# Study on Decentralized Integral Nested Sliding Mode Control for Constrained Reconfigurable Manipulator with Harmonic Drive Transmission

**Bo Dong[1], Zeyu Dong[1], Bo Zhao[2], Yan li[1], Fumitoshi Matsuno[3] and Yuanchun Li[1,*]**

[1]*Department of Control Engineering, Changchun University of Technology*
*Changchun 130012, China*
[2]*The State Key Laboratory of Management and Control for Complex Systems, Institute of Automation, Chinese Academy of Sciences, Beijing 100190, China*
[3]*Department of Mechanical Engineering and Science*
*Graduate School of Engineering, Kyoto University, Japan*
*E-mail*:[1]liyc@ccut.edu.cn(*Corresponding Author) [2]zhaobo@ia.ac.cn [3]matsuno@me.kyoto-u.ac.jp

**Abstract**

This paper addresses the problems of trajectory tracking control of a constrained reconfigurable manipulator with harmonic drive transmission under a decentralized integral nested sliding mode control (INSMC) method, and a high-performance control is achieved without using force/torque sensor. The dynamic model of the constrained reconfigurable manipulator is formulated with a nonlinear harmonic drive model. Based on only local dynamic information of each module, a decentralized integral nested sliding mode control method is proposed to reduce the chattering effect of the controller and compensating the model uncertainties. Finally, simulations are performed for a constrained 2-DOF reconfigurable manipulator to study the effectiveness of the proposed method.

*Keywords*: Reconfigurable manipulator, harmonic drive, decentralized control, sliding mode control

## 1. Introduction

Reconfigurable manipulator consists of the manipulator modules that incorporate power electronics, computing systems, sensors and actuators. These modules can be serially connected with standard electromechanical interfaces and assembled to desirable configuration for satisfying the requirements of various tasks. Besides, reconfigurable manipulator needs an appropriate control system to provide accuracy and stability.

Harmonic drives have been widely used in manipulator design due to the excellent properties such as high reduction ratio, compact size, light weight, and coaxial assembly. A typical harmonic drive includes a wave generator, a circular spline, and a flexspline placed in between. Numerous studies have been carried out on analytical description of harmonic drives based systems[1-5]. However, in conventional methods, the kinematic error[6] between the measured and expected flexspline output is always neglected and this may lead to a local torque ripple, which is introduced in harmonic harmonic drive should be considered when formulating the dynamic model of reconfigurable manipulator.

Decentralized control is a particularly promising concept in implementing reconfigurable manipulator system. Some researchers have studied the decentralized control method for reconfigurable man-ipulator[7-9], and combining it with the sliding mode control method[10, 11]. However, the main drawback for these control strategies is the so-called "chattering effect", which will be aggravated due to harmonic drive based reconfigurable manipulator is with the joint flexibility. Therefore, an excellent control approach for reconfigurable manipulator should be able to compensate the model uncertainty accurately and reduce the chattering effect of the controller.

In this paper, a decentralized integral nested sliding mode control method is proposed for constrained reconfigurable manipulator with harmonic drive transmission. The dynamic model of the constrained reconfigurable manipulator is formulated with a nonlinear harmonic drive model. An integral nested sliding surface[12], which is designed by employing a pseudo-sliding surface block, is implemented to reduce the chattering effect of the controller. Model uncertainties, including unmodeled subsystem dynamics, friction modeling error and the interconnected dynamic coupling, are compensated by using a variable gain super twisting algorithm (VGSTA) based decentralized controller. Finally, simulations are performed for a constrained 2-DOF reconfigurable manipulator to illustrate the effectiveness of the proposed method.

## 2. Problem Formulation

According to the dynamic model of a $n$-DOF reconfigurable manipulator which is formulated as a synthesis of interconnected subsystems[7], the dynamic model of $i$th subsystem of reconfigurable manipulator is given as follows

$$I_{mi}\gamma_i\ddot{\theta}_i + f_i(\theta_i,\dot{\theta}_i) + I_{mi}\sum_{j=1}^{i-1} z_{mi}^T z_{\theta j}\ddot{\theta}_j + I_{mi}\sum_{j=2}^{i-1}\sum_{k=1}^{j-1} z_{mi}^T\left(z_{\theta k}\times z_{\theta j}\right)\dot{\theta}_k\dot{\theta}_j + \frac{\tau_{fci}}{\gamma_i} = \tau_i \tag{1}$$

