Model-less control of a flexible robotic catheter

Michael C. Yip, Paul. J. Wang and David B. Camarillo, *Member, IEEE*

***Abstract*—Flexible robotics are capable of navigating through unstructured environments such as a human body, where it can safely conform around environmental obstacles and constraints due to its compliant body. Because these environmental disturbances can affect the configuration of the robot in an unknown and unpredictable manner, conventional kinematics- and mechanics-based control methods can be inaccurate and can lead to robot singularities and controller instabilities. Using *model-less control*, we demonstrate control of a flexible robot manipulator without requiring a model. Furthermore, we show its application in a tissue ablation task using a flexible catheter. Model-less control provides a robust control strategy for flexible manipulators in unstructured environments, and offers a simple and effective alternative for controlling robots with complex kinematics and mechanics.**

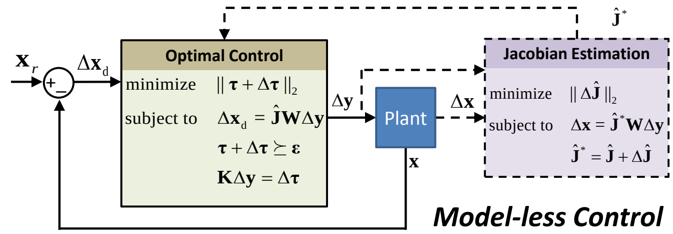

Fig. 1: Flowchart showing the closed-loop control for a tendon-driven continuum manipulator (solid lines) and the constrained optimization method for model-less control (dashed lines). $\mathbf{x}$ is the manipulator position, $\mathbf{y}$ is the actuator positions, τ is the cable tensions, $\mathbf{K}$ is a stiffness mapping, and $\hat{\mathbf{J}}$ is the robot Jacobian estimate.

I. Introduction

The major benefit of flexible robotic manipulators is that they can utilize their compliant bodies to navigate environments in a safe manner. Constraints and obstacles in the workspace cause the manipulators to conform into irregular configurations. Traditional closed-loop control techniques require a model (e.g. kinematics, mechanics) to estimate the configuration of the robot during each control cycle [1]. However, for a flexible manipulator, modeling the conformed configurations of its body can be extremely difficult, and current models tend only to be accurate for structured environments, and do not address interactions between the manipulator and unknown and unstructured environments. This leads to a diminished reachable workspace and possible instability issues [2].

Because of the complexity of the kinematics and mechanics of these manipulators, including the fact that they often exhibit over- or under-actuation (n actuators, m degrees of freedom, $n \neq m$), an alternative method is presented. We demonstrate that closed-loop task-space control can be achieved without using a model using *model-less control*, providing a simple and efficient way to control complex robot manipulators, and furthermore overcoming limitations of model-based systems.

II. Methods

A. The model-less control framework

In this paper, the model-less controller [2] is defined for a tendon-driven continuum manipulator (Figure 1). Model-less control comprises a Jacobian estimation method that is applied to a task-space closed-loop controller, described below.

Manuscript received March 9, 2013.

M.C. Yip and D.B. Camarillo are with the Department of Bioengineering at Stanford University, Stanford, CA, 94305 USA. (e-mail: mcyip@stanford.edu, dcamarillo@stanford.edu)

P.J. Wang is with the School of Medicine (Cardiovascular Medicine) and with the Department of Bioengineering at Stanford University, Stanford, Ca 94305 USA. (email: paul.j.wang@stanford.edu)

