Enhanced Performances for Cable-Driven Flexible Robotic Systems with Asymmetric Backlash Profile

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Abstract—Cable-conduit mechanism (CCM) or tendon-sheath mechanism (TSM) is widely used in many flexible robotic systems such as prosthetic hand robots, rehabilitation robots, and surgical robots because it offers efficient transmission of forces/torques from the external actuator to the end effector with light weight and high flexibility. However, the accurate position control is challenging in such mechanism due to friction and backlash-like hysteresis between the cable and the conduit. In this paper, a new control approach is proposed to enhance the trajectory tracking performances of the CCM using in flexible robotic systems. Unlike current approaches for the CCM in the literature, the proposed scheme considers the position transmission of the CCM as an approximation of backlash-like hysteresis nonlinearities without requiring the exact values of model parameters and their bounds. Online estimation of unknown system parameters are also established. In addition, the designed controller can adapt to any changes of the cable-conduit configuration and it is stable. The results of the proposed control techniques have been experimentally validated on a real flexible robotic system using a flexible endoscope. Experimental validations show substantial improvements on the performances of position tracking for the use of CCM regardless of the arbitrary changes of the cable-conduit configurations.

Keywords—Flexible robotic systems; compensation control; cable-conduit mechanism; backlash.

I. INTRODUCTION

Flexible mechanisms like parallel linkage or cable-driven actuation have been widely used in many applications like surgical robots, robot hands, rehabilitation robots to execute complex tasks [1], [2], [3], [4]. These mechanisms are very useful for driving and grasping determined objects where actuators are placed away from the operation sites. In addition, they are able to reduce the bulkiness of actuators that are too heavy in current robotic components. Although parallel linkage mechanism has been widely used to develop underactuated planar mechanism, they are limited by rigid links that are too cumbersomes to work in complex environments and narrow paths. In contrast, cable-conduit mechanism (CCM) or tendon-sheath mechanism (TSM) is a potential transmission mode which allows for the separation between the actuator site and the joint site. Compared to parallel linkage mechanisms, CCM offers light weight and inertia, simplified modelling of dynamics, cost efficiency, ease of transportation and reconfiguration, and better safety [1], [5]. Hence many applications have also utilized the CCM as the main mode of transmission such as wearable robot [6], robot hands [7], surgical robot [8], and exoskeleton robots [2]. Although the CCM offers many advantages, the interactions between the cable and the conduit generally introduce large friction, deadzone, hysteresis, and backlash that degrade the accurate control of position and system performances [9], [10], [11], [12], [13]. Due to these limitations, the control of cable-conduit systems could be challenging and thereby affect the use of CCM in the developments of flexible robotic systems.

The motion in the CCM is transmitted from the external actuator to the end effector joint through a cable routed along a conduit. It was known that the friction, backlash, and hysteresis vary with the change of cable-conduit configuration. To enhance the efficient use of CCM, mathematical models for the cable-conduit transmission are desired for the analysis of nonlinear behaviors and compensation control needs [12], [14]. The characteristics of cable-conduit transmission have been previously discussed by various researchers and groups. There are two main discussions for the transmission problems: (i) Tension transmission analyses, and (ii) Motion analyses. The former focuses on the tension transmission of the cable across the conduit, in which the friction between the cable and the conduit is modelled by static friction like Coulomb or dynamic friction like LuGre models. The latter concentrates on the motion analyses and control, in which an approximation of backlash-like hysteresis or smooth inverse of backlash are used to compensate the position tracking error. For most cases, many researchers focus on the motion and tension analyses for the CCM using lumped mass model or discontinuous backlash profile under the assumption of known cable-conduit configuration and equal distribution of cable elements along the conduit [15], [16], [17], [18], [19]. Three major limitations are found in these approaches. Firstly, the use of lumped mass model parameters becomes more complex if more segments are used. Secondly, the assumption of uniform distribution for pretension is impractical. Lastly, the mathematical models require the measurements of cable-conduit configurations. In practice, the pretension for each of segments is unequal and it is hard to obtain the configuration information. Although Do and his colleagues presented novel friction models to address the tension transmission for the CCM, no motion control schemes were introduced to compensate the tracking error [20], [21]. Based on the system dynamics, the motion control of cable-conduit transmission can be approximately modelled as backlash-like hysteresis profile [22]. Kaneko et al. [12] described the tension and motion transmission of the CCM as a backlash-like hysteresis profile with input dependent stability. Agrawal et al. [23] used a smooth inverse of backlash...
model to compensate the tracking error of the CCM. For the applications of robotic catheter and flexible endoscope, Bardou et al. [24], Kesner et al. [25], and Reilink et al. [26] used an inverse backlash model to compensate the phase lags between the output position and the desired trajectory. However, a switching function for the velocity was required and the slope of the backlash profile was ignored. Although Do et al. [22] used a direct inverse model-based feedforward compensation to overcome the above limitations, the designed controller was not able to deal with the change of the cable-conduit configuration. In addition, the values of backlash-like hysteresis parameters must be known in advance.

