iteratively, which starts with discretizing the hollow cuboid design domain with a fine FEM mesh, and assigning the discritized elements with homogeneous material distribution. Then, yield the displacement field through FEM and calculate the values of the objective function, constraints as well as the sensitivities. Sequentially, filter the design variables and sensitivities with a density filter to ensure existence of solutions and avoid checkboard patterns [26][27]. Fourthly, update the design variables through the MMA method and check the termination criteria. If not satisfied, repeat the iteration loop until the termination criteria satisfy. Finally, plot the optimal structure and export it as a STereoLithography (STL) format file for post-processing fabrication, i.e. 3D printing.

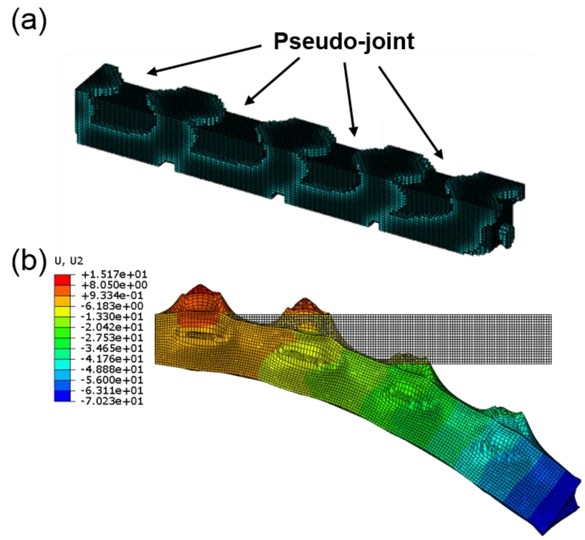

Fig. 3 Topology optimized soft gripper finger for $t = 0.2W$ includes (a) optimal material distribution and (b) FEM simulation results of soft gripper finger

In particular, to guarantee the actuation pressure applied onto the intra-surface of the finger, a thin passive solid intra-layer around the actuation tube with thickness of $0.05W$ is preserved. In the optimization process, the densities of the actuation chamber elements are retained as void phase, and the passive layers are fixed to be solids. Moreover, the updating and the filtering processes are only invoked for the density variables within the hollow cuboid design domain (see solid area in Fig. 2).

B. Optimization Results

The gripper finger is meshed with 160*20*20 elements, and the volume fraction V^* is set to be 0.5. The optimized solutions of a single soft gripper finger, as well as the corresponding bending deformations with an actuation pressure of 0.1MPa (FEM results in Abaqus without geometrical and material nonlinearity), are presented in Fig. 3. The optimal gripper finger consists of four pseudo-joints, where the composed layer is thinner and the structure is softer in terms of subjecting to actuation pressure. In structure construction perspective, the soft gripper is asymmetric along its major-plane due to these pseudo-joints, generating bending deflection when it is actuation. The supplementary video S1 shows the iteration history of the optimization process. It can be observed that pseudo-joints occur on the top layer sequentially from proximal to distal of two ends.

IV. Experimental Setup and Results

In this section, considering the fingers of the gripper are identical, we fabricate only one soft finger and test it in terms of evaluations of its free travel and blocked force, from which we are able to basically infer the performance of the whole gripper.

A. *Material Selection*

The optimized gripper is fabricated through an Objet 260 printer because of its complex shape. The gripper is required to support its own weight and sustain large strain, therefore the Young's modulus and rupture strain are two key factors in selecting the 3D printing material. The 3D printable soft materials are quite limited, however, the Objet 3D printer is able to mix two materials with varying mass ratio, resulting in a broader material set in regards to mechanical properties. Because the 3D printed material is inhomogeneous, the in-layer printing direction affect the mechanical properties of 3D printed parts.

Specifically, in this paper, we investigated the effect of mixing ratio and in-layer printing direction in regards to TangoBlack+ and VerClear, where the former is a 3D printable soft material and the latter is a hard material. Regarding the mixing ratios, pure TangoBlack+ and mixtures of TangoBlack+ and VeroClear are investigated, labelled as 9040, 9050 and 9060 by the 3D printer, in a sequence of increasing mass ratio of VeroClear. For the in-layer printing direction, we tested the samples whose printing directions is either along or perpendicular to the major axial, i.e. the longitudinal and latitudinal directions. Each type with three standard samples based on the BS ISO37-2011 standard is printed and tested with uniaxial tensile experiments through Instron machine. Hence, the loading direction is parallel with the longitudinal printed specimens, and perpendicular to the latitudinal ones. The experimental result shows an excellent stabilization for the deviation are within a range of 5% for each type of specimen.

