Kinematic modeling and workspace analysis of a multi-dual cross-module cable-driven continuum robot

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https://doi.org/10.5937/vojtehg73-56975

FIELD: mechanical engineering
ARTICLE TYPE:original scientific paper

Abstract:

The flexibility and capability of continuum robots to navigate complex and constrained environments make them highly suitable for diverse applications, including minimally invasive surgery, industrial manipulation, and exploratory operations in hazardous or confined spaces. Despite these advantages, accurately modeling their kinematics and conducting comprehensive workspace analysis, particularly for multi-section cable-driven continuum robots with dual cross-module configurations, remain significantly challenging. This study begins by presenting a design of a three-section dual-cross cable-driven continuum robot. The forward kinematics model is analytically derived based on the constant curvature assumption, while the inverse kinematics model is formulated as an optimization problem. To support trajectory generation, the robot's workspace is analyzed using MATLAB and SOLIDWORKS software. The simulation example illustrates the robot's trajectory-tracking performance.

Key words: continuum robot, cable-driven continuum robot, kinematics modeling, workspace analysis, trajectory tracking

Introduction

Continuum robots have attracted significant attention in recent years due to their exceptional shape-morphing capabilities, expansive workspaces, and adaptability to navigate complex environments. Inspired by biological organisms (Hannan & Walker, 2003; McMahan et al, 2004), these robots feature continuous, flexible movement, enabling safe operation in obstacle-rich settings. Their capacity to adopt diverse configurations makes them highly versatile, with notable applications in minimally invasive surgery (Burgner-Kahrs et al, 2015) and industrial manipulation within confined spaces (Liu et al, 2016).

According to the literature, there are several types of continuum robots, including flexible and rigid ones. This paper focuses on a rigid type known as cable-driven continuum robots. These robots use cables for actuation instead of traditional rigid components (Hemami, 1985; Murphy et al, 2013). This approach offers advantages such as reduced weight, increased flexibility, and a more compact form factor, which are particularly valuable for tasks that require high adaptability in constrained environments. Additionally, cable-driven robots can provide enhanced safety in delicate applications due to their soft, non-colliding nature. However, while these benefits enhance the robot's capabilities, they also present challenges related to precise control and accurate prediction of the robot's movement, due to the nonlinear mathematical expressions that govern its kinematic and dynamic behavior and the associated modeling complexities.

Kinematic modeling of CDCRs is essential for describing and analyzing their movements without considering the forces that cause them, with the aim of predicting the position, velocity, and orientation of the robot's components. This is crucial for ensuring precise kinematic control, workspace generation, and trajectory planning, especially in complex environments where precision and adaptability are essential. However, one of the primary challenges is modeling the robot's deformation during its motion. This challenge is often simplified using various methods, such as those proposed by Linn (2016), Mahl (2014), Amouri (2019), and Webster & Jones (2010). In Linn (2016) and Mahl (2014), the authors treat the robot's backbone as a one-dimensional elastic rod with bending and twisting characteristics. Nevertheless, the constant curvature assumption (Amouri, 2019; Webster & Jones, 2010) offers the simplest approach. This assumption allows each section of the robot to be represented as a curve with a constant radius, thereby simplifying the complex behavior of a flexible, multi-sectional system into a more manageable form. While this approach provides an effective approximation for many applications, it may not fully capture the intricacies of the robot's deformation in highly dynamic or constrained environments. Further refinements and models may be required for more accurate predictions in such cases.

In the same context, focusing on a specific type of cable-driven continuum robot known as the Dual Cross-Module Cable-Driven Continuum Robot, only a few kinematic studies have been proposed in the literature (Zhou et al, 2022; Amouri et al, 2023). In Zhou et al. (2022) and Amouri et al. (2023), the authors introduced a bio-inspired novel dual cross-module section cable-driven continuum robot that combines the flexibility of continuum robots with the stability of rigid robots. These papers presented the design and kinematics of the manipulator. However, Zhou et al. (2022) did not address several important aspects such as generalizing the inverse kinematic model and calculating the robot's workspace. In contrast, Amouri et al. (2023) focused on a robot with two sections. However, a robot with fewer than three sections faces significant limitations, as it lacks the necessary Degrees of Freedom (DoFs) to independently adjust both position and orientation. Consequently, such a robot is constrained to a limited set of feasible trajectories and cannot achieve the same level of versatility in motion. In this study, we explore the design and kinematic modeling of a dual cross-module cable-driven continuum robot with three sections. This approach aims to address the limitations associated with fewer sections and provide a more versatile solution for complex tasks.