Various linear and nonlinear control schemes have been reported in the literature. Recent works on the mechanical systems such as magnetic devices or piezoelectric actuators have focused on the perfect cancellation of backlash-like hysteresis using inverse models and nonlinear adaptive algorithms [27], [28], [29], [30], [31], [32], [33]. However, little experimental validations have been carried out. Unlike those aforementioned approaches for the CCM, new nonlinear and adaptive control scheme will be discussed in this paper. The motion transmission of the CCM is characterized as an approximation of backlash-like hysteresis profile (see [22]). The proposed controller can adapt to any changes of the cable-conduit configuration. In addition, exact values of backlash-like hysteresis parameters are not required. To validate the effectiveness of the proposed control schemes, a dedicated experimental platform of a single-degree of freedom (DOF) flexible robotic system will be introduced. Using the designed system, the proposed controller is experimentally validated using real-time tasks such as gripping a determined elastic object. There are significant enhancements on the position tracking error between the measured output position and the desired trajectory. The rest of this paper are presented as follow: In section II, a review of the asymmetric backlash-like hysteresis model on the CCM will be introduced. Section III addresses the new control approach for the CCM. The design of the flexible robotic system and experimental validations will be given in section IV. Finally, discussion and conclusion are presented in section V.

II. ASYMMETRIC BACKLASH-LIKE HYSTERESIS PROFILE IN FLEXIBLE CABLE-CONDUIT MECHANISM

The tension transmission characteristics of the CCM were investigated by Do et al. [13], [34]. However, in this paper, we are interested in the accurate position control for the CCM. In our previous work [22], [35], the backlash profile for the CCM is asymmetric and it was approximated using an asymmetric form from the modified asymmetric Bouc-Wen model. The model was named as a backlash-like hysteresis profile and it can be rewritten by:

\[
\begin{align*}
\dot{\zeta} &= \alpha \dot{x} - \vartheta |\dot{x}| \zeta + \delta |\dot{x}| \\
\Phi &= \alpha_x (\dot{x}) x + \zeta
\end{align*}
\]

where \(x\) and \(\dot{x}\) are the input position and velocity, respectively; \(\alpha_x (\dot{x}) = (\alpha_1 e^{2\dot{x}} + \alpha_2) / (e^{2\dot{x}} + 1)\) is a continuous function that allows for a smooth transition from the loading to unloading phases and vice versa (see [22]); \(\alpha_1 > 0, \alpha_2 > 0, A, \vartheta, \delta\) are parameters that control the shape of hysteresis loops in the loading and unloading phases; \(\zeta\) is the internal state variable; and \(\Phi\) is the output position; the dot at the top of variables represents for the first derivative with respect to time.

The model given by (1) and (2) represents for the asymmetric backlash-like hysteresis with asymmetric slope \(\alpha_1, \alpha_2\) in the loading and unloading phases, respectively. In addition, it is able to provide smooth transition from the loading to unloading phases and vice versa (see [22] for more details).

To use the asymmetric backlash-like hysteresis model given by (1) and (2), some assumptions have been made: (i) the values of backlash hysteresis parameters such as \(\alpha_1, \alpha_2, A, \vartheta, \delta\) must be known in advance; (ii) the cable-conduit configuration must be unchanged; and (iii) the cable is always maintained at a suitable pretension in order to avoid the cable slacking. Although the direct inverse model-based feedforward controller efficiently reduced the position tracking error for the CCM, the three above assumptions limit the flexibility of the control approaches. In practice, these parameters are usually unknown because there are hardly instances for measuring and calculating the exact values of the parameters during the operation process. In addition, the model parameters always vary with respect to the change of cable-conduit configuration.

III. COMPENSATION CONTROL DESIGN

For the proposed control approach in this paper, the exact values of model parameters and their bounds are not required in advance. The cable-conduit configuration can be freely changed during the operation. Online learning of unknown parameters will be introduced to relax these above limitations.