where $I_{mi}\sum_{j=1}^{i-1} z_{mi}^T z_{\theta j}\ddot{\theta}_j + I_{mi}\sum_{j=2}^{i-1}\sum_{k=1}^{j-1} z_{mi}^T\left(z_{\theta k}\times z_{\theta j}\right)\dot{\theta}_k\dot{\theta}_j$ is the dynamic coupling term, $I_{mi}$ is the moment of inertia of the rotor about the axis of rotation, $\tau_i$ is the motor output torque, $z_{mi}$ and $z_{\theta i}$ are the unity vectors along the axis of rotation of the $i$th rotor and joint respectively, $\tau_{fci}$ is the certain part of the estimated joint torque using only position measurements[5], and can be represented as following

$$\tau_{fci} = \frac{1}{c_f}\tan\left(c_f k_{f0}\left(\Delta\theta_i - \frac{\mathrm{sgn}(\tau_{wi})}{\gamma_i c_w k_{w0}}(1-e^{-c_w|\tau_{wi}|})\right)\right) \tag{2}$$

where $k_{f0}$, $k_{w0}$, $c_f$ and $c_w$ are the constants to be determined, $\mathrm{sgn}(\cdot)$ is the normal sign function, $\Delta\theta_i$ is the torsional angle of the harmonic drive, which is obtained by combining the measured link side with the motor side position measurements, and the wave generator torque $\tau_{wi}$ can be approximated by the motor torque command. Note that the term $f_i(\theta_i,\dot{\theta}_i)$ in (1) is the frictional torque term which is considered as a function of the joint position and velocity[13], and given as follows

$$f_i(\theta_i,\dot{\theta}_i)=b_{fi}\dot{\theta}_i+\left(f_{ci}+f_{si}e^{(-f_{\tau i}\dot{\theta}_i^2)}\right)\mathrm{sgn}(\dot{\theta}_i)+f_{\theta i}(\theta_i,\dot{\theta}_i) \tag{3}$$

where $f_{ci}$ denotes the Coulomb friction-related parameter; $f_{si}$ denotes the static friction-related parameter; $f_{\tau i}$ is a position parameter about the Stribeck effect, $b_{fi}$ is the viscous friction coefficient, $f_{\theta i}(\theta_i,\dot{\theta}_i)$ is the position dependency of friction and friction modeling errors. Let $x_i=[x_{i1},x_{i2}]^T=[\theta_i,\dot{\theta}_i]^T$ for $i=1,2,\cdots,n$. According to (1), the following state equation is obtained:

$$S_i:\begin{cases}\dot{x}_{i1}=x_{i2}\\ \dot{x}_{i2}=Fr_i(\theta_i,\dot{\theta}_i)+\Psi_i(\theta_i,\dot{\theta}_i)+h_i(\theta_i,\dot{\theta}_i,\ddot{\theta}_i)-b_iu_i\\ y_i=x_{i1}\end{cases} \tag{4}$$

where $x_i$ is the state vector and $y_i$ is the output of $S_i$. $b_i=\left(I_{mi}\gamma_i\right)^{-1}\in\mathbb{R}^+$, $\Psi_i(\theta_i,\dot{\theta}_i)$, $Fr_i(\theta_i,\dot{\theta}_i)$ and $h_i(\theta_i,\dot{\theta}_i,\ddot{\theta}_i)$ is defined as

$$\begin{aligned}&\Psi_i(\theta_i,\dot{\theta}_i)=-\left(I_{mi}\gamma_i\right)^{-1}\left(\tau_{fci}/\gamma_i\right)\\ &Fr_i(\theta_i,\dot{\theta}_i)=-\left(I_{mi}\gamma_i\right)^{-1}f_i(\theta_i,\dot{\theta}_i)\\ &h_i(\theta_i,\dot{\theta}_i,\ddot{\theta}_i)=-\left(I_{mi}\gamma_i\right)^{-1}\begin{pmatrix}I_{mi}\sum_{j=2}^{i-1}\sum_{k=1}^{j-1}z_{mi}^T\left(z_{\theta k}\times z_{\theta j}\right)\dot{\theta}_k\dot{\theta}_j\\ +I_{mi}\sum_{j=1}^{i-1}z_{mi}^T z_{\theta j}\ddot{\theta}_j+\tau_{ui}\end{pmatrix}\end{aligned} \tag{5}$$

where $\tau_{ui}$ is the output torque ripple that is considered as a model uncertain term and will be compensated in the next section.