This paper begins by presenting an overview of the robot's design and structural components. Next, kinematic models are developed under the constant kinematic assumption. The forward kinematic models are derived analytically, while the inverse kinematic model for the entire robot is formulated as an optimization problem and solved using Knowledge-Based Particle Swarm Optimization. Additionally, the workspaces of a module and a section are generated and analyzed. Subsequently, a simulation example is presented to illustrate line-shaped trajectory tracking with a fixed end-tip orientation of the robot. Lastly, the main conclusions and future perspectives are summarized in the final section.

Design of a dual-cross module continuum robot

Similar to the work of Amouri et al. (2023), the robot developed in this study is a fish-like, bio-inspired continuum robot designed to balance rigidity and flexibility, allowing it to seamlessly adapt to diverse environments and effectively perform a wide range of tasks. By mimicking the structural adaptability found in biological organisms, this robot can navigate complex or constrained spaces, providing both the strength necessary for stability and the flexibility required for maneuverability. Its unique design enables smooth, continuous movements, making it ideal for a wide range of applications.

The robot consists of two main parts: rigid components and flexible backbones. The rigid components provide stability and contain the actuation cables, while the flexible backbones enable a wider workspace and greater range of motion. The backbone is made of rectangular elastic sheets, each measuring 90 mm in length, 26 mm in width, and 3.4 mm in thickness, and is constructed from ASTM X36 steel which provides the necessary flexibility for the robot's operation. The rigid components, in the form of cross-shaped sheets, are made from a lightweight 3D-printed ABS material, chosen for its low weight and suitability for constrained environments. The advantage of using this cross-shaped design, rather than the traditional disk shape, is that it conserves material, reduces weight, and makes the robot better suited for navigating tight spaces. For more details on the design development and illustrations, refer to (Amouri et al, 2023). In summary, a rectangular elastic sheet and 15 cross-shaped sheets, with uniform spacing between them, form a module that enables 2D motion. Subsequently, two successively mounted modules create a section enabling 3D motion. The entire robot under consideration is composed of three sections.

Typically, common designs use three or four cables per module, arranged symmetrically around the backbone. However, in this design, each module is actuated by only two cables, reducing the complexity of actuation and control while requiring fewer motors. The guiding holes in the cross-shaped sheets ensure that the cables form an arc-like shape within the designated bending module. In theory, as the number of cross-shaped sheets increases, the bending shape of the cables will become more circular.

Kinematic modeling

Description of a dual-cross module continuum robot

The systematic development of kinematic models requires, first and foremost, an appropriate method for describing the morphology of the robot. Various methods and notations have been proposed in the literature for the kinematic description of continuum robots (Webster & Jones, 2010; Jones & Walker, 2006). In this context, the constant curvature assumption is employed, wherein the central axis of the structure is considered inextensible. This approach simplifies several modeling challenges and enables a more efficient representation of the robot's kinematics, as illustrated in Figure 1 (for further details on the development, refer to (Amouri, 2017).

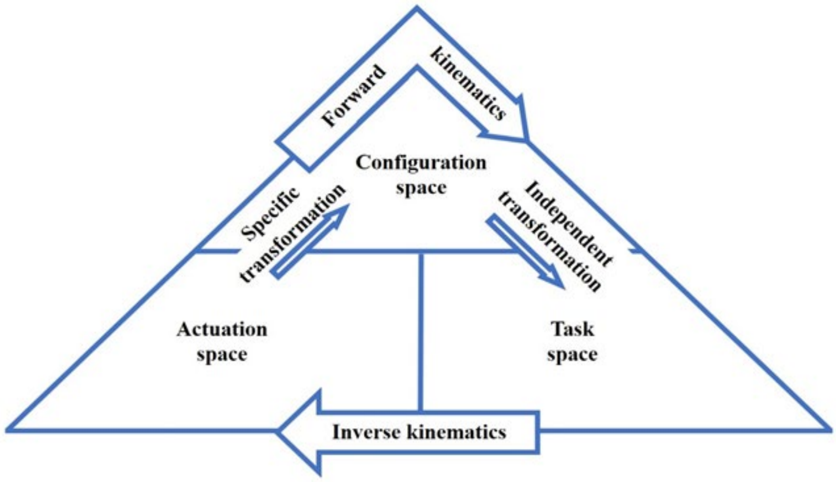


Figure 1 – Overview of the kinematic mapping of a continuum robot using the constant curvature assumption

However, this assumption holds only under specific conditions: (i) the gravitational influence on the robot is disregarded; (ii) only the controlling forces from the cables are considered, while all other external forces are neglected; (iii) the frictional interaction between the cables and the routing holes is ignored; (iv) the elastic sheet backbone is assumed to undergo pure bending without any expansion, contraction, or torsion; and (v) the cable is treated as inextensible, meaning it cannot stretch or extend.

