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Force Sensing along Continuum Robots using Compliance Matrix and Shape Acquisition

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INTRODUCTION

Continuum robots are promising for minimally invasive surgery. They consist of thin and flexible structures whose shape can be continuously deformed using remote actuators, allowing them to be inserted in small tubular cavities. For safety reasons, it is important to be aware of the forces applied to surrounding tissue during deployment. Because common force sensors are too cumbersome to be embedded into continuum robots, alternative shape-based force estimation methods have been developed. Such methods estimate the contact location and the corresponding force based on the comparison between a measured robot shape (for instance using Fiber Bragg Gratings sensors or vision sensors) and the one predicted from robot modeling (typically computed using Cosserat rod modeling and actuator positions [1]). The applied force is then estimated through optimization procedures, with [2] or without [3], [4] explicit knowledge of the force application point. These algorithms have shown promising performance but are restricted to passive Cosserat rods models, whereas in practice continuum robots are active structures. Recently, Aloï et al. extended the work from [4] in the case of a 2-DOF tendon-driven robot, for which they experimentally validated their method [5].

All the previous solutions have two limitations. First, they assume contact forces to be perpendicular to the robot's curvilinear axis: hypothesis (H1). Since continuum robot shapes can be highly curved, one might question how strongly the tangential component of the force can affect the global deformation of the robot. Second, they consist of iterative optimizations during which the whole robot model is computed at each iteration using convex optimization routines. Such an approach can be computationally time-consuming and does not necessarily yield a global optimum.

The present paper introduces a new Compliance-based approach to estimate an external force applied to a continuum robot in any direction. Results obtained with a simulated Concentric Tubes Continuum Robot (CTCR) are presented and discussed.

MATERIALS AND METHODS

Let us consider a continuum robot of length L modeled using Cosserat rod theory. In a given configuration, the

robot shape p_{init} can be computed using the model. It is discretized into N points $p(s_i)$, associated with its discretized arc-length $s_i \in [0, L]$ with $i \in \llbracket 1, N \rrbracket$. Let us assume the robot is loaded with external forces, denoted $f(s_j)$, with $j \in \llbracket 1, N \rrbracket$. We define the Generalized Compliance matrix $C_{s_j}(s_i)$ of the robot as:

$$C_{s_j}(s_i) = \frac{\partial p(s_i)}{\partial f(s_j)}. \quad (1)$$

$C_{s_j}(s_i)$ can be efficiently computed by extending the method from [6] to forces applied at any point of the robot. The robot shape under external load p_{mes} is assumed to be measured in order to estimate the robot deformation under external loads, $\Delta p(s_i)$. By considering a linear approximation of the robot deformation, $\Delta p(s_i)$ can be defined as:

$$\forall i \in \llbracket 1, N \rrbracket, \Delta p(s_i) \approx \sum_{j \in \llbracket 1, N \rrbracket} C_{s_j}(s_i) \Delta f(s_j) \quad (2)$$

The problem is then to estimate the forces $\Delta f(s_j)$ that generate the observed deformation $\Delta p(s_i)$.

A. Single Force Estimation

In this study, a unique force $\Delta f(s_0)$ is considered, where s_0 refers to the loaded point abscissa. Therefore, the problem is to find the vector force and the loaded point $\Delta f(s_0)$ that has led to the observed deformations $\Delta p(s_i)$:

$$\forall i \in \llbracket 1, N \rrbracket, \Delta p(s_i) \approx C_{s_0}(s_i) \Delta f(s_0) \quad (3)$$

For a given loaded point s_j , the estimated force vector $\Delta \tilde{f}(s_j)$ is computed by iterative optimization of the cost function (4) :

$$\Delta \tilde{f}(s_j) = \arg \min_{\Delta f} \left(\sum_{i \in \llbracket 1, N \rrbracket} \|C_{s_j}(s_i) \Delta f - \Delta p(s_i)\|^2 \right) \quad (4)$$

This approach speeds up the force estimation by substituting multiple computations of the robot model with simple computations of linear algebra. Since the Generalized Compliance matrix is computed once for a given robot shape, it is possible to perform the minimization in equation (4) in parallel for every application point s_j . The loaded point arc-length \tilde{s}_0 can then be estimated

