Dynamic Control of Soft Robots Interacting with the Environment

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Introduction

- The Control of soft robots is intrinsically difficult because it requires controllers for systems with infinite dimensions.
- This paper considers an alternative formulation of soft robot dynamics which connects the robot behavior with one of a rigid bodied robot with elasticity in the joints. The matching between the two systems is exact under the common hypothesis of Piecewise Constant Curvature (PCC).
- Based on this connection, the paper introduces two control architectures.

Introduction ot Control Architecture

- The one is the control of the Curvature.
- The other is Cartesian controller of robot impedance.
- The Curvature controller accounts for natural softness of the system
- While the Cartesian controller adapts the impedance of the end effector for interactions with unstructured environment.

Piecewise Constant Curvature (PCC) Model, Kinematics

- In the Piecewise Constant Curvature (PCC) model the infinite dimensionality of the soft robot’s configuration is resolved by considering the robot’s shape as composed of a fixed number of segments with constant curvature(CC) merged such that the resuting curve is everywhere differentiable. Consider a PCC soft robot composed by n CC elements, and consider a set of reference systems
- {S[0]},…..{S[n]} attached at the ends of each segment.
- The Figure at the next slide presents an example of a soft robot composed by four CC segments. Using the constant curvature hypothesis, S[i-1] and S[i] fully define the configuration of the ith segment.

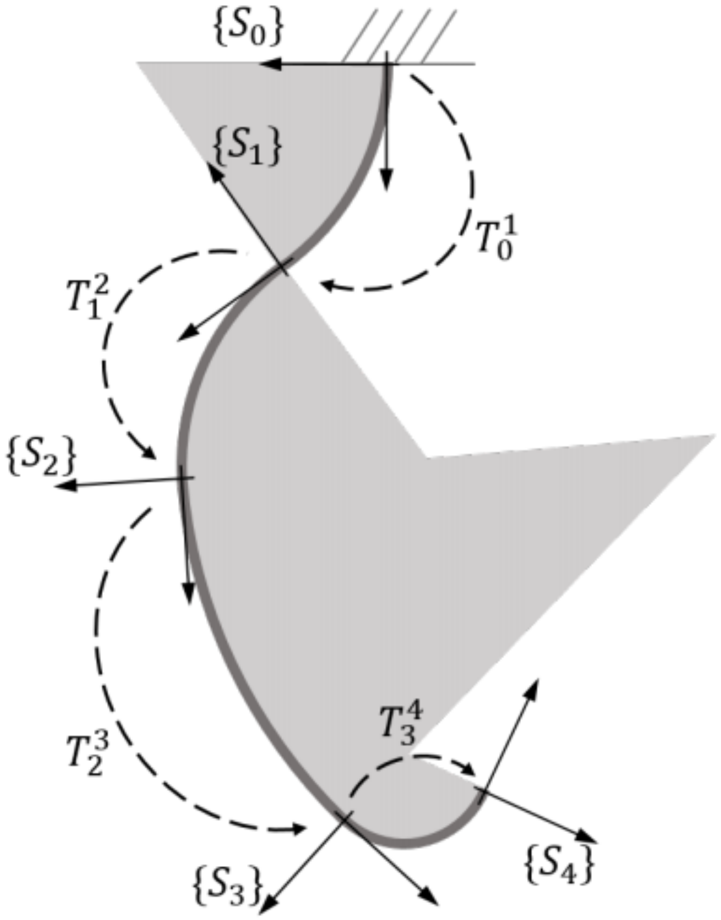


Fig. 2. Example of a Piecewise Constant Curvature robot, composed by four constant curvature elements. $\{S_0\}$ is the robot's base frame. A reference frame $\{S_i\}$ is connected at the end of each segment. T_{i-1}^{i} is the homogeneous transformation mapping $\{S_{i-1}\}$ into $\{S_i\}$.

Next slide shows the kinematic representation of planar constant curvature segment

- The robot's kinematics can be defined by n homogenous transformations T1[0],…..Tn[n-1].which map each reference system to the subsequent one. The figure 3. (next slide) shows kinematics of a isngle CC segment. Under the hypothesis of non-extensibility one variable is sufficient to describe the segment's configuration . We use the relative rotation between the two reference systems, called the degree of curvature , as the configuration variable.