To define the quantities involved in the kinematic description of the robot under consideration, four primary reference frames are established. The first is the absolute frame $\Re_w$. Next, the frames $\Re_k$, with $k = 1,2,3$, are assigned to the upper cross-shaped sheet of each section k, while the frame $\Re_0$ is fixed at the base of the first section (Figure 2a). Additionally, three intermediate frames $\Re_{int,k}$ designated for the first module of each section, provide a localized reference for kinematic calculations (Figure 2b).

As previously mentioned, each module is modeled as an inextensible circular arc lying in a plane, as illustrated in Figure 2 (Amouri et al, 2023). This arc is characterized by its length $\ell_{j,k}$ and its bending angle $\theta_{j,k}$. In this configuration, the orientation angle $\varphi_{j,k}$ of each module, with $j = 1, 2$, is equal to 0 and $\pi/2$, respectively.

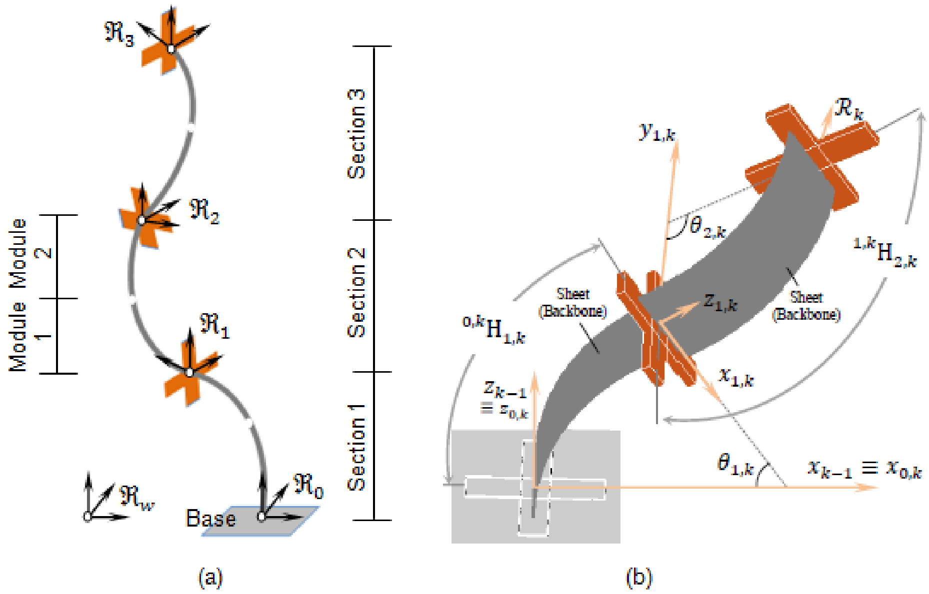


Figure 2 – Depiction of the reference frames defined for the three-section dual-cross cable-driven continuum robot: (a) global reference frames, and (b) intermediate frames

Forward kinematics of the module

Typically, the forward kinematic model of such a robot serves as the foundational step in the modeling process. This subsection aims to establish a relationship that predicts the position and orientation of the module's end-tip based on the varying lengths of the actuation cables. This relationship is described by the following homogeneous transformation matrix:

$$\mathbf{H}_{j,k} = \begin{bmatrix} \mathbf{R}_{j,k} & \mathbf{P}_{j,k} \\ 0_{1\times3} & 1 \end{bmatrix} \quad (1)$$

where $\mathbf{R}_{j,k}$ represents the 3×3 rotation matrix $\mathbf{R}_{j,k}$, and $\mathbf{P}_{j,k}$ denotes the 3×1 vector position. These components are determined using the following equations:

$$\mathbf{R}_{j,k} = \mathbf{rot}(u, \theta_{j,k}) \quad (2)$$

$$\boldsymbol{P}_{j,k} = \begin{cases} x_{j,k} = \dfrac{\ell_{j,k}}{\theta_{j,k}}\left(1 - cos(\theta_{j,k})\right) cos(\varphi_{j,k}) \\ y_{j,k} = \dfrac{\ell_{j,k}}{\theta_{j,k}}\left(1 - cos(\theta_{j,k})\right) sin(\varphi_{j,k}) \\ z_{j,k} = \dfrac{\ell_{j,k}}{\theta_{j,k}} sin(\theta_{j,k}) \end{cases} \quad (3)$$

where u represents the axis of rotation, which aligns with the y −axis for the first module and the x −axis for the second module, respectively.

