

Model-free Position Control of a Soft Continuum Manipulator in Cartesian Space

Shen Treratanakulchai^{1,2,3}, Enrico Franco², and Ferdinando Rodriguez y Baena^{1,2}

Abstract—This work investigates the position control in Cartesian space of a soft continuum manipulator with pneumatic actuation. To this end, we employ a feedback integral action initialized using an optimized mapping between pressure and tip position. This approach is detailed for a manipulator consisting of either a single actuated segment or of two actuated segments connected in series. Experiments are conducted on individual prototypes and with a teleoperation setup including a master unit from our track record.

I. INTRODUCTION

Soft manipulators are ideally suited for minimally invasive surgery [1], [2], due to their compliance and light weight. Nevertheless, controlling these systems poses remarkable challenges since their deformability results in a large number of degrees of freedom (DOF) and in underactuation. Further control challenges are related to external forces, which are ubiquitous in real-world settings, and to the hyperelastic materials used for manufacturing, which result in nonlinearities and hysteresis affecting the system dynamics and kinematics.

Research on control of soft manipulators has been exploring two main approaches: model-free, which relies on training data to construct a numerical mapping between control input and system states, and model-based, which instead relies on a dynamic model of the system constructed from first principles. The advantages of model-free approaches include their conceptual simplicity and their generality. Their main drawbacks are their computational load, which increases with the complexity of the control goal, the need for comprehensive training data, and the empirical tuning of the controller parameters. Model-free approaches have proved effective for kinematic control of soft robots, which disregards external forces and dynamic effects under the assumption of quasi-static conditions [3], [4]: this assumption drastically reduces the size of the required training data, which is often limited by the durability of soft robots. Conversely, model based controllers do not require training data, are theoretically superior in case of fast dynamics, and can provide rigorous proofs of stability. However, they

typically rely on the exact knowledge of the system model, which is often not available in engineering practice. In an attempt to address the former drawback, adaptive algorithms, nonlinear observers, and integral actions have recently been investigated [5], [6]. In addition, model-based control of higher-order models, for instance due to the pressure dynamics in soft manipulators with fluidic actuation [7], [8], can result in complex control laws, which can be undesirable in engineering practice. Finally, most research on control of soft manipulators has been focusing on regulation or tracking in joint space, and only few works have investigated the regulation in task space [9], which is often more relevant to practical applications. Typically, the control problem in task space poses additional challenges, since it also requires exact knowledge of the kinematic model. Effective approaches for kinematic mapping include the constant curvature (CC) and the piecewise-constant curvature model (PCC) [10], the Cosserat rod model [11], the Euler Bernoulli beam model [12], and polynomial models [13]. However, none of these approaches allows accounting for hysteresis, nonlinearities, and for the effect of external forces in a general fashion.

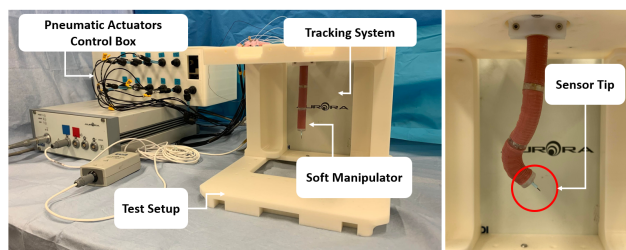


Fig. 1. Experimental setup consisting of soft manipulator with EM tracker.

In this paper, we investigate the model-free position control in Cartesian space of a soft continuum manipulator with pneumatic actuation presenting the following new results.

- A feedback integral action that accounts for external forces is outlined in general form and is then implemented for a single actuated segment and for two actuated segments connected in series. The integral action is initialized using an optimized mapping between actuation pressures and Cartesian space in quasi-static conditions. As a result, the size of the training data is considerably reduced, while the control algorithm is robust to external forces, nonlinearities, and hysteresis.
- Experimental testing with our prototype and with a teleoperation setup demonstrate the effectiveness of the proposed approach.

¹The Hamlyn Centre for Robotic Surgery, Imperial College, London, United Kingdom. This research was supported by the Engineering and Physical Sciences Research Council (grant number EP/W004224/1) and by a collaboration with the Multi-Scale Medical Robotics Centre, The Chinese University of Hong Kong. For the purpose of open access, the authors have applied a Creative Commons Attribution (CC BY) license to any Accepted Manuscript version arising.

²The Mechatronics in Medicine Laboratory, Imperial College, London, United Kingdom.

