**A pre-programmable continuum robot inspired by elephant trunk for dexterous manipulation**

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**Abstract**

Cable-driven continuum robots with hyper-redundant deformable backbones show great promise in applications, such as inspection in unstructured environments, where traditional rigid robots with discrete links and joints fail to operate. However, the motion of existing continuum robots is still constrained by their homogeneous backbones, and limited to environments with modest geometrical complexity. Here, inspired by highly deformable elephant trunks, we presented a modular tensegrity structure with pre-programmable stiffness for continuum robots. Then, we derived a mechanical model based on a positional formulation finite element method for predicting the configuration of the structure in different deformation scenarios. Theoretical predictions revealed that the curvature of each segment could be regulated by pre-programming their spring stiffness. Hence, our customizable design could offer an effective route for efficient robotic interactions. We further fabricated a continuum robot consisting of 12 modules, and showcased its deformation patterns under multiple scenarios. By regulating the distribution of spring stiffness, our robot could move through channels with varying curvatures, exhibiting its potential for applications where varying curvature, conformal and efficient interactions are needed. Leveraging the inherent intelligence, this robotic system could simplify the complexity of the required actuation and control systems.

**Keywords:** Pre-programmable stiffness, cable-driven continuum robot, modular tensegrity structure, varying curvatures, morphing

1. **Introduction**

Continuum robots, featured by their lightweight, high compliance, and remarkable dexterity [1], show great promise in challenging scenarios, in which conventional rigid robots with discrete links and joints fail to operate [2]. These include many practical applications, such as minimally invasive surgery [3], urban search and rescue [4], and inspection of cluttered environments [5]. The concept of continuum robots was first proposed by Robinson and Davies [6]. Since then, various types of continuum robots have emerged, which in terms of actuation mechanisms can be categorized as cable-driven [7], pneumatic-driven [8], and advanced materials-driven [9].

Among these actuation mechanisms, cable-driven actuation is one of the most frequently used ones because of its both high payload and fairly high kinematic accuracy [10, 11]. The representative configuration of cable-driven continuum robots includes an elastic backbone with infinite passive degrees of freedom (DoFs), spacer disks that are fixed to the backbone equidistantly, and cables that pass through the spacer disks parallel to the backbone [12-14]. An example of this is the continuum robot developed by Simaan *et al*. The robot, which was able to operate in narrow spaces, had a hyper-elastic nickel-titanium (Ni-Ti) alloy as a backbone, and was used in minimally invasive surgeries. The backbone not only allows for structural simplicity, but also prevents hard collision [15]. Recently, a few other backbone designs have been developed, and used in continuum robots [16, 17]. However, in almost all the existing designs, a single set of actuators always configures a deformation pattern that has a uniform global curvature because of their homogeneous backbones, which limits dexterity when interacting with objects/environments with varying curvatures [18].

In situations where robots should adapt to varying curvatures, a new design principle is needed to generate adaptive configurations in a simple, yet robust way. To meet this demand, researchers have turned to natural systems and studied deformation of snake body, octopus tentacles, and elephant trunks for inspiration [8, 19]. Elephant trunks function as a muscular hydrostat: the coordinated contraction of antagonist muscles is translated into torsion, bending, tension, and compression, not by an articulated skeleton, but through shape changes that rely almost entirely on self-supporting trunk muscular tissues [20, 21]. Through combinations of basic movements, the trunk exhibits multiple DoF, that make it one of the most dexterous hydrostats among both natural and engineering systems [22, 23]. For operations with varying curvature requirements, the trunk can be functionally subdivided into finite segments that are connected by pseudo-joints. The stiffness of each segment can be adjusted independently, allowing the trunk to tune its local bending properties [22] (Fig. 1, Video S1). This specific design enables the trunk to undergo complex deformations and adapt to objects with various shapes. Inspired by elephant trunks, we might be able to overcome the limitations of existing continuum robots when dealing with varying curvature scenarios.