On the other hand, the relationship between the cable lengths $l_{i,j,k}$ and the bending angle $\theta_{j,k}$ can be expressed by the following equation:

$$\theta_{j,k} = \frac{\ell_{j,k} - \Delta l_{i,j,k}}{r} \quad (4)$$

where $\Delta l_{k,i,j}$ represents the value of the change in cable length due to bending, and r denotes the radial distance between the cables and the neutral z −axis of the backbone.

Forward kinematics of the section

The forward kinematic model of the section k describes the relationships that express the expression of the position and orientation of the upper cross-shaped sheet as a function of the cable lengths. As previously mentioned, the section k consists of two modules connected in series. This model can be obtained by successively multiplying the transformation matrices of each module (j, k), treating them as a simple open-chain system. This model is represented by the following transformation matrix:

$$\mathbf{H}_k = \prod_{j=1}^{2} \mathbf{H}_{j,k} \quad (5)$$

Forward kinematics of the entire robot

The forward kinematic model of the multi-sectional robot is obtained by successively multiplying the transformation matrices of each section k along with the transformation matrix of the static reference frame. The resulting matrix is expressed by the following equation:

$$\mathbf{H}_3 = \mathbf{H}_0 \prod_{k=1}^{3} \mathbf{H}_k = \begin{bmatrix} \mathbf{R}_3 & \mathbf{P}_3 \\ \mathbf{0} & 1 \end{bmatrix} \quad (6)$$

where $\mathbf{H}_0$ represents the transformation matrix that defines the robot's base frame $\Re_0$ with respect to the global reference frame $\Re_w$.

Workspace analysis

The determination of the workspace is a crucial aspect in the design of a robot, as it defines its range of motion and determines the set of points that can be reached during its operation. This section focuses on determining and analyzing the workspace of the module, the section, and the entire robot, respectively.

Figure 3 illustrates the workspace of the modules within a section as they bend independently, forming a set of points that trace a curve. These curves are plotted for bending angles in the range $[-\pi/2, \pi/2]$ which represents the maximum values that prevent overlap between adjacent cross-shaped sheets.

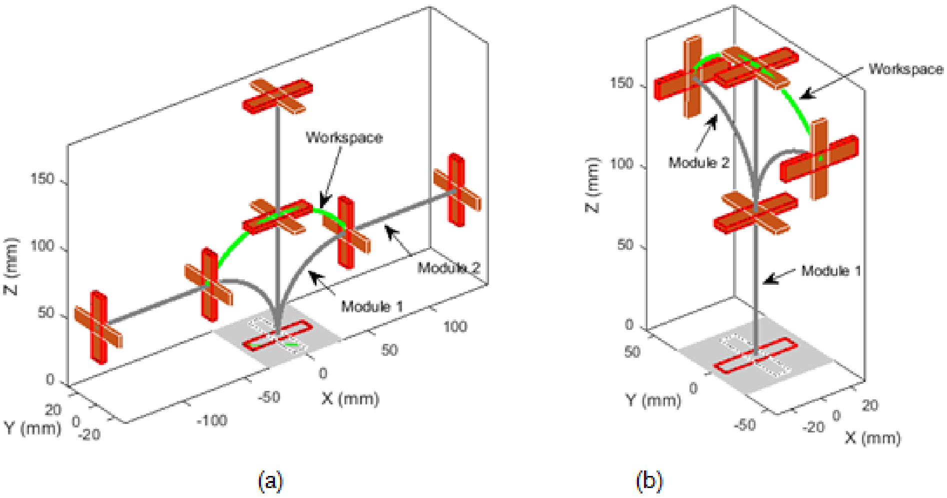


Figure 3 – Workspace of a single module within a section as it bends independently: (a) workspace of the first module during bending, and (b) workspace of the second module during bending. For clarity, the intermediate cross-shaped sheets and the rectangular backbones are not shown

For such a section, this results in an enveloping surface, as shown in Figure 4. The figure also includes the workspace of a section with a cylindrical backbone. These workspaces were computed using Solidworks software.

