Reconfigurable Soft Robots based on Modular Design

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Abstract. With the development of new materials, structures and design methods, soft robot technology shows the trend of multi-functional modularization and has diverse applications in many fields. Soft robots are required to be reconfigurable with different tasks and environments, which encounter problems including mass-scale fabrication, complex movement implementation, and assembly-disassembly convenience. To solve these challenges, a modular design method for reconfigurable soft robots is proposed. Three basic modules are designed to provide stretch, bending, and twisting movements, respectively, and a method is presented to decompose complex operational movements into the combinations of these three. The FEA-based simulation results demonstrated that the actuation successfully achieved the designed movement patterns. A criterion is proposed to guide the users to select the actuation modules. A novel structure for a self-align magnet connector is provided which is friendly for the assembly-disassembly process. A case study is shown for a complex pick-and-place task that requires complex end-effector movements. With the three movements based actuations and self-align connectors, the proposed modular reconfigurable soft robots hold the potential to adapt to diverse environments and tasks.

Keywords: Soft robots, Reconfigurable, Modularization, Motion decomposition, Finite element analysis
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1 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 inherently 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 [2, 4].

Modularization is a general design trend in modern industry [1], 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 was first proposed by Onal and Rus in 2012 [9]. 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. Some modular design cases for soft robots have been listed in Fig.1. Lee et al. [8] proposed a modular soft robot prototype named soft LEGO, which was featured by three modules including pneumatically inflatable soft brick, flexible bending brick, and channel brick. Yun et al. [13] proposed an easily customizable modularized soft pneumatic assistive glove. Wang et al. [12] built the homogeneous quadrilateral modular units via a magnetic connection, which are deployable and mobile. Phillips et al. [10] used modular design to create a soft robotic arm for delicate deep-sea biological exploration. Jiao et al. [7] proposed an origami structure based reconfigurable soft robots, which can perform multiple motions, including contraction, bending, twisting, and radial motions. Zhang et al. [14] explored the modularization of the multi-DoF pneumatic robotic actuators and applied it in invasive surgery. More modular designs of soft robots can be found in [11, 6, 3, 5]. 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.

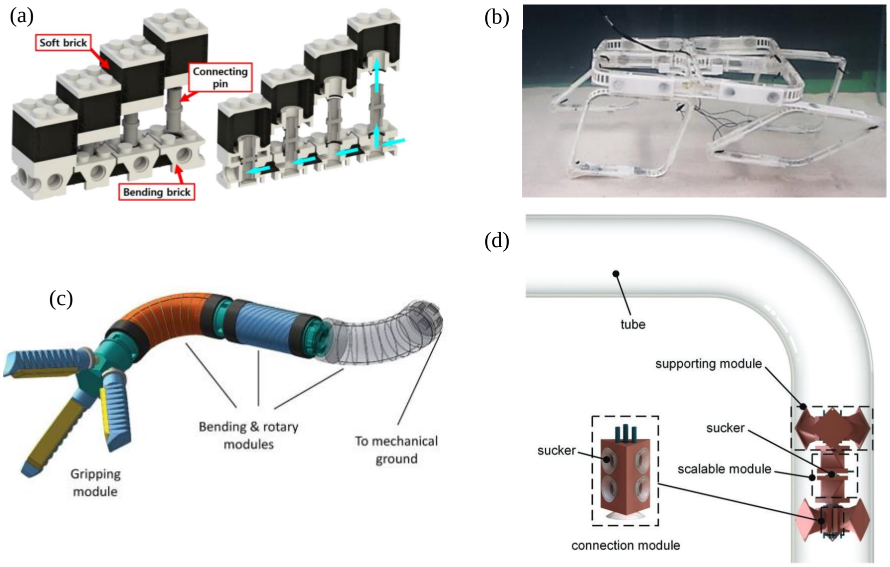

Figure 1: Some examples of modular soft robots: (a) Lee et al. [8] (b) Wang et al. [12] (c) Phillips et al. [10] (d) Jiao et al. [7].

In this paper, a new modular design strategy for reconfigurable pneumatic soft robots is proposed, Sec.2 illustrates the modular design system based on pneumatic soft robots. Sec.3 introduce the decomposed methods for a 3D movement. Sec.4 and Sec.5 discuss the design methods of actuations and connectors, respectively. A novel 6-DoFs gripper based on the proposed modules is presented in Sec.6. Finally, some concluding remarks and the future direction are provided.

