Title:
Reconfigurable Soft Robots based on Modular Design

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Introduction:

Soft robots are a category of robots that are made of soft materials and whose movement is mainly realized by the elastic deformation of the structure itself. Because of their inherent high-flexibility, great compliance and adaptability, and safety for human-robot interaction, soft robots have received increasing research attention in recent years and have potential applications in the field of medical equipment, wearable devices, and industrial systems [1, 2].

Modularization is a general design trend in modern industry [3], in which a large-scale and complex product or system can be decomposed into many concise, assembled, and controllable modular units. Different from fixed-morphology soft robots, modularization for soft robots is an effective scheme that is adaptive to diverse environments and tasks by reconfiguring the robotic modules and achieving complicated functionalities such as self-assembly, self-driven, self-repair. Modularized soft robots take advantage in terms of easy maintenance, configurability, mass manufacture, and reusability. The idea of modulization for soft robots first occurred in 2012 proposed by Onal and Rus [4]. After that, modular units design, simulation, fabrication, connection mechanics, sensor, and control have become the research hot points in the field of modulization for soft robots. Lee et al. [5] proposed a modular soft robot prototype named soft LEGO, which design three modules including pneumatically inflatable soft brick, flexible bending brick, and channel brick. Yun et al. [6] proposed an easily customizable modularized soft pneumatic assistive glove. Wang et al. [7] built the homogeneous quadrilateral modular units via a magnetic connection, which are deployable and mobile. Phillips et al. [8] used modular design to create a soft robotic arm for delicate deep-sea biological exploration. Some cases about modular soft robots are listed in Fig.1. More modular designs of soft robots can be found in [3, 9, 10]. Albeit the proliferation of research activities on modular soft robots, the systematic theories for the design and implementation of soft robots still stay in the preliminary stage. Most of the previous designs only had the fixed connection, or the actuations were single-function without adaptability, which limits their implementation in practice. To achieve the high-level modular design, self-awareness of modular units, modular intercommunication, and assembly-disassembly techniques are the challenges.

In this paper, a new modular design strategy for reconfigurable pneumatic soft robots is proposed, in which the modules are divided into two categories: actuation and connector. Three actuation modular units are designed with special structures to implement axis stretch, plane bending, and spacial twisting

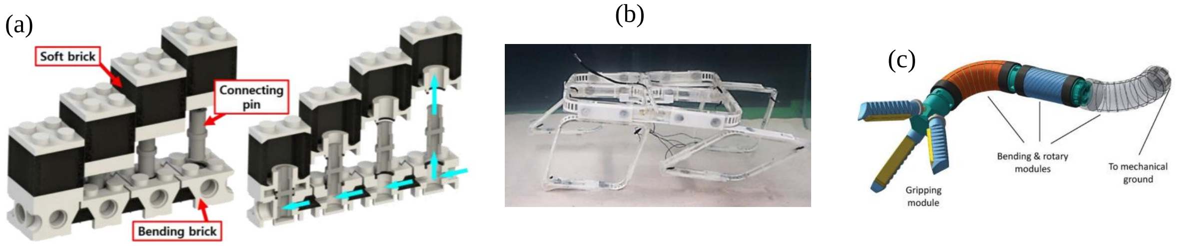

Fig. 1: Some examples of modular soft robots: (a) Lee et al. [5] (b) Wang et al. [7] (c) Phillips et al. [8].

by structural deformation. A special magnet-connector structure is proposed with the functionalities of self-align assembly. Finite element analysis (FEA) is adopted to simulate their deformation and the application scenarios are discussed.

Actuation modular design based on movement decomposition:

It is difficult to mimic complex 3D movements, but it is feasible to perform the decomposed movements with concise structures. A 3D movement in the real world, including 6-DoFs translation and rotation, can be decomposed into several simple movements. For pneumatic soft robots, axis stretch, plane bending, and spacial twisting are the three kinds of most typical deformation patterns. In this section, three kinds of modularized actuation of pneumatic soft robots are designed to implement these three movements, which can achieve 1-DOF translation, 2-DOFs translation, and 1-DOF rotation, respectively. The stretch and twisting modules are important to position adjustment, while the bending module play a key role in manipulation tasks. And their structures and key design parameters are illustrated in Fig. 2. As for the stretch module, the structural design is inspired by Chinese lanterns with folded zone, which can stretch longitudinal. As for the twisting module, we design a propeller-like structure. The twisting module is constructed with two parallel square plates with an angle of 90°, connected with four twisted blades. The air blowing through the chamber cause an unbalanced force distribution, resulting in twisting deformation. For the bending module, we adopt a bezier curve to design the chambers' surfaces. With the bezier curve frameworks, a small number of design variables are used to describe the chamber geometric, which greatly reduces the computational cost in the optimization process.

