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Design and Kinematic Modeling of a Hybrid Stiffness Cable-Driven Continuum Manipulator with Distributed Compliant Support

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ABSTRAC : *Cable-driven continuum robots (CDCRs) have attracted increasing attention due to their intrinsic compliance, high dexterity, and suitability for operation in confined and unstructured environments. This paper presents the design, structural analysis, and kinematic modeling of a novel cable-driven continuum manipulator featuring a hybrid compliant-support architecture. The proposed manipulator integrates four elastic tendon-like rods and inter-disk stainless-steel compression springs to form a distributed stiffness backbone. This configuration enhances lateral rigidity and load-bearing capacity while preserving continuous bending flexibility. Four symmetrically arranged actuation cables are employed to generate spatial deformation through differential tension control. A kinematic modeling framework based on the piecewise constant curvature assumption is established to describe the mapping between cable length variations and the end-effector pose. Compared with dynamic modeling approaches, the proposed kinematic formulation achieves a favorable balance between computational efficiency and modeling accuracy, making it suitable for real-time trajectory planning and control. The modular disk–spring assembly further enables stiffness tuning and structural scalability. The developed manipulator demonstrates strong adaptability in multi-obstacle and narrow-space scenarios, offering smooth curvature transitions, enhanced safety, and compatibility with advanced model-based control strategies. The results provide a structural and theoretical foundation for high-performance continuum robotic systems in medical, industrial, and exploratory applications.*

KEYWORDS - *Cable-driven continuum robot, compliant mechanism, hybrid stiffness structure, kinematic modeling, piecewise constant curvature, tendon-driven actuation*

I. INTRODUCTION

With the rapid development of next-generation information technologies, intelligent manufacturing, and human–robot collaboration, robotic systems are gradually evolving from traditional structured industrial environments toward more complex, dynamic, and highly uncertain application scenarios. In this process, robots are no longer required only to achieve high positioning accuracy and execution efficiency, but must also demonstrate enhanced compliance, environmental adaptability, and safe physical interaction with humans and surroundings. In particular, in fields such as medical intervention, service robotics, special operations, and close-proximity human–robot collaboration, safety and flexibility have become key criteria for evaluating the advancement and practical value of robotic systems.

Conventional rigid serial or parallel manipulators rely on discrete rigid joints and well-defined kinematic chains, and thus exhibit excellent repeatability, stiffness, and load-carrying capacity in industrial automation. However, their inherent high stiffness and limited degrees of freedom significantly constrain their adaptability in complex environments. In confined spaces, tortuous paths, or cluttered environments with multiple obstacles, rigid manipulators often struggle to complete tasks without collisions. Moreover, in human–robot collaboration or near-human operation scenarios, unexpected contact involving rigid structures can easily cause damage to the environment or injury to operators, severely limiting their applicability in safety-critical tasks. For example, in minimally invasive surgery [1], the anatomical cavities are narrow, complex, and fragile, making it difficult for rigid manipulators to achieve high dexterity while ensuring safety. Similar limitations arise in complex pipeline inspection and operations in unstructured environments, where flexibility and safety must be simultaneously guaranteed.

To overcome the inherent limitations of traditional rigid robots in terms of flexibility and safety, researchers have increasingly drawn inspiration from biological systems, exploring more compliant and adaptive robotic morphologies. Many organisms in nature—such as octopus tentacles [2], elephant trunks [3], snake spines [4], and soft-bodied limbs [5]—exhibit highly continuous and flexible structures that enable efficient and safe motion in complex environments. Inspired by these biological counterparts, continuum robots have emerged as a novel class of robotic systems distinct from conventional rigid-link robots and have become an important research direction in the robotics community.

Unlike traditional robots that rely on discrete joints to generate motion, continuum robots typically lack explicit rigid joints and achieve movement through continuous bending, twisting, and extension of their structures [6]. This continuous deformation capability endows continuum robots with high compliance and, theoretically, infinite degrees of freedom, allowing them to maneuver flexibly within confined spaces and interact with the environment in a safer and more natural manner. As a result, continuum robots offer significant advantages over rigid manipulators in tasks such as navigating narrow passages, avoiding complex obstacles, and conforming to target surfaces [7–9].