Pre-programming the structural stiffness is an efficient strategy for controlling behavior and customizing the response of mechanical systems under both external and internal stimuli [24, 25]. In recent years, this design concept has been widely used in robotic applications and was found to enhance the performance of existing robots, by enabling strong conformal and efficient interactions in curvature varying scenarios [25-27]. However, most of the customized schemes that are currently available can be merely used in those specific-purposed, single, and repetitive applications. A design strategy that can be pre-programmed is required to satisfy the requirements of more practical applications.

Here, we proposed a tensegrity topology for the cable-driven continuum robotic design, in which the springs could be easily replaced to tune stiffness. By pre-programming the distribution of the springs in robotic systems, the complexity of actuation and control systems could be significantly simplified. To assess the influence of the regulated spring stiffness, we developed a mechanical model based on a positional formulation finite element method, and used that for predicting the morphing characteristics of a robotic system. Taking advantage of the model, we analyzed the curvature of each segment for various stiffness distributions. To exhibit the performance of our design in application, we fabricated a continuum robot consisting of twelve modules. By regulating the distribution of the spring stiffness, our bio-inspired robot not only demonstrated various deformation patterns, but could also move through pipelines with varying curvatures. The results show the potentials of our design for efficient robotic manipulation, inspection and exploration.

1. **Materials and Methods**

***2.1 Motion characterization of an elephant trunk***

We recorded the motion of an Asian elephant trunk at the Shenzhen Safari Park (Shenzhen, China) (Video S1). In Fig. 1, the trunk can be divided into several segments by pseudo-joints, and the local stiffness of each segment could be regulated independently for the purpose of forming varying curvatures, based on which the trunk conformed to a variety of profiles for dexterous manipulations, such as intercepting rolling apples (Fig. 1A), and curling apples to grip (Fig. 1B) [22]. According to motion characteristics of the trunk, the pre-programmable stiffness behavior might be useful to overcome the limitations caused by homogeneous backbones in common continuum robots.

***2.2 Modular design***

We designed a stiffness pre-programmable continuum robot based on tensegrity structure (Fig. 2). The robot was composed of *n* identical tensegrity modules, each of which has a height of *H*e. One module contained two hexagonal ring-like layers, which were alternately connected by three rigid transverse rods and three tension-loaded springs, and six longitudinal rods divided into three groups linked two adjacent layers by hinges. Then, the cables (No. 1 to 6) are routed along the long axis of the structure through the prefabricated channels evenly spaced in the radial dimension.

In this system, the individual springs could be exchanged in seconds, allowing the robot to configure various stiffness gradient. To elaborate effects of spring stiffness on module deformation, we selected three types of springs with varying stiffness, namely, type *A*, *B*, and *C*, and calculated the corresponding spring stiffnesses, as *K*A = 39.99 ± 4.88 N/m, *K*B = 102.71 ± 13.02 N/m, and *K*C = 399.21 ± 56.39 N/m (Fig. 3A, and Fig. S1). Then, we measured the structural stiffness after attaching springs to the module, discovering that the stiffness of implementing type *C* was 1.62 times that of type *A* (Fig. 3B). Because of the diversity in structural stiffness, the springs with the initial length of 20 mm were stretched to 43.17 ± 0.62 mm, 34.67 ± 0.85 mm, and 21.67 ± 0.47 mm in these modules, respectively (Fig. S2), causing the robotic module to exhibit varying bending deformation under the identical actuation condition, as depicted in Fig. 3C. Therefore, the combination of modules with different stiffness into a continuum robot could display a variety of deformation patterns. Specifically, a continuum robot composed of three modules (i.e., *M*1, *M*2, and *M*3) was initially developed (Fig. 3D), in which the stiffness of all springs was set as *K*C. When the springs of modules (*M*1, *M*2, and *M*3) were replaced with lower stiffness *K*A, respectively, the robot exhibited three distinct configurations after deformation under the consistent actuation criterion, each of which showed specific curvatures. Therefore, the robot might be able to interact with unstructured environments with varying curvatures by regulating distribution patterns of spring stiffness [18].