³Biomedical and Robotics Technology Laboratory, Mahidol University, Nakhon Pathom, Thailand.

Email: [s.treratanakulchai17,f.rodriguez}@imperial.ac.uk

An overview of our soft manipulator and its kinematic model is provided in Section II. The control strategy is detailed in Section III. Experimental results are presented in Section IV, and Section V contains concluding remarks.

II. SOFT MANIPULATOR

A. System overview

We have developed a soft continuum manipulator for minimally invasive surgery [14] which has a tubular geometry and consists of three actuated segments connected in series by rigid separation disks. The actuated segments have a uniform cross section divided into three equal chambers, which can be pressurized independently. Each actuated segment can bend in any direction providing two actuated DOF, thus three segments in series provide six actuated DOF at the distal end. An inextensible tube is located at the center of the section to provide a central working channel and to prevent axial elongation, thus increasing the bending angle and the force output to a range compatible with minimally invasive surgical tasks. In this work, the position and orientation of the tip of the manipulator are measured with an electromagnetic (EM) tracking system (Aurora, NDI) by employing a 5 DOF EM sensor mounted inside the central working channel. The internal chambers of the manipulator are supplied each by one proportional valve (Tecno Basic, Hoerbiger, Germany), which regulates the pressure in the range 0 to 2 bar. A Matlab script communicates the control input to the proportional valves through a microcontroller (LPC1768 mbed, NXP) and collects measurements from the EM sensor.

B. Kinematic model

The mapping between control pressures and bending angles (i.e. orientation of the bending plane ϕ_i and bending angle θ_i on the bending plane of segment i) in the absence of external forces and model uncertainties is given by [15] as $\theta_i = \frac{1}{k} P_{net,i}$, and $\phi_i = \tan^{-1} \left(\sqrt{3} \frac{p_{i,2} - p_{i,3}}{p_{i,2} - p_{i,3} - 2p_{i,1}} \right)$, where $P_{net,i} = \sqrt{p_{i,1}^2 + p_{i,2}^2 + p_{i,3}^2 - p_{i,1}p_{i,2} - p_{i,1}p_{i,3} - p_{i,2}p_{i,3}}$, and $p_{i,j}$ are the pressures in the internal chambers $j = 1, 2, 3$ of segment i , while k is the bending stiffness of the actuated segment, which is typically assumed constant.

To account for manufacturing tolerances that would result in asymmetries between chambers, the pressures $p_{i,j}$ are multiplied by scalar coefficients, that is

$$P^m = \begin{bmatrix} p_1^m \\ p_2^m \\ p_3^m \end{bmatrix} = \begin{bmatrix} a_1 p_1 \\ a_2 p_2 \\ a_3 p_3 \end{bmatrix}, \quad (1)$$

where P^m is the vector of scaled pressures and a_j is the coefficient relative to chamber j , to be optimized based on training data collected at steady state. To account for a non-constant bending stiffness and for differences between actuated segments we have employed the polynomial fitting

$$\theta_i = \sum_{r=1}^3 \sum_{m=0}^5 C_{i,r} (P_{net,i}^m)^r, \quad (2)$$

where r is the polynomial order (i.e. $r = 5$ in this work), and $C_{i,r}$ are coefficients to be optimized based on training data. Similarly, the orientation of the bending plane is defined as

$$\phi_i = \tan^{-1} \left(\sqrt{3} b \frac{p_{i,2}^m - p_{i,3}^m}{p_{i,2}^m - p_{i,3}^m - 2p_{i,1}^m} \right), \quad (3)$$

where b is a scalar coefficient to be optimized.

The kinematic model of the soft continuum manipulator constructed according to PCC assumptions [14] yields the transformation matrix relating sensor frame and base frame

$$T_{home}^{sensor} = T_{home} T_d T_1 T_d T_2 T_d T_3 T_d T_{sensor} \quad (4)$$

where T_1, T_2, T_3 refer to the actuated segments and T_d to the separation disk, while T_{home} is the transformation of the base frame, which is defined as

$$T_{home} = \begin{bmatrix} \cos(\theta'_Z) & -\sin(\theta'_Z) & 0 & 0 \\ \sin(\theta'_Z) & \cos(\theta'_Z) & 0 & 0 \\ 0 & 0 & 1 & t_z \\ 0 & 0 & 0 & 1 \end{bmatrix}, \quad (5)$$

where t_z is the translation along the Z axis, that is

$$t_z = -([l_1 + l_2 + l_3 + 3t_d] + l_{sensor}), \quad (6)$$

and θ'_Z is the rotation around the Z axis. The parameter t_d is the thickness of the separation disks between actuated segments, which is known, while l_i is the length of the actuated segment and l_{sensor} is the length of the sensor, both of which are optimized based on training data.