	$\frac{\ \Delta f(s_0) - \Delta \tilde{f}(\tilde{s}_0)\ }{\ \Delta f(s_0)\ }$ [%]				$\frac{ s_0 - \tilde{s}_0 }{L}$ error [%]				$\langle \Delta f(s_0), \Delta \tilde{f}(\tilde{s}_0) \rangle$ [deg]			
	min	median	IQR	max	min	median	IQR	max	min	median	IQR	max
2D ^(a)	1.88	16.42	23.41	108.19	0.00	3.41	1.71	4.88	0.00	1.14	0.80	10.31
3D ^(b)	8.67	21.19	9.91	82.61	0.00	3.41	1.71	5.85	19.18	35.08	9.76	47.50

TABLE I Performances of the proposed force sensing algorithm applied to simulated CTCR described in Table II. Two scenarios have been simulated: when (H1) is assumed (a) and when it is not (b).

by selecting the global optimum (see Fig. 1a) from the previous computations:

$$\tilde{s}_0 = \arg \min_{s_j} \left(\sum_{i \in \llbracket 1, N \rrbracket} \|C_{s_j}(s_i) \Delta \tilde{f}(s_j) - \Delta p(s_i)\|^2 \right) \quad (5)$$

The method described above yields the application point \tilde{s}_0 and the associated force $\Delta \tilde{f}(\tilde{s}_0)$. Finally, the Cosserat-based robot model is computed only once to compute the robot deformed shape p_{est} under this loading. Fig. 1b shows an example of a result in a given configuration.

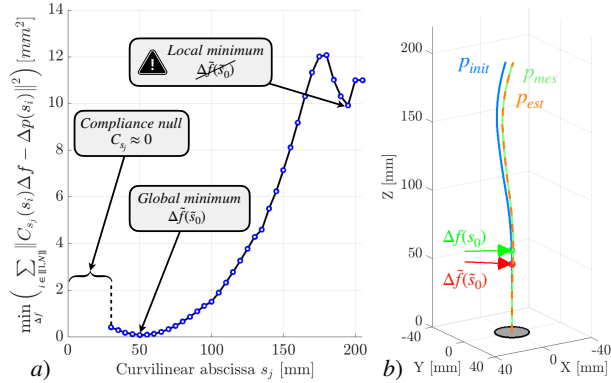


Fig. 1 Sample result on a simulated CTCR. a) Evolution of the minimum (5) evaluated for all possible loaded points s_j . Note the presence of a local minimum that could induce wrong results using convex optimization. b) Initial, measured, and estimated robot shape under a force $\Delta f(s_0)$, compared with the estimated one $\Delta \tilde{f}(\tilde{s}_0)$.

RESULTS

The algorithm was tested in simulation with a CTCR (see Table II) of $L = 200$ mm, with $N = 39$.

	L_r	L_c	R_c	$K_{x,y}$	ν	θ_c	β_c
Units	mm	mm	mm	N.mm ²	-	deg	mm
Tube 1	165	50	160	$2.2 \cdot 10^5$	0.3	90	100
Tube 2	235	50	242	$1.2 \cdot 10^5$	0.3	180	150
Tube 3	450	50	118	$6.0 \cdot 10^4$	0.3	270	200

TABLE II Parameters of the simulated CTCR. L_r : straight length; L_c : curved length; R_c : radius of curvature; $K_{x,y}$: stiffness along x and y; ν : Poisson's ratio; θ_c : actuator rotation; β_c : actuator translation.

To ensure a fair distribution of forces and application points, we selected 20 evenly spaced loaded points (s_0

from 10% to 90% of the robot length) and force magnitude $\Delta f(s_0)$ from 1N to 8N. For each set of $(s_0, \Delta f)$, the force vector was simulated for 10 random directions. The results obtained were averaged and used to extract force magnitude errors, loaded point location errors and force direction errors. Table I presents the results obtained when hypothesis (H1) is considered and when it is not. It can be noticed that the performance for the force magnitude and the loaded point estimations do not seem to be strongly affected by (H1). However, the force direction estimation is significantly affected by it: the median error increases from 1.14 deg to 35.08 deg.

DISCUSSION

This paper presents the first Compliance-based force sensing algorithm for arbitrarily located forces along the robot. To the best of the authors' knowledge, the algorithm is the first one to avoid computing the whole robot model at each iteration and to consider non-perpendicular forces. The simulation results show the efficiency of the Compliance-based force estimation algorithm for continuum robots. The results also illustrate that it can be challenging to estimate the tangential component of external forces, and it would be instructive to compare the estimation error of the tangential component with the deformation intensity generated by it. An algorithmic strategy for estimating multiple forces at once while preserving the effectiveness of the Compliance-based approach is currently under study. Future work will include experimentally testing the method to demonstrate the possibilities for practical medical applications.

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