## 3. Control Design

In this section, a decentralized integral nested sliding mode control approach is proposed based on VGSTA.

*Assumption 1.* Desired trajectory $y_{ir1}(t)$ is bounded and second order derivable.

*Assumption 2.* The interconnected dynamic coupling term $h_i\left(\theta_i,\dot{\theta}_i,\ddot{\theta}_i\right)$ is bounded, and satisfy

$$\left|h_i\left(\theta_i,\dot{\theta}_i,\ddot{\theta}\right)\right| \le g_{i0}+\sum_{j=1}^{n}g_{ij} \tag{6}$$

where $g_{i0}$ is a positive constant, $g_{ij}$ is a smooth Lipschitz function. Define the tracking position error and its time derivative as

$$e_{i1}=x_{i1}-y_{ir1}(t),\quad \dot{e}_{i1}=x_{i2}-\dot{y}_{ir1}(t) \tag{7}$$

Define the pseudo-sliding surface $s_{i1}$ for the first block as

$$s_{i1}=e_{i1}+z_{i1},\quad z_{i1}(0)=-e_{i1}(0) \tag{8}$$

and the derivative of $s_{i1}$ can be given as follows

$$\dot{s}_{i1}=\dot{e}_{i1}+\dot{z}_{i1}=x_{i2}-\dot{y}_{ir1}(t)+\dot{z}_{i1} \tag{9}$$

In (8) and (9), $z_{i1}$ is an integral variable which will be defined later. It is of importance to introduce the second block of sliding surface, defined as follows

$$s_{i2}=e_{i2}+z_{i2},\quad z_{i2}(0)=-e_{i2}(0) \tag{10}$$

where $z_{i2}$ is an integral variable to be determined, and $e_{i2}$, which is used to design the second block of sliding surface, can be defined as

$$e_{i2}=x_{i2}-y_{ir2}(t) \tag{11}$$

where $y_{ir2}(t)$ is defined as

$$y_{ir2}(t) = y_{ir2,0}(t) + y_{ir2,1}(t) \tag{12}$$

In (12), $y_{ir2,0}(t)$ is the nominal part of the control design, and $y_{ir2,1}(t)$ is used to design the control law for the purpose of compensating the unmodeled subsystem dynamics.

Substituting (11) into (10), one can obtain that

$$x_{i2} = s_{i2} + y_{ir2}(t) - z_{i2} \tag{13}$$

Combining (9) with (13), the derivative of the pseudo-sliding surface $s_{i1}$ can be rewritten as

$$\dot{s}_{i1} = s_{i2} - z_{i2} + y_{ir2,0}(t) + y_{ir2,1}(t) - \dot{y}_{ir1}(t) + \dot{z}_{i1} \tag{14}$$

Choose $\dot{z}_{i1}$ as the form of

$$\dot{z}_{i1} = -\left(s_{i2} - z_{i2} + y_{ir2,0}(t)\right) \tag{15}$$

Then, combining (10), (14), with (15), the derivative of $s_{i1}$ and $z_{i1}$ can be represented as

$$\dot{s}_{i1} = y_{ir2,1}(t) - \dot{y}_{ir1}(t), \quad \dot{z}_{i1} = -e_{i2} - y_{ir2,0}(t) \tag{16}$$

With the initial condition $z_{i1}(0) = -e_{i1}(0)$, define $y_{ir2,0}(t)$ and $y_{ir2,1}(t)$ as

$$y_{ir2,0}(t) = -k_1 e_{i1}, \quad y_{ir2,1}(t) = -\sigma_1 sigm(\varepsilon_1, s_{i1}) \tag{17}$$

where $k_1$, $\sigma_1$ and $\varepsilon_1$ are positive constants to be determined. $sigm(\cdot)$ is a sigmoid function which can be defined as follows

$$sigm(\varepsilon_1, s_{i1}) = \tanh(\varepsilon_1 s_{i1}) \tag{18}$$

Then, we can obtain the time derivative of $s_{i2}$ as

$$\dot{s}_{i2} = \dot{e}_{i2} + \dot{z}_{i2} = \dot{x}_{i2} - \dot{y}_{ir2}(t) + \dot{z}_{i2} \tag{19}$$

