



Kinematics Control of Continuum Robots Based on Screw Theory

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ABSTRACT

Controlling continuum robotic arms presents significant challenges due to their highly nonlinear nature and inherently uncertain and complex structure. This complexity affects the application of continuum arms in various areas such as routing, maneuvering on complex paths, and other applications. This paper addresses a real-time kinematic control of continuum robotic arms using screw theory to develop a controller that offers accuracy, speed, and low computational load for real-time implementation. The inherent flexibility and nonlinear nature of these arms complicate precise position control. To overcome these challenges, we use a PID controller, enhancing the robot's position control capabilities. Experimentally validated results for the designed path demonstrate the controller's effectiveness in improving path tracking and real-time control performance. This controller was implemented on the actual RoboArm system, achieving a 6cm error.

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1. Introduction

In recent years, researchers in the field of robotics have adopted Continuum Robotic (CR) arms due to their shape-changing and adaptability to unpredictable environments, drawing inspiration from living organisms and nature, including snakes, octopus arms, creeping plants, and elephant trunks. The applications of these arms can be mentioned in minimally invasive surgery (MIS), underwater equipment inspection, and search and rescue [1], and [2]. The advantages of CR arms include excellent maneuverability and adaptability compared to rigid robots [3], safe contact with environmental obstacles [4] due to low inertia, and less weight and friction due to the reduction of rigid joints in their design.

The study of these robotic arms faces many challenges in real-time control. Some of these challenges and limitations include kinematic complexities, geometric measurement uncertainties, dynamic nonlinearity, and computational limitations. CR arms have a very complex structure that is difficult to control due to the large number of degrees of freedom (DOF) and the nonlinear behavior of the robot parts. These complications necessitate the use of complex methods for inverse kinematics and path generation calculations. To date, researchers have investigated various methods based on analytical and numerical techniques to model continuum manipulators. Due to the complex nature of continuum manipulators, simplifications are made to create analytical models, such as ignoring nonlinear effects like gravity and friction, movement with constant curvature (CC), and movement at low speed. Analytical modeling is one of the kinematic modeling methods that enable closed-form solutions to be easily implemented in practice [5], [6], and [7]. Numerical methods have also been developed to solve the complex relationships of these manipulators that cannot be solved analytically [8], and [9]. The data driven identification method through linear and nonlinear models such as ARX and NARX models has been used in [10] as a modeling approach.

Considering the importance of moving CR arms in limited task spaces and addressing the challenges they face, some researchers have investigated the use of screw theory as one of the analytical methods for more accurate modeling of robotic arms, including continuum/soft robotic arms. This innovative approach improves the accuracy and efficiency of real-time control and helps transform these challenges into an understandable and computable form. With the increase in the number of DOF and the complexity of the robotic arms, the volume of calculations increases significantly. However, real-time control requires fast and

accurate calculations, which can affect the real-time performance of the system. By simplifying the kinematic equations, screw theory allows calculations to be performed more efficiently and quickly [11]. In [12], the kinematic modeling of Multi-Body Systems (MBS) was carried out by considering an arbitrary coordinate frame as fixed to derive the equations of motion using screw theory and Lie group algebra. Cheng et al. [13] proposed a real-time shape recognition framework for CR arms using a piecewise polynomial curvature (PPC) kinematic model based on orientation estimation using orientation sensors and screw theory.

The adoption of screw theory in continuum robotics offers distinct advantages in both computational efficiency and accuracy, warranting closer examination. The method's effectiveness stems from several fundamental characteristics. At its core, screw theory employs a unified mathematical framework that simultaneously handles rotational and translational motions through twist coordinates. This integrated approach significantly reduces error propagation compared to traditional methods that process position and orientation components separately.