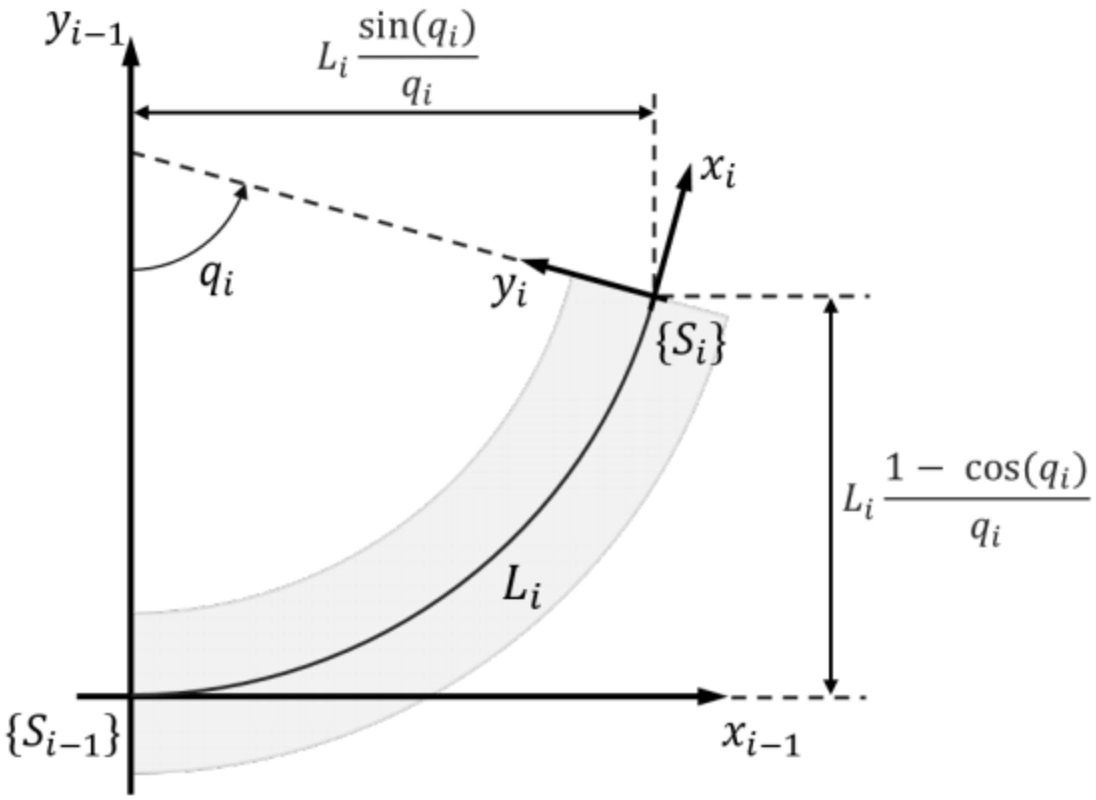


Fig. 3. Kinematic representation of the i-th planar constant curvature segment. Two local frames are placed at the two ends of the segment, $\{S_{i-1}\}$ and $\{S_i\}$ respectively. The length of the segment is L_i, and q_i is the degree of curvature.

Homogeneous transformation, where L[i] is the length of the segment

$$T_{i-1}^{i}(q_i) = \begin{bmatrix} \cos(q_i) & -\sin(q_i) & L_i \frac{\sin(q_i)}{q_i} \\ \sin(q_i) & \cos(q_i) & L_i \frac{1-\cos(q_i)}{q_i} \\ 0 & 0 & 1 \end{bmatrix}, \qquad (1)$$

Dynamically Consistent Augmented Configuration

- The paper uses Denavit-Hartenberg (DH) parametrization.
- The soft robot, connected via basic CC elements, is represented by Augmented State representation of the PCC soft robot.
- Introduce X with dimension of n, m as a map m(q) ,called augmented configuration ,where m is the number of joints per CC segments and n is the number of segments.

$$m : \mathbb{R}^{n} \rightarrow \mathbb{R}^{n\,m} \,.$$

- The X map assures that the end points of each CC segment coincide with the corresponding reference points of the rigid robot.
- While from the kinematic point of view any augmented representations satisfying this condition is equivalent, this is not the case for the dynamics.
- Inertial properties must be considered.