2 SYSTEM OVERVIEW FOR MODULAR PNEUMATIC SOFT ROBOTS

With the rapid growth of modern industry, the tasks in the manufacturing system are becoming more and more complex and diverse, which require more advanced and flexible machine structures. Fig.2 illustrates the overview and the workflow of the proposed reconfigurable soft robots for a manipulation case. The internet of things is adopted in the overview system, which brings significant benefit to communication between machines. The cloud server, including computers, microchips or cellphones, can implement the functionalities of record, inspection, analysis and control. The object's attributes (e.g., size, shape and position) should be detected by the sensor at the beginning. Secondly, the required movement also should be clarified by task analysis, then the target movement can be decomposed into 6 DoFs. Combining the object attributes and decomposed movement, the cloud server can analyze the data and provide a selection scheme of modules, where the actuation modules can implement stretch, bending and twisting motions. Finally, the selected modules are picked up and assembled as a gripper, where the assembly process can be manual or automatic. When the sensor finds the objects are changed, the assembled gripper can be reconfigured to different structures through the assembly/disassembly system. For example, the number of bending modules at the end can be increased to manipulate the bigger objects; the twisting module can be added to pick up the objects with complex structures, which can adjust the manipulated angle; the number of the stretch modules can be increased to enlarge the graspable range.

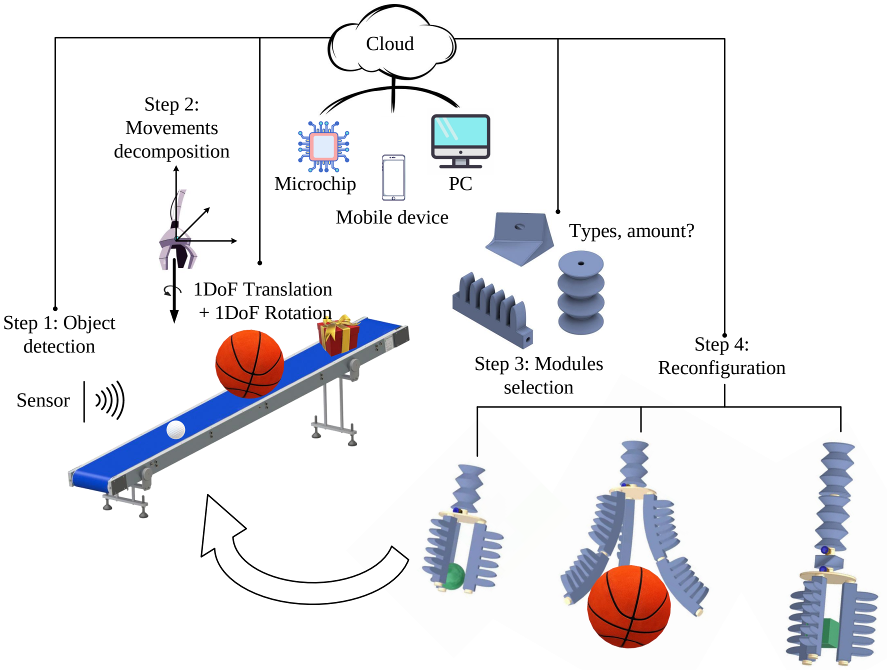

Figure 2: Overview of modular design based on reconfigurable pneumatic soft robots.

3 METHODOLOGY OF 3D 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. The posture of the gripper can be described by the position and orientation (assumed as a rigid body). The illustration of the coordinate system can be seen in Fig.3, where the base coordinate system is OXYZ, and the coordinate system fixed in the gripper is O'X'Y'Z'. When the movement occurs, the coordinate system of the gripper change accordingly. The position of the gripper can be described by a 3x1 position vector, which can be written as

$$p = \begin{bmatrix} p_x & p_y & p_z \end{bmatrix}^T \tag{1}$$

where p_x, p_y and p_z are the coordinate value on the X, Y and Z axes respectively. The orientation of the gripper can be described as a 3x3 matrix as,

$$R = \begin{bmatrix} \cos\angle X'X & \cos\angle Y'X & \cos\angle Z'X \\ \cos\angle X'Y & \cos\angle Y'Y & \cos\angle Z'Y \\ \cos\angle X'Z & \cos\angle Y'Z & \cos\angle Z'Z \end{bmatrix} \tag{2}$$

where the first column represents the components of the O'X' axis of the gripper coordinate system along with the three axes of the base coordinate system. Similarly, the second and third columns are the components of the O'Y' and O'Z' axes of the gripper's coordinate system along the three axes of the base coordinate system respectively.