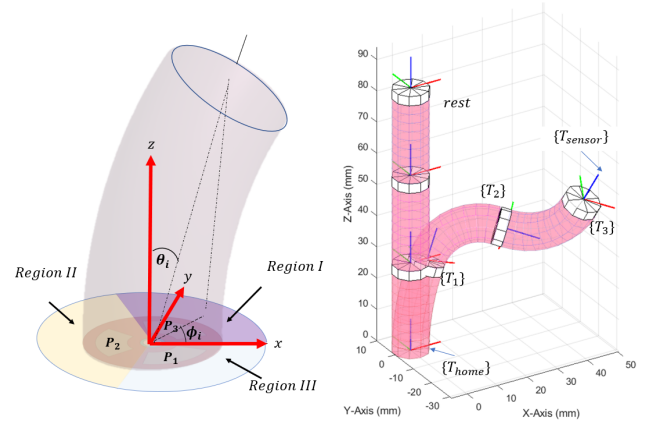


Fig. 2. (left) Schematic showing the cross section of an actuated segment with regions of the workspace corresponding to different chambers (i.e. Region I corresponds to $p_1 \geq 0$, $p_2 \geq 0$ and $p_3 = 0$). (right) Kinematic model of the manipulator.

A genetic algorithm implemented with the Matlab's Global Optimization Toolbox has been used to optimize the parameters $C_{i,r}, a_j, b_i, l_i$ and l_{sensor} for $i = 1..3$, $j = 1..3$, and $r = 5$. The cost function is the Euclidean distance between measured position (with the EM sensor) and computed positions with (1-4). The algorithm updates the parameters until either the cost is lower than a predefined tolerance or the number of iterations exceeds the limit. A Fast Forward Neural Network (FFNN) with 50x30x20 hidden layers and

Bayesian regularization has been implemented for comparison purposes (see Figure 3). The Genetic algorithm yields a mean squared error of 55.47 mm, while the FFNN yields 65.3 mm. It must be noted that neither the FFNN nor the proposed method account for hysteresis or external forces, thus a purely kinematic controller might not yield sufficient accuracy and a feedback control action is required.

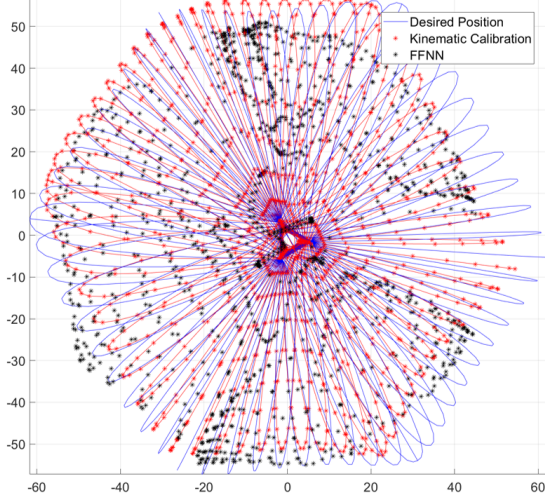


Fig. 3. Comparison of desired tip position (blue), FFNN algorithm (black), and proposed approach (red).

III. POSITION CONTROL IN TASK SPACE

A. Overview of the control strategy

The control input corresponding to the regulated pressure p_i is given by

$$p_i = p_0 + \hat{p}, \quad (7)$$

where p_0 is computed offline from the optimized kinematic model (1-4), and $\hat{p}$ is the feedback integral action employed to improve the position accuracy in the presence of gravity and hysteresis. The control strategy consists in: i) (offline) incrementing p_0 and computing the corresponding position w with (1-4) until the Euclidean distance between w and the prescribed position $w^* = (x^*, y^*, z^*)$ is smaller than a given tolerance; ii) increasing p_i linearly in time until $p_i = p_0$; iii) activating $\hat{p}$ which depends on the position feedback measured with the EM tracking system.