According to (17), one can obtain that $\dot{y}_{ir2}(t)$ is represented as

$$\dot{y}_{ir2}(t) = -k_1\dot{e}_{i1} + \sigma_1\varepsilon_1\left(1 - \tanh^2(\varepsilon_1 s_{i1})\right)\left(\sigma_1 sigm(\varepsilon_1, s_{i1}) + \dot{y}_{ir1}(t)\right) \tag{20}$$

Substituting (4) into (19), we can rewrite $\dot{s}_{i2}$ as

$$\dot{s}_{i2} = \Psi_i(\theta_i, \dot{\theta}_i) + Fr_i(\theta_i, \dot{\theta}_i) + h_i\left(\theta, \dot{\theta}, \ddot{\theta}\right) - b_i u_i - \dot{y}_{ir2}(t) + \dot{z}_{i2} \tag{21}$$

where $\dot{z}_{i2}$ is chosen as

$$\dot{z}_{i2} = -k_2\dot{e}_{i1} + \sigma_2\varepsilon_1\left(1 - \tanh^2(\varepsilon_1 s_{i1})\right)\left(\sigma_1 sigm(\varepsilon_1, s_{i1}) + \dot{y}_{ir1}(t)\right) \tag{22}$$

where $k_2$ and $\sigma_2$ are positive constants to be determined. For the purpose of compensating the different terms of the derivative of the sliding surface, we can design the control law as the form of $u_i = u_{i0} + u_{i1} + u_{i2}$. So that (21) can be rewritten as

$$\begin{aligned}\dot{s}_{i2} = {} & Fr_i(\theta_i, \dot{\theta}_i) - b_i u_{i0} + \Psi_i(\theta_i, \dot{\theta}_i) - b_i u_{i1} \\ & + h_i\left(\theta, \dot{\theta}, \ddot{\theta}\right) - b_i u_{i2} - \dot{y}_{ir2}(t) + \dot{z}_{i2}\end{aligned} \tag{23}$$

First, design the control law $u_{i0}$ to compensate the effect of joint friction $Fr_i(\theta_i, \dot{\theta}_i)$.

$$u_{i0} = \hat{b}_{fi}\dot{\theta}_i + \left(\hat{f}_{ci} + \hat{f}_{si} e^{(-\hat{f}_{\tau i}\dot{\theta}_i^2)}\right)\mathrm{sgn}(\dot{\theta}_i) + u_{i0}^1 + Y(\dot{\theta}_i)\left(u_{i0}^2 + u_{i0}^3\right) \tag{24}$$

where $Y(\dot{\theta}_i)$ can be defined as follows

$$Y(\dot{\theta}_i) = \left[\dot{\theta}_i, \mathrm{sgn}(\dot{\theta}_i), e^{(-\hat{f}_{\tau i}\dot{\theta}_i^2)}\mathrm{sgn}(\dot{\theta}_i), -\hat{f}_{si}\dot{\theta}_i^2 e^{(-\hat{f}_{\tau i}\dot{\theta}_i^2)}\mathrm{sgn}(\dot{\theta}_i)\right] \tag{25}$$

In order to incorporate variable parametric model uncertainty compensation, we can design

$$\tilde{F}^i = \left[\hat{b}_{fi} - b_{fi}, \hat{f}_{ci} - f_{ci}, \hat{f}_{si} - f_{si}, \hat{f}_{\tau i} - f_{\tau i}\right]^T = \tilde{F}_c^i + \tilde{F}_v^i \tag{26}$$

where $\tilde{F}_c^i$ and $\tilde{F}_v^i$ are constant and variable unknown vector respectively. And $\tilde{F}_v^i$ is bounded as

$$\left|\tilde{F}_{vn}^i\right| < \rho_n^i, n = 1, 2, 3, 4 \tag{27}$$

In (25), $\hat{b}_{fi}$, $\hat{f}_{ci}$, $\hat{f}_{si}$, $\hat{f}_{\tau i}$ are the normal friction parameters, $u_{i0}^1$ is the term designed to compensate the nonparametric uncertainty $f_{\theta i}(\theta, \dot{\theta})$ in (3). The terms $u_{i0}^2$ and $u_{i0}^3$ are designed to compensate for the parameter uncertainty $\tilde{F}_c^i$ and $\tilde{F}_v^i$, respectively. The friction compensation is of the same form for all the joints, and hence, for the $i$th joint, the compensators, $u_{i0}^1$ $u_{i0}^2$, $u_{i0}^3$ are defined by