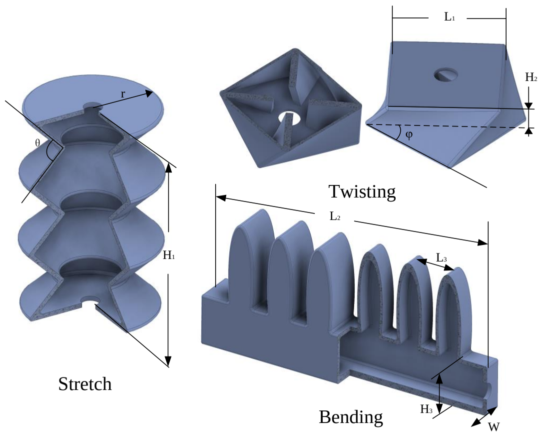

Fig. 2: Structural illustration for three actuation modules.

The general structural optimization model can be described as:

$$\min \quad \Phi[\boldsymbol{\chi}] := -v \tag{2.1}$$

subjected to

$$\begin{cases} \Psi_Y[\boldsymbol{\chi}] : \sigma - \sigma_{max} <= 0 \\ \chi_i \in \left[\underline{\chi}_i, \quad \bar{\chi}_i\right], \quad i = 1, 2, \cdots, \end{cases} \tag{2.2}$$

where $\Phi[\boldsymbol{\chi}]$ is the cost function, v is the output displacement, and $\min -v$ means to find the maximum output displacement. $\Psi_Y[\boldsymbol{\chi}]$ is the required constraint, which can be a stress constraint. i is the ID of design variables, while $\underline{\chi}_i$ and $\bar{\chi}_i$ are the lower and upper bounds of χ_i, respectively. The structural optimization model can be changed flexibly, such as the design variables comprise the design parameters of three actuation modules. The objective function and the constraints can be displacement, output linearity, structural stiffness, and so on.

Self-align magnet connector modular design:

The connector is essential in modular design, which connects the actuator modules to finish different tasks. The magnetic connector has advantages in assembly-friendly, self-aligning, easy attachment, and high connection strength. Users can reconfigure the modules distribution according to different environments and tasks. The extra actuation to disconnection is required and the rigid magnets are attached to soft modules [3]. According to the characters of magnet connect, a staggered magnet poles structure is proposed, shown in Fig 3. The structure is a ring with the surface distributing six tiny magnets, with different arrangements of magnets, the assembly pattern can be changed. For example, the modular units can be assembled with $0°, 120°$ and $240°$ with the connector's magnetic pole being "+ - + - + -". For different actuation modular units, different pressure loading is available with a valve module, in which one side is open while another side is closed, an extra air tube is attached to provide the pressure loading. At the end module, an end cap is required to seal the air chamber. In order to guarantee airtightness, each connective assembly should use a rubber gasket. The design targets of the above connectors are both manual and automatic reconfiguration, and a mechanism for automatic connection and disconnection is under development. With automatic connection and disconnection, the modular design can achieve self-reconfigurable functionalities, which can autonomously transform their modular arrangements according to different environments and tasks.

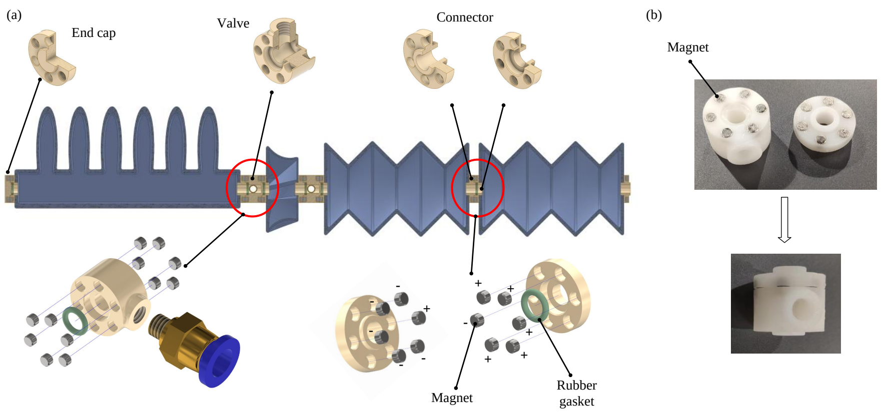

Fig. 3: The structure illustration for connector modules.

