Compliant Motion Control of Robotic Catheter based on Long-Short Term Memory Network

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INTRODUCTION

Thanks to the advances in surgical technique, Minimally Invasive Surgery (MIS) is becoming increasingly popular. Despite the advantages brought by MIS such as reducing post-operative discomfort and quicker recovery [1], these procedures are often more difficult for clinicians to conduct. Due to this reason, robotic approaches have been introduced to ease the steep learning curve of MIS. Continuum robots are commonly used in MIS because of their flexibility and small size. However, understanding the model and actively navigating these continuum tremendousrobots during procedure remains a challenge. A reason for this complexity is that the robot configuration is dictated by both the steering actions and the complex interaction with the environment, e.g. a lumen. Robot can be controlled so as to prevent exerting too much force on the soft tissue which might result in a number of problematic consequences including perforation [2].

Several methods have been proposed in the literature to avoid tissue damage. One interesting approach tries to reduce the compliance of the continuum robot beyond its natural flexibility. *Kesner et al.* presented a method in which a force sensor was integrated in the tip of a robotic catheter to lower the tip interaction force below the potentially damaging forces [3]. This method requires a dedicated force sensor. Other approaches make use of the complicated mechanical models of the continuum robots [4], [5]. Accurate model requires tremendous modeling efforts. Also, the non-ideal behavior of the used catheter actuation adds to the complexity. Backlash and hysteresis, for example, have been reported in cable or pneumatically driven robots [6], which greatly complicates the input-output behavior, making precise control a challenge.

To address the shortcomings of the previous methods, this abstract presents a compliant motion control algorithm which requires only tip position sensing. A Long Short-Term Memory (LSTM)-based compliant motion control is deployed to minimize the interaction force between the catheter tip and the surrounding environment. This method is also empirically validated.

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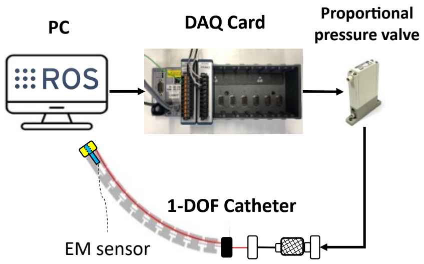

Fig. 1: Control and actuation system for a 1-DOF catheter: the catheter segment is controlled by pressure provided a the proportional valve (Festo Corporation, Germany), which receives command signals from a PC through an NI® CompactRIO system.

MATERIALS AND METHODS

To demonstrate the proposed method, a single degree of freedom (1-DOF) experimental setup has been built as shown in Fig.1. The setup includes a steerable catheter segment which is actuated by an embedded Pneumatic Artificial Muscles (PAM). The catheter backbone is made of Nitinol and is cut with laser to reduce the stiffness and ensure that the segment is steerable. The flexible section of the catheter is 40 mm long and 6 mm in diameter. A 6-DOF Electromagnetic Tracking (EM) sensor (Northern Digital Inc., Ontario, Canada) is mounted at the tip of the catheter to measure the tip pose. A custom-made PAM is connected off-center to the tip of the catheter by a steel wire.

For the sake of simplicity, the presented technique assumes that contact occurs at the robotic catheter's tip. Since this is the most acute and hence dangerous portion of the catheter, methods that manage to limit force levels at this point are the most important. The goal of the compliant motion control method is to reduce the external applied force on the robot tip.

It is assumed that B and T are attached to the base and tip of the catheter as shown in Fig. 2b), respectively. $\hat{T}$ is the tip reference frame in unload situation. Frame T moves depending on the external tip wrench W. The transformation matrix from B to T is defined as g_{BT} and

