Kinematics and Shape Sensing of a Collaborative Continuum Robot

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***Abstract*— Current robotic systems are not suitable for collaborative manufacturing in confined spaces due to their inability to reach into deep confined spaces while maintaining passive and active safety measures. Minimal actuation and distributed sensory awareness can enable the passive and active safety measures needed to overcome these challenges. Use on continuum robots for manufacturing further enhances passive safety at the cost of challenges in modeling and control. External loads on robots using continuum segments result in direct kinematics and statics modeling uncertainty. We therefore incorporate intrinsic sensing using string potentiometers to augment joint-level sensing for the aim of enabling real-time shape estimation under deflected conditions. We present a kinematic formulation that allows general robot shapes, leads to a product of exponentials formula, and allows for general string routing designs for shape sensing. We discuss integration of the string sensors into a continuum segment and the implementation of the kinematics in a ROS system. Our validations are limited to simulation studies, so future work will include experimental validation on the physical system.**

I. Introduction

Manufacturing and maintenance in confined spaces (e.g. aircraft assembly/repair) requires workers to exert sustained forces in unergonomic postures. A collaborative robot could alleviate these issues, but existing systems are not suitable for this application due to a lack of ability to reach deep into a confined space and lack of sensory awareness for safety. To address these limitations, we are developing an *in-situ collaborative robot* (ISCR) that will facilitate both *in-situ* physical human-robot interaction for collaborative tasks and *ex-situ* teleoperation to prevent a worker from entering a confined space at all. The robot (shown in Fig. 1) consists of a statically-balanced set of revolute joints at the base, and a flexible distal arm that consists of both revolute joints and tendon-actuated continuum modules.

As with any continuum or soft robot, external loads result in increased uncertainty in the kinematics and shape. Several sensing modalities have been proposed in prior work to address this problem [1]. Due to the need to operate in a semi-structured confined space, it is not practical for an ISCR to use external sensing methods like cameras, magnetic sensors, or optical trackers. Instead, proprioceptive sensing methods (e.g. force sensors on the robot, fiber Bragg grating optical fibers) are needed for shape sensing.

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This work was supported by NSF award #1734461 and by Vanderbilt University funds. A. Orekhov was partly supported by the NSF Graduate Research Fellowship under #DGE-1445197.

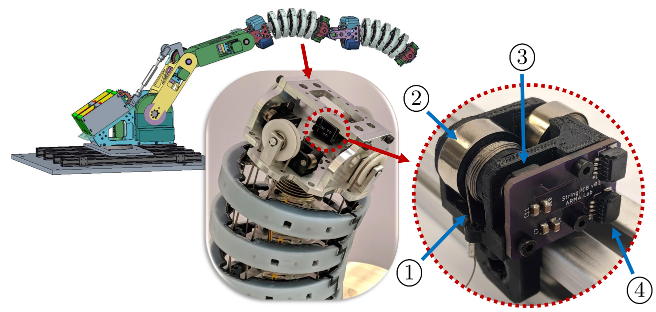

Fig. 1: In-situ collaborative robot with revolute joints and continuum segments. Each string sensor consists of ① a string, ② a constant torque spring, ③ a magnetic encoder, and ④ I^{2}C bus connectors.

In this work, we study the use of string potentiometers for proprioceptive shape sensing. When embedded within a continuum segment, these sensors measure changes in length along their routing path. Such low-cost sensors facilitate integration of many sensors within a bending continuum segment. This approach has been used in several prior works [2–4], but these works assume constant-curvature sections or do not consider general string sensor routings. Continuum robot models that handle general tendon routing have been presented [5], [6], but these works rely on a Cosserat-rod mechanics model and do not discuss how to incorporate passive string sensor measurements. In this work, we are interested in a computationally efficient method for online shape sensing, so we are pursuing a kinematics-only approach that allows general backbone shapes and general tendon routings without requiring a mechanics model.

II. Lie Group Kinematics and Shape Sensing

Our description of the segment shape closely follows [7]. Referring to Fig. 2, we describe the central backbone using its moving frames $\mathbf{T}(s) \in SE(3)$ where s is the arc length parameter. $\mathbf{T}(s)$ is made up of $\mathbf{p}(s)$ and $\mathbf{R}(s)$ (the origins and orientations of central backbone frames). The coordinates describing the location of the tendon routing in the moving frame $\mathbf{T}(s)$ is given by $r_{x_i}(s)$ and $r_{y_i}(s)$.

Assuming shear strains are negligible, the twist distribution along the segment (expressed in the moving frame) is written as $\boldsymbol{\eta}(s) = [\mathbf{u}(s), \mathbf{e}_3]^{\mathrm{T}} \in \mathbb{R}^6$, where $\mathbf{e}_3 = [0, 0, 1]^{\mathrm{T}}$. We describe the curvature $\mathbf{u}(s)$ using a modal representation:

$$\mathbf{u}(s) = \begin{bmatrix} \boldsymbol{\phi}_x^{\mathrm{T}}\mathbf{c}_x \\ \boldsymbol{\phi}_y^{\mathrm{T}}\mathbf{c}_y \\ \boldsymbol{\phi}_z^{\mathrm{T}}\mathbf{c}_z \end{bmatrix} = \begin{bmatrix} \boldsymbol{\phi}_x^{\mathrm{T}} & 0 & 0 \\ 0 & \boldsymbol{\phi}_y^{\mathrm{T}} & 0 \\ 0 & 0 & \boldsymbol{\phi}_z^{\mathrm{T}} \end{bmatrix} \begin{bmatrix} \mathbf{c}_x \\ \mathbf{c}_y \\ \mathbf{c}_z \end{bmatrix} = \boldsymbol{\Phi}\mathbf{c} \qquad (1)$$

where $\boldsymbol{\phi}_x(s)$, $\boldsymbol{\phi}_y(s)$, and $\boldsymbol{\phi}_z(s)$ are vectors of Chebyshev polynomials and $\mathbf{c}$ the modal coefficients. Using $\widehat{\boldsymbol{\eta}}(s)$ (the

2020 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS) workshop on "Application-Oriented Modelling and Control of Soft Robots", Nov 2020.