***2.3 Mechanical model***

To characterize effects of spring stiffness distribution on the configuration of the continuum robot after deformation, a general mechanical model was developed. In the robotic system, the longitudinal and transverse rods functioning as compressive components were considered as rigid struts. The springs and cables were assumed to be subjected to tension only (Fig. S3). These assumptions allowed for the development of analytic models for the deformation, without the need for a more complex finite element simulation [28]. Here, we used a positional formulation finite element method to build the mechanical model [29], and the general governing equations could be written as (Supplementary Note)

|  |  |  |
| --- | --- | --- |
|  |  | (1) |

where,  was the Jacobian matrix of the boundary conditions,  was Lagrange multiples corresponding to the boundary conditions, and  was the generalized internal force vector, formulated by assembling the generalized force vector of components.  and  represented the generalized coordinate vector in the system and the length variation of the cables being pulled, respectively.

***2.4 Construction of robot paradigm***

To evaluate the accuracy of the mechanical model, we assembled the components with the geometrical parameters listed in Table 1 into a continuum robot to conduct kinematic experiments. The robot, consisting of six modules (*M*1 to *M*6), had a total length of 0.36 m (Fig. 4). For the components in the robot, both springs and cables were commercially available, and the rest of the components were fabricated by three-dimensional (3D) printing of photosensitive resin (EvoLVe 128, Somos, Netherlands). We then developed an experimental setup, and captured the motion by using a video camera (HandyCam, Sony, Japan).

1. **Results and Discussion**

***3.1 Experimental validation of mechanical model***

We introduce springs of type *A* into our continuum robot (Fig. 3A). The continuum robot is able to bend about certain axes by regulating the stretchable cables, performing three typical spatial configurations 1-3 exampled in Fig. 5A (Table S2, Video S2). For instance, when the length variation of the cables satisfies the criteria of Δ*L*1=Δ*L*6, Δ*L*2=Δ*L*5, Δ*L*3=Δ*L*4=0, and Δ*L*1:Δ*L*2=5:1, the robot bends about *Y*-axis in the *XOZ* plane, transforming into configuration 1 from the initially straight configuration. We then extract both experimental and predicted bending angles from configuration in Fig. 5B. According to the results presented in Fig. 5C, there is a good agreement between the predicted and experimental configurations. Specifically, when both cables 1 and 6 are pulled by 7 cm, the bending angle measured from experiments is 74.43 ± 5.48°, which is 9.14% larger from 67.63° obtained from the simulation. This difference can be due to insufficient pre-tension in cables, and the friction between cables and/or rods that is not considered in the modeling [30].

We then evaluate the predicting angles of each module with both cables 1 and 6 shortened by 7 cm (Fig. 5C). Here, bending angles of *M*1 and *M*6 arrive at 5.08° and 8.92°, respectively, noticeably lower than the other modules with an average bending angle of 13.41°. Except for the above two modules, the other ones exhibit an approximately constant curvature of  = 3.28 m-1, indicating that the robot has the ability of interacting conformal scenarios with uniform curvature. However, this pattern, demonstrating a homogeneous deformation behavior, may have limitations in dealing with nonlinear scenarios [31]. To overcome these limitations, we propose a novel design paradigm using the bio-inspired concept of pre-programming by organizing springs with varying stiffnesses.

***3.2 Effects of spring stiffness on bending***

To characterize the effects of spring stiffness on the bending deformation, we select two other types of springs with varying stiffnesses, i.e., types *B*, and *C* (Fig. 3A). First, we exchange the springs in both *M*1 and *M*2 from type *A* to type *B* (i.e., case 1). In this state, the continuum robot can be practically subdivided into two segments: segment 1 (Seg*.* 1) consisting of *M*1 and *M*2, and segment 2 (Seg. 2) consisting of *M*3, *M*4, *M*5, and *M*6 (Fig. 6A). Maintaining the same actuation criterion, after shortening cables 1 and 6 by 7 cm, the bending angle decreases to 60.36°. Here, as Seg. 1 has a spring stiffness 2.5 times that of Seg*.* 2, the bending angles of *M*1 and *M*2 decline by 63.58% and 65.75%, respectively. Moreover, we discover that the bending angle reduces only by 7.28°; however, the curvatures  of the two segments change remarkably to  = 0.88 m-1 and  = 3.94 m-1, respectively. These segments with varying spring stiffness enable the robot to interact with multi-curvature scenarios.