If we consider the change of cable-conduit configuration as an unexpected disturbance \(d\), the asymmetric nonlinearity given by (2) can be rewritten by:

\[
y = \alpha x (\dot{u}) u + \zeta + d = \alpha_1 x (\dot{u}) u + \Delta_n \quad (3)
\]

where \(\Delta_n = \zeta + d\) represents the variation of the internal state variable \(\zeta\) when the configuration changes; \(\alpha_1 x = (\alpha_1 e^{2\dot{u}} + \alpha_2) / (e^{2\dot{u}} + 1)\) denotes the asymmetric slope of the backlash-like hysteresis profile; \(u = x\) is the control input; \(y = \Phi\) is the output position.

Some assumptions are made for the controller design: (i) The cable is kept at a suitable pretension to avoid the slack; (ii) Exact values of model parameters and their bounds are not required.

Let the positive value \(\Delta_n\) be the bound of \(\Delta_n (|\Delta_n| \leq \Delta_n^*)\) and \(\alpha\) is a positive number. Define a new coordinate transformation \(\omega\) and \(n\) for the system (3) and a position tracking error \(e_r = (y - y_r)\) by:

\[
n = \int_0^t (y(\tau) - y_r(\tau)) \, d\tau \quad (4)
\]

\[
\omega = e_r(t) + \alpha \int_0^t e_r(\tau) \, d\tau \quad (5)
\]

The first order derivative of the new variable \(\omega\) given by (5) can be expressed by:

\[
\dot{\omega} = \alpha e_r + \dot{e}_r = \alpha (\alpha x (\dot{u}) u + \Delta_n - y_r) + \dot{e}_r = \alpha ((\alpha_1 e^{2\dot{u}} + \alpha_2) / (e^{2\dot{u}} + 1) u + \Delta_n - y_r) + \dot{e}_r \quad (6)
\]
In order to simplify the controller design $u$ in (6), a new form of $u$ will be established with respect to new virtual controllers $\hat{u}_i$, ($i = 1, 2$). Denote the estimate of $\Delta^*_n$ as $\hat{\Delta}^*_n$ and define the control input by $u_i = \hat{\chi}_i \hat{u}_i$ where $\hat{\chi}_1 = 1/\alpha_1$ and $\hat{\chi}_2 = 1/\alpha_2$ be the inverse of parameters $\alpha_1$ and $\alpha_2$, respectively. $\hat{\chi}_i$ ($i = 1, 2$) are estimates of $\chi_i$. One can reformulate the controller $u$ as follow:

$$u = \sum_{i=1}^{2} u_i$$

(7)

where $u_i$ ($i = 1, 2$) are defined as $u_1 = u e^{2a_1}/(e^{2a_1} + 1)$ and $u_2 = u/(e^{2a_1} + 1)$. From (7), one can obtain:

$$(\alpha_1 e^{2a_1} + \alpha_2)u/(e^{2a_1} + 1) = \alpha_1 u_1 + \alpha_2 u_2$$

(8)

Let $\hat{\chi}_1 = \chi_1 - \hat{\chi}_1$, $\hat{\chi}_2 = \chi_2 - \hat{\chi}_2$ be error estimates of $\chi_1, \chi_2$, respectively. Then the term $\alpha_i u_i$ ($i = 1, 2$) can be expressed by:

$$\alpha_i u_i = \alpha_i \hat{\chi}_i \hat{u}_i = \hat{u}_i - \alpha_i \hat{\chi}_i \hat{u}_i$$

(9)

Define the error tracking between $\Delta^*_n$ and its estimate $\hat{\Delta}^*_n$ by $\Delta^*_n = \Delta^*_n - \hat{\Delta}^*_n$. From system (6) and its control input $u$ as well as its coordinate transformation (4) to (9), parameter adaptive laws and control input are designed as follow:

$$u = \sum_{i=1}^{2} \hat{\chi}_i \hat{u}_i$$

(10)

$$\hat{\chi}_1 = -k_1 \omega - \tanh(\omega/\epsilon) \hat{\Delta}^*_n + y_r - (1/\alpha) \dot{e}_r$$

(11)

$$\hat{\chi}_2 = -k_2 \omega$$

(12)

$$\hat{\Delta}^*_n = \delta_3 \omega \tanh(\omega/\epsilon) - \sigma_3 \hat{\Delta}^*_n$$

(15)

where $\sigma_i$ ($i = 1, 2, 3$) are small positive numbers that help to avoid the estimates $\hat{\chi}_i$ ($i = 1, 2$) and $\Delta^*_n$ drift to large values; $\epsilon$ is a small positive value that helps to accurately control the smoothness of the tanh function. $\delta_i$ ($i = 1, 2, 3$) are positive parameters for the controller and update laws.