A key advantage of screw theory over conventional Denavit-Hartenberg (DH) parameters lies in its representation of rigid body motion. While DH parameters necessitate multiple coordinate frame transformations, screw theory utilizes direct exponential mappings, thereby minimizing the accumulation of numerical errors in forward kinematics calculations. Furthermore, screw theory's natural preservation of SE(3) geometric properties enables more precise representation of continuum robot configurations, which is particularly crucial given their highly nonlinear nature.

This combination of mathematical elegance and computational efficiency positions screw theory as an ideal framework for real-time control applications in continuum robotics. However, it's worth noting that comprehensive quantitative comparisons between screw theory and alternative approaches, such as DH parameters or Euler angles, remain an area open for further research and validation.

As mentioned, CR arm control is of most importance, and many studies have been conducted to control these robots. However, these investigations are ongoing to achieve more accurate methods and algorithms and to solve many existing challenges. CR arms are primarily controlled in three main ways: position control, motion control, and force control. Due to the motion trajectories of these robotic arms designed

to operate in unknown environments and their deformation characteristics, accurately approaching the target while moving is still a significant challenge. In [14], the authors investigated trajectory tracking control based on differential kinematics, which used a closed-loop control method based on iterative Jacobian to improve tracking performance. Chien and colleagues [15] investigated the model predictive control (MPC) using velocity kinematics assuming a constant curvature of a flexible rod for an aerial cable continuum robot (CCR) to control the position of this robot, thereby eliminating the dynamic model with a high computational load. Weiming-Ba et al. presented a new model-based controller for single-segment CR control, featuring: 1) an analytical differential kinematic model, directly from the task space to the actuator space, describing the end-effector position in a cylindrical coordinate system, and applying piecewise linear approximation; 2) a hybrid control scheme to separate the displacement control of the cables to monitor tension and avoid slack or overstretched states of the drive cables [16]. In [17], based on the exact model, an open-loop controller is realized by combining the piecewise constant curvature (PCC) modeling method and machine learning. In [16], a model-based controller for analytical differential kinematics control of single section CR suggests that the proposed controller performs well in terms of global stability for final actuator positioning and cable tension fluctuations for path tracking.

One popular controller often used to control robots is the PID controller. In [18], using two separate PID controllers to control the path in each part of the multi section CR, an optimized discrete control algorithm proportional integration derivative (OPID) is proposed to control the robot, aiming to control the position of the CR as a nonlinear system, which is very unstable. In [19], by using system identification through a black box, the desired model is extracted and used along with a hybrid PID fuzzy controller to control the position of the end-effector. Xavier and colleagues investigated the precise control of the bending angle in soft pneumatic actuators driven by a pressure source and an on/off solenoid using a combination of nonlinear estimation and control methods [20]. One of the first attempts to control the kinematics of continuum manipulators using a fuzzy model-based approach is presented in [21], where a fuzzy controller was proposed to independently implement end-effector path tracking tasks for a continuum manipulator. Additionally, studies have been conducted to achieve the relationship between the length variable of tendons and the position and orientation of the final actuator of tendon-driven

continuum robots (TDCR), aiming to provide an adaptive algorithm for the controller that estimates the unknown position of the final actuator online [22].

Therefore, we present real-time kinematic control based on screw theory for continuum robotic arms and examine the results of its implementation on a TDCR arm called RoboArm. First, we will introduce the RoboArm system in terms of structure in section II, followed by a brief description of the modeling (forward and inverse kinematics) in section III. In section V, we will design the appropriate path planning, and in section VI, we will present the control strategy used. Finally, we will discuss the results of implementation, validation, and conclusion.