To further reduce the curvature of Seg. 1, we replace type *B* with type *C* springs. By that, the bending angle of *M*1 and *M*2 reduced to 0.17° and 0.39°, respectively (Fig. 6B), resulting in the curvature of Seg*.* 1 ( = 0.08 m-1) being only 1.91% of that of Seg*.* 2 ( = 4.18 m-1). Hence, in this case, the bending of the robot is only caused by the deformation of Seg*.* 2. The theoretical predictions indicate that, by adjusting the spring stiffness, the robot can switch between varying configurations, facilitating programmable morphing behaviors of continuum robots for specific operations and interaction demands. Hence, to further enrich a better control over the deformation patterns of the robot, pre-programming the distribution of spring stiffness may be a feasible strategy.

***3.3 Robot configuration versus module connecting sequence***

To better understand the influence of the spring stiffness distribution on the robotic profile, we replace the position of the modules in the two segments. Here, Seg. 1 is made of *M*1 and *M*2, and Seg. 2 is formed by the other modules. By reversing the order of the two Segs*.* 1 and2, the robot can transform between two deformation modes I and II (Fig. 7A). When both cables 1 and 6 are shortened by 7 cm, the bending angle of mode II is close to that of mode I (57.78° vs. 54.29°). However, the robots exhibit different in bending deformations. Specifically in mode I, the curvatures of Segs*.* 1 and 2 are 0.08 m-1 and 3.91 m-1, whereas those in mode II are 0.90 m-1 and 3.75 m-1, respectively. This suggests that the curvature of the robot can be encoded by changing the order of segments.

Next, we move *M*3 from Seg*.* 2 to Seg*.* 1 (i.e., the spring stiffness of *M*3 is replaced with *K*C), forming the deformation mode III (Fig. 7B). Like the previous step, we also replaced the order of the Segs. 1 and 2 with each other, which leads to the deformation mode IV. The mode III has two curvatures of 0.10 m-1 and 4.37 m-1, whereas the corresponding curvatures of mode IV are 0.78 m-1 and 4.25 m-1, respectively. Using a similar approach, we create two other robotic configurations, with the deformation modes V and VI (Fig. 7C). Our results suggest that a continuum robot, in which spring stiffness can be pre-programmable, can adjust to varying geometries and adapt to varying-curvature scenarios. It is also important to mention that, by comparing the curvatures of Seg. 1 in modes I, III, and V, one would notice that multi-module segments can hardly maintain their initially straight profile during deformation. Therefore, when the segments are needed to conform a straight line (i.e., a zero-curvature scenario), higher-stiffness springs are necessary to be applied in modules to avoid undesired bending motion.

***3.4 Application demonstrations***

To assess the performance of the concept of pre-programmable stiffness, we fabricate a continuum robot consisting of 12 modules, and mount the first module on a rigid robotic arm (SJ 602-A, Anno, China), as illustrated in Fig. 8A. The robot is actuated by six cables pulled by three motors, all of which are coordinated by a microcontroller (Fig. 8B). Here, we construct five distributions of spring stiffness. By programming the distribution of spring stiffness, the continuum robot is practically subdivided into one to three segments. Despite applying the same displacement in the cables, the robot exhibits various configuration patterns after deformation resembling English letters, including the types O, J, L, V, and U (Fig. 8C, Fig. S5, Video S3). During approaching the final configurations, the robotic distal end demonstrates various trajectories, as shown in Fig. 8D.