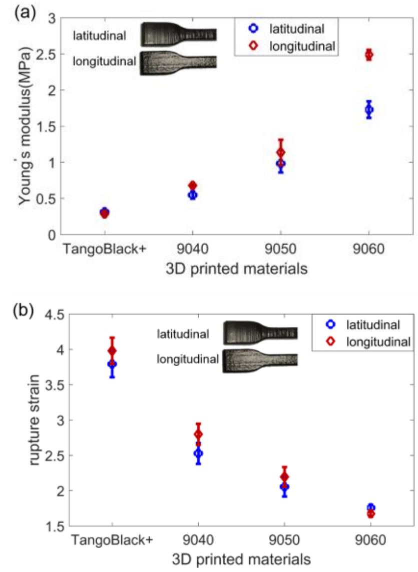

Fig. 4 3D printed material test. (a) Young's modulus and (b) rupture strain of each 3D printed material with different mixing ratios and printing directions

Figs. 4(a) and (b) show the relationships of mechanical properties in terms of Young's modulus and rupture strain with the mixing ratios and in-layer printing directions, respectively. It can be concluded that the Young's modulus increases with the mixing ratio (VeroClear to TangoBlack+), while the rupture strain shows an entirely opposite tendency. When it comes to the effect of in-layer printing direction, obvious differences in both Young's modulus and rupture strain were observed in Fig. 4. The longitudinal printing direction shows better performance in sustain tensile loads, which is indicated by higher rupture strain.

Because the soft gripper finger is actuated by pressure, every element of it is subject to biaxial loading conditions, which means that loads both parallel with and perpendicular to the in-layer printing direction exist. In Fig. 3b, the principle

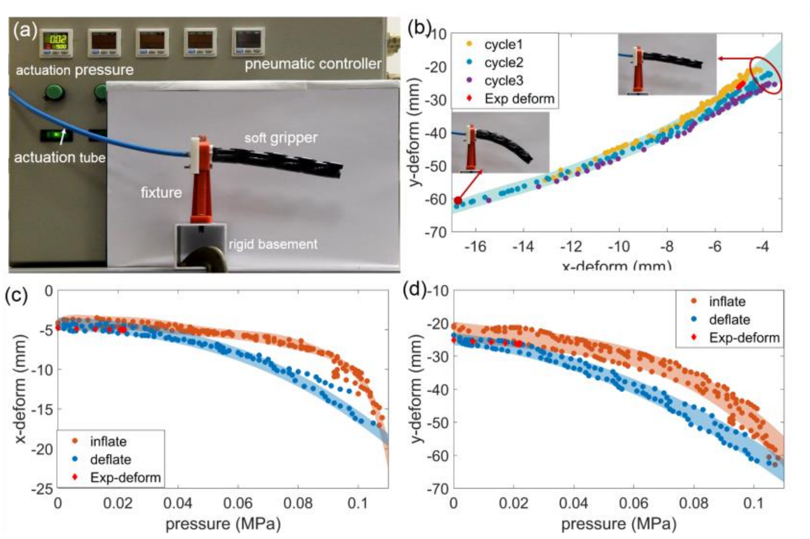

Fig. 5 Free travel trajectory tracking experimental (a)setup and (b) deflection on fingertip. (c) actuation pressure versus horizontal deflection. (d) actuation pressure versus downwards deflection.

strain direction is along the major axial of the finger, hence longitudinal in-layer printing direction is set during the fabrication process for the sake of enhancing the soft finger performance and saving fabrication time. In consideration of both the stiffness and rupture strain, the 9050 material is chosen to build the soft finger. In the following sections, we characterize the gripper finger performance by its free tavel trajectory and blocked force (supplementary video S2).

B. Free Travel Tracking

The test setup for the former is shown in Fig. 5a, where the left end is clamped on a rigid fixture and the right end is free, emulating the same boundary conditions as defined during the topology optimization process (Fig. 2b). The soft finger is preliminarily bended 8.9° because of gravity (Fig. 5a). A high resolution camera (Canon EOS 600D) is used to capture the bending trajectory of the deformed finger. To estimate the free travel trajectory of the fingertip, the optimized gripper finger was pressurized and depressurized three times, the high-resolution camera captured the motion frames of each state. Post-processing of each frame of the motion figured out the fingertip trajectory under different actuation pressure(Fig. 5b-d). The maximum bending angle is 41°, with its downward deformation of 49.1% of its length L. The trajectory of the fingertip, in terms of deflection in horizontal and vertical directions, was shown in Fig. 5b, it can be concluded that the performance of the soft finger is quite stable. Moreover, actuation pressure versus horizontal and vertical deflection during inflating and deflating process are figured out in Figs 5c and 5d, where obvious hysteresis is observed due to material viscoelasticity.