Center of mass placed in the middle of the chord, the segment map in the DH parametrization is

$$m_i(q_i) = \begin{bmatrix} \frac{q_i}{2} \\ L_i \frac{\sin(\frac{q_i}{2})}{q_i} \\ L_i \frac{\sin(\frac{q_i}{2})}{q_i} \\ \frac{q_i}{2} \end{bmatrix} .$$

$$m(q) = \begin{bmatrix} m_1(q_1)^{\mathrm{T}} & \dots & m_n(q_n)^{\mathrm{T}} \end{bmatrix}^{\mathrm{T}} .$$

Control design: There will be two controllers

- One: Curvature Dynamic Control and
- the other Cartesian Impedance Control and Surface Following.in the soft robot’s space:
- The Curvature Dynamic Control for implementing trajectory following
- In the soft robot’s state space:
- Where q and their derivatives are degrees of curvature vectors. B is robot’s inertia, C=Coriolis, K=stiffness,D=Damping.I [q] is gain

$$\tau = K\bar{q} + D\dot{\bar{q}} + C(q,\dot{q})\dot{\bar{q}} + B(q)\ddot{\bar{q}} + G_{\mathrm{G}}(q) + I_{\mathrm{q}}\int(\bar{q} - q)$$

A. Curvature Dynamic Control

We propose the following controller for implementing trajectory following in the soft robot's state space

$$\tau = K\bar{q}+D\dot{\bar{q}}+C(q,\dot{q})\dot{\bar{q}}+B(q)\ddot{\bar{q}}+G_{\mathrm{G}}(q)+I_{\mathrm{q}}\int(\bar{q}-q) \quad (12)$$

where $q, \dot{q}, \ddot{q}$ are the degree of curvature vector and its derivatives. $\bar{q}, \dot{\bar{q}}, \ddot{\bar{q}}$ are the desired evolution and its derivatives expressed in the degree of curvature space. B is the robot's inertia, C is the Coriolis and centrifugal matrix, K and D are respectively the robot's stiffness and damping matrices. The constant I_{q} is the gain of the integral action.

The resulting form of the closed loop system is

$$\begin{aligned} B(q)(\ddot{q}-\ddot{\bar{q}}) + C(q,\dot{q})(\dot{q}-\dot{\bar{q}}) - J^{T}(q)f_{\mathrm{ext}} \\ = K(\bar{q}-q) + I_{\mathrm{q}}\int(\bar{q}-q) + D(\dot{\bar{q}}-\dot{q})\,. \end{aligned} \quad (13)$$

The closed loop system is below

The feed forward action K and D is combined with the physical impedance of the system generating a natural proportional (PD) action In this way the natural softness of the orbot is preserved during possible interaction with an external environment. The Integral action is included for compensating the mismatches between the real system and the approximate model considered here. Note that I [q] is the only parameter that needs to be tuned, since K and D are defined by the physics of the system.

$$B(q)(\ddot{q} - \ddot{\bar{q}}) + C(q, \dot{q})(\dot{q} - \dot{\bar{q}}) - J^T(q) f_{\mathrm{ext}}$$
$$= K(\bar{q} - q) + I_{\mathrm{q}} \int (\bar{q} - q) + D(\dot{\bar{q}} - \dot{q}) \, .$$

Cartesian Impedance Control and surface Following

- A correct regulation of the impedance at the contact point is essential to implement robust and reliable interactions with the environment.
- Without loss of generality , we will consider in the following as point of contact the soft robot’s end effector. We define a local frame
- (n tangential, n normal) connected to the end effector, shown in the next slide. Since both N Tangential and normal are unit vectors their
- N tangential transpose . N normal is = zero.
- In order to follow the surface we assume the following knowledge:
- The coordinate x[0] of the point is included within the environment.