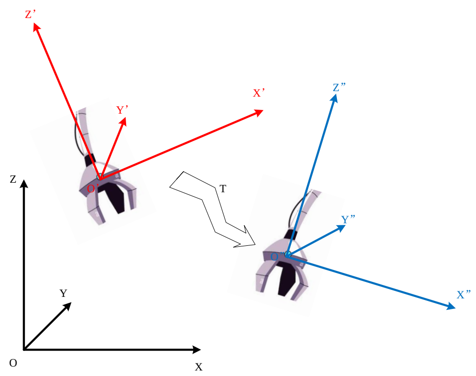

Figure 3: The illustration for coordinate system and transformation process.

A homogeneous coordinate in 4x4 metric can be utilized to represent the gesture including the position and orientation,

$$G = \begin{bmatrix} R(3\times 3) & p(3\times 1) \\ O(1\times 3) & 1 \end{bmatrix} \tag{3}$$

The transformation process mapping a gesture vector $G^{'}$ to another $G^{''}$, can be expressed as

$$G^{''} = T \cdot G^{'} \tag{4}$$

where T is a 4x4 homogeneous transformation matrix,

$$T=\left[\begin{array}{cc} Rot(3\times 3) & Trans(3\times 1) \\ O(1\times 3) & 1 \end{array}\right]=\begin{pmatrix} t_{1,1} & t_{1,2} & t_{1,3} & t_{1,4} \\ t_{2,1} & t_{2,2} & t_{2,3} & t_{2,4} \\ t_{3,1} & t_{3,2} & t_{3,3} & t_{3,4} \\ 0 & 0 & 0 & 1 \end{pmatrix} \tag{5}$$

in which Rot is a 3x3 matrix denoting the rotation process and $Trans$ is a 3x1 vector denoting the translation process. When the $G^{''}$ and $G^{'}$ are known, the transformation matrix T can be calculated according to Eq.4.

Given a original gesture G_o ,

$$G_o=\begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{6}$$

Since rotation is a motion with three degrees of freedom, a set of three independent parameters are sufficient to describe an orientation in space. The transformation process from G_o to final gesture G_{final} can be decomposed into 3 rotation around the X, Y, Z axis, i.e., $\mathrm{Rot}\left(X_i, \theta_x\right), \mathrm{Rot}\left(Y_i, \theta_y\right), \mathrm{Rot}\left(Z_i, \theta_z\right)$ and 3 translation on the X, Y, Z axis, i.e., $\mathrm{Trans}(d_x, d_y, d_z)$, shown as follows:

$$\begin{aligned} G_{\mathsf{final}} &= \mathrm{Rot}\left(Z_i, \theta_z\right)\cdot \mathrm{Rot}\left(Y_i, \theta_y\right)\cdot \mathrm{Rot}\left(X_i, \theta_x\right)\cdot \mathrm{Trans}(d_x, d_y, d_z)\cdot G_o \\ &= \begin{bmatrix} \cos\theta_z & -\sin\theta_z & 0 & 0 \\ \sin\theta_z & \cos\theta_z & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}\cdot\begin{bmatrix} \cos\theta_y & 0 & \sin\theta_y & 0 \\ 0 & 1 & 0 & 0 \\ -\sin\theta_y & 0 & \cos\theta_y & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}\cdot\begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & \cos\theta_x & -\sin\theta_x & 0 \\ 0 & \sin\theta_x & \cos\theta_x & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}\cdot\begin{bmatrix} 1 & 0 & 0 & d_x \\ 0 & 1 & 0 & d_y \\ 0 & 0 & 1 & d_z \\ 0 & 0 & 0 & 1 \end{bmatrix} \\ &= \\ &\begin{bmatrix} \cos\theta_y\cos\theta_z & \sin\theta_x\sin\theta_y\cos\theta_z-\cos\theta_x\sin\theta_z & \cos\theta_x\sin\theta_y\cos\theta_z+\sin\theta_x\sin\theta_z & d_x \\ \cos\theta_y\sin\theta_z & \sin\theta_x\sin\theta_y\sin\theta_z+\cos\theta_x\cos\theta_z & \cos\theta_x\sin\theta_y\sin\theta_z-\sin\theta_x\cos\theta_z & d_y \\ -\sin\theta_y & \sin\theta_x\cos\theta_y & \cos\theta_x\cos\theta_y & d_z \\ 0 & 0 & 0 & 1 \end{bmatrix}=T. \end{aligned} \tag{7}$$