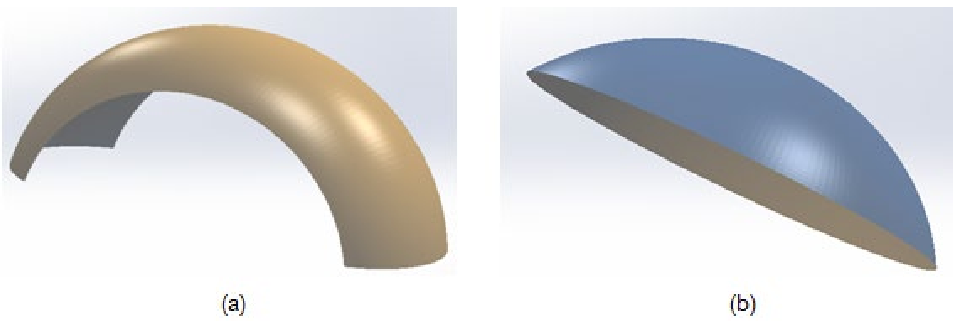
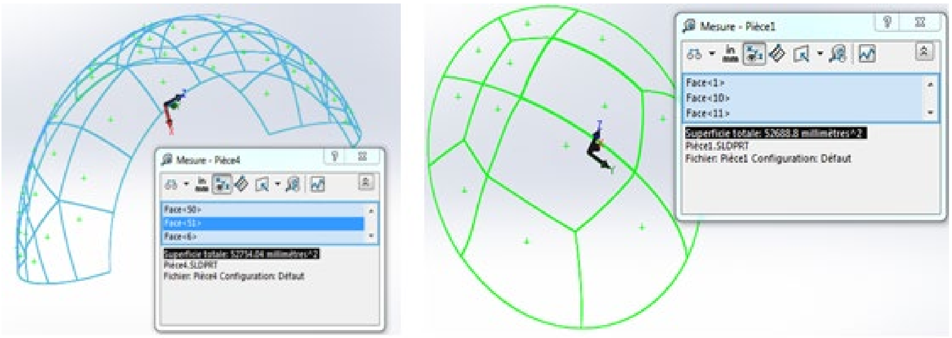


Figure 4 – Workspace of a single section: (a) workspace of the section for the considered robot, and (b) workspace of a section for a robot with a cylindrical backbone

Despite the differences in their shapes, the areas of the workspaces are equivalent, as demonstrated in Figure 5. This difference in workspace shape is advantageous for the robot when adapting to tasks requiring diverse movement patterns or navigating through constrained environments, as it provides greater flexibility and operational versatility.



(a) (b)

Figure 5 – Meshing process for calculating the area of a single section: (a) section of the considered robot, and (b) section of a robot with a cylindrical backbone

However, for a three-section dual-cross cable-driven continuum robot or any robot with more than two sections, the workspace extends from a curve or surface to a three-dimensional volume. This volumetric workspace encompasses all possible positions and orientations that the robot's end-tip can achieve within its physical constraints. The complexity of this workspace increases with the number of sections, making its representation challenging to comprehend.

Inverse kinematics of the entire robot: optimized problem formulation

The hyper-redundancy of the robot enables the inverse kinematics problem to be addressed using an optimization algorithm that minimizes a quadratic criterion (Iqbal et al, 2009). While previous studies considered only the Cartesian position in the cost function (Amouri et al, 2023), this work incorporates both the Cartesian position and the orientation of the robot's end-tip. Accordingly, the cost function to be optimized, which determines the necessary adjustments in the actuation cables for the robot's end-tip to accurately follow the desired trajectory, is formulated as:

$$\begin{cases} F(\theta_{j,k}) = \lambda \left\| \mathbf{P}_{\text{trajet}} - \mathbf{P}_3 \right\|^2 + (1-\lambda) \left\| \overline{\mathbf{P}}_{\text{trajet}} - \overline{\mathbf{P}}_3 \right\|^2 \\ \text{s.t.} \\ \left| \theta_{j,k} \right| \le \theta_{\max} \end{cases} \quad (7)$$