Cartesian Impedance contorller

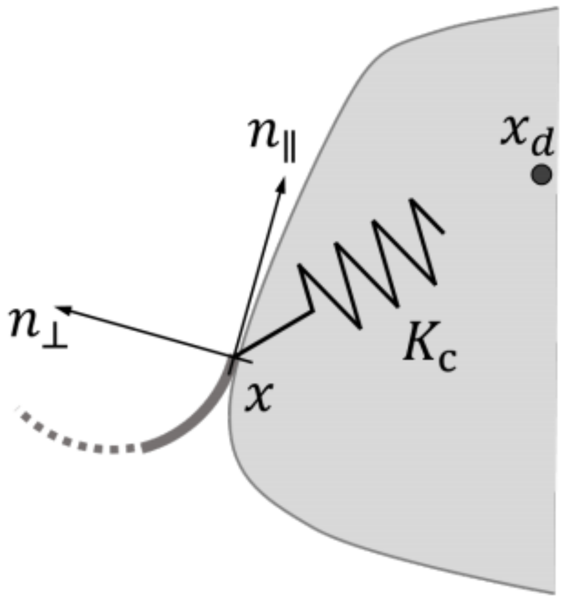


Fig. 6. The goal of the proposed Cartesian impedance controller is to simulate the presence of a spring and a damper connected between the robot's end effector and a point in space x_{d}. The frame $(n_{\parallel}, n_{\perp})$ defines the tangent and parallel directions to the environment in the contact point.

Leveraging these knowns and the robot's dynamic model, we propose to implement the desired compliant behavior through the following dynamic feedback loop

$$\begin{aligned}\tau = {} & J^{\mathrm{T}}(q)(K_{\mathrm{c}}(x_{\mathrm{d}} - x) - D_{\mathrm{c}} J(q)\dot{q}) \\ & + C(q,\dot{q})\dot{q} + G_{\mathrm{G}}(q) + K\, q \\ & + I_{\mathrm{c}}\, J^{\mathrm{T}}(q)\, n_{\|} \int n_{\|}^{T} (x_{\mathrm{d}} - x)\ ,\end{aligned} \tag{14}$$

where $q, \dot{q}$ are the degree of curvature vector and its derivative. $J(q)$ is the Jacobian mapping those derivatives into the end effector velocity $\dot{x}$. x_{d} is a reference position for the end effector, and x is the current end effector position.

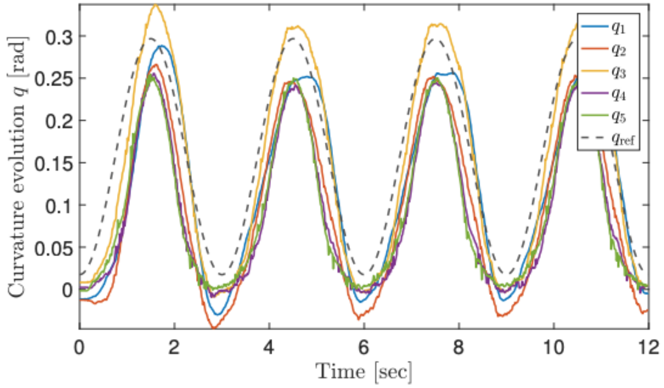
The term $J^{\mathrm{T}}(q)(K_{\mathrm{c}}(x_{\mathrm{d}} - x) - D_{\mathrm{c}}J(q)\dot{q})$ simulates the presence of a spring and a damper connected between the robot's end effector and x_{d}. This imposes the desired Cartesian impedance. K_{c} and D_{c} are the desired Cartesian stiffness and damping matrices. We choose them to be diagonal in order to implement a full decoupling within the degrees of freedom.

We specify the values of x_d and $n_\parallel$ on-line through Algorithm 1. Algorithm 1 consists of two phases: approaching and exploring. In the first phase (lines 1-5), a generic point inside the environment x_0 is selected as reference for the impedance controller. No integral action is considered here. When the soft robot makes contact with the environment, the second phase begins (lines 6-10). Here, the desired end effector position is chosen as the final target x_t. A constant displacement $\delta \in \mathbb{R}^+$ in the direction $-n_\perp$ is manually defined to ensure maintenance of contact with the environment. Algorithm 1 terminates when the seminorm of the error weighted on $n_\parallel n_\parallel^T$ is under a manually defined threshold. In this way, only the error along the surface is considered.