Jacobian estimation: At the heart of the model-less control method is the Jacobian estimation method (dashed lines in Figure 1). It is defined as a constrained optimization method that finds an estimate of the Jacobian, $\hat{\mathbf{J}}$, that satisfies the mapping $\Delta\mathbf{x} = \hat{\mathbf{J}}\mathbf{W}\Delta\mathbf{y}$. This is always an under-constrained problem; therefore, a least-norm solution is chosen such that the change in $\hat{\mathbf{J}}$ is minimized at every estimation step, resulting in smooth changes in the Jacobian estimate, shown below:

$$\begin{aligned} \underset{\hat{\mathbf{J}}^*}{\text{minimize}} \quad & \|\Delta\hat{\mathbf{J}}\|_2 \\ \text{subject to} \quad & \Delta\mathbf{x} = \hat{\mathbf{J}}^*\mathbf{W}\Delta\mathbf{y} \\ & \hat{\mathbf{J}}^* = \hat{\mathbf{J}} + \Delta\hat{\mathbf{J}} \end{aligned} \tag{1}$$

where the new Jacobian estimate is $\hat{\mathbf{J}}^*$. It should be noted that more constraints can be added to the optimization method to further constrain the solution space and potentially improve the Jacobian estimate (e.g. geometric constraints).

Optimal control: The Jacobian estimate is used in a task-space closed-loop method (shown in solid lines in Figure 1). For a continuum manipulator driven by co-activated tendons, this is an over-constrained system and therefore we again use constrained optimization to solve for actuator displacements $\Delta\mathbf{y}$. In this solution, the controller minimizes tendon tensions τ and therefore reduces internal manipulator loading.

B. Experimental Setup

The model-less controller was implemented on a continuum manipulator, comprising a flexible backbone (280 mm length) and two 0.6 mm steel tendons. Tension sensors measure cable tensions during tendon actuation, and an insertion motor drives the robot forwards and backwards. A 50 Hz camera provides position tracking at a resolution of approximately 0.5 mm per pixel. In addition to closed-loop position tracking, a minimum tendon tension of $\tau = 0.3$ N was maintained using the constrained optimization method during each control cycle.

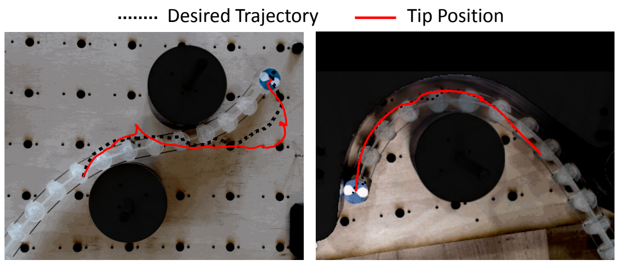

Fig. 2: A flexible manipulator tracks a trajectory without knowledge of environment. Tracking of the trajectory is maintained in spite of unknown obstacles that constrain and conform the manipulator into irregular configurations.

Since the problem is convex, optimization was performed in $\sim 10\mu$ sec using the CVXgen convex optimization solver [3].

III. Results

A. Movement in Obstacles

Figure 2 shows the model-less controller navigating two environments with obstacles. The first environment involves navigating two posts that results in an s-shaped conformation of the robot. In the second case, the model-less control moves the robot through a channel resulting in an approximately $135°$ turn. In both cases, model-less control is effective in following the trajectory despite the significant environmental effects at unknown locations along the manipulator body. The channel constraint presents a case where one actuation input (insertion) becomes inverted as the robot moves through the constraint; without explicit knowledge of the environment, model-based methods would not be able to account for the inversion and would therefore result in a positive feedback loop and instability.

B. Tissue contact simulation

One promising medical application for flexible robots is catheter ablation. Applying sufficient pressure to soft tissue and performing ablation allows for targeted necrosis of cells that cause cardiac arrhythmia. Contiguous linear ablations segregate healthy tissues from erroneous and arrhythmia-inducing electrical signals. Control of these contiguous paths are most effectively done in task-space and therefore is a good environment for applying the proposed model-less controller.

Figure 3 shows the continuum manipulator applying pressure and tracing a linear path on different silicone tissue phantoms. For various stiffnesses, the model-less controller is able to trace a user-defined desired trajectory while applying pressure to the environment. Because the forces are not being explicitly controlled, The indentation of the tissue and the compliance of the manipulator dictate the forces applied to the environment, and this is also reflected in the cable tensions. Rise in cable tensions and force reflect the controller's attempt to reduce the y-axis position error. The compliance of the tissue environment and the compliance of the manipulator together keep interaction forces to a safe level.