With the control laws from (10) to (15), $\omega$ in (6) can be rewritten by:

$$\dot{\omega} = \alpha ( \sum_{i=1}^{2} (k_i \omega + \alpha_i \hat{\chi}_i \hat{u}_i) - \tanh(\omega/\epsilon) \Delta^*_n + \Delta_n)$$

(16)

**Theorem 1:** Consider the nonlinear system (6) and the designed adaptive laws given by (10) to (15), the following statements hold:

1. The tracking error $e_r$ and updated parameters $\hat{\chi}_1, \hat{\chi}_2, \hat{\Delta}^*_n$ in the closed-loop system are uniformly ultimately bounded (UUB).

2. In the presence of unknown model parameters and their bounds, the position tracking error $e_r = (y - y_r)$ converges to a desired compact region $\Omega_2 = \{ |e_r| |e_r| \leq 2 \sqrt{29}/\rho \}$ and the controller $u$ is smooth.

The derivative of (17) along (16) with controller and updated laws given by (10) to (15) can be expressed by:

$$\dot{V} = \omega \dot{\omega} - (1/\mu) \hat{\Delta}^*_n / \Delta^*_n - \sum_{i=1}^{2} (\alpha_i / \rho_i) \hat{\chi}_i \hat{u}_i = \omega (\alpha (1/\mu) e^{2a_1} / (e^{2a_1} + 1) u + \Delta_n - y_r + \dot{e}_r) - (1/\mu) \hat{\Delta}^*_n / \Delta_n \sigma_3 \hat{\Delta}^*_n + \delta_3 \omega \tanh(\omega/\epsilon) - \sum_{i=1}^{2} (\alpha_i / \rho_i) \hat{\chi}_i (\delta_1 \omega \hat{\chi}_i - \sigma_1 \hat{\chi}_i)$$

(17)

$$= -\alpha \sum_{i=1}^{2} (k_i \omega^2 - (\alpha_i / \rho_i) \hat{\chi}_i \hat{u}_i) + (\sigma_3 / \mu) \hat{\Delta}^*_n \hat{\Delta}^*_n + \Delta_n \sigma_3 \omega \tanh(\omega/\epsilon) + \sigma_3 \hat{\Delta}^*_n |\dot{\omega}| + (\sigma_3 / \mu) \hat{\Delta}^*_n \hat{\Delta}^*_n - \alpha \sum_{i=1}^{2} (k_i \omega^2 - (\alpha_i / \rho_i) \hat{\chi}_i \hat{u}_i)$$

$$\leq \alpha \sum_{i=1}^{2} (k_i \omega^2 + \sigma_3 / \mu) \hat{\Delta}^*_n \hat{\Delta}^*_n + \sigma_3 / \mu \hat{\Delta}^*_n \hat{\Delta}^*_n + \delta_3 \omega \tanh(\omega/\epsilon)$$

(18)

As introduced in [36], the $\tanh(\omega/\epsilon)$ function obeys the following property: $|\dot{\omega}| - \omega \tanh(\omega/\epsilon) \leq 0.2785 \epsilon$. Apply the Young’s inequality for two numbers $a$ and $b$, i.e. $ab \leq 0.5(a^2 + b^2)$, the second term and the third term in (18) can be reformulated as:

$$\sum_{i=1}^{2} (\alpha_i / \rho_i) \hat{\chi}_i \hat{u}_i$$

$$\leq (\alpha_i / \rho_i) \hat{\chi}_i^2 + (\alpha_i / \rho_i) \hat{\chi}_i^2$$

(19)

$$\sum_{i=1}^{2} (\alpha_i / \rho_i) \hat{\chi}_i^2$$

$$\leq (\alpha_i / \rho_i) \hat{\chi}_i^2 + (\alpha_i / \rho_i) \hat{\chi}_i^2$$

(20)

Put (19) and (20) to (18), $\dot{V}$ becomes:

$$\dot{V} \leq -2 \alpha \sum_{i=1}^{2} (0.5k_i \omega^2 - (\mu / \rho_i) \hat{\chi}_i^2 + \sigma_3 (\Delta^*_n)^2 / \mu) + (0.2785 \alpha \Delta^*_n \epsilon + \sum_{i=1}^{2} (\alpha_i / \rho_i) \hat{\chi}_i^2 + \sigma_3 (\Delta^*_n)^2 / \mu)$$

$$\leq -\rho V + \Psi$$

(21)
Solving (21) and from (17), one can obtain:
\[ 0 \leq 0.5\omega^2 \leq V \leq (V(0) - \Psi/\varrho)e^{-\varrho t} + \Psi/\varrho \]  
(22)