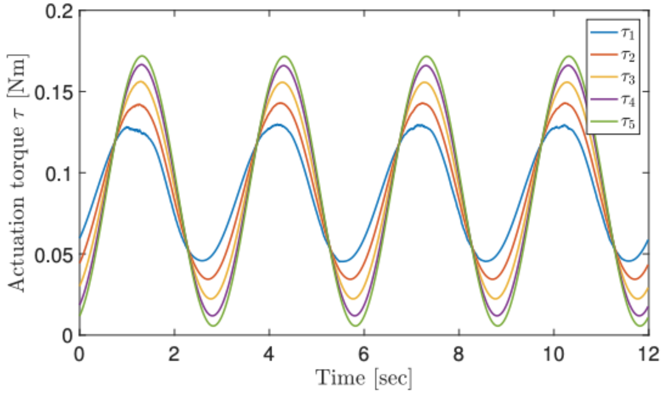
Some experimental results/evaluation

- The paper tell us that the soft robot used her is composed of five
- Bidirectional segments with inflatable cavities. Each segment of soft arm is 6.3cm long. The independent pneumatic actuation of the bidirectional arm segments I achieved through an array of 10 pneumatic cylinders. The connection element between each segment is supported vertically by two ball transfers that allow the arm to move with minimal friction on a level plane. A motion tracking system provides real-time measurements of marked points along the inextensible back of the soft arm. A rigid frame holds all the sub-system together providing reliable hardware experiments without need for camera recalibration. The basic Dynamic equation has several parameters that need to be identified.

Curvature Control



(a) Curvature



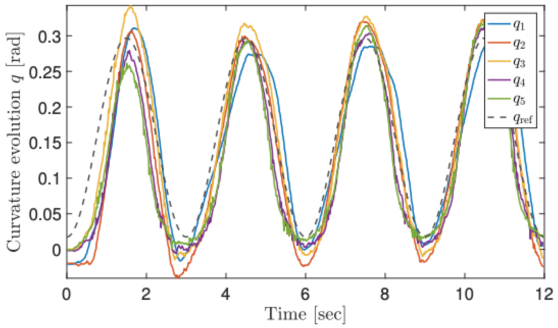
(b) Torques

Fig. 7. Evolutions resulting from the application of the dynamic controller (12) to the tracking of a trajectory (15). The integral gain is $I_{\mathrm{q}} = 0\,\frac{\mathrm{Nm}}{\mathrm{s}}$. Panel (a) shows the evolution of the degree of curvature q. Panel (b) presents the corresponding actuation torques.

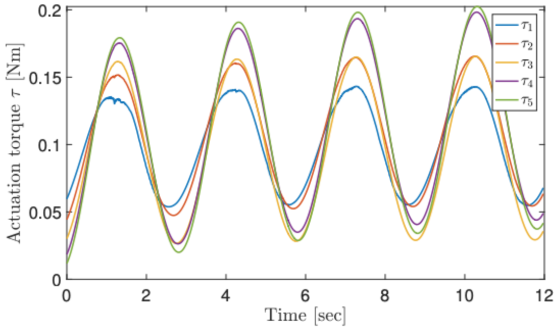
Curvature Control ,results see in next slide

- Which presents the evolution of measured degrees of curvature and applied torques with the integral action set to I[q] =0 Nms{-1}.
- Even without any integral compensation of the model uncertainties , the algorithm is able to produce a stable oscillation close ot the commanded one. In next slide we show the evolution of the same quantities for I[q]= 0.08Nms[-1]. The low gain feedback appears to scarcely modify the torque profile.
- However the small variation reduces sensibility the trackin error, resulting in L[2] norm equal to 0.0961 rad.

The evolution ,change in integral gain I[q]



(a) Curvature



(b) Torques

Fig. 8. Evolutions resulting from the application of the dynamic controller (12) to the tracking of a trajectory (15). The integral gain is $I_{\mathrm{q}} = 0.08\,\frac{\mathrm{Nm}}{\mathrm{s}}$. Panel (a) shows the evolution of the degree of curvature q. Panel (b) presents the corresponding actuation torques.

Cartesian Impedance Contorl and Surface Following

- The robot’s goal is to first reach the wall and then slide along it until the desired position is reached.
- The input to the pneumatic cylinders is produced by filtering torque in (14) through a filter. We gte the desired impedance K, and damping D.
- The integral gain is I[c] =1.9 N mrad[-1] sec[-1].
- After contact is established, it triggers the execution of the follower and tracking algorithm, the commanded actuation torques are shown in fig.11 and the evolution of the end effector in Cartesian space is shown in Figure 12