In order to define the integral action $\hat{p}$, the mapping between the actuation space $P = (p_i)$ and the Cartesian space $w = (x, y, z)$ is assumed to be a continuously differentiable and monotonic function within a defined pressure range. This assumption holds if the bending angle is limited to the range 0 to 90° and the orientation of the bending plane corresponds to either one or two pressurized chambers. The former condition is verified if the maximum control pressure is bounded, that is $p_i < \sigma_P$, where $\sigma_P = 2$ bar in this work. This condition is formalized in the following assumption.

Assumption 1: given a continuously differentiable and monotonic uncertain mapping $w = f(P)$, there exist a

function η and positive values σ_0 and σ_1 , such that $w^* - w = \eta(P^* - P)$, with $\eta > \sigma_0$, and $\|\dot{\eta}\|/\eta^2 < \sigma_1$ anywhere in the portion of the workspace corresponding to P .

Proposition 1: Consider a single actuated segment with two adjacent chambers pressurized at $\hat{p}_1$ and $\hat{p}_2$, which are defined by the update laws

$$\begin{aligned} \dot{\hat{p}}_1 &= K_I(w_1^* - w_1), \\ \dot{\hat{p}}_2 &= K_I(w_2^* - w_2), \end{aligned} \quad (8)$$

where $K_I > 0$ is a tuning parameter. Then (w_1, w_2) converge to (w_1^*, w_2^*) exponentially with rate $\gamma = K_I - \sigma_1 > 0$ for all $K_I > \sigma_1$, provided that *Assumption 1* is verified.

Proof: Define the storage function

$$\begin{aligned} W_0 &= \frac{1}{2}(w_1^* - w_1)^2 + \frac{1}{2}(w_2^* - w_2)^2 \\ &= \frac{1}{2}\eta_1^2(p_1^* - \hat{p}_1)^2 + \frac{1}{2}\eta_2^2(p_2^* - \hat{p}_2)^2, \end{aligned} \quad (9)$$

where η_1 and η_2 correspond to the chambers pressurized with p_1 and p_2 respectively. Computing the time derivative of (9) for a constant setpoint w_1^*, w_2^* corresponding to p_1^*, p_2^* yields

$$\begin{aligned} \dot{W}_0 &= \eta_1^2(p_1^* - \hat{p}_1)(-\dot{\hat{p}}_1) + \eta_2^2(p_2^* - \hat{p}_2)(-\dot{\hat{p}}_2) \\ &\quad + \eta_1\dot{\eta}_1(p_1^* - \hat{p}_1)^2 + \eta_2\dot{\eta}_2(p_2^* - \hat{p}_2)^2. \end{aligned} \quad (10)$$

Substituting (8) in (10) and recalling that $w_1^* - w_1 = \eta_1(p_1^* - p_1)$ and $w_2^* - w_2 = \eta_2(p_2^* - p_2)$ from *Assumption 1* yields

$$\begin{aligned} \dot{W}_0 &= -\eta_1^3(p_1^* - \hat{p}_1)^2 K_I - \eta_2^3(p_2^* - \hat{p}_2)^2 K_I \\ &\quad + \eta_1\dot{\eta}_1(p_1^* - \hat{p}_1)^2 + \eta_2\dot{\eta}_2(p_2^* - \hat{p}_2)^2. \end{aligned} \quad (11)$$

Substituting in (11) the inequalities $\|\dot{\eta}_1\|/\eta_1^2 < \sigma_1$, $\|\dot{\eta}_2\|/\eta_2^2 < \sigma_1$ and $\eta_1, \eta_2 > \sigma_0$ from *Assumption 1* yields

$$\begin{aligned} \dot{W}_0 &\leq -\sigma_0\eta_1^2(p_1^* - \hat{p}_1)^2(K_I - \sigma_1) \\ &\quad -\sigma_0\eta_2^2(p_2^* - \hat{p}_2)^2(K_I - \sigma_1), \end{aligned} \quad (12)$$

or equivalently

$$\dot{W}_0 \leq -\sigma_0((w_1^* - w_1)^2 + (w_2^* - w_2)^2)(K_I - \sigma_1). \quad (13)$$

Thus $\dot{W}_0 \leq -\gamma W_0 < 0$, with $\gamma = K_I - \sigma_1 > 0$ if $K_I > \sigma_1$ hence (w_1, w_2) converge to (w_1^*, w_2^*) exponentially $\square$