2. ROBOARM SYSTEM DEFINITION

Due to their high flexibility and dexterity, TDCRs provide a wide range of motion in 3D space within a workspace defined by a manipulator, enabling them to perform more complex and precise tasks. The RoboArm (Figure 1) is a tendon-driven continuum robot with 6 Dynamixel AX-12 servo motors and 6 tendons connected to the servo motors by pulleys that stretch and activate the tendons. The robot structure includes holder tablets at a specific distance, designed to keep the tendons exactly parallel to the backbone and ensure smooth and controlled movement during operation. Controlling the rotation and changing the position of the robot is achieved by tightening or loosening the active driving tendon connected to the motor, which inclines the rotation of the driving motor, the backbone, and the end-effector of the RoboArm in the direction of the driving tendon. In this robotic arm, to increase accuracy and enhance the system's capabilities, load cells are used to accurately measure the tension of the tendons along with the drive motors, as well as two cameras to detect the position of the arm.

To determine the position of the end effector at the moment, two cameras represent the movement of the robot along the X, Y, and Z directions. Two Tech4A cameras, MJ-750PK and MJ-710PK, are used in this system. Both models are powered by a 5V voltage and 150mA current and are easily connected to a laptop through the USB port. The data obtained from the system can be used to monitor the performance of the manipulator and make any necessary adjustments to ensure optimal performance. Overall, the ability to achieve complex movements in unknown environments and accurately measure stresses in this continuum tendon-driven robotic arm makes it a valuable tool in robotics.

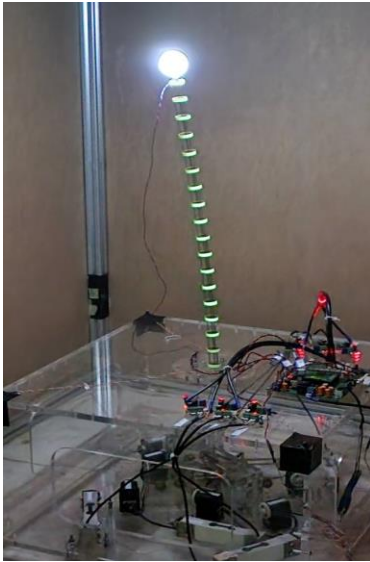


Figure 1- The RoboArm setup

3. KINEMATICS MODELING BASED SCREW-THEORY

One of the most important steps to achieve precise control of robotic arms is modeling. Robot modeling is divided into two parts: kinematics and dynamics, each of which can be extracted in either forward or inverse modes. One kinematic modeling method for CRs is the use of screw theory, a mathematical framework for modeling deformation and movement that represents twists and translations in three-dimensional space through a series of screw movements. Kinematics modeling of CR arms using this theory is of interest due to the reduced computational load in achieving real-time control. The behavior of a CR arm can be visualized by creating a mathematical model of its configuration, which refers to the positions that fully describe the geometry of the robot. This modeling process considers the governing equations of torsional systems. In this robotic arm, when the actuator tendon contracts and rotates, it causes the backbone to rotate in the direction of the tendon contraction, thereby affecting the end position and orientation of the CR arm. To model RoboArm, we divided its activity space into four spaces and three mappings. The spaces include actuation, joint, configuration, and task space, while the mappings include conversion from the actuation space to the joint space, from the joint space to the configuration space, and from the configuration space to the task space and vice versa (Figure 2).

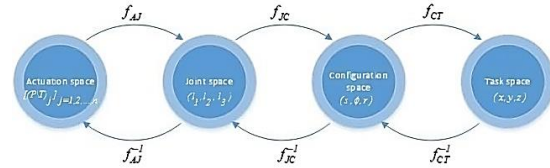


Figure 2- Space mapping diagram for continuum robot

3.1. Forward Kinematics

The kinematics of CR arms is important due to the complexity and non-linearity of their movements, making precise and real-time control necessary. Forward kinematics (FK) in CRs involves studying and analyzing the movement of these arms by calculating the position and direction of different parts of the arm based on primary control inputs. We will use screw theory to derive the equations of the kinematics model for CR arms. To simplify the calculations, we assumed the bending curve to be constant during movement, neglected the effects of gravity and friction, and only considered the effect of tendon tension as the internal force/torque. In this model, three mappings between four spaces are determined: 1- a mapping from the actuation space to the joint space, 2- a mapping from the joint space to the configuration space, and 3- a mapping from the configuration space to the task space.