Among various implementations of continuum robots, cable-driven continuum robots (CDCRs) have attracted considerable attention in recent years due to their relatively simple mechanical structure, fast response, and high control precision. CDCRs typically employ multiple flexible cables to apply tensile forces to a compliant backbone, enabling complex spatial motions such as bending, twisting, and extension. Owing to these advantages, CDCRs show great potential in applications including minimally invasive surgery [10], on-orbit space maintenance, deep-sea exploration and operation, flexible grasping [11], and inspection in complex environments.

However, in practical applications, CDCRs are often required to operate in cluttered environments containing multiple obstacles. Such scenarios not only demand accurate trajectory planning and tracking, but also impose stringent requirements on trajectory continuity and smoothness. Due to the highly compliant structure and large degrees of freedom of continuum robots, system performance is particularly sensitive to discontinuities in position, velocity, and acceleration. Trajectories with abrupt curvature or velocity changes can easily induce structural vibrations, sudden cable tension variations, and control instability, thereby degrading tracking accuracy, compromising safety, and even increasing the risk of secondary collisions.

In addition, continuum robots typically possess highly redundant degrees of freedom. While redundancy provides flexibility for obstacle avoidance and performance optimization, it also significantly enlarges the search space of trajectory planning and control problems. In multi-obstacle environments, narrow passages, or scenarios with incomplete environmental information, conventional planning and optimization methods are prone to local minima, leading to unnecessarily long trajectories, low efficiency, or even planning failure. This issue is particularly pronounced for cable-driven continuum robots, whose strong nonlinearity and coupling characteristics further exacerbate the difficulty of global optimization.

Therefore, how to fully exploit the compliance and environmental adaptability of cable-driven continuum robots while developing a unified planning and control framework that simultaneously ensures obstacle avoidance safety, trajectory smoothness, and control feasibility has become a critical challenge in continuum robotics research. In-depth investigation of safe, efficient, and smooth motion planning and tracking control for CDCRs in multi-obstacle environments is of great significance not only for advancing the theoretical foundations of continuum robot motion planning and control, but also for enabling their reliable deployment in complex engineering applications such as medical intervention, space operations, and deep-sea exploration.

II. COMPOSITION AND STRUCTURE OF CONTINUUM ROBOTS DRIVEN BY CABLES

The cable-driven continuum robot investigated in this study mainly consists of a flexible backbone, a cable actuation system, and supporting joint disks, as illustrated by the prototype model shown in Fig. 1. The flexible backbone is typically fabricated from homogeneous compliant materials or constructed using a segmented flexible structure, enabling continuous bending and shape deformation. Four actuation cables are symmetrically arranged along the circumferential direction of the backbone, and variations in cable lengths generate global bending, twisting, and other complex motions. The actuation unit is composed of servo motors or linear actuators, which are responsible for precisely regulating the tension or displacement of each driving cable.

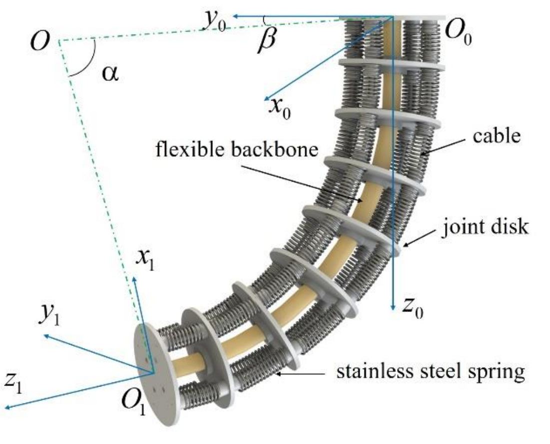

Fig. 1 Schematic diagram of a rope-driven continuum robot

The proposed flexible manipulator is a cable-driven continuum robotic arm characterized by a multi-segment compliant architecture. The backbone structure consists of four elastic tendon-like rods (artificial sinew rods) symmetrically distributed along the circumference and longitudinally aligned to provide structural support and constraint. These elastic rods are serially connected through a series of rigid joint disks, which act as discrete constraint nodes to maintain geometric alignment and regulate curvature distribution.