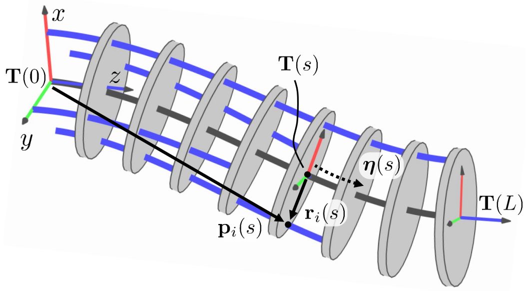

Fig. 2: Variables in our continuum segment kinematic model.

twist of the moving frame), $\mathbf{T}(s)$ is found by integrating:

$$\mathbf{T}'(s) = \mathbf{T}^{-1}(s)\widehat{\boldsymbol{\eta}}(s), \quad \widehat{\boldsymbol{\eta}}(s) = \begin{bmatrix} \widehat{\mathbf{u}}(s) & \mathbf{e}_3 \\ 0 & 0 \end{bmatrix} \in se(3) \quad (2)$$

Where $(\cdot)\prime$ designates a derivative with respect to s. There are several ways to solve (2) for $\mathbf{T}(s)$, but using a geometric integration method based on the Magnus expansion [7], [8] provides $\mathbf{T}(s)$ as a product of matrix exponentials, which allows deriving standard kinematic Jacobians as in [8].

Following the approach in [5], the position of a point along the i^{th} tendon path $(i = 1 \dots p)$ is given in world frame by:

$$\mathbf{p}_i(s) = \mathbf{p}(s) + \mathbf{R}(s)\mathbf{r}_i(s) \quad \mathbf{r}_i(s) = [r_{x_i}(s), r_{y_i}(s), 0]^{\mathrm{T}} \quad (3)$$

The length of the ith tendon is given by:

$$l_i = \int_0^{s_{t_i}} \|{}^b\mathbf{p}_i'\| \mathrm{d}s \quad i = 1, 2, \dots, p \quad (4)$$

where ${}^b\mathbf{p}_i'$ is the derivative of the tendon path expressed in the moving frame and s_{t_i} is the arc length where the tendon is terminated.

To solve shape sensing problem, we must find $\mathbf{c}$ for a given $\boldsymbol{\ell}^* \in \mathbb{R}^p$ of string potentiometer measurements. We concatenate (4) and solve this system of equations for $\mathbf{c}$:

$$\boldsymbol{\ell}(\mathbf{c}) - \boldsymbol{\ell}^* = 0, \quad \boldsymbol{\ell} \in \mathbb{R}^p \quad (5)$$

Equation (5) is a system of nonlinear equations that must be solved numerically with an iterative method, e.g. Gauss-Newton. For special cases (e.g. planar parallel routing) this problem has a closed-form solution.

The Jacobian relating changes in the modal coefficients to changes in the tendon lengths is $\mathrm{d}\boldsymbol{\ell} = \mathbf{J}_{\ell c}\mathrm{d}\mathbf{c}$. Taking partial derivatives of (4) leads to the i^{th} row of $\mathbf{J}_{\ell c}$ being given as:

$$\frac{\partial \ell_i}{\partial \mathbf{c}} = \int_0^{s_{t_i}} \left(\mathbf{r}_i \times \frac{({}^b\mathbf{p}_i')}{\|{}^b\mathbf{p}_i'\|} \right)^{\mathrm{T}} \boldsymbol{\Phi} \, \mathrm{d}s \quad (6)$$

A similar expression to (6) is given in [9].

The Jacobian (6) is useful for 1) computing the residual Jacobian in an iterative method when solving (6) and 2) for providing local estimates of how string sensor measurement error propagates to error in the modal coefficients.

III. System Integration

In our system, four string sensors are mounted within the distal endplate assembly of each continuum segment, as shown in Fig. 1. The string sensors contain a Vulcan Spring SV3D48 constant-torque spring, a ⌀0.33 mm wire rope, and a custom PCB with an RLS AM4096 magnetic encoder for measuring the output angle. Each sensor is connected to an I^{2}C bus on which all sensor data (including proximity and contact sensing [10]) is passed to a microcontroller mounted in the base of the segment. Sensory data is then passed via UDP to a high-level control computer.

Our overall system utilizes the Robot Operating System (ROS), but our kinematic model is not captured by the standard URDF joint types, so we use `<floating>` joint types for all joints, and a custom C++ library computes the forward kinematics (using the product of exponentials formula) to update the transformations of each joint frame. We use the URDF `<visual>` and `<collision>` tags for visualization in RVIZ and collision queries, respectively.

IV. Conclusions

We have presented a kinematic formulation that allows general shapes and general tendon routings for the purposes of shape sensing. We show how string sensors can be incorporated into a modular continuum segment and describe our implementation within a ROS system. Our results are preliminary and have not been experimentally validated. Future work will include experimental validation on the physical robot and optimization of the tendon routing functions to reduce sensing error.

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