where $\mathbf{P}_{\text{trajet}}$ and $\overline{\mathbf{P}}_{\text{trajet}}$ are the 3×1 vectors representing the desired Cartesian position and the orientation of the robot's end-tip, respectively. Similarly, $\mathbf{P}_3$ and $\overline{\mathbf{P}}_3$ denote the actual position and orientation of the robot's end-tip. The parameter λ is set to 0.5 to balance the position and orientation objectives. The components of the vector $\mathbf{P}_3$ correspond to the fourth column of the matrix $\mathbf{H}_3$, as defined in Equation (6), while $\overline{\mathbf{P}}_3$ can be computed based on the rotation matrix $\mathbf{R}_3$ using the following equation:

$$\overline{\mathbf{P}}_3 = \begin{cases} \mathrm{a} = \tan^{-1}\left(\frac{\mathrm{r}_{21}}{\mathrm{r}_{11}}\right) \\ \mathrm{b} = \tan^{-1}\left(\frac{-\mathrm{r}_{31}}{\mathrm{r}_{11}\mathrm{c}\alpha + \mathrm{r}_{21}\mathrm{s}\alpha}\right) \\ \mathrm{c} = \tan^{-1}\left(\frac{\mathrm{r}_{13}\mathrm{s}\alpha - \mathrm{r}_{23}\mathrm{c}\alpha}{-\mathrm{r}_{12}\mathrm{s}\alpha + \mathrm{r}_{22}\mathrm{c}\alpha}\right) \end{cases} \quad (8)$$

where r_{nm} is the (n, m) element of the direction cosine matrix $\mathbf{R}_3$.

To solve this optimization problem, various algorithms can be employed. As demonstrated in, the Knowledge-based Particle Swarm Optimization (Kb-PSO) algorithm, originally proposed by (Kennedy & Eberhart, 1995), is utilized due to its simplicity and fast convergence properties. The algorithm ensures efficient computation and reliable results, making it well-suited for the inverse kinematics problem of hyper-redundant robots.

Simulation results

This section presents the application of the solution to the inverse kinematics problem of a three-section dual-cross cable-driven continuum robot, formulated as an optimization problem and addressed through numerical simulation. The reference trajectory is defined as follows:

$$\mathbf{P}_{\text{trajet}} = \begin{cases} x = 10t \\ y = 10t \\ z = 540 - 10t \end{cases}, \text{and } \overline{\mathbf{P}}_{\text{trajet}} = \begin{cases} \mathrm{a} = 0 \\ \mathrm{b} = 0 \\ \mathrm{c} = 0 \end{cases} \quad (9)$$

The simulation results, which illustrate the required bending angles, execution time, and combined error for tracking a line-shaped trajectory while maintaining a fixed end-tip orientation, are presented in Figures 6, 7, and 8, respectively.

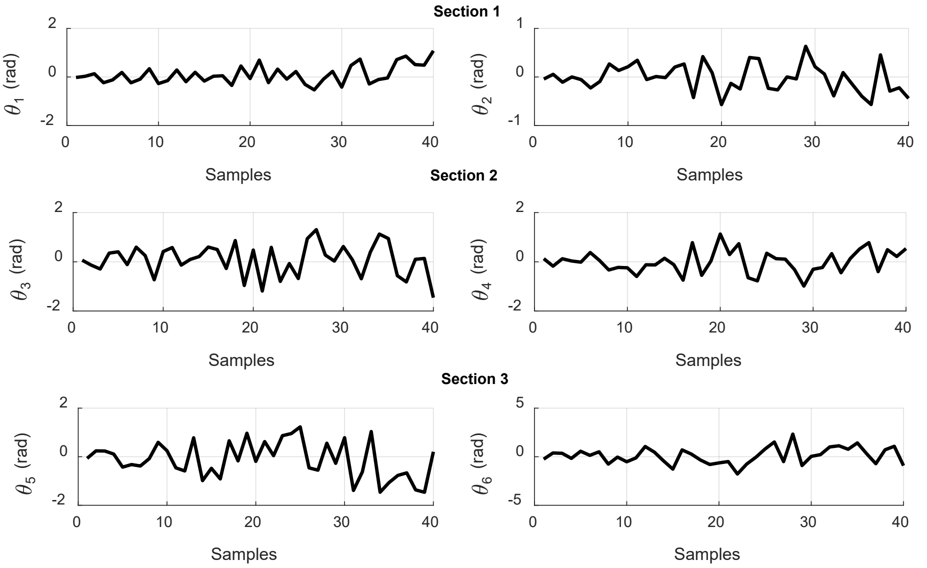


Figure 6 – Required bending angles to track the line-shaped trajectory in a fixed robot's end tip orientation