Therefore, a 3D movement, i.e., a transformation matrix T, can be decomposed into 6 DoFs as d_x, d_y, d_z translation and $\theta_x, \theta_y, \theta_z$ rotation. When transformation matrix T is obtained, the decomposed movement, defined as $[d_x, d_y, d_z,\theta_x, \theta_y, \theta_z]$, can be calculated by

$$\begin{aligned} d_x &= t_{1,4} \\ d_y &= t_{2,4} \\ d_z &= t_{3,4} \\ \theta_z &= \operatorname{atan}2\left(t_{2,1}, t_{1,1}\right) \\ \theta_y &= \operatorname{atan}2\left(-t_{3,1}, \cos(\theta_z)t_{1,1}+\sin(\theta_z)t_{2,1}\right) \\ \theta_x &= \operatorname{atan}2\left(\sin(\theta_z)t_{1,3}-\cos(\theta_z)t_{2,3}, -\sin(\theta_z)t_{1,2}+\cos(\theta_z)t_{2,2}\right) \end{aligned} \tag{8}$$

4 MODULAR DESIGN FOR ACTUATION

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 bending, and 1-DOF rotation, respectively.

4.1 Geometric Construction

The structures of stretch, bending, and twisting modules are illustrated in Fig.4. As for the stretch module, the structural design is inspired by Chinese lanterns with folded zone, where the folded surfaces have an angle $\theta = 90°$, 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 a twisting angle of $\varphi = 45°$, 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, which brings more design freedom and is beneficial to optimization.

The key design parameters for the stretch module are the angle of folded surfaces θ, the radius of bottom surface r and the total height H_1. When the θ is smaller, the folded surface is getting closer, the stretch module can have a larger deformable domain. In the twisting module, the key parameters are the length of square surfaces L_1, the total height H_2, and the twisting angle of two parallel square plates φ. When the angle φ increases, the deformable domain of twisting is also enlarged. As for the bending module, the key parameters are the total length L_3, the gap length L_3 between chambers, the height H_3 and width W of the bottom chamber, and the Bezier curves surface. All the geometric parameters of three actuation modules can be optimized based on the required objective and constraint.

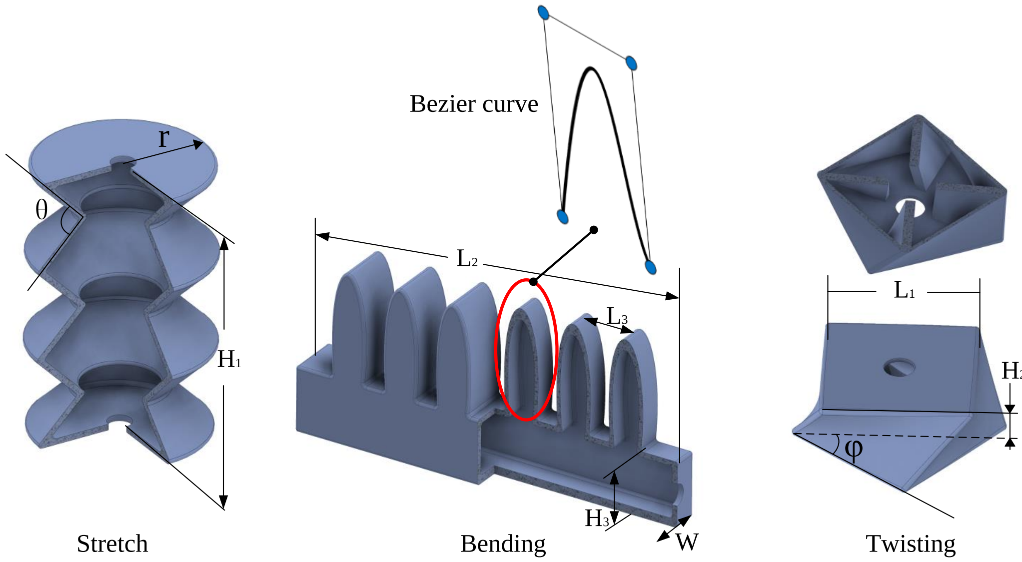

Figure 4: Structural illustration for three actuation modules.

