Research paper

Design, characterization and applications of a novel soft actuator driven by flexible shafts

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\textbf{A R T I C L E  I N F O}

Article history:
Received 20 July 2017
Revised 26 December 2017
Accepted 26 December 2017

Keywords:
Soft actuator
Tendon-driven
Continuum robotics
Workspace
Kinematics

\textbf{A B S T R A C T}

This work presents a novel soft actuator with a 3D-printed elastic body based on a fused-deposition-modeling technique and with tendon actuation based on flexible shafts, which allow push, pull, and twist torque transmissions. The combination of the soft body and flexible shaft furnishes an easy-making, modular and functional unit that possesses softness and enables three degrees of freedom. We derive the kinematics and statics of the actuator based on the assumption of piecewise constant curvature, and identify the parameters experimentally. To understand the performance of the soft actuator in different design and fabrication settings, extensive experiments are performed to compare different shapes of cross sections, infill densities, infill patterns, dentation structures and moment arms in terms of generating forces under the same pulling forces. In addition, experimental validations are performed to characterize other properties such as workspace, hysteresis, pushing force, transmitted torque, and tip force under both bending and twisting. Finally, three potential applications, i.e., a soft robotic hand, a multisegment continuum robot, and a miniaturized drilling device, are prototyped and presented experimentally where the flexibility endowed by the shafts is demonstrated and highlighted. The scalability and modularity are also showcased in the three applications.

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1. Introduction

Soft actuators and robots are special types of machines that are composed entirely or primarily of soft materials with low modulus, which lead to theoretically infinite degrees of freedom (DOFs). Soft machines have many distinguishing characteristics when compared to traditional hard robots. Domain-specific concerns that play more important roles than the conventional accuracy and strength requirements call for the use of soft robots, which are, for example, (1) safe human-robot interaction, (2) light weight, (3) low cost, and (4) more DOFs for manipulation and navigation dexterity.

Looking at the existing fabrication approaches, the vast majority of soft robots rely on the top-down processes such as soft lithography and shape deposition manufacturing \cite{1–3}. These methods generally consist of several steps where molds are used to cast the elastomeric cavities and tunnel-like structures with liquid silicone rubber. Then, all the components are cured and joined together. Recently, some new miniature soft pneumatic manipulators have been developed following...
new procedures. A new kind of microscale soft pneumatic actuator was made following the streamlined and standardized fabrication procedure based on PDMS (polydimethylsiloxane) [4]. A comparative design of robotic tentacles was fabricated using a dipping method [5]. However, these approaches suffer from multiple labor-intensive procedures which also lead to low repeatability. Alternatively, the soft robotics community uses bottom-up processes such as fused deposition modeling (FDM) to make soft machines. FDM generally uses thermoplastic materials extruded layer-by-layer to form a 3D shape. Recently, pneumatically driven soft actuators were made using projection stereolithography [6] and low-cost 3D printers [7]. Morrow et al. presented a modified FDM 3D printer to print silicone elastomer for a linear pneumatic actuator using a thickening additive and heat curing techniques [8]. To ensure the airtightness of the printed actuators, some fabrication rules are strictly followed, such as not-too-low extruder temperature, small layer height, cleanliness and size of the nozzle, and well-designed printing trajectory. A recent application of 3D printing technology to continuum robots is the 3D-printed soft concentric tube robot, which utilizes different materials for its inner and outer tubes [9].

Among the commonly used actuation principles in soft robotics, pneumatic elastomeric actuation is the most popular, upon which a great number of soft robots rely [10–12]. Usually, a serial of manual procedures is needed to fabricate robots which have complex internal structures [13]. To remedy this, a soft actuator powered by the pneumatic actuation system was proposed, based on 3D-printing fabrication, to generate high lifting force [7]. There is another actuation principle which relies on varying the lengths of tendons (such as cables and wires) routing along the backbone. Compared to pneumatic actuation, tendon-driven approaches have several advantages: (i) the design is quite simple and relatively straightforward to realize in hardware [14]. (ii) The pneumatic fluid-powered design has advantages over the tendon actuation. One example is suitability for modular design, but it typically involves a pumping air source, which might be undesirable if a compact system is demanded. Actuation systems (e.g., DC motors) are usually more light-weight than pneumatic pumps. (iii) Since there is no fluidic energy involved, the fabrication of tendon-driven soft actuators avoids strict printing guidelines for ensuring airtightness. For example, when printing the soft pneumatic actuators, the temperature of 3D printer extruders cannot be too low, otherwise air leaks would result due to microgaps, which are induced by incomplete melting [7]. (iv) Similarly, the fabrication of tendon-driven soft actuators would allow more freedom in choosing printing materials without the need of considering airtightness and high pressure. (v) Since pneumatic energy sources are far less immature than the actuation systems used in tendon-driven mechanisms [15], the control issue of tendon-driven systems is more straightforward than pneumatic systems. (vi) Tendon-driven mechanisms allow for a much easier merge between links and joints, which is preferable for making soft-hard hybrid manipulators [16].

