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A Soft-Rigid Tendon-Driven Continuum Robot with Multi-Curvature Actuated by a Single Set of Tendons

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Abstract— **This work presents a novel design of achieving multiple curvatures in a tendon-driven continuum robot (TDCR) system with only a single set of acturation tendons. The TDCR used in this work is assembled from multiple subsections made of low-melting point alloy (LMPA), which each of them has independent binary stiffness by localized thermal phase transitions. Through localized thermal phase transitions, the robot can dynamically ”lock” or ”release” specific subsections, enabling multi-curvature configurations, enabling independent curvature control with only one set of actuation tendons. This approach eliminates the need for additional segments or complex locking mechanisms, significantly reducing mechanical complexity and control challenges. Experimental validation confirms the system’s ability to execute complex shapes (C/J/S-shape configurations), maintain structural rigidity in locked states, as well as different spatial movements can be achieved by changing the configuration of subsegments. The SR-TDCR demonstrates potential for confined-space applications merging dexterity with actuation efficiency.**

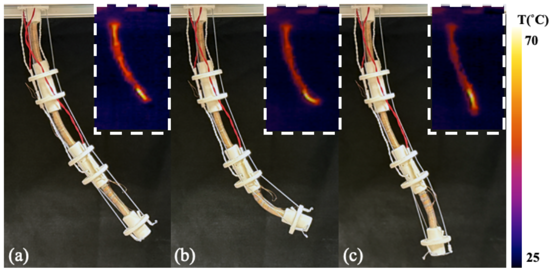

Fig. 1. SR-TDCR utilizes a multi-segment backbone with independently variable stiffness, enabled by localized thermal phase transition of low-melting-point alloy (LMPA). This allows selective softening of specific subsegments, facilitating multile curvature modulation within a single tendon-driven continuum robot (TDCR). (a) The SR-TDCR assumes a uniform C-shape, while heating is applied to the distal subsegment; (b) J-shape: the proximal and middle segments remain rigid (LMPA in solidification form) while the distal segment softens (LMPA in liquefied form) and deforms; (c) S-shape: deforming the distal segment in the opposite direction while keeping it soft. The thermal camera view shows the temperature of each subsegment, with the approximate temperature referenced by the color bar on the right-hand side.

I. INTRODUCTION

Continuum robotics (CR) has emerged as a prominent area of research within the field of robotics. Inspired by nature, they mimic the form and structure of elephant trunks and snakes with a slender, deformable body, resulting in high dexterity, flexibility, and compliance. The body of a CR is typically made of flexible or deformable materials, such as silicone [1], a backbone made of springs [2] [3], or shape-memory alloys with high elasticity, and is actuated by one or more sets of tendons [4] or pneumatic cavities [5]. Due to these advantages, CRs are widely used for delicate tasks in complex environments, such as pipeline inspection [6], engine maintenance [7] and minimal-invasive surgery [8] [9].

In a tendon-driven continuum robot (TDCR), each active segment is typically actuated by one set of tendons. When actuated, each segment generally exhibits a bending behavior that approximates a constant-curvature arc in three-dimensional space [4]. However, the workspace of a single constant-curvature segment is spatially limited. To achieve greater dexterity and curvature variation along the structure in free space, the robot must support multiple curvatures—a capability that necessitates the use of multiple segments. A common approach to realize multiple curvatures is to increase the number of driving tendon sets. Nevertheless, this introduces additional active degrees of freedom (DoFs), which in turn elevates the mechanical complexity and actuation cost of the system. Moreover, the increased DoFs impose significant challenges on the control architecture, complicating motion planning and real-time coordination. Under actuation (UA) [10] is an intuitive solution, which aims to use as few actuating tendons as possible to achieve multiple curvatures.

Prior research on multi-curvature actuation in continuum and serial multi-joint robots can be broadly categorized into two strategies: the incorporation of locking mechanisms and the internal modulation of backbone stiffness. The first approach involves installing locking devices onto the robot structure to decouple tendons from specific subsegments or to mechanically fix the bending angle of the backbone. Examples include magnetic locking systems [11] and set-screw-based mechanisms [12], which lock secondary backbones to enable multiple curvatures within a single tendon-driven continuum robot (TDCR) segment. Electromagnetic brakes have also been employed to immobilize joints in multi-joint wire-driven arms [13]. The second strategy focuses on internally adjusting the stiffness of the backbone to influence subsegment curvature. For instance, [14] developed a robot with subsegments comprising a polyurethane foam core enclosed by ABS plastic, where stiffness is modulated by compressing or expanding the plastic segments to mechanically lock the shape. Shape-memory alloys (SMAs) are utilized to enhance friction in clutch-tendon systems [10] or to achieve modular stiffness variation via thermal phase transition between austenite and martensite [15].

Owing to the significant stiffness contrast between solid and liquid states, low-melting-point alloys (LMPAs) have emerged as effective materials for stiffness tuning. By encapsulating LMPA within the robot structure, researchers have achieved directional stiffness control [16] or curvature fixation in subsegments [17]. For example, [16] developed a laparocendoscopic manipulator that exhibits a significant stiffness increase in the rigid state while retaining soft-state flexibility. Similarly, [18] designed a self-reconfigurable mobile agent using LMPA to lock the curvature of a dual-segment bridge, ensuring sufficient rigidity even during locomotion. Although some previous studies have demonstrated that the use of LMPA can lock the backbone of CR to form multiple curvatures, the field of using this feature to achieve multiple curvatures with fewer actuating tendons remains relatively blank.

In this paper, we propose a novel variable-stiffness backbone design that uses LMPA to achieve multiple independent variable-stiffness degrees of freedom and realize various curvatures on a single-segment TDCR (Fig. 1), eliminating the need for additional robotic segments and auxiliary actuation tendons. The variable-stiffness segment design in [18] was adapted into modular units and embedded with a nickel-titanium alloy wire as the backbone. In this study, we propose a novel variable-stiffness backbone design that uses LMPA to achieve multiple independent variable-stiffness DoFs and realize multiple curvatures within a single-segment TDCR, eliminating the need for additional robotic segments and auxiliary actuation tendons. The variable-stiffness segment design from [18] was adapted into modular units and embedded with a nickel-titanium alloy wire as the backbone. The contributions of this paper are as follows: First, we propose an innovative variable-stiffness backbone with multiple independent DoFs for TDCRs. Second, we propose a hybrid kinematic model for tendon-actuation of this system. Finally, we experimentally verify the working principle and demonstrate how SR-TDCR can achieve multiple curvatures in 2D and 3D space within a single-segment TDCR without the need for additional segments or actuation tendons.

II. CONCLUSIONS

This work presents the Soft-Rigid Tendon-Driven Continuum Robot (SR-TDCR), which introduces a novel design for achieving multiple curvatures in a single-segment tendon-driven continuum robot. By incorporating low-melting-point alloy (LMPA)-based variable-stiffness units, the system enables multiple independent stiffness degrees of freedom, allowing diverse curvature configurations without additional segments or complex locking mechanisms. Through localized thermal phase transition of the LMPA, the robot dynamically modulates the stiffness of individual subsegments, facilitating independent curvature control using only one set of actuation tendons. This approach significantly reduces mechanical complexity and simplifies control challenges. Experimental results validate the robot's capability to achieve complex shapes (e.g., C-, J-, and S-shapes), maintain structural rigidity in locked states, and perform varied spatial movements by reconfiguring subsegment stiffness states. The SR-TDCR shows promising potential for applications, combining high dexterity with actuation efficiency.

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