Simulation and validation:

Soft robots exhibit infinite degrees of freedom and are conflicted with the traditional rigid robot simulation method. Finite element analysis (FEA) is a powerful and wide-used method for numerical solutions to complex problems in computing mechanics, which is suitable to calculate the modules' deformation patterns. The actuation modules are simulated in an FEA-based platform COMSOL . The material model is silicone rubber, with Young's modulus 3×10^6Pa and Poisson ratio 0.49, and geometric nonlinearity is considered. The simulation results of actuation modules are plotted in Fig.4, which demonstrated the design modules' deformation of stretch, bending, and twisting. A general phenomenon can be observed that higher pressures result in greater deformation. The positive and negative pressure conditions cause inverse deformation patterns. For stretch and twisting modules, they are more sensitive to negative pressure. The negative pressure causes larger deformation compared with the positive cases under the same value of pressure.

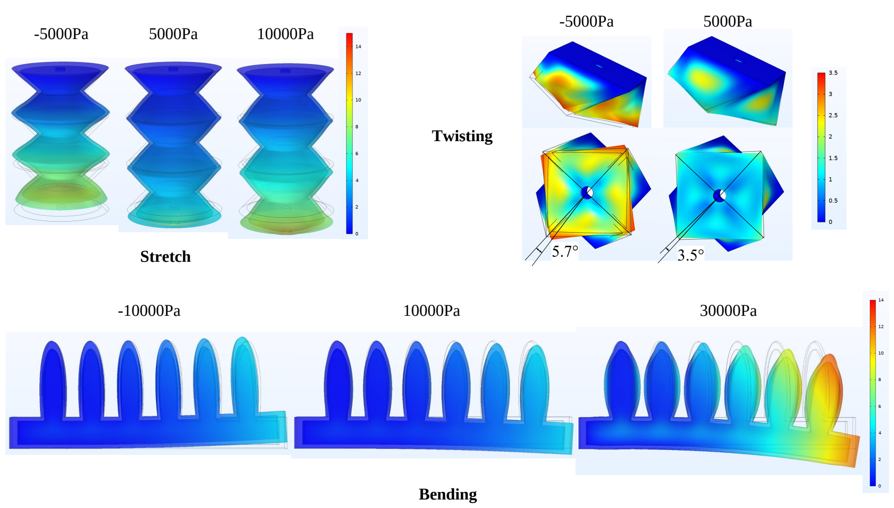

Fig. 4: Displacement of stretch, bending and twisting modules with different pressures. (unit mm)

Case study:

Taking the manipulation task as an example, it is difficult to grasp different-sizes and different-positions objects with traditional fixed-configuration soft robots, but it is capable with modularized soft robots. The gripper using modular units (see Fig.5) can achieve the complex 6-DoFs movement composed of stretch, bending and twisting modules. And the claw's configuration can be changed to adapt to the object's attributes.

Conclusions:

In this paper, we proposed a modular design method for reconfigurable pneumatic soft robots, which is movement adaptable and assembly-friendly. The module units are divided into two categories: actuation and connector. A novel structural design method (including the geometric construction and optimization model) is used to design the actuation modules which can implement the movement of stretch, bending, and twisting. The actuation module units are simulated in FEM-based software, which demonstrated the mechanical performance has fulfilled the designed requirement. For connector modules, magnet connectors are proposed to achieve the functionalities of self-align connecting. The future work will include

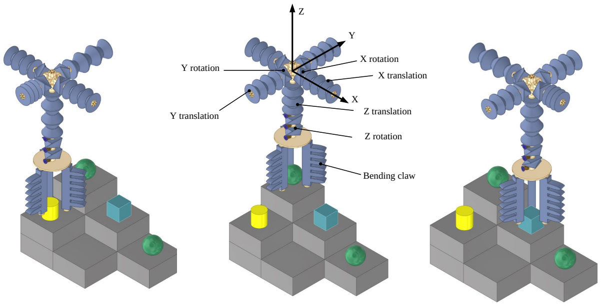

Fig. 5: The reconfigurable manipulated claw based on modular soft robots.

3 main parts: (1) prototype fabrication, (2) sensor and control system design, and (3) implementations in application scenarios. Not limited to conventional cases, more usages of modular soft robots should be explored in the field of human-robot interaction, metaverse, and so on.

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