The soft gripper finger is designed with assumption of linear elasticity and small deformation. To investigate its performance accurately, post-processing FEM analysis shall be conducted with consideration of both geometrical nonlinearity and inhomogeneous 3D printing material property. Currently, limited convergent solutions have been achieved at low actuation pressure in Abaqus as shown in Fig. 5b-d. The FEM simulation results show excellent consistence with the corresponding experimental ones for the deviations are less than 2%.

C. Blocked Force Measurement

To characterize the grasping capability of the soft finger, an experimental setup to measure the blocked force is shown in Fig. 6a, where the bending deformation of the fingertip is blocked by a rigid clamp. Upon the rigid clamp, a Mark-10 force gauge with resolution of 0.005N is adopted to capture the interaction force, i.e. the blocked force. In the experiment, we recorded the blocked force during the pressurization process. The experimental result of blocked force over actuation pressure is shown in Fig.6b, where the soft finger is found to generate a maximal force of 0.68N at the fingertip with 0.11MPa actuation pressure. Moreover, the deviation of the grasping force at a certain actuation pressure is less than 10% according to the error band in Fig.6b. The blocked force experimental results reflect the grasping capability of a soft gripper, which is composed of optimal gripper fingers proposed in this paper. It can be expected that the gripper shown in Fig. 1a is able to lift up tens of grams objects. In addition, the soft finger is inherently soft, resulting in a stable

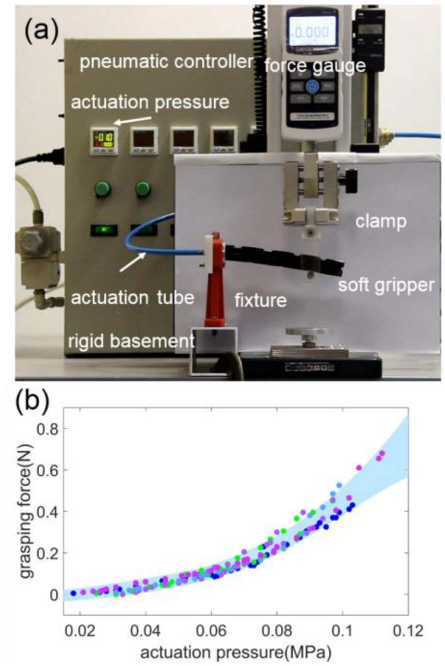

Fig. 6 Blocked force experimental (a) setup and (b)

grasping during operation. Moreover, the forces generated on the soft grippers are distributed along the entire length of the gripper finger, thus avoiding stress concentration.

As observed during the experiments, the material failure is the critical factor that constraints the maximal bending of the soft gripper finger. It is because the rupture strain of PolyJet 3D printed material is relatively low compared with silicone rubbers, which are widely adopted in fabricating conventional soft robots. This 3D printed material limitation undermine the capability of the printed optimal gripper. In the future research, the flexible fused deposition modeling (FDM) 3D printing technique will be implemented in fabricating soft grippers, because of high rupture strain of the 3D printed material. Furthermore, a gripper composing of 3 optimal fingers as shown in Fig. 1a will be fabricated and tested to grasp objects of different shapes. To achieve close-loop control of grasping process of the soft gripper, compressive soft sensors will be integrated in the future work [28][29].

V. CONCLUSION

Soft robots gain their mobility through deformation of a continuum body, since it can either actuated through pneumatic, hydraulic or cable-driven approach. The control strategy of these kind of devices are greatly simplified. However, to generate complex locomotion, complex-shaped devices are in need, which increases the expense on designing and manufacturing. In this paper, we have proposed a systematic design methodology based on topology optimization for soft robots. As a representative case, a soft gripper is designed, which is capable of undergoing a free travel and delivering a grasping force. Specially, it is noted that the optimized finger shows some similar features to human fingers, as indicated by the pseudo-joints in Fig. 3a.

This work is a first trial of designing soft robotics apart from intuitive brainstorm and bio-mimic designing methods. Moreover, the topology optimization designed devices are printable by 3D additive manufacturing, regarding the complex shapes, which inherently simplifies the fabrication and assembly process comparing with the conventional widely used molding and casting techniques. Herein, the design methodology proposed in this paper shows a powerful potential in designing and fabrication, and it is extendable to designing other soft devices if only the optimization model is build up. However, the current topology optimization model is under the framework of homogeneous material assumption, fabrication parameters including inhomogeneous materials properties of 3D printing materials and directional rupture strain are not considered. Moreover, geometrical nonlinearity under high actuation pressure is also ignored in designing soft gripper finger. These assumptions may cause inaccuracy in developing soft robots, more efforts will be spared on completing the optimization modeling in further research.

ACKNOWLEDGMENT

Hongying Zhang and Feifei Chen are supported by NUS (National University of Singapore) research scholarships.

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