Adjacent joint disks are interconnected via stainless-steel compression springs, forming a compliant inter-disk spacing mechanism that enables continuous bending while preserving axial elasticity. The springs provide passive restoring torque and axial compliance, ensuring smooth curvature transitions and mitigating local stress concentration. Four actuation cables are routed through evenly spaced holes on each joint disk and anchored at the distal end-effector. By selectively tensioning or releasing these cables, bending in arbitrary spatial directions is achieved through differential actuation.

The actuation system is typically driven by high-precision servo motors coupled with cable winding mechanisms (e.g., capstan or pulley systems), enabling accurate tension control. Tension feedback can be integrated using load cells or inline tension sensors to enhance closed-loop stability. The proximal base houses the motor assembly, control electronics, and possibly a real-time controller implementing model-based strategies such as nonlinear MPC.

This configuration results in a lightweight, modular, and redundantly actuated continuum structure capable of smooth spatial deformation. The distributed compliance and cable-driven architecture provide inherent safety, mechanical simplicity, and adaptability for complex environments.

In continuum robot modeling, although dynamic modeling can provide a more comprehensive description of the system's mechanical behavior, it is often characterized by high model complexity, difficulties in parameter identification, and substantial computational burden for online solution, making it unsuitable for real-time planning and control. In contrast, kinematic modeling focuses on the geometric mapping between actuation inputs and the robot's shape as well as end-effector pose, and can offer sufficient scenarios. As a result, it has been widely adopted in trajectory planning and control studies of continuum robots. Common modeling approaches include the piecewise constant curvature (PCC) model, simplified forms of the Cosserat rod model, and parameterized models based on geometric mappings. Among these, the piecewise constant curvature model achieves a favorable balance between computational efficiency and modeling accuracy, and can clearly describe the relationship between cable length variations and the spatial configuration of the robot. Therefore, it is selected in this work for subsequent kinematic modeling and control design.

III. Structural Innovation and Technical Contributions

The primary innovation of this manipulator lies in the hybrid compliant-support architecture combining elastic rods and inter-disk springs to form a distributed stiffness backbone. Unlike conventional single-backbone continuum robots or purely spring-based designs, the integration of four elastic sinew rods introduces enhanced lateral stiffness while preserving bending flexibility. This hybridization enables improved load-bearing capability without significantly increasing structural mass.The use of discrete joint disks combined with axial compression springs creates a quasi-continuous curvature approximation while maintaining mechanical manufacturability. Compared with monolithic elastomeric backbones, this segmented design allows controllable stiffness tuning by adjusting spring constants or rod elasticity, thereby enabling task-specific mechanical impedance adaptation.

Another innovative aspect is the symmetric four-cable actuation layout, which provides actuation redundancy and isotropic bending capability. This configuration enhances controllability in three-dimensional space and reduces singular configurations typically encountered in underactuated continuum robots. The distributed routing of cables through precision-aligned disk holes improves force transmission linearity and minimizes friction-induced hysteresis.

Furthermore, the architecture is highly compatible with advanced control strategies such as nonlinear model predictive control (NMPC) or artificial potential field (APF)-based obstacle avoidance, due to its smooth curvature behavior and well-defined kinematic parameterization. The modular disk-spring assembly also facilitates rapid replacement, scalability in length, and experimental validation of stiffness modeling assumptions.

Overall, the design presents a structurally efficient, mechanically tunable, and control-friendly continuum robotic system suitable for precision-oriented applications.

IV. Kinematic Modeling of Continuum Robots Driven by Cables

Considering the structural characteristics of cable-driven continuum robots, this study adopts a kinematic modeling approach based on continuous curve assumptions, transforming the infinite degrees-of-freedom nature of the flexible structure into a finite-dimensional parametric representation.

Before establishing the kinematic model of the cable-driven continuum robot, the following assumptions are made:

(1) The cable-driven continuum robot bends with constant curvature;
(2) The flexible backbone of the cable-driven continuum robot is assumed to be inextensible;
(3) The four actuation cables are uniformly distributed around the backbone.