4.2 Structural Optimization

Taking the bending module as an example, Bezier curves are adopted to express the surface of the air chamber, as shown in Fig. 4, the explicit form of the curve is:

$$\mathbf{B}(t) = (1-t)^3\mathbf{P}_0 + 3(1-t)^2 t\mathbf{P}_1 + 3(1-t)t^2\mathbf{P}_2 + t^3\mathbf{P}_3, 0 \le t \le 1 \tag{9}$$

where P_i is the control points. Changing the positions of control points, the geometric varies accordingly. We can set the coordinate of control points as the design variables $\boldsymbol{\chi}$, the objective is the output displacement at the end, the structural optimization model can be described as:

$$\min \quad \Phi[\boldsymbol{\chi}] := -v \tag{10}$$

subjected to

$$\begin{cases} \Psi_Y[\boldsymbol{\chi}] : \sigma - \sigma_{max} <= 0 \\ \chi_i \in \left[\underline{\chi}_i,\ \bar{\chi}_i\right], \quad i = 1, 2, \cdots, \end{cases} \tag{11}$$

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. 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. The structural optimization model can be changed flexibly, such as the design variables can be other geometric parameters of three actuation modules; the objective function and the constraints can be displacement, output linearity, structural stiffness and so on. The proposed optimization model can be regarded as an integration of size and shape optimization. The design variables can be the critical sizes of the structures, which belong to size optimization, and the position of the control points in Bezier curves, which belong to shape optimization. Such integration optimization model can be customized by the designers, where the design variables of the modules are selected according to practical applications, balancing between the computational cost and design freedom.

4.3 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 of 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.5, 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. The deformation curve with respect to the pressure change is present in Fig.6. 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. As the pressure increases, the increasing rates of deformation become slower, which is similar to the testing result of [7]. For the FEA-based simulation, it is difficult to simulate the large-angle twisting deformation. According to [7], the twisting angle can reach $80°$.

It is time-consuming to simulate the bending module in 3D since self-contact occurs between the adjacent air chambers in the inflation or deflation process. Therefore, we simulated bending modules in consideration of the self-contact in a 2D case, which has a similar deformation pattern, shown in Fig.7. Driven by the pressure,

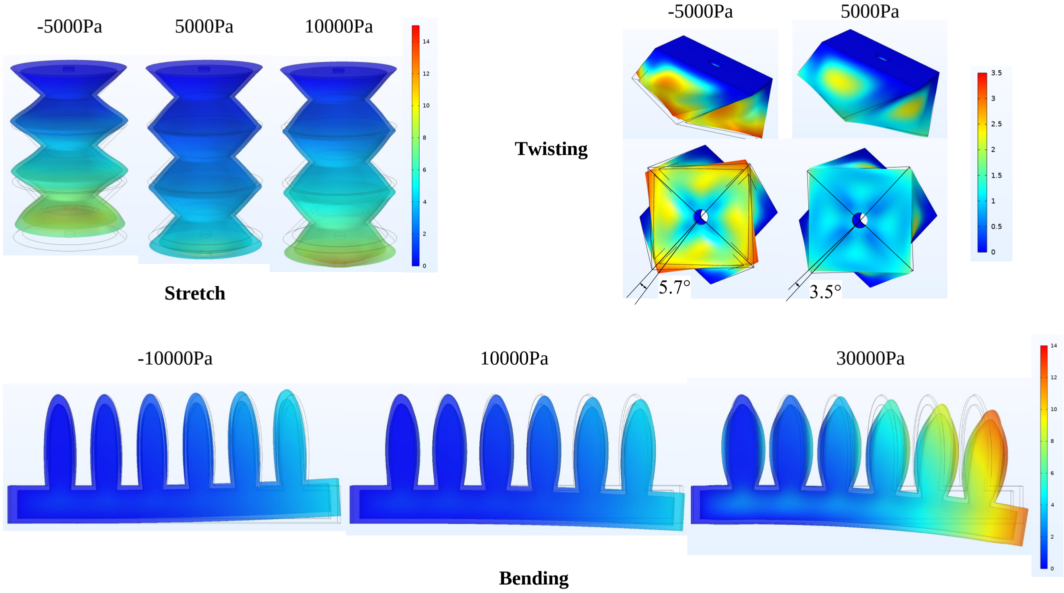

Figure 5: Displacement of stretch, bending and twisting modules with different pressures. (unit mm)