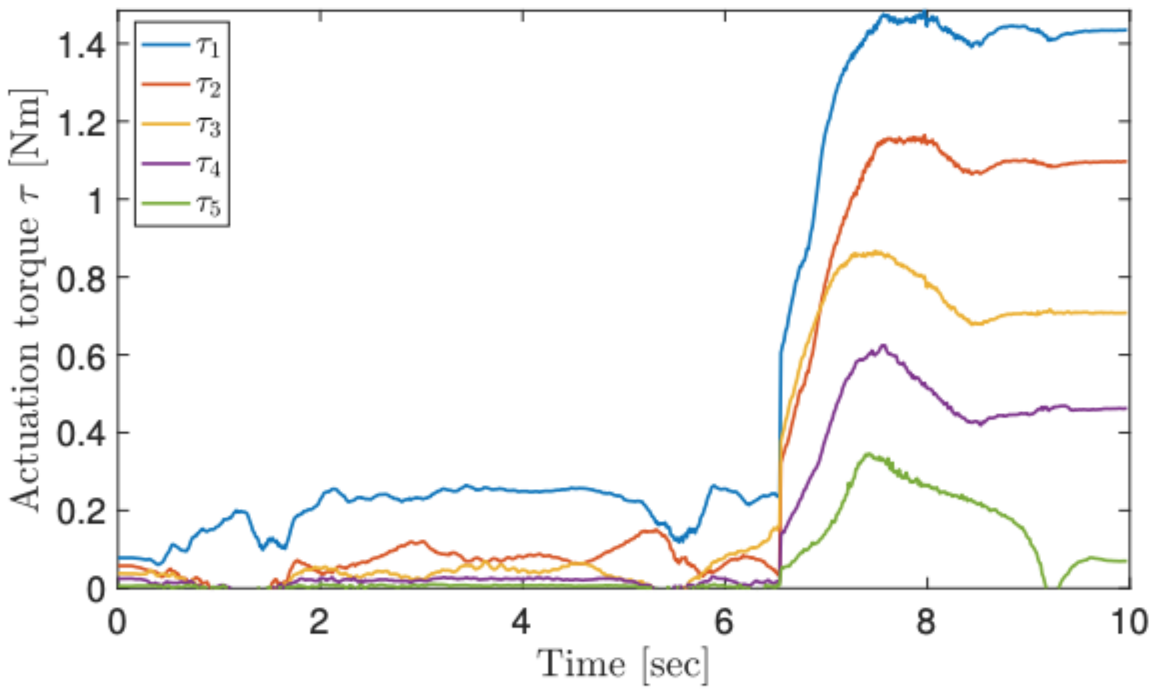


Fig. 11. Actuation torques commanded by the proposed Cartesian impedance controller (14) while executing the Algorithm 1. The contact detection happens at 6.5 s.

