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Research paper

Design and modeling of a soft robotic surface with hyperelastic material

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ABSTRACT

While most existing soft robots have tentacle-like morphology, this paper extends the morphology of a soft robot from a curve to a surface. The presented robotic surface is fabricated using hyperelastic silicone material, and its morphology and deformation can be actively controlled through two pneumatic soft bending actuators embedded along the edges. Quasi-steady-state models of the embedded actuators and the surface structure are established using the principle of virtual work and elastic plate theory, respectively, and then combined to relate the input pressure and external force to the deformation of the soft surface. The complete model is validated experimentally against a robotic prototype where the error is within 5% of the side length of the surface for a number of actuation levels.

1. Introduction

Traditional discrete robots constructed by a series of rigid links and joints can generate high precision movements repetitively, but often with limited flexibility and safety for interaction with unstructured environment due to the lack of compliance [1]. Recently, inspired by biological structures (e.g. mammalian tongues, octopus arms, inchworms), soft robotics has attracted growing interest for their intrinsic compliance. With a soft structure these robots have the potential to deform their bodies continuously to achieve dexterous motions. They further produce little resistance to compressive forces and can thus adapt to surroundings and carry fragile payloads without causing damage. Additionally, they are able to absorb energy arising from a collision and therefore are better suited to achieve safe interactions with humans [1,2].

Existing soft robots usually have a "tentacle-like" morphology. For instance, Trimmer et al. designed a soft caterpillar-like robot actuated by tendons for terrestrial locomotion [3]. Walker et al. proposed several continuum octopus-like robots based on pneumatic artificial muscles [4–6]. Mutlu et al. used electroactive polymer actuators to build a soft mechatronic mechanism [7]. Shepherd et al. developed a unique class of locomotive soft robot composed exclusively of elastomeric polymers [8]. The kinematics of these robots are normally recognized as a combination of multiple curved lines [9].

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Observing biological structures in nature, such as birds' wings and Rajiformes' fins, these are flexible surfaces with a "sheet-like" structure. In such systems, movements are generated by internal skeletons or muscles and transmitted throughout the surfaces. As surface structures have one more geometric dimension than tentacle-like ones, they are able to produce more complicated shapes and motions. It is then natural to consider if steerable surface robots can mimic such natural animal structures to perform tasks. Potential applications that require the use of robotic surfaces include compliant manipulation and locomotion, morphing wing aircraft, wearable devices, and reconfigurable antenna. Suzumori et al. used pneumatic actuators to drive a soft-bodied manta swimming robot [10]. Similar design was used by Cai et al. to develop a robotic fish inspired by cow-nosed ray [11]. Deng et al. presented a soft machine table inspired by caterpillar to manipulate objects [12]. Khan et al. designed a reconfigurable conformal antenna array that can be attached to a changing surface [13]. Medina et al. presented a flexible, redundant, manifold-shaped-like mechanism actuated by shape memory alloy wires [14,15]. From a design point of view, though the aforementioned systems exhibited significant flexibility at actuators and joints, rigid or semi-rigid components were still utilized largely to form the body structure, thus they are not fully soft and continuous. On the other hand, modeling of such robots is challenging due to the large nonlinear deformation across all dimensions [2]. In [10,11] the mathematic models of the sheet-like robotic fishes were not given. In [12] a piecewise method was utilized to describe the curvature of each cell on the table. In [14,15] the kinematics for the manifold-shaped-like mechanism were solved by using a grid method. Moreover, Kano et al. proposed a continuum model and decentralized control scheme for a sheet-like robot which has been validated by simulation [16]. Walker et al. used an interpolation method to determine curvature between bending edges on a continuum surface [17]. In recent years, plate theories, such as Kirchhoff–Love and Cosserat plate theories, have also been employed to investigate the statics of soft surfaces [18,19]. However, these existing models generally focus on the surface structures while ignoring the effects of the embedded actuators, thus they fail to explain how the actuator and the surface structure are coupled. In addition, previous models using plate theory usually neglect the thickness of the actuator and surface, and assume small deflections. It is not clear that such models are capable of capturing the full characteristics of a robotic surface undergoing large deformations.

The contribution of this paper is to provide a comprehensive design and modeling method for soft robotic surfaces. A pneumatically actuated sheet-like structure fabricated by hyper-elastic silicone without rigid elements is presented as a paradigm for such soft robotic surface. This surface is able to bend toward predefined directions and consequently generate desired deformations. The principle of virtual work is then proposed to determine the relationship between the input pressure and output bending torque of the soft actuator while the elastic plate theory utilized to describe the deformation of the surface structure subjected to the bending torque from the actuator and external forces from the environment. The obtained model takes into account the force interaction between the embedded actuators and the surface structure, and expresses the surface deformation with respect to actuating and external forces.

We begin this paper with an introduction to the design of the soft robotic surface in Section 2. In Section 3, the derivation of the quasi-steady-state models for the soft actuator and surface structure are described respectively, and then combined together. Section 4 gives the validation of the proposed model through experiments on the surface prototype and investigates the influence of the design parameters on surface deformation. In Section 5, conclusions are presented.

2. Soft robotic surface prototype

This section firstly defines the design requirements for the soft robotic surface, based on which, the detailed construction of the surface is then introduced.

2.1. Design requirements

The deformation of the surface is generated through the use of controllable embedded actuators composed of pneumatic elements that are fully soft. Individually these actuation elements are capable of bending motion along their axes in a single direction, through proper arrangement and orientation of these actuators across a surface, multiple, complex, planar deformations thus become possible. There are two basic requirements for our design: (1) allowing for active control of two degrees of freedom (DOF) bending deformations about the orthogonal edges of the surface, i.e. the x and y axes in Fig. 1; (2) maximizing the deflection along the z-axis. To meet requirement (1), at least two soft actuators are needed. Fig. 1(a)–(c) show a series of possible schemes to arrange the actuators and a general shape of the resulting surface. In all cases the surface is assumed constrained along one edge as will be found in the final prototype. It was found that the deflection along the z-axis in scheme Fig. 1(a) is smaller than the others as the deflection is only contributed by one actuator. In scheme Fig. 1(b), the two actuators intersect, so it is practically difficult to place them at one plane into a surface structure. Hence, scheme Fig. 1(c) is adopted in our design. The surface will bend about the x and y axes if the two actuators are activated in different levels while reaching maximum deflection along the z-axis if the two actuators are activated in the same level.

2.2. Construction of the robotic surface

Two actuators are placed along a pair of parallel side edges of the surface, and each actuator can be controlled independently. A detailed design of the soft actuator is shown in Fig. 2(a). There is an eccentric chamber with circular section in the dorsal side of the cylindrical body fabricated by silicone rubber (Ecoflex 00-50). On the ventral side of the body, an