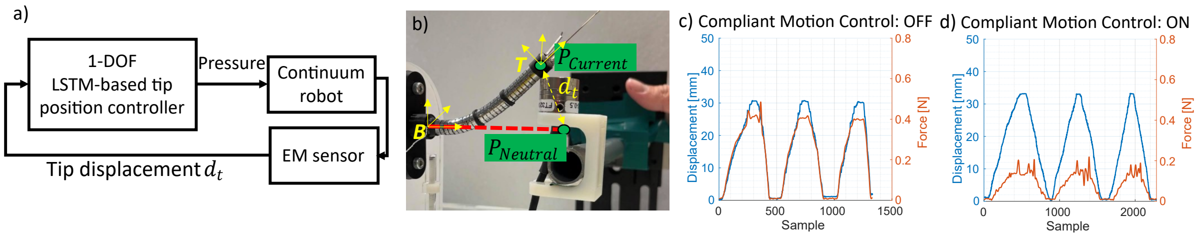

Fig. 2: The proposed compliant motion control algorithm is described in a). The validation experiment and the experimental result in case the compliant motion control is off and on are shown in b), c) and d), respectively. The tip displacement is calculated as $d_t = ||P_{Neutral} - P_{Current}||$ where $P_{Current}$ and $P_{Neutral}$ are the current tip position and the tip position when the catheter is in straight configuration, respectively, measured by the EM sensor.

can be described as follow:

$$g_{BT}(q, W) = g_{B\hat{T}}(q) g_{\hat{T}T}(q, W) \tag{1}$$

where q is the input variable (e.g. muscle pressure), $g_{B\hat{T}}$ and $g_{\hat{T}T}$ are the transformation matrix from B to $\hat{T}$ and $\hat{T}$ to T, respectively. $g_{B\hat{T}}$ and $g_{\hat{T}T}$ can be calculated with the forward kinematic and the deflection model of the catheter, respectively. Assuming in the application, the catheter undergoes an external wrench W_d, while have an actuator input at this time is q_d. The tip is maintained stationary at a given measured tip configuration g^m_{BT}. Then the relation between g^m_{BT}, desired tip wrench W_d and actuator input variable q_d can be expressed as:

$$g^m_{BT}(q_d, W_d) = g_{B\hat{T}}(q_d) g_{\hat{T}T}(q_d, W_d) \tag{2}$$

The aim of the here presented compliant motion control algorithm is to find a q_d that minimizes the force applied to the robot tip ($W_d = 0^{6\times1}$) such that $g_{T\hat{T}} = I^{4\times4}$. Thus, to minimize the external tip force applied on the catheter, a multidimensional inverse kinematic function for the catheter in unloaded condition $\Phi(\cdot)$ can be used to calculate the input kinematic variable that can bring the tip to the current pose measured by the EM sensor ($q_d = \Phi(g^m_{BT})$).

In this work, instead of spending effort on modelling the robotic catheter, we proposed to use the LSTM-based tip position controller. This LSTM network is trained by data collected while the catheter is moving in free-space. The adopted data training generation process is described in [6]. The trained LSTM network allows predicting a pressure value that can bring the tip to the desired position in free-space. The network input is defined as tip displacement d_t calculated by the Euclidean distance between the current tip position and the tip position when the catheter is in the straight configuration. The construction of the network is fine-tuned from [6]. The proposed LSTM-based compliant motion control algorithm can be seen in Fig. 2a).

The method has been evaluated with an experiment. In this verification experiment, a F/T sensor (Nano17, ATI, USA) mounted on a linear translation stage was utilized to push the catheter at the tip as illustrated in Fig. 2b). This contact simulates the external contact with the environment. The experiments are first carried out without the use of a compliant motion controller, and subsequently the controller is activated.

The measured force and the tip displacement in case the compliant motion controller is turned off and on are shown in Fig. 2c) and d), respectively. The tip stiffness defined as the displacement of the catheter tip divided by the applied force is computed in the two experiments to show the efficiency of the compliant motion controller. The figure shows that the tip stiffness is reduced by 66% from 0.015 N/mm to 0.005 N/mm thanks to the compliant motion controller.

CONCLUSIONS AND DISCUSSION

In this abstract, we have shown that the proposed LSTM-based compliant motion controller can help reducing the applied force on the catheter tip. This shows that complicated mechanic models of the robotic catheter are not required for these tasks. Another advantage of the proposed method is that the integrated EM sensor can at the same time provide information for navigation and the compliant motion controller.

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