Remark 1: The existence of a function η postulated in *Assumption 1* is guaranteed for any continuously differentiable and monotonic function f on the basis of the Implicit Function Theorem. Nevertheless, assuming that $w = f(P)$ is a static mapping is only appropriate in quasi-static conditions. This point is captured by the inequality $\|\dot{\eta}\|/\eta^2 < \sigma_1$, where σ_1 is related to the system dynamics, and by the condition $K_I > \sigma_1$, which implies that a larger gain is required in case of a faster dynamics. Since the system is nonlinear, the bound σ_1 would realistically increase with $|w^*|$, thus requiring a more aggressive tuning that could lead to overshoot and vibrations. To mitigate this shortcoming, the integral action $\hat{p}$ is initialized using p_0 . As a result, provided that p_0 yields a sufficiently small error, the purpose of $\hat{p}$ is confined to the position regulation for small displacements.

B. Integral action for one actuated segment

If each actuated segment is aligned to the Z axis, pressurizing either a single chamber or two adjacent chambers results in a movement of the tip along the Z axis and along either one or both the X and Y axes. In principle, the workspace can be divided into three regions depending on which chambers are pressurized (see Figure 2 (left)), that is

$$\phi_i = \begin{cases} 0 \text{ to } \frac{2\pi}{3}, & \text{if } p_1 \geq 0, p_2 \geq 0, p_3 = 0, \\ \frac{2\pi}{3} \text{ to } \frac{4\pi}{3}, & \text{if } p_1 \geq 0, p_3 \geq 0, p_2 = 0, \\ \frac{4\pi}{3} \text{ to } 2\pi, & \text{if } p_2 \geq 0, p_3 \geq 0, p_1 = 0. \end{cases}$$

For simplicity and without loss of generality, we focus here on the first condition, that is $0 \leq \phi_i \leq \frac{2}{3}\pi$ corresponding to $p_3 = 0$. It follows from (2) that θ increases with both p_1 and p_2 , which results in a smaller z . Conversely, increasing p_1 alone yields a smaller x and a larger y , while increasing p_2 alone yields a larger x but does not affect y . In summary, the mapping $w = f(P)$ yields in this case $z - z^* = \eta_1(p_1^* + p_2^* - p_1 - p_2)$, $x^* - x = \eta_2(p_2^* - p_1^* - p_2 + p_1)$, and $y^* - y = \eta_3(p_1^* - p_1)$ in accordance with *Assumption 1*. Note however that, since there are only two actuated DOF (i.e. the pressures p_1 and p_2), the control goal can only refer to two coordinates.

Corollary 1: Consider a single actuated segment with two adjacent chambers pressurized at $\hat{p}_1$ and $\hat{p}_2$, and the regulation goal $(x, z) = (x^*, z^*)$. Define the update laws

$$\begin{aligned} \dot{\hat{p}}_1 &= K_I(z - z^* + x - x^*), \\ \dot{\hat{p}}_2 &= K_I(z - z^* + x^* - x). \end{aligned} \quad (14)$$

Then (x, z) converge to (x^*, z^*) for all $K_I > \sigma_1$.

Proof: Defining the storage function $W_0 = \frac{1}{2}(x^* - x)^2 + \frac{1}{2}(z^* - z)^2$, computing its time derivative, and following the same procedure of *Proposition 1*, where derivations are omitted for conciseness, yields in this case

$$\dot{W}_0 \leq -\sigma_0(K_I - \sigma_1)((z - z^*)^2 + (x^* - x)^2) < 0, \quad (15)$$

for all $K_I > \sigma_1$, thus (x, z) converge to (x^*, z^*) $\square$

C. Integral action for two actuated segments in series

Connecting in series two actuated segments, denoted with A and B, results in four actuated DOF, which in principle allows controlling the tip position of the manipulator in all three coordinates. Assuming for consistency that the chambers of the segments are aligned and that $0 \leq \phi_i \leq \frac{2}{3}\pi$ in both cases, the mapping $w = f(P)$ yields in this case $z - z^* = \eta_1(p_{1A}^* + p_{2A}^* - p_{1A} - p_{2A} + p_{1B}^* + p_{2B}^* - p_{1B} - p_{2B})$, $x^* - x = \eta_2(p_{2A}^* - p_{1A}^* - p_{2A} + p_{1A} + p_{2B}^* - p_{1B}^* - p_{2B} + p_{1B})$, and $y^* - y = \eta_3(p_{1A}^* - p_{1A} + p_{1B}^* - p_{1B})$ in accordance with *Assumption 1*. Clearly, the corresponding pressures in A and B result in a tip movement along the same direction. Thus, the integral action should be defined in such a way to avoid redundancy and to make full use of the actuated DOF.