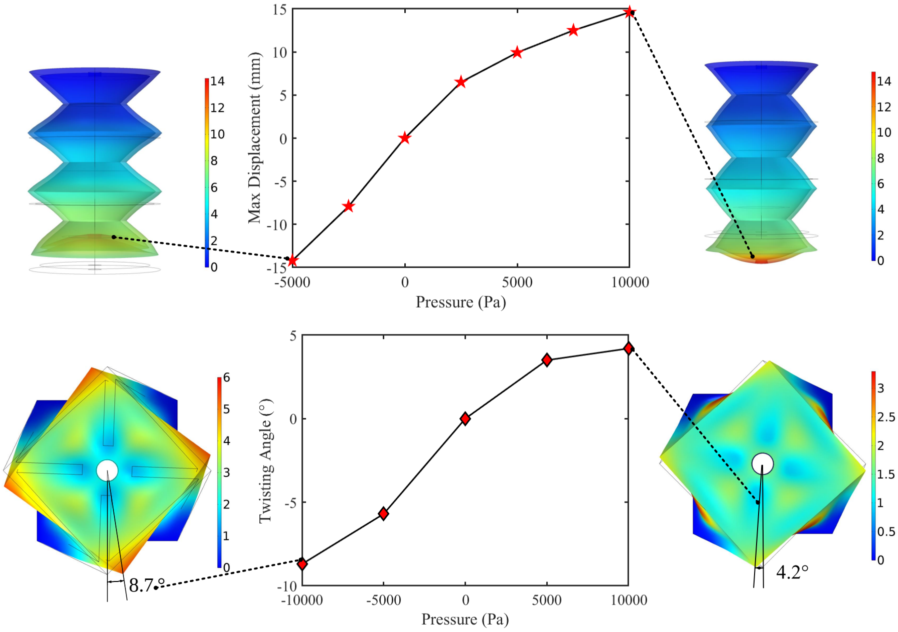

Figure 6: Deformation curves of stretch and bending modules with respect to pressure change.

the structure bent upward or downward according to positive or negative pressure. The output displacement at the end respect with to different pressures is listed in the middle of Fig.7 which reports its nonlinearity.

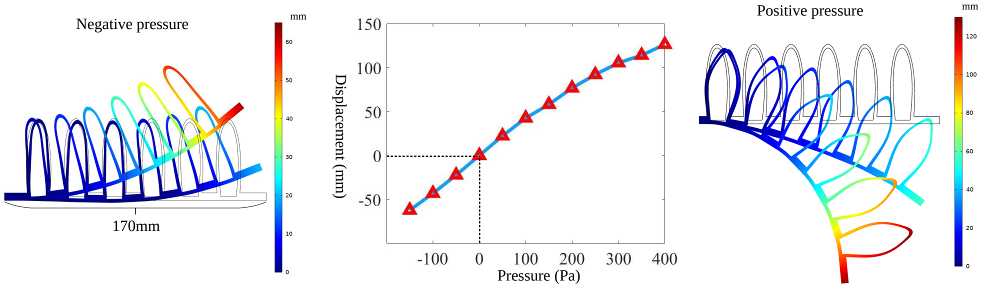

Figure 7: Displacement output respect with positive and negative pressure of bending modules in 2D case.

4.4 The Criterion for Modules Selection

Since the deformation curves are obtained, the deformation-pressure functions $f_i(p)$ of the actuations can be fit. The fitting functions can guide the users to choose the actuations according to the demand of the tasks. For a task that needs axial motion d_x, d_y, d_z and twisting angles $\theta_x, \theta_y, \theta_z$ in 6 DoFs, the highest pressure load is *H* Pa, the modules selection scheme should fulfill the constraint:

$$\begin{cases} \sum f_i(H)_m > d_m, m = x, y, z; \\ \sum f_i(H)_n > \theta_n, n = x, y, z, \end{cases} \tag{12}$$

where i represents the ID of the actuation modules, the sum of decomposed deformation of actuation modules should be larger than the task demand in each DoF.

4.5 Prototypes Fabrication

Finally, we used silicone rubber to fabricate the modular soft robots. Their deformations with pressure are listed in Fig.8. The top is the bending module with positive pressure, and the bottom is the stretch module and twisting module with negative pressure. For the three actual modular robots, they successfully implemented the deformation including stretch, bending and twisting as we designed, which demonstrates the feasibility of the proposed design methods.