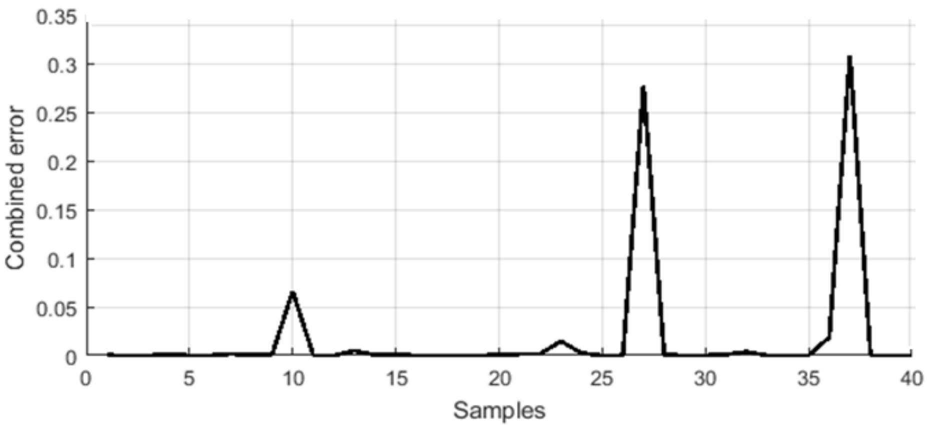


Figure 7 – Combined error for tracking the line-shaped trajectory with a fixed robot end-tip orientation

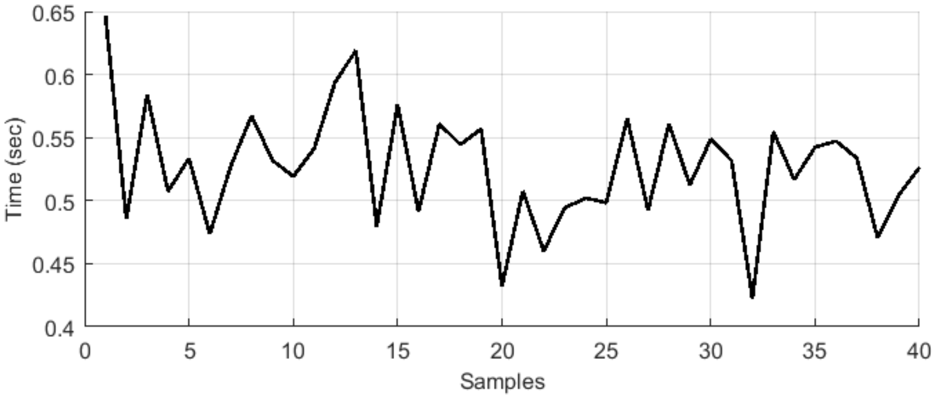


Figure 8 – Execution time for tracking the line-shaped trajectory with a fixed robot end-tip orientation

The combined error, shown in Figure 7, quantifies the deviation between the desired and actual end-tip configuration. Specifically, it represents the weighted sum of the mean squared errors in both position and orientation. The position error is measured as the squared Euclidean distance in the three-dimensional space, while the orientation error is computed as the squared deviation in a three-dimensional representation of orientation. Thus, the combined error accounts for discrepancies across six dimensions: three for position and three for orientation.

Conclusion

This paper introduces the design, kinematic modeling, and workspace analysis of a novel Multi-Dual Cross-Module Cable-Driven Continuum Robot. The proposed robot consists of three sections, each incorporating two planar bending modules. Unlike previous designs in the literature, this configuration enhances adaptability to diverse environments and expands the range of possible tasks. Additionally, it offers several advantages, including a lightweight structure, smooth deformation, enhanced rigidity, lower energy consumption, and a non-uniform workspace.

First, the principal components and materials of the proposed design are discussed in detail. Second, the forward kinematic model is developed using the constant curvature assumption, and the workspaces of the robot, as well as those of the section and module individually, are generated and analyzed using MATLAB and SOLIDWORKS. Given the complexity and highly nonlinear nature of the forward kinematic model, the inverse kinematics problem is formulated as an optimization task with a quadratic

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cost function that accounts for both the position and orientation of the robot's end-tip. This optimization problem is solved using the Knowledge-based Particle Swarm Optimization (Kb-PSO) algorithm. Finally, to demonstrate the effectiveness of the Kb-PSO algorithm in solving the inverse kinematics problem, a numerical example of point-to-point tracking along a line-shaped trajectory is presented.