Based on the assumption of uniform curvature, the radius of curvature of the four drive ropes can be expressed as:

$$\zeta_i = \zeta - r \cdot \cos \beta_i \tag{1}$$

Here, ζ and ζ_i $(i = 1,2,\ldots,4)$ denote the radii of curvature of the flexible backbone and the i-th actuation cable, respectively. The parameter $r$represents the radius of the pitch circle on which the cable holes of the joint disk are located. β_i is the rotation angle corresponding to the i-th actuation cable induced by cable actuation, with:

$$\beta = \beta i + (i-1)\frac{\pi}{2} \tag{2}$$

The actuation cables are assumed to experience the same bending angle as the flexible backbone. Therefore, by combining equation (2) with the cable rotation angle β, the length variations of the four actuation cables can be derived as ($i = 1,2,\ldots,4$):

$$\Delta L_i = L - L_i = (\zeta - \zeta_i)\alpha = r\alpha \cdot \cos\beta_i \quad (3)$$

In the above equations, $L$and $L_i$denote the overall length of the cable-driven continuum robot and the length of the i-th actuation cable, respectively. According to equation (2), the mapping from the actuation space to the joint space can be obtained as:

$$\beta = \arctan(\Delta L_{i+1} / \Delta L_i) \quad (4)$$

$$\alpha = \Delta L_i / (r \cdot \cos\beta) \quad (5)$$

Here, $\mathbf{C}_t$represents the position vector of the end effector, and the kinematic model of the cable-driven continuum robot can be expressed as:

$$\mathbf{C}_t = \left[\left(\frac{L}{\alpha}\right)\cos\beta(1-\cos\alpha) \quad \left(\frac{L}{\alpha}\right)\sin\beta(1-\cos\alpha) \quad \left(\frac{L}{\alpha}\right)\sin\alpha \right]^{\mathrm{T}} \quad (6)$$

V. APPLICATION SCENARIOS AND ENVIRONMENTAL ADVANTAGES

The proposed flexible manipulator demonstrates significant advantages in confined, unstructured, and safety-critical environments. Due to its intrinsic compliance and smooth curvature deformation, it is particularly suitable for minimally invasive surgical systems, endoscopic manipulation, and biomedical interventions where interaction safety and spatial dexterity are paramount. The distributed compliance reduces the risk of tissue damage during unintended contact. In industrial inspection and maintenance scenarios—such as pipeline inspection, turbine internal examination, or aerospace structural diagnostics—the manipulator can navigate narrow passages and complex geometries inaccessible to rigid-link robots. Its cable-driven configuration allows remote placement of actuators at the base, minimizing distal mass and enabling extended reach without compromising maneuverability.

The architecture also performs effectively in human–robot collaborative environments. The passive elasticity provided by springs and elastic rods absorbs impact energy, enhancing operational safety. This makes the system well-suited for service robotics, wearable assistive devices, and rehabilitation platforms. In underwater or space-constrained environments, such as remotely operated vehicles (ROVs) or satellite servicing systems, the lightweight and modular nature of the structure offers deployment advantages. The absence of heavy distributed actuators along the arm reduces inertia and simplifies sealing requirements in harsh environments.

Moreover, the design allows stiffness tuning, enabling adaptation to tasks requiring either high precision under load or high flexibility for navigation. Consequently, this manipulator exhibits superior adaptability across medical, industrial, and exploratory applications where traditional rigid manipulators are limited by geometric constraints and safety concerns.

VI. CONCLUSION

In this paper, a novel cable-driven continuum manipulator with a hybrid compliant-support architecture has been presented and systematically analyzed. The proposed design integrates four elastic tendon-like rods with inter-disk stainless-steel compression springs to construct a distributed stiffness backbone, while four symmetrically arranged actuation cables enable spatial bending through differential tension control. This structural configuration achieves a favorable balance between flexibility and load-bearing capability, effectively overcoming the inherent limitations of conventional rigid-link manipulators in confined and safety-critical environments.