Corollary 2: Consider two actuated segments in series with the corresponding chambers pressurized at $\hat{p}_{1A}, \hat{p}_{1B}, \hat{p}_{2A}$ and

$\hat{p}_{2B}$, and the regulation goal $(x, y, z) = (x^*, y^*, z^*)$. Define the update laws

$$\begin{aligned} \dot{\hat{p}}_{1A} &= K_I(z - z^* + x - x^*), \\ \dot{\hat{p}}_{2A} &= K_I(z - z^* + x^* - x), \\ \dot{\hat{p}}_{1B} &= K_I(z - z^* + y^* - y), \\ \dot{\hat{p}}_{2B} &= K_I(z - z^* + x^* - x). \end{aligned} \quad (16)$$

Then (x, y, z) converge to (x^*, y^*, z^*) for all $K_I > \sigma_1$.

Proof: Defining the storage function $W_0 = \frac{1}{2}(x^* - x)^2 + \frac{1}{2}(y^* - y)^2 + \frac{1}{2}(z^* - z)^2$, computing its time derivative, and substituting (16) yields finally

$$\begin{aligned} \dot{W}_0 &\leq -\sigma_0(K_I - \sigma_1)(z - z^*)^2 \\ &\quad -\sigma_0(K_I - \sigma_1)(y^* - y)^2 - \sigma_0(K_I - \sigma_1)(x^* - x)^2. \end{aligned} \quad (17)$$

Thus $\dot{W}_0 < -\gamma W_0 < 0$, where $\gamma = K_I - \sigma_1 > 0$ for all $K_I > \sigma_1$, hence (x, y, z) converge to (x^*, y^*, z^*) exponentially with rate γ $\square$

Remark 2: Inspecting (14) and (16) suggests an algebraic interpretation of the update laws in relation to the regulation goal. Considering first (14) at the equilibrium (i.e. $\dot{\hat{p}}_1 = \dot{\hat{p}}_2 = 0$) yields the system of equations

$$\begin{aligned} z - z^* + x - x^* &= 0, \\ z - z^* + x^* - x &= 0, \end{aligned}$$

which admits the unique solution $(x, z) = (x^*, z^*)$. Similarly, (16) at the equilibrium yields the system of equations

$$\begin{aligned} z - z^* + x - x^* &= 0, \\ z - z^* + x^* - x &= 0, \\ z - z^* + y^* - y &= 0, \\ z - z^* + x^* - x &= 0, \end{aligned}$$

where the second and the fourth equations are identical, while solving the first three yields the unique solution $(x, y, z) = (x^*, y^*, z^*)$. In summary, the regulation goal is achieved by exploiting the asymmetry arising from different pressurized chambers, or by introducing an asymmetry in the update laws compatibly with the effect of the pressures. The same principle can be employed when pressurizing different pairs of chambers in each actuated segment, thus resulting in different update laws, which allows controlling the position in another portion of the workspace. The case of three actuated segments in series, which will be investigated in the future, is similar in principle and provides further actuated DOF that could be used to regulate also the tip orientation.

IV. EXPERIMENTAL RESULTS

The control strategy (7) has been implemented in Matlab for the soft continuum manipulator depicted in Figure 1. The input pressure to the proportional valves has been set to 6 bar, while the regulated pressure has been limited below 2 bar to avoid damaging the prototype. A standard calibration procedure has been implemented to refer the EM sensor frame to the manipulator frame, which has its origin at the tip of the manipulator and the Z axis aligned with the actuated segments at rest and pointing toward the base.