Eq. (22) can be obtained from (17), \[ V = 0.5\omega^2 + (0.5/\mu)(\Delta_n^* + \sum_{i=1}^{\delta_1} (\alpha_i/2\rho_i)(\chi_i)^2) \geq 0.5\omega^2 \geq 0. \] From (22), the variable \( \omega \) can be expressed by:
\[ |\omega| \leq \sqrt{2(V(0) - \Psi/\varrho)e^{-\varrho t} + 2\Psi/\varrho} \]  
(23)

It can be seen that there exists a time \( T_1 \) such that \( \forall t > T_1, |\omega| \leq \sqrt{2\Psi/\varrho} \) since \( 2(V(0) - \Psi/\varrho)e^{-\varrho t} \to 0 \) as \( t > T_1 \). From the inequality \[ |\omega| = \hat{n} + \alpha \omega \leq \sqrt{2\Psi/\varrho}, \]
two cases for \( n \) exist: Case (i) \( \omega = \hat{n} + n\alpha \leq \sqrt{2\Psi/\varrho} \) or \( n \leq (n_0 - (1/\alpha)\sqrt{2\Psi/\varrho})e^{-\varrho t} + (1/\alpha)\sqrt{2\Psi/\varrho}. \) There exists \( t > T_2 > T_1 > 0 \) such that \( n \leq (1/\alpha)\sqrt{2\Psi/\varrho} \) since \( (n_0 - (1/\alpha)\sqrt{2\Psi/\varrho})e^{-\varrho t} \to 0 \) for any \( t > T_2 > T_1 > 0 \). Case (ii) \( \omega = \hat{n} + n\alpha \geq -\sqrt{2\Psi/\varrho} \) or \( n \geq (n_0 + (1/\alpha)\sqrt{2\Psi/\varrho})e^{-\varrho t} - (1/\alpha)\sqrt{2\Psi/\varrho}. \) There exists \( t > T_2 > T_1 > 0 \) such that \( n \geq -(1/\alpha)\sqrt{2\Psi/\varrho} \) since \( (n_0 + (1/\alpha)\sqrt{2\Psi/\varrho})e^{-\varrho t} \to 0 \) for any \( t > T_2 > T_1 > 0 \). For both cases, we have:
\[ |n| \leq (1/\alpha)\sqrt{2\Psi/\varrho} \]  
(24)

With \[ |\omega| = \hat{n} + \alpha \omega \leq \sqrt{2\Psi/\varrho} \] and (24), one can obtain:
\[ |\dot{n}| - \alpha |\omega| \leq |\omega| = \hat{n} + \alpha \omega \leq \sqrt{2\Psi/\varrho} \]
or \[ |\hat{n}| \leq \alpha(1/\alpha)\sqrt{2\Psi/\varrho} + \sqrt{2\Psi/\varrho} = 2\sqrt{2\Psi/\varrho} \]  
(25)

Then, one can prove that the UUB tracking performance for \( |e_\rho| = |\dot{n}| \) is guaranteed. From (22), one has \( 0 < V < \Psi/\varrho, \forall t > T_1 \). From (17), it is easy to observe that all signals \( \hat{\Delta}_n, \hat{\chi}_i \) and \( \hat{\Delta}_n, \hat{\chi}_i \) are proved to be UUB. The proof is completed here.}

IV. REAL-TIME EXPERIMENTAL VALIDATIONS

A. Experimental Setup

The experimental setup is shown in Fig. 2. It consists of a single DOF of telerobotic system where the user controls a motion device and the slave manipulator with a single DOF grasper is actuated by a DC-motor (Faulhaber 2642W024CR) via a CCM. The motor is controlled by a simple PI controller \( (P=2.8, I=2) \). The CCM which is provided by Asahi Intecc Co. consists of a Teflon coated wire cable with a specification of WR7x7DO.27mm and a round wire coil conduit with an inner diameter of 0.36mm and an outer diameter of 0.8mm. The CCM has a length of 1.5m and is routed along a flexible endoscope GIF-2T160 from Olympus, Japan. Necessary signals from the user’s hand \( (\text{desired trajectory } y) \) are recorded by the encoder SCA16 (E1) with resolution of 6000 pulses/revolution from SCANCON while the position of the grasper \( y \) at the end effector is measured by the encoder E2. At the motor side, the cable is fixed on a pulley \( \text{P_in} \) which is connected to the DC-motor by a bolt screw while at the end effector side, the cable is connected to a spring via an output pulley \( \text{P_out} \) (the grasper) as shown in Fig. 2.