[1]Elastic stiffness for in-vivo heart tissue fall between $0.0249 - 0.136$ MPa (healthy to congenital cardiomyopathy) [4].

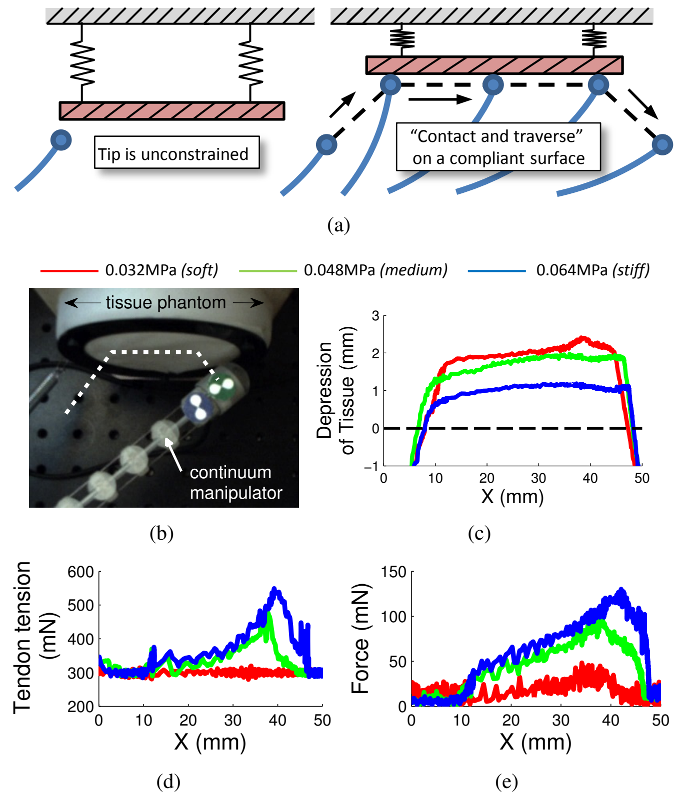

Fig. 3: A robot manipulator coming into tip-contact with soft constraint and tracing a path along the constraint (a), as is done for cardiac tissue ablation. (b) shows the environmental setup. For a given trajectory, the tracking accuracy (c), tendon tensions (d) and interaction forces (e) vary for different tissue elastic stiffnesses $(0.32, 0.48, 0.64 \text{ MPa})$[1].

IV. Discussion

Model-less control provides a valuable approach to controlling a robot manipulator in the following situations: (1) when the robot has complex kinematics or mechanics that are difficult to model, and (2) when there are unknown disturbances (e.g. environmental constraints) that affect the manipulator in an unpredictable way. It can be considered a local learning method that identifies the approximate mapping between actuator displacements and actuator outputs while satisfying any number of user-defined constraints. The compliance of a flexible manipulator can then be used advantageously in constrained environments without concerning the user with modeling its complex bending properties. Future work will involve investigating force regulation as a control constraint.

References

[1] B. Siciliano and O. Khatib, *Springer handbook of robotics*. Springer, 2008.

[2] M. Yip and D. Camarillo, "Model-less feedback control of continuum manipulators in unknown environments," *IEEE Transactions on Robotics*, vol. 30, no. 4, 2014. 10 pages.

[3] J. Mattingley and S. Boyd, "Cvxgen: A code generator for embedded convex optimization," *Optimization and Engineering*, vol. 13, no. 1, pp. 1–27, 2012.

[4] I. Mirsky and W. Parmley, "Assessment of passive elastic stiffness for isolated heart muscle and the intact heart," *Circulation research*, vol. 33, no. 2, pp. 233–243, 1973.