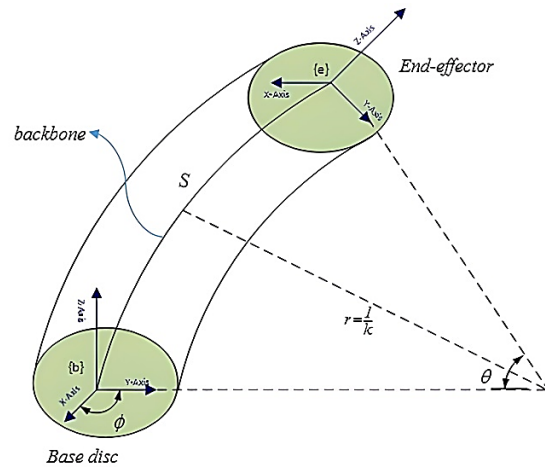


Fig. 3. The structure of a continuum robot.

Figure 3 shows a schematic of the structure of the CR arm, which includes the base frame (b), end frame (e), the angle between the base and tip disks (θ , which varies from 0 to θ), the bending angle between the movement plane and the positive direction of the X-axis in the base frame (ϕ , which varies from 0 to 2ϕ), the bending radius of the spine (r), and the fixed length of the spine (S) [11].

Considering the impact of continuum manipulator movements on the position and orientation of the end-effector, and utilizing screw theory as in our previous work, we derived the kinematic equations

represented here. For details, you can refer to reference [11]. To derive the equations, we divide the motion transfer from the base to the tip of the continuum arm into three simple movements: 1- translation of the base frame to the end frame, 2- rotation of the arm around the z-axis with an angle ϕ , and 3- rotation of the arm around the y-axis with an angle θ . These three motions are represented by torsion vectors in eq.1. According to screw theory, the following equations are obtained for the FK of continuum arms:

$$\xi_1 = \begin{bmatrix} -r \sin \phi (\cos \theta - 1) \\ r \cos \phi (\cos \theta - 1) \\ 0 \\ 0 \\ 0 \\ 0 \end{bmatrix} \quad \xi_2 = \begin{bmatrix} 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 1 \end{bmatrix} \quad \xi_3 = \begin{bmatrix} 0 \\ 0 \\ 0 \\ 1 \\ 0 \\ 0 \end{bmatrix} \quad (1)$$

$$T_b^e = \exp(\hat{\xi}_1) \exp(\hat{\xi}_2) \exp(\hat{\xi}_3) \quad (2)$$

$$T_b^e = \begin{bmatrix} R_b^e & P_b^e \\ 0 & 1 \end{bmatrix} \quad (3)$$

$$T_b^e = \begin{bmatrix} \cos \phi \cos \theta & -\sin \phi & \cos \phi \sin \theta & r \cos \phi (\cos \theta - 1) \\ \sin \phi \cos \theta & \cos \phi & \sin \phi \sin \theta & r \sin \phi (\cos \theta - 1) \\ -\sin \theta & 0 & \cos \theta & r \sin \theta \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (4)$$

In Equation 4, the rotation matrix R and the position matrix P of the end-effector coordinate system relative to the base coordinate system can be obtained.

3.2. Inverse Kinematics

Inverse kinematics (IK) for CR is a complex problem due to their highly flexible and continuum structure. Unlike traditional rigid-link robots, which have a fixed number of discrete joints, CRs exhibit a continuum of possible configurations. This section delves into the mathematical formulation for the IK of the RoboArm. From the previous section and using FK relationships, we obtain the values (x, y, z) in Cartesian coordinates for each point on the designed path. These points are then transferred from the workspace to the configuration space using a mapping function, allowing us to extract the parameters of the configuration space (Eq.5).