According to the classification by Trivedi et al. [17], soft robots are a subclass of continuum robots. Some continuum robots which are composed of hard components also have flexible and soft capabilities. There have been numerous tendon-driven continuum actuators developed and presented in literature in the past. Several typical examples are given in Table 1. These examples could be classified into two categories, i.e., rigid segment and soft body. The manipulators/actuators are compared in terms of feature and material of body frames, number and material of tendons, generating degrees of freedom, and applications. In the continuum robots with rigid segments, the body frames were made of either metal like NiTi alloy or 3D printing materials such as ABS and photosensitive resin; the tendons used in most of them are only capable of pulling. The only tendon-driven robot that achieved motion beyond pulling was developed by Simaan et al. [18]. The robot

### Table 1
Comparison of tendon-driven continuum manipulators/actuators.

<table>
<thead>
<tr>
<th>Type</th>
<th>Reference</th>
<th>Body frame feature</th>
<th>Material</th>
<th>Number</th>
<th>Tendon material</th>
<th>DOF</th>
<th>Application</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rigid segment</td>
<td>[21]</td>
<td>3D printed</td>
<td>Photosensitive resin</td>
<td>4</td>
<td>Steel cable</td>
<td>pull</td>
<td>Surgery</td>
</tr>
<tr>
<td></td>
<td>[22]</td>
<td>Ortho-planar spring</td>
<td>ABS polymer</td>
<td>3</td>
<td>Fishing line</td>
<td>pull</td>
<td>Manipulator</td>
</tr>
<tr>
<td></td>
<td>[23]</td>
<td>Layer jamming</td>
<td>Mylar film</td>
<td>3</td>
<td>NiTi wire</td>
<td>pull</td>
<td>MIS manipulator</td>
</tr>
<tr>
<td></td>
<td>[24]</td>
<td>Variable neutral line</td>
<td>ABS polymer</td>
<td>4</td>
<td>Dyneema fiber</td>
<td>pull</td>
<td>MIS manipulator</td>
</tr>
<tr>
<td></td>
<td>[25]</td>
<td>Helical structure</td>
<td>ABS polymer</td>
<td>4</td>
<td>Polyethylene fiber</td>
<td>pull</td>
<td>MR-compatible cardiac catheter</td>
</tr>
<tr>
<td></td>
<td>[26]</td>
<td>Two bending sections</td>
<td>NiTi alloy</td>
<td>4</td>
<td>PEEK</td>
<td>pull</td>
<td>Neuroendoscopy</td>
</tr>
<tr>
<td></td>
<td>[27]</td>
<td>3D printed Cable-guide disk</td>
<td>Polypropylene</td>
<td>2</td>
<td>Steel cable</td>
<td>pull</td>
<td>Manipulator</td>
</tr>
<tr>
<td></td>
<td>[28]</td>
<td>Spacer disk</td>
<td>NiTi</td>
<td>3</td>
<td>Super-elastic NiTi rod</td>
<td>pull</td>
<td>Surgery</td>
</tr>
<tr>
<td>Soft body</td>
<td>[19]</td>
<td>Soft body with rigid joints</td>
<td>Urethane rubber, polyimide</td>
<td>4</td>
<td>Kevlar</td>
<td>pull</td>
<td>MIS</td>
</tr>
<tr>
<td></td>
<td>[20]</td>
<td>Soft</td>
<td>Silicone rubber, plastic disc</td>
<td>4</td>
<td>Dyneema fiber</td>
<td>pull</td>
<td>Manipulator</td>
</tr>
<tr>
<td></td>
<td>[21]</td>
<td>3D printed, soft</td>
<td>TPU</td>
<td>1</td>
<td>Normal cable</td>
<td>pull</td>
<td>Robotic hand</td>
</tr>
<tr>
<td></td>
<td>[22]</td>
<td>3D printed, soft</td>
<td>NinjaFlex TPU</td>
<td>1</td>
<td>Flexible shaft</td>
<td>Pull</td>
<td>Robotic hand, manipulator, drilling device</td>
</tr>
</tbody>
</table>
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