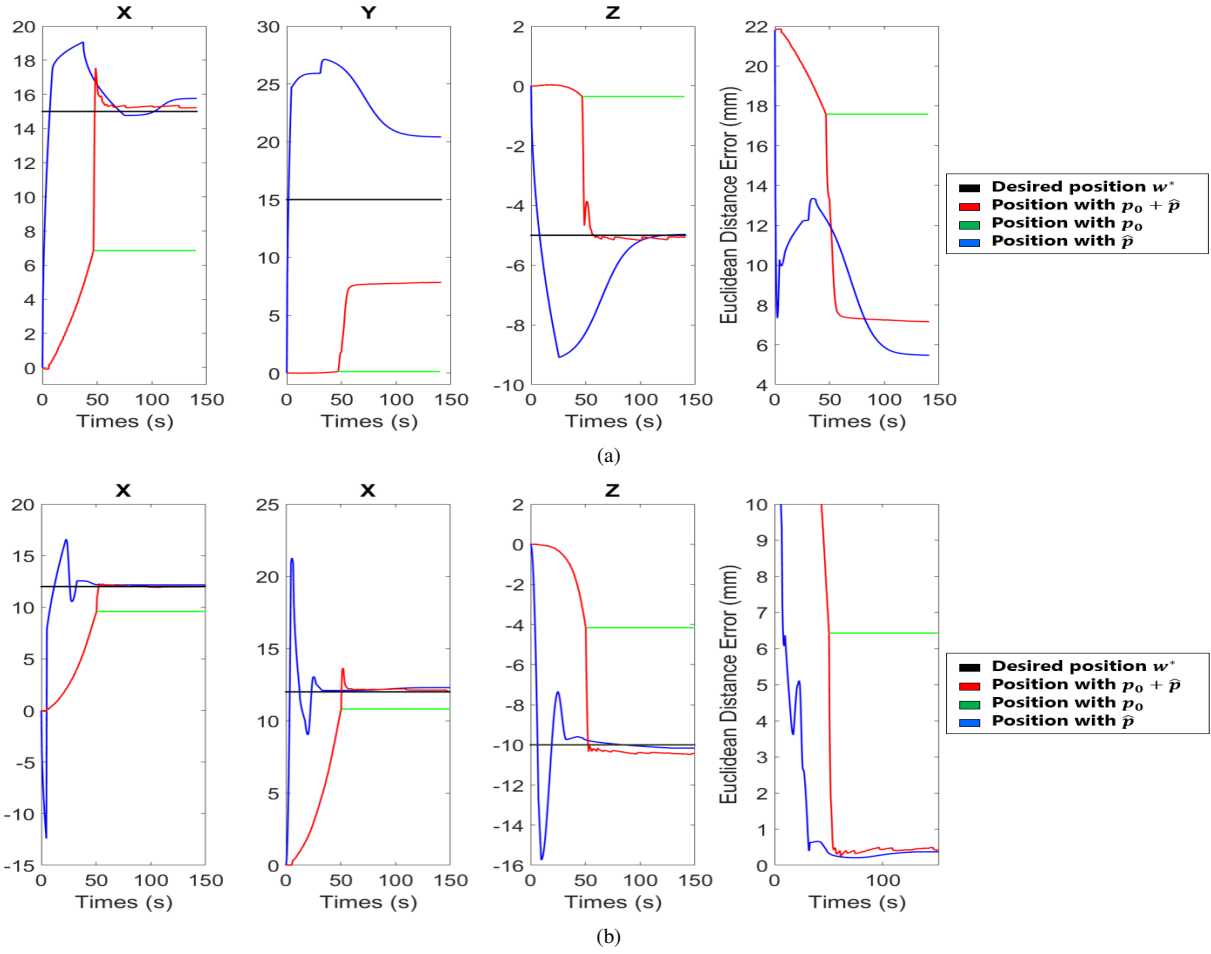


Fig. 4. Experimental results for: (a) one actuated segment; (b) two actuated segments in series.

To avoid oscillations, the pressure has been progressively increased from 0 to p_0 over 50 seconds, after which the integral action $\hat{p}$ has been activated. The parameter K_I has been tuned empirically to $K_I = 0.1$ for the middle segment and $K_I = 0.05$ for the distal segment in all experiments. These values represent a good compromise between fast convergence and limited overshoot.

Figure 4a shows the experimental results corresponding to one actuated segment, namely the middle one, while the remaining segments are not actuated. The proposed control strategy allows achieving the regulation goal $(x, z) = (15, -5)$, while the coordinate y does not reach a prescribed value. This is expected since the update law (14) does not depend on y . Instead, the control action $\hat{p}$ effectively cancels the residual position error in x and z .

Figure 4b shows the experimental results for two actuated segments in series, namely the middle one and the distal one, while the proximal segment is not actuated. In this case, the regulation goal $(x, y, z) = (12, 12, -10)$ is correctly achieved with the update law (16). In comparison, a simple data-driven kinematic controller yields a larger residual error (i.e., see green line in the figures), while employing the integral action without initializing it yields larger overshoot (i.e., see blue line in the figures). The small residual error

observed in z is due to the simultaneous pressurization of two actuated segments which might not be perfectly aligned.