$$\begin{aligned}
u_{i0}^1 &= -\rho_{fi}\frac{s_{i2}}{\left|s_{i2}\right|} \quad \left|s_{i2}\right| > \varepsilon^i, \quad -\rho_{fi}\frac{s_{i2}}{\varepsilon^i} \quad \left|s_{i2}\right| \le \varepsilon^i \\
u_{i0}^2 &= -k_3\int_0^t Y(\dot{\theta}_i)^T s_{i2}\,dt \\
u_{i0}^3 &= -\rho_n^i\frac{\delta_n^i}{\left|\delta_n^i\right|} \quad \left|\delta_n^i\right| > \varepsilon_{pn}^i, \quad -\rho_n^i\frac{\delta_n^i}{\varepsilon_{pn}^i} \quad \left|\delta_n^i\right| \le \varepsilon_{pn}^i
\end{aligned} \tag{28}$$

where $\delta^i = Y\left(\dot{\theta}_i\right)^T s_{i2}$, and $\rho_{fi}$, $\rho_n^i$ are the parametric uncertainty bounds. $\varepsilon^i$, $\varepsilon_{pn}^i$ are parameters to be determined.

Second, design the control law $u_{i1}$ to compensate the terms of $\Psi_i(\theta_i, \dot{\theta}_i)$, $\dot{y}_{ir2}(t)$, and $\dot{z}_{i2}$

$$u_{i1} = b_i^{-1}\begin{pmatrix}(k_1 - k_2)\dot{e}_{i1} + k_3 sat(\varepsilon_s, s_{i2}) \\ +(\sigma_1 - \sigma_2)\left(1 - \tanh^2(\varepsilon_1 s_{i1})\right)\end{pmatrix} \tag{29}$$

where $\varepsilon_s$ and $k_3$ are positive constants to be determined. $sat(\cdot)$ is a saturation function. which is defined as follows

$$sat(\varepsilon_s, s_{i2}) = \begin{cases}\mathrm{sgn}(s_{i2}) & \left|s_{i2}\right| > \varepsilon_s \\ s_{i2}/\varepsilon_s & \left|s_{i2}\right| \le \varepsilon_s\end{cases} \tag{30}$$

Third, based on the VGSTA theory[8, 14], design the control law $u_{i2}$ to compensate the interconnected dynamic coupling term $h_i\left(\theta, \dot{\theta}, \ddot{\theta}\right)$ which is represented as the following form

$$h_i\left(\theta, \dot{\theta}, \ddot{\theta}\right) = g_{i1}(\theta_i, t) + g_{i2}(\theta_i, t) \tag{31}$$

where $g_{i1}(\theta_i, t)$ and $g_{i2}(\theta_i, t)$ are bounded by

$$\left\{\begin{aligned} &\left|g_{i1}(\theta_i,t)\right|\le\varsigma_{i1}\left(\theta_i,t\right)\left|\phi_{i1}(s_{i2})\right| \\ &\left|\frac{dg_{i2}(\theta_i,t)}{dt}\right|\le\varsigma_{i2}\left(\theta_i,t\right)\left|\phi_{i2}(s_{i2})\right| \end{aligned}\right. \tag{32}$$

where $\varsigma_{i1}\left(\theta_i,t\right)>0$ and $\varsigma_{i2}\left(\theta_i,t\right)>0$ are known continuous functions. $\phi_1(s_{i2})$ and $\phi_2(s_{i2})$ are defined as

$$\begin{cases} \phi_{i1}(s_{i2})=\left|s_{i2}\right|^{1/2}\operatorname{sgn}(s_{i2})+\kappa_{i3}(t)s_{i2} \\ \phi_{i2}(s_{i2})=\dfrac{1}{2}\operatorname{sgn}(s_{i2})+\dfrac{3}{2}\kappa_{i3}(t)\left|s_{i2}\right|^{1/2}\operatorname{sgn}(s_{i2})+\kappa_{i3}^2(t)s_{i2} \end{cases} \tag{33}$$

where $\kappa_{i3}(t)$ is a positive gain to be determined. Substituting (31) into (23), one can obtain that

$$\begin{aligned} \dot{s}_{i2} = {} & Fc_i\left(\theta_i,\dot{\theta}_i\right)-b_iu_{i0}+\Psi_i\left(\theta_i,\dot{\theta}_i\right)-b_iu_{i1} \\ & +g_{i1}(\theta_i,t)+g_{i2}(\theta_i,t)-b_iu_{i2}-\dot{y}_{ir2}(t)+\dot{z}_{i2} \end{aligned} \tag{34}$$