$$f_{CR}^{-1} = f((x, y, z) \rightarrow [\phi, \theta, r]) = \begin{cases} \phi = \tan^{-1}\left(\frac{y}{x}\right) \\ r = \frac{2\sqrt{x^2 + y^2}}{x^2 + y^2 + z^2} \\ \theta = \begin{cases} \cos^{-1}\left(1 - \frac{1}{r}\sqrt{x^2 + y^2}\right) & z > 0 \\ 2\pi - \cos^{-1}\left(1 - \frac{1}{r}\sqrt{x^2 + y^2}\right) & z \leq 0 \end{cases} \end{cases} \quad (5)$$

In the next step, as described by Equation 6, we use the mapping function from the configuration space to the joint space to calculate the length of the tendons. Here, S represents the initial length of the tendons or the length of the backbone, which is a fixed value equal to 0.525 meters. In this equation, α represents the placement angle of the tendon on the holding tablets (Fig.4).

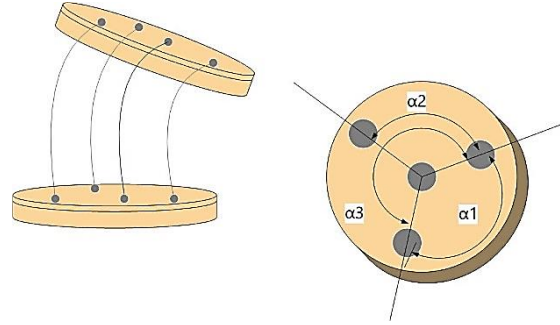


Figure4- The α represents the placement angle of the tendon on the holding tablets.

$$f_{JC}^{-1} = f([\phi, \theta, r] \rightarrow [L_{i,j=1:n}]) = S - r_{servo} \theta (\cos(\alpha_i - \phi)) \quad (6)$$

Finally, by applying the mapping function from the joint space to the actuator space, we determine the input required for the servo motors, which corresponds to their rotation or the amount of tension in the tendons. When the tendons connected to the actuators are tightened, the relationship between the length change of the tendons and the angle of the motor is linear. According to Equation 7, the relationship between the motor angle and the angle of deformation of the tendons is defined as follows:

$$f_{AJ}^{-1} = f([L_{i,j=1:n}] \rightarrow [\beta_{i,j=1:n}]) = \Delta \beta_i = \frac{L_i - S}{r_{servo}} \quad (7)$$

4. Path Planning

Given the important role of path planning in the successful implementation of CRs across various applications, this section delves into this essential aspect. The path design here employs a hybrid method, incorporating both geometry and

kinematics, to achieve the path planning. Continuum robots face several challenges in path planning, including complex kinematics, redundancy, environmental interaction, and real-time computation. This section addresses some of these challenges through the design of a path. The RoboArm, due to its flexible nature, would experience significant unwanted vibrations if it were to move directly from the origin (0,0,0) to a point on the circle. To reject these vibrations, a two-part movement path was designed. In the first part, the RoboArm moves from the origin (0,0,0) along an arc with a 0.225-meter radius, following this arc until it reaches a point on the circle with a radius of 0.22 meters. In the second part, the robot tracks the circle (Fig. 5). This two-part design effectively eliminates the unwanted vibrations that may occur at the beginning of the movement.

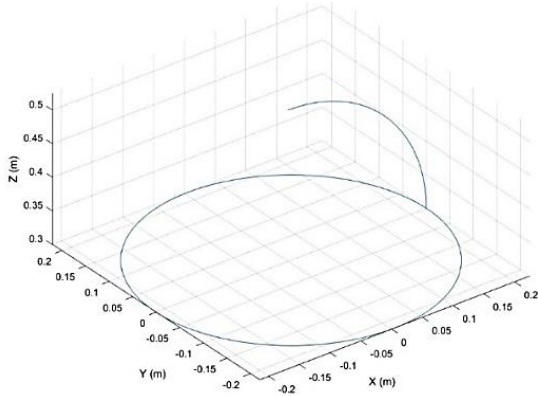


Figure 5- The Path Planning for RoboArm that includes the arc and circle.