Figure 5 shows the experimental results corresponding to a teleoperation setup consisting of a master unit developed in our previous work [16] and the soft manipulator serving as slave unit. The operator moves the controls of the master unit, and the desired tip position w^* is reconstructed from the joint sensors and the master's kinematic model as

$$w^* = w_0 + \mu_t \Delta w_m, \quad (18)$$

where Δw_m is the change in position of the master, while $\mu_t = 0.01$ introduces motion scaling on the soft manipulator. Motion scaling is frequently used in surgical robotics, and it is employed here to map the larger workspace of the master unit with the smaller workspace of the slave manipulator. In this experiment, the operator follows a 5-segment path, and the control strategy (7) effectively achieves path following on the manipulator. The small oscillations observed on the manipulator's position are due to the discrete nature of (18), and to quantization effects arising from the sensors on the master unit. A video of this experiment has been provided as supplementary file.

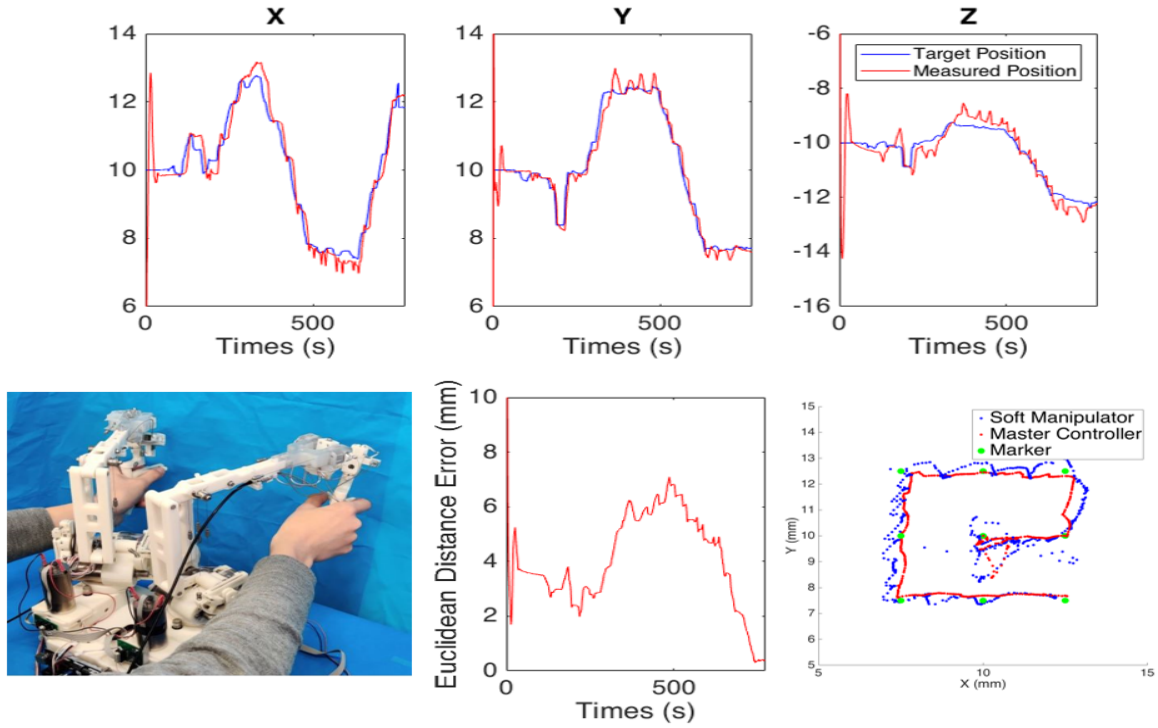


Fig. 5. Master unit [16] and experimental results for teleoperation setup.

V. CONCLUSIONS

In this work we have presented a model-free control strategy for the position regulation of a soft continuum manipulator with pneumatic actuation. The proposed approach employs a feedback integral action to compensate the effect of gravity and hysteresis due to manufacturing tolerances. The experimental results indicate that the control strategy is effective for position regulation in quasi-static conditions. Initializing the integral action with the optimized kinematic model, which only requires a relatively small training dataset, resulted in smaller overshoot. Compared to more sophisticated model-based control algorithms, the proposed approach is simpler to implement and to tune, since it employs a single tuning parameter.

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