As a future perspective, the dynamic model of the robot will be developed, and both classical and advanced control strategies will be implemented to further enhance its capabilities.

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Modelado cinemático y análisis del espacio de trabajo de un robot continuo accionado por cable con módulos cruzados multidual

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CAMPO: Ingeniería Mecánica.
TIPO DE ARTÍCULO: Artículo científico original.

Resumen:

La flexibilidad y capacidad de los robots continuos para navegar en entornos complejos y restringidos los hacen muy adecuados para diversas aplicaciones, como cirugía mínimamente invasiva, manipulación industrial y operaciones exploratorias en espacios peligrosos o confinados. A pesar de estas ventajas, modelar con precisión su cinemática y realizar un análisis exhaustivo del espacio de trabajo, en particular para robots continuos multisección accionados por cable con configuraciones de doble módulo cruzado, sigue siendo un desafío considerable. Este estudio comienza presentando el diseño de un robot continuo de tres secciones

accionado por cable de doble módulo cruzado. El modelo de cinemática directa se deriva analíticamente con base en el supuesto de curvatura constante, mientras que el modelo de cinemática inversa se formula como un problema de optimización. Para facilitar la generación de trayectorias, el espacio de trabajo del robot se analiza mediante MATLAB y SOLIDWORKS. El ejemplo de simulación ilustra el rendimiento de seguimiento de trayectoria del robot.
Palabras clave: robot continuo, robot continuo accionado por cable, modelado cinemático, análisis del espacio de trabajo, seguimiento de trayectoria

Кинематическое моделирование и анализ рабочего пространства многодуального кросс-модульного кабельного робота непрерывного действия

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РУБРИКА ГРНТИ: 81.09.00 Материаловедение
ВИД СТАТЬИ: оригинальная научная статья

Резюме:
Гибкость и способность роботов непрерывного действия ориентироваться в сложных и стесненных условиях делают их удобными для применения в различных сферах, включая малоинвазивную хирургию, промышленные манипуляции и поисковые работы во взрывоопасных или замкнутых пространствах. Несмотря на эти преимущества, точное моделирование их кинематики и проведение всестороннего анализа рабочего пространства, особенно для многосекционных роботов непрерывного действия с тросовым приводом и двухмодульной конфигурацией, все еще остается сложной задачей. В первой части статьи представлена конструкция трехсецционного параллельного робота непрерывного действия с тросовым приводом. Модель прямой кинематики разработана аналитически на основе предположения о постоянной кривизне, в то время как модель обратной кинематики формулируется как задача по оптимизации. Для генерации траектории рабочее пространство робота анализируется с использованием программных пакетов MATLAB и SOLIDWORKS. Пример моделирования показывает эффективность отслеживания траектории робота.
Ключевые слова: робот непрерывного действия, *робот непрерывного действия* с тросовым приводом, кинематическое

моделирование, анализ рабочего пространства, отслеживание траектории.

Кинематичко моделовање и анализа радног простора вишеструко дуалног унакрсно-модуларног кабловски вођеног континуалног робота

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ОБЛАСТ: машинство
КАТЕГОРИЈА (ТИП) ЧЛАНКА: оригинални научни рад

Сажетак:
Флексибилност и способност континуалних робота да се сналазе у сложеним и ограниченим окружењима чини их веома погодним за разноврсне примене у областима као што су минимално инванзивна хирургија, индустријско руковање и истраживачке операције у опасним или скученим просторима. И поред оваквих предности, прецизно моделовање њихове кинематике и спровођење свеобухватне анализе радног простора (нарочито када је реч о вишеделном кабловски вођеном континуалном роботу са двоструким унакрсно-модуларним конфигурацијама) представљају значајан изазов. раду је представљен пројекат троделног двострукоунакрсног кабловски вођеног континуалног робота. Модел директне кинематике изведен је аналитичким путем на основу претпоставке о константној закривљености, док је модел инверзне кинематике формулисан као проблем оптимизације. Ради генерисања путање, радни простор робота анализиран је уз помоћ софтверских пакета MATLAB и SOLIDWORKS. Пример симулације илуструје перформансе праћења путање робота.
Кључне речи: континуални робот, кабловски вођен континуални робот, моделовање кинематике, анализа радног простора, праћење путање

Paper received on:22.02.2025.
Manuscript corrections submitted on:28.03.2025.
Paper accepted for publishing on:09.04.2025.