Two methods, geometric and kinematic, were employed in this path planning process. The geometric method involved dividing the robot workspace into a set of discrete points along the arc and circle. This simplification made the environment more manageable and allowed the path planning algorithm to operate within a feasible number of positions. For each point, the possible positions and movements of the robot were calculated. Subsequently, the FK model was used to determine the robot final position and orientation. Finally, IK were applied to generate commands for the servo motors, calculating the necessary input to the actuators based on the lengths of the tendons. This process ensured that the actuators followed the designed movement path accurately which will be explained in the Implementation section. By integrating these methods, the path planning approach effectively addresses the inherent challenges of CRs, facilitating smoother and more precise movements.

5. Controller Design

As previously mentioned, the control of continuum robotic arms is of the utmost importance. This

section explores the control of continuum robotic arms, presenting a control strategy that uses Proportional-Integral-Derivative (PID) control. The primary goal of enhancing the accuracy and efficiency of position control in CRs is to address their nonlinear and highly flexible nature. PID control is a widely used feedback control mechanism in robotics that combines three types of control: proportional (P), integral (I), and derivative (D). The proportional component depends on the current error, the integral component depends on the accumulation of past errors, and the derivative component depends on the prediction of future errors. The purpose of the PID controller is to minimize the error by adjusting the control inputs, thereby achieving the desired system behavior. The PID controller output is typically based on the error signal, which represents the difference between the desired set point ($r(t)$) and the actual system output ($y(t)$). The PID controller output $u_{PID}(t)$ can be expressed as:

$$u_{PID}(t) = K_p e(t) + K_i \int_0^t e(\tau) d\tau + K_d \frac{de(t)}{dt} \quad (8)$$

where:

- K_p and K_i and K_d are the proportional, integral, and derivative gains of the PID controller, respectively.
- $e(t) = r(t) - y(t)$ is the error signal at time.
- $\int_0^t e(\tau) d\tau$ is the integral of the error signal over time.
- $\frac{de(t)}{dx}$ is the derivative of the error signal with respect to time.

In CR arms, the implementation of PID control involves several steps: 1) applying the extracted kinematic model (FK\IK), 2) calculating the error ($e(t)$) by comparing the desired final position of the actuator with its actual position, 3) calculating the control inputs using the control law (eq.8). The proportional term addresses the current error, the integral term mitigates accumulated past errors, and the derivative term predicts future errors based on the rate of change. 4) Finally, the calculated control inputs are applied to the actuators (motors). Figure 6 shows the control block diagram for RoboArm.