5 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 [15]. According to the characters of magnet connect, a staggered magnet poles structure is proposed, shown in Fig.9a. 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

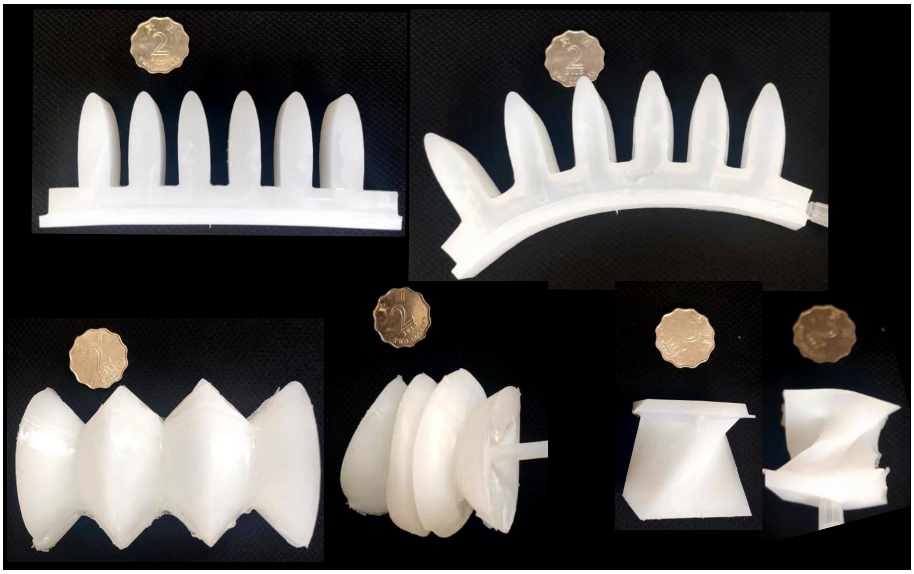

Figure 8: Actual deformation of three modular soft robots with pressure loading.

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. These connectors can be fabricated by additive manufacturing, a connected case is presented in Fig.9b. 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. The conventional connecting ways mainly are adhesion and mechanical connection. Most adhesion connections, such as glue or hot-melt, are one-off and irreversible, where the disconnection process may cause damage to the initial parts. Threaded and other mechanical connections need extra complex operations (such as screwing) in the connect/disconnect process. The magnet connection is advancing in assembly/disassembly because the modules can be connected/disconnected easily and frequently without harming the modules and complex operations. And it has high connection strength between the modules. Combined with the proposed structural design, it has a self-aligned function, saving time in location.

6 CASE STUDY

Manipulation is an important case study in the robotics industry. The human's hands can manipulate objects of various shapes, sizes, and materials and control the objects' position in confined spaces with advanced dexterity capabilities. It is difficult to grasp different-sizes and different-postures objects as human's hands with traditional fixed-configuration soft robots, but it is capable with modularized soft robots. The gripper using modular units (see Fig.10) can achieve the complex 6-DoFs movement composed of stretch, bending and twisting modules. Based on the decomposed movement, the gripper can perform 6-DoFs movement $[d_x, d_y, d_z, \theta_x, \theta_y, \theta_z]$ to reach the object's position, and adjust the orientation to grasp the object. For example in Fig.10, to pick up the yellow cylinder, the stretch modules in the Y and Z axis are activated to move left and down; to pick up the blue block, the stretch modules in the Y, Z axis and the twisting modules in Z-axis