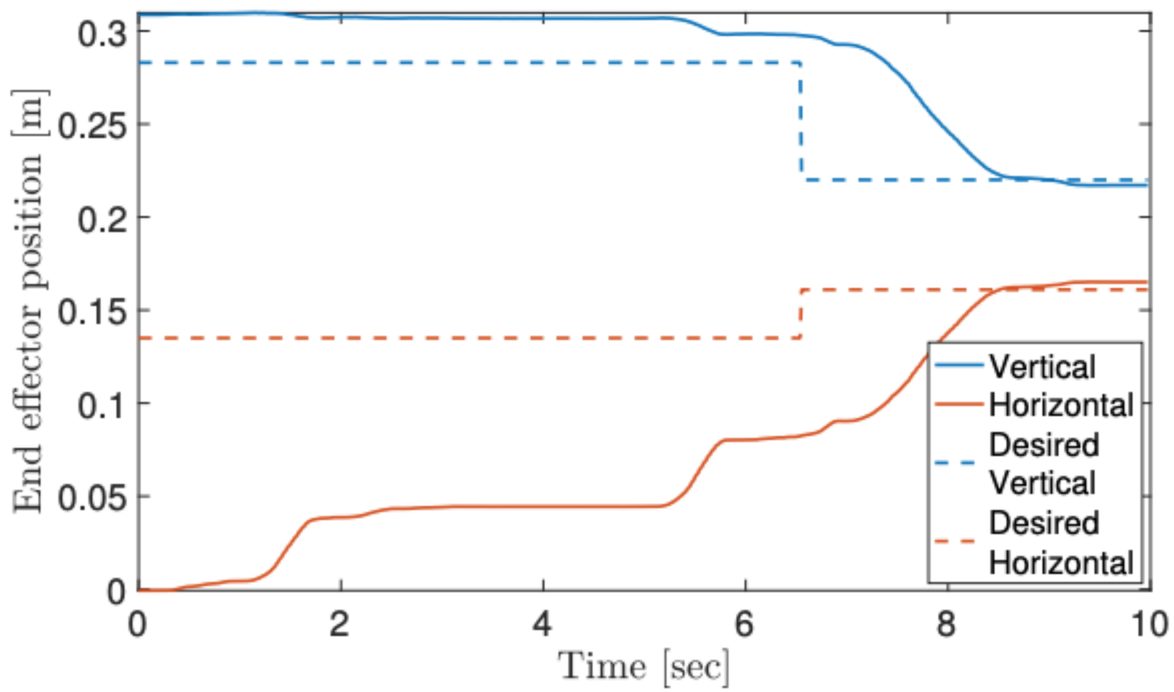
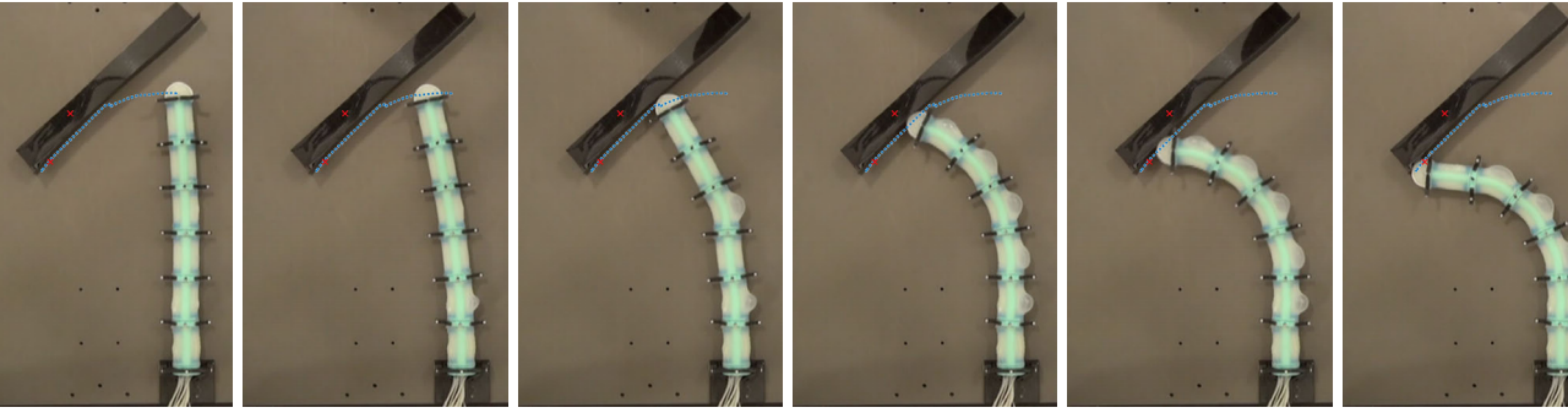


Fig. 12. End effector's evolution in Cartesian space resulting by the application of the proposed Cartesian impedance controller (14) and Algorithm 1. The contact detection happens at 6.5 s.



(a) (b) (c) (d) (e) (f)

. 10. Photo sequence of the soft robot controlled through the proposed Cartesian impedance controller (14). We report superimposed the two refere
itions commanded by Algorithm 1 (red crosses) and the trajectory of the end effector (blue dashed line). Panels (a-c) show the first phase of
orithm: the robot's tip is attracted toward the environment by a virtual spring connected to a reference point inside the surface. Panels (d-f) illust
second phase of the algorithm: the robot traces along the surface toward the desired end position. Note that the bottom segment is not actuated
strained in its vertical position through a mechanical stop.

Additional References

- Gregory S. Chirikjian and Joel W. Burdick: The Kinematics of Hyper-Redundant Robot Locomotion, IEEE Transaction on Robotics and Automaiton, Vol.11,No.6 December 1995
- Florian Enner, David Rollinson and Howie Chosett;
- Simplified motion modeling for snake robots, proceedings of IEEE International Conference on Robotics and Automation, May 2012.