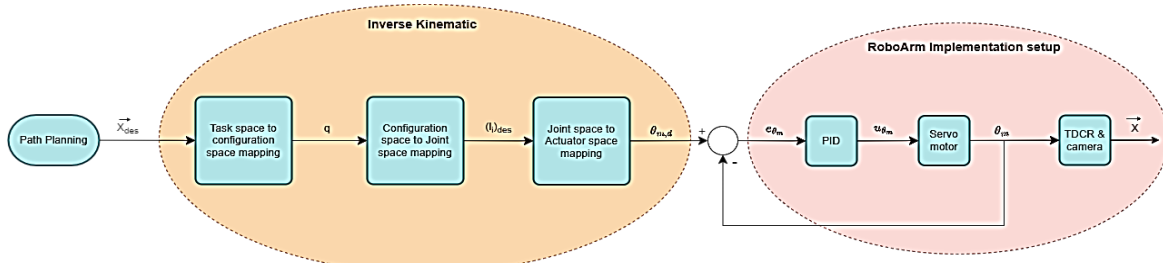


Figure 6- Control block diagram of the RoboArm

6. Results, Implementation, and Discussion

This section discusses the results obtained from the RoboArm control implementation. These results provide valuable insights into the behavior and control performance of this robot. The analysis of these results also highlights potential areas for optimization and improvement in the design and real-time control of tendon-driven continuum robots. After designing the movement path, we determined the desired coordinates that the robot should travel in task-space (X_{des}), which were then converted into the required input for the servo motor using inverse kinematic equations and maps. The input to the servo motor is the amount of motor rotation ($\theta_{m,d}$), as shown in Figure 6 under the title of desired input. Feedback is taken from the output of the servo motor (θ_m), and the difference between it and the desired input is considered the controller's input. When the command is applied to the servo motors, based on the desired coordinates where the robot should be placed, the motors release or tension the tendons. After reaching the new coordinates, these positions are identified by the cameras, and their Cartesian coordinates are measured. The specified path for RoboArm movement is represented in section 4.

Figure 7 shows the designed path and the actual path taken during implementation in the X-Y plane, which is a circular path. In the implementation, the robot travels the path with an error between 2 and 6 cm. Figures 8a, 8b, and 8c compare the Cartesian components of the trajectory in simulation and implementation, showing the trajectory over time.

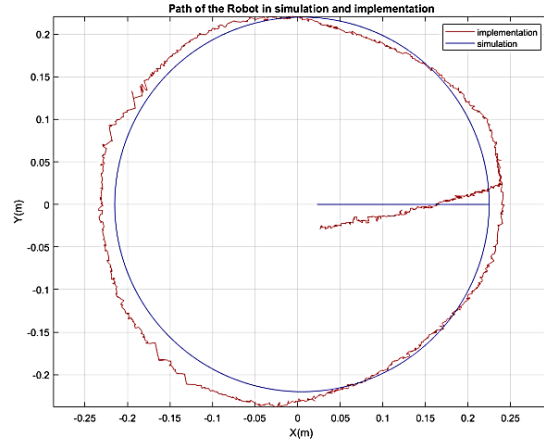


Figure7- Path tracking of RoboArm, experimental result (red) versus the designated path (blue).

The robot exhibits relatively more oscillations in the X and Y directions, with a maximum error of 6 cm in these directions. In the Z direction, the movement of the robot is divided into two parts: the first part is an arc of a circle where the robot's height varies. As shown in Figure 8c, the robot travels this path with great accuracy, with a maximum error of about 2 mm. In the second part, the height remains constant as the robot travels the full circle, which is maintained with good accuracy, as seen in Figure 8c. The graphs indicate that the PID control can somewhat correctly follow the path, but there are errors and fluctuations in the actual implementation. These errors can be attributed to sensor inaccuracies, environmental noise, controller response delays from the microcontroller, vibrations due to the spine's flexibility, and camera reading errors.