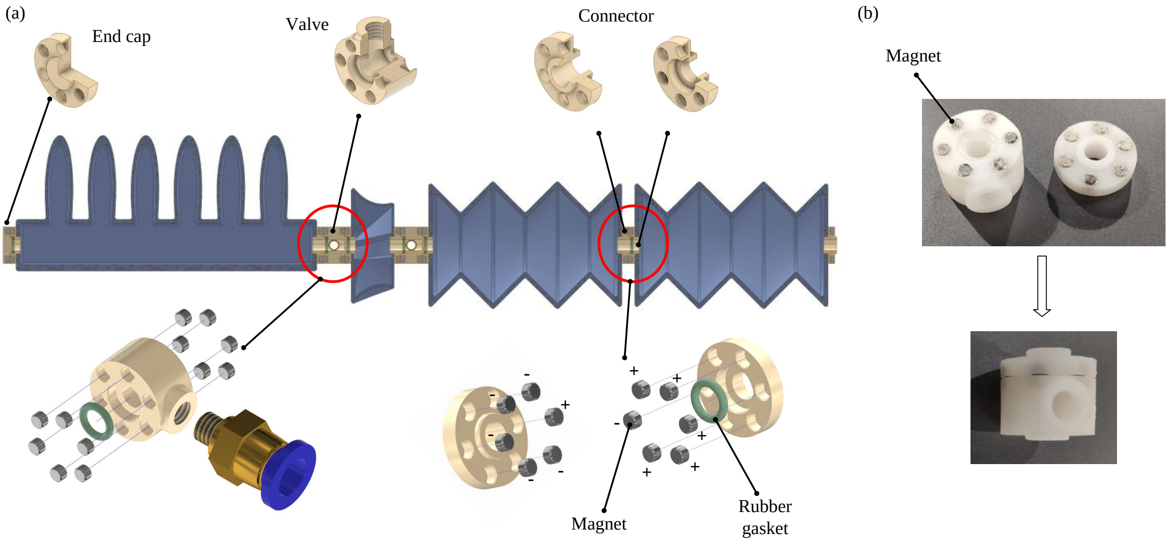

Figure 9: The structure illustration for connector modules.

are activated to move forward and down, meanwhile adjust the orientation. The gripper's configuration can be changed to adapt to the objects' attributes and postures. The amount of the stretch and twisting module can be increased or decreased according to the objects' postures, fulfilling the constraint in Eq.12. The amounts of ending bending actuations are adaptive to the objects' sizes, ensuring that the bending modules encase the objects. The application scenarios of proposed modular pneumatic soft robots are not only limited to manipulation, they can be utilized in rescue robots, server robots, bioinspired robots and so on.

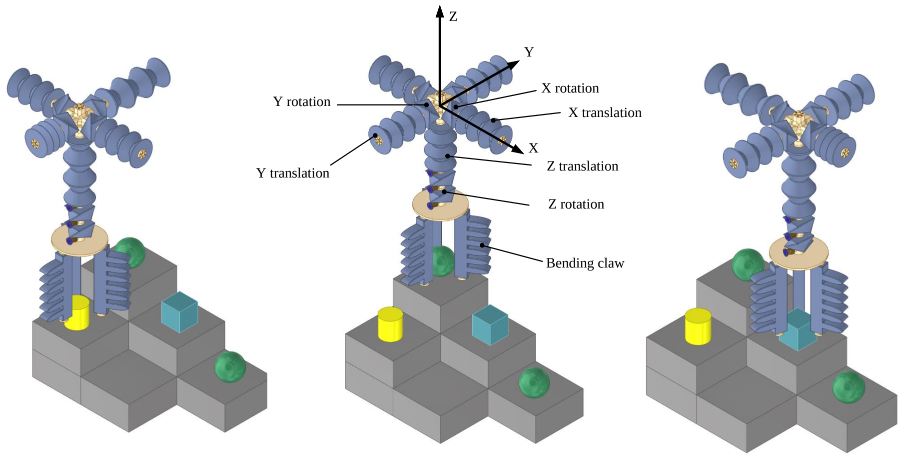

Figure 10: The reconfigurable 6-DoFs gripper based on modular pneumatic soft robots.

7 CONCLUSIONS

This paper presented a modular design framework for reconfigurable pneumatic soft robots, mainly including movement decomposition, actuation and connector design, which is adaptable to complex tasks and environments. The robots can complete complex functionalities, such as:

- Movement adaptable. The proposed actuation modular design is based on the decomposed movements in real life, which is suitable to mimic complicated movement via modular units configurations changing.
- Assembly-friendly. With the self-align magnet-connector, it is easy to reconfigure the arrangement of modular units. Self-assembly, self-repair, reusability and self-replication can be achieved effectively.
- Balance between personal and mass customization. It is suitable to fabricate the modular unit on a mass scale, meanwhile, the users can reconfigure the modular units according to their actual needs.

The module units of proposed reconfigurable soft robots are divided into two categories: actuation and connector. For actuation, we proposed a novel structural designs method (including geometric construction, simulation and optimization model) to design three kinds of modules, which can implement the movement of stretch, bending, and twisting. FEA-based simulations are performed, which demonstrate the proposed actuation module can implement the objective movements, and also report the relationship between deformation and pressure. Movement decomposition is conducted to simplify the 3D complex movements into 6 DoFs respectively. Combine with the deformation-pressure relationships, a criterion is provided for modules selection. For the connector, a novel self-align magnet-based structure is proposed, which brings significant convenience to the assembly/disassembly process. The future work will include 3 main parts: (1) prototype iteration, (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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