B. Validation Results

The nonlinear and adaptive control laws are given by (10) to (15) are used with the designed parameters \( k_1 = 20, k_2 = 10, \delta_1 = 10, \delta_2 = 10, \delta_3 = 10, \epsilon = 0.05, \sigma_1 = \sigma_2 = \sigma_3 = 0.01, \alpha = 5 \). The initial values for updated laws are \( \hat{\chi}_1(0) = \hat{\chi}_2(0) = \hat{\Delta}_n(0) = 0 \). These designed parameters are obtained from some simulations based trial-and-error method using MATLAB Simulink environment. The obtained parameters are subsequently used in real-time experiments.

For easy comparison, a sinusoidal input signal of amplitude 0.8 rad and frequency of 0.3 Hz is applied to the system under the change of cable-conduit configuration during the operation and the grasper is contacted with the elastic object. Fig. 3 presents the experimental result for the CCM using our previous compensation control scheme (see compensation structure from Fig. 1b) [22]. There is a large error of \( RMSE = 0.0755 \text{ rad} \sim 4.326^\circ \) compared to the case of proposed adaptive control with \( RMSE = 0.0156 \text{ rad} \sim 0.894^\circ \) (see Fig. 4).

The effectiveness of the proposed nonlinear controller will also be validated with random input signal from the control
motion device. For all cases, five trials will be carried out. For illustration purposes, one of the trials will be presented only as shown in Fig. 5. The upper panel of Fig. 5 shows the time history of the desired trajectory and measured output without using the designed control scheme. It can be seen that \( y \) always lags \( y_r \) with a high error values of root mean square error (RMSE = 0.1327 rad \( \sim 7.6^\circ \)) without using the compensation scheme (see scheme in Fig. 1a). The corresponding error between \( y \) and \( y_r \) can be seen from the lower panel of this figure. To reduce the tracking error under the change of the configuration, the proposed nonlinear control is applied to the system. It can be seen from Fig. 6 that the proposed control scheme is able to deal with any change in the endoscope configuration. The tracking performances between the desired trajectory \( y_r \) and measured output \( y \) are good. There is a significant decrease of the tracking error when the new control scheme is used. It seems that the change of endoscope configuration does not affect the tracking results significantly. As shown in the Fig. 6, the RMSE = 0.0447 rad \( \sim 2.56^\circ \). The quantitative measures of trials are illustrated in Table I.

V. Conclusion

This paper introduces a new adaptive control scheme to enhance the tracking performances for flexible robotic system using cable-conduit mechanisms. The proposed control laws are able to deal with nonlinearities in the presence of time varying configuration of the conduit. Unlike current approaches of the cable-conduit control, our control scheme has efficiently reduced the tracking error regardless of the change of the cable-conduit configuration. Experimental validations have been carried out using a real flexible robotic system to evaluate the controller performances. It has been demonstrated that the model approach works well on a real flexible system to carry out the task of gripping a real object and/or in free motion. In addition, no exact values of backlash-like hysteresis parameters are required. The proposed control scheme provides potential benefits to any flexible robotic system for enhancing tracking performances of precise motion. The approaches in this paper have used traditional encoders to get the position feedback from the distal end. In the case of no output position feedback, our previous approach [22] can help to reduce the tracking error. However, they are not able to deal with the change of conduit configuration. For the use in surgical robots, it is known that some applications can utilize advanced techniques such as 3D ultrasound probe or image-based methods to achieve the position output feedback [24], [25], [26], [37]. Hence, these non-conventional methods should be applied to fulfill the needs for the real applications. Future activities will be conducted to validate the designed controllers for higher DOFs of flexible robotic systems.

REFERENCES

TABLE I. QUANTITATIVE MEASURES OF THE ERROR RMSE USING THE DESIGNED CONTROLLER WITH VARYING CONFIGURATION OF THE ENDOSCOPE

| Trials (Tracking results-RMSE) | 0.045 rad (2.56°) | 0.0374 rad (2.144°) | 0.0316 rad (1.81°) | 0.0424 rad (2.43°) | 0.0458 rad (2.625°) |