To further elaborate effects of different combinations of spring stiffness on the robotic curvature, we measure the curvature of each segment in various letter types (Fig. 8E). Taking the triple-segment robot which still consist of 12 modules as an example, we discover that the curvature of the first, second, and third segments change to 8.29 ± 0.21 m-1, 0.26 ± 0.04 m-1, and 13.43 ± 0.18 m-1 from 0.04 ± 0.02 m-1, 18.27 ± 0.33 m-1, and 0.09 ± 0.01 m-1, respectively, with the robot profile switching from V to U shape. This suggests that the programmed stiffness distribution can be used to efficiently regulate the curvature of each segment. Therefore, the robot can potentially be used in various deformation scenarios without altering the actuation scenario.

Next, we 3D print two kinds of elbow pipes with intersection angles of 135° (blue line, Fig. 9), and 90° (pink line, Fig. 9), respectively. By combining the two elbow pipes, we construct four typical application scenarios (Figs. 9A - 9D), of which the geometric parameters are listed in Table 2. We then arrange four continuum robots with different stiffness distributions using type *A*, *B*, and *C* springs, and fix their base to the rigid robotic arm, simulating the insertion routine typically for exploring the unstructured environments. Benefiting from the stiffness distributions, the robot can successfully transverse through the elbow pipes in all the scenarios (Video S4).

To quantify the adaptability of the robots, we calculate the deviations between the experimental and expected bending angles. In scenario 1, the robot forms two visible pseudo-joints at *M*7 and *M*10, and the bending angles at these joints are 133.75 ± 4.92° and 136.25 ± 5.41°, respectively. Thus, the deviations between the experimental and intersection angles are merely 0.93% and 0.92%, respectively (Fig. 9A). The robot in scenario 2 forms two new joints in *M*6 and *M*8 because of the re-regulation of spring distribution, and the current deviations become 0.09% and 2.50%, respectively (Fig. 9B). By regulating the spring distribution, the robot exhibits a range of various curvatures, enabling it to be conformal with other scenarios (see the comparisons in Figs. 9C and 9D). The fine agreement between experimental and the intersection angles indicates that our stiffness pre-programming concept is an effective strategy for robots that must work in curvature varying scenarios. We would also like to highlight that the robot can achieve multi-functions by installing various end-effectors, such as grippers and sensors [32]. By equipping the robot with an infrared camera (PS5268, Luoke, China) installed at the distal end, we can navigate internal walls of pipelines with dim environment with pre-programmed configurations (Figs. 9E and 9F, Video S5).

1. **Conclusion**

In this paper, inspired by motions of elephant trunks, we presented a modular design to encode stiffness distribution in continuum robots for curvature varying scenarios. By means of this design method, we were capable of not only simplifying the control complexity, but enabling the robot to adaptively travel through the narrow pipelines. Our design can be effectively used to customize continuum robots, and enable them to be more easily used in high-precision operations, such as ultra-gentle human machine interaction. Future studies should develop strategies that can enhance the ability of robots in exploring unpredictable scenarios in real-time by enhancing the shape adaptability, for example, by using smart materials as spring elements [33] or by employing compliant mechanisms that allow for large, yet controlled, reversible deformations [34].

**Author Contributions**

Z.W., H.P, and J.W. conceived the concept. J.Z and Z.K. performed the simulations. J.Z., Y.L., and Q.Y. carried out experiments and data processing. J.Z., H.R., and J.W. analyzed the data and interpreted the results. H.R., H.P. and J.W. directed the project. All authors commented on the article.

**Author Disclosure Statement**

No competing financial interests exist.

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**Supplementary Materials**

Supplementary Note

Supplementary Figure S1

Supplementary Figure S2

Supplementary Figure S3

Supplementary Figure S4

Supplementary Figure S5

Supplementary Table S1

Supplementary Table S2

Supplementary Video S1

Supplementary Video S2

Supplementary Video S3

Supplementary Video S4

Supplementary Video S5

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