A kinematic modeling framework based on the piecewise constant curvature assumption was established to describe the mapping between cable length variations and end-effector pose. Compared with dynamic formulations, the adopted kinematic approach significantly reduces computational complexity while retaining sufficient accuracy for real-time planning and control. The modular disk–spring assembly not only improves manufacturability and structural scalability but also facilitates stiffness tuning for task-specific mechanical impedance adaptation.

The proposed manipulator demonstrates strong adaptability in multi-obstacle and narrow-space scenarios, offering smooth curvature transitions, inherent compliance, and enhanced operational safety. Its compatibility with advanced control strategies, such as model predictive control and potential-field-based obstacle avoidance, further enhances trajectory smoothness and robustness in complex environments.

Future work will focus on incorporating dynamic effects, friction modeling, and cable tension constraints into a unified control framework, as well as conducting experimental validation under practical loading conditions. The results of this study provide a solid structural and theoretical foundation for the development of high-performance continuum robotic systems in medical, industrial, and exploratory applications.

REFERENCES

[1] L. Mao, P. Yang, C. Tian, X. Shen, F. Wang, H. Zhang, and H. Xie. "Magnetic steering continuum robot for transluminal procedures with programmable shape and functionalities," Nature Communications 15 no. 1 (2024): 3759.

[2] H. Tian, Z. Gao, and Y. Gong. "Rapidly fabricated soft spring actuator via laminated laser-lithographed 2D polyurethane layers," Mechatronics 92 (2023): 102985.

[3] J. Zhang, Y. Li, Z. Kan, Q. Yuan, H. Rajabi, Z. Wu, H. Peng, and J. Wu. "A preprogrammable continuum robot inspired by elephant trunk for dexterous manipulation," *Soft Robotics* 10 no. 3 (2023): 636-646.

[4] P. Polygerinos, Z. Wang, K. C. Galloway, R. J. Wood, and C. J. Walsh. "Soft robotic glove for combined assistance and at-home rehabilitation," *Robotics and Autonomous Systems* 73 (2015): 135-143.

[5] J. F. Duhé, S. Victor, and P. Melchior. "Contributions on artificial potential field method for effective obstacle avoidance," *Fractional Calculus and Applied Analysis* 24 (2021): 421-446.

[6] Y. Shang, F. Liu, P. Qin, Z. Guo, and Z. Li. "Research on path planning of autonomous vehicle based on RRT algorithm of Q-learning and obstacle distribution," *Engineering Computations* 40 no. 5 (2023): 1266-1286.

[7] S. Zhu, Y. Zhang, X. Zong, and R. Li. "Finite-time constrained attitude regulation for spacecraft formation with disturbances on SO (3)," *International Journal of Robust and Nonlinear Control* 33 no. 8 (2023): 4459-4489.

[8] T. Zhu, J. Mao, L. Han, C. Zhang, and J. Yang. "Real-Time Dynamic Obstacle Avoidance for Robot Manipulators Based on Cascaded Nonlinear MPC With Artificial Potential Field," *IEEE Transactions on Industrial Electronics* 71 no. 7 (2024): 7424-7434.

[9] R. V. Hoek, J. Ploeg, and H. Nijmeijer. "Cooperative driving of automated vehicles using B-splines for trajectory planning," *IEEE Transactions on Intelligent Vehicles* 6 no. 3 (2021): 594-60.

[10] L. Piegl and W. Tiller. *The NURBS book* Springer Science & Business Media, 2012.

[11] T. Zhu, J. Mao, L. Han, C. Zhang, and J. Yang. "Real-Time Dynamic Obstacle Avoidance for Robot Manipulators Based on Cascaded Nonlinear MPC With Artificial Potential Field," *IEEE Transactions on Industrial Electronics* 71 no. 7 (2024): 7424-7434.

[12] Y. Shang, F. Liu, P. Qin, Z. Guo, and Z. Li. "Research on path planning of autonomous vehicle based on RRT algorithm of Q-learning and obstacle distribution," *Engineering Computations* 40 no. 5 (2023): 1266-1286.