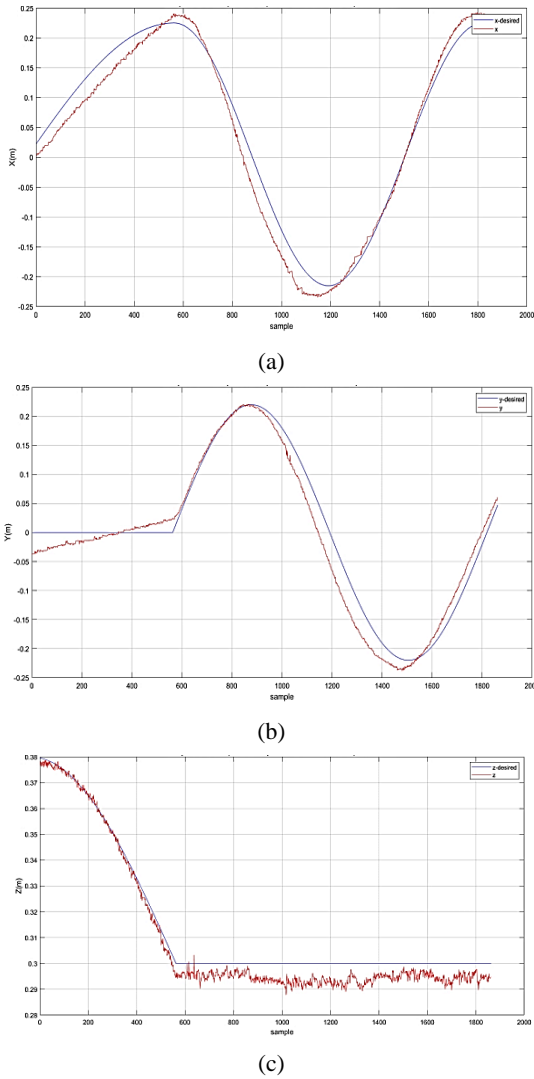


Figure 8- The difference between implementation and simulation along the Cartesian axes. a) x-component, b) y-component, c) z-component for RoboArm.

We created a comparative analysis table of our work with some of the relevant papers in the field of continuum robot control using screw theory to illustrate better the advantages and position of our work in the field, Table 1 presents a comparison with other notable approaches in continuum robots control.

As shown in Table 1, our screw theory-based approach achieves competitive positioning accuracy (2-6 cm error) compared to other methods while maintaining lower computational complexity. The integration of screw theory with PID control provides several advantages:

- **Computational Efficiency:** Unlike methods such as UKF, [21] or fuzzy-model-based approaches, [22], our method requires fewer mathematical operations for kinematic calculations.

- **Implementation Simplicity:** Compared to complex control schemes like those in [16] and [23], our approach offers a more straightforward implementation while achieving better positioning accuracy.
- **Real-time Performance:** The low computational overhead of screw theory allows for true real-time control, which is not always achievable with computationally intensive methods like those in [21] and [22].
- **Accuracy:** Our method's positioning error (2-6 cm) represents an improvement over most comparable hardware implementations in the literature, particularly considering the length and complexity of our robot's structure.

Table 1: Comparison of Different Control Approaches in Continuum Robotics (H: High, M:Medium, L:Low)

Ref.	Control Method	Accuracy	Computational Complexity	Real-time Capability	Implementation Type	Position Error (range)
Our Work	Screw Theory + PID	H	L	Yes	Hardware (Robo Arm)	2-6 cm
Cheng et al. [13]	Screw Theory + PPC	M	M	Yes	Simulation	Not reported
Weiming-Ba et al. [16]	Analytical Differential Kinematics	M	M	Yes	Hardware	8-10 cm
Xavier et al. [21]	Nonlinear UKF	H	H	Limited	Hardware	5-7 cm
Qi et al. [22]	Fuzzy Model-Based	M	H	Limited	Hardware	7-12 cm
Wang et al. [23]	Visual Servo Control	M	M	Yes	Hardware	10-15 cm

7. CONCLUSIONS

This paper presented an approach to real-time kinematics control of continuum robots based on screw theory. The proposed method demonstrated its efficacy through the RoboArm implementation, revealing several key insights and areas for improvement. The results showed that the inverse kinematics model effectively translates desired spatial coordinates into servo motor inputs, enabling precise control of the robot movements path. However, the implementation also highlighted challenges such as sensor inaccuracies, environmental noise, and controller response delays, which led to errors and oscillations in the robot path. The comparison between simulation

and implementation underscored the robot oscillatory behavior in the X and Y directions, with a maximum error of 6 cm, while achieving high accuracy in the Z direction, particularly in the circular arc segment of the path with a maximum error of about 2 mm. The PID control system was able to follow the path to a reasonable extent, although improvements are necessary to reduce fluctuations and enhance precision.

Future work will focus on optimizing sensor accuracy, reducing environmental noise, and improving the real-time responsiveness of the controller. Enhancements in these areas are expected to significantly improve the overall performance and reliability of continuum robots in real-time applications. This study contributes to the growing body of knowledge on continuum robot control and provides a foundation for further advancements in the field.

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