Design the control law $u_{i2}$ to compensate the inter-comnected dynamic coupling term, shown as follows

$$u_{i2}=b_i^{-1}\left(\kappa_{i1}(t)\phi_{i1}(s_{i2})+\int_0^t\kappa_{i2}(t)\phi_{i2}(s_{i2})dt\right) \tag{35}$$

where the variable gains $\kappa_{i1}(t)$ and $\kappa_{i2}(t)$ are chosen as

$$\begin{cases} \kappa_{i1}(t)=\dfrac{1}{\rho_v}\left\{\begin{aligned}&\frac{1}{4\varepsilon_2}\left(2\varepsilon_2\varsigma_{i1}+\varsigma_{i2}\right)^2+2\varepsilon_2\varsigma_{i2} \\ &+\varepsilon_2+\left(2\varepsilon_2+\varsigma_{i1}\right)\left(\rho_v+4\varepsilon_2^2\right)\end{aligned}\right\}+\varphi \\ \kappa_{i2}(t)=\rho_v+4\varepsilon_2^2+2\varepsilon_2\kappa_{i1}(t) \end{cases} \tag{36}$$

where $\varphi$, $\rho_v$, $\varepsilon_2$ are positive constants to be determined. Therefore, combine (24), (29) with (35), the decentralized integral nested sliding mode control law $u_i$ for the $i$th joint can be defined as follows

$$u_i=b_i^{-1}\left(\begin{aligned} &b_i\left(\begin{aligned}&\hat{b}_{fi}\dot{\theta}_i+Y(\dot{\theta}_i)\left(u_{i0}^2+u_{i0}^3\right)+u_{i0}^1 \\ &+\left(\hat{f}_{ci}+\hat{f}_{si}e^{\left(-\hat{f}_{\tau i}\dot{\theta}_i^2\right)}\right)\operatorname{sgn}(\dot{\theta}_i)\end{aligned}\right)+\left(k_1-k_2\right)\dot{e}_{i1} \\ &+\left(\sigma_1-\sigma_2\right)\left(1-\tanh^2(\varepsilon_1s_{i1})\right)+k_3sat(\varepsilon_s,s_{i2}) \\ &+\kappa_{i1}(t)\phi_{i1}(s_{i2})+\int_0^t\kappa_{i2}(t)\phi_{i2}(s_{i2})dt \end{aligned}\right) \tag{37}$$

**Theorem.** Given a constrained $n$-DOF reconfigurable manipulator, with the dynamic model as formulated in (1), and the model uncertainties that existed in (5). The closed-loop system is stable under the decentralized integral nested sliding mode control law defined by (37).
**Proof.** Refer to Ref. 12.

## 4. Simulations

To study the effectiveness of the proposed decentralized control approach, in this paper, two different configurations of the constrained reconfigurable manipulator with harmonic drive transmission are used to conduct the simulations. The dynamic model and the parameters of controller are chosen as Ref. 12.

To verify the effectiveness and precision of the proposed control method, in this paper, the simulations are conducted with two different controllers respectively, that including the conventional one-order sliding mode controller (SMC) and the proposed integral nested sliding mode controller (INSMC). The simulation results are shown in the following figures. Fig. 1 shown the joint position error curves and the control torque curves of two different configurations under the SMC. Fig. 2 shown the joint position error curves and the control torque curves of configurations A and B under the INSMC. Fig. 3 shown the constrained force and trajectory tracking curves of the end-effector.

From these figure we can conclude that the chattering effects in both the error curves and the control torque curves are relatively obvious under the conventional SMC method. However, the tracking performance of the joint positions is improved under the INSMC method because the model uncertainty has been compensated accurately. The chattering effect can be reduced in a short time interval by using the proposed integral nested sliding surface design, and the desired trajectory of end-effector can be tracked accurately under the proposed INSMC method.

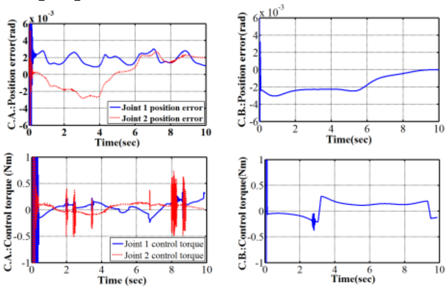

Fig. 1. Position error and control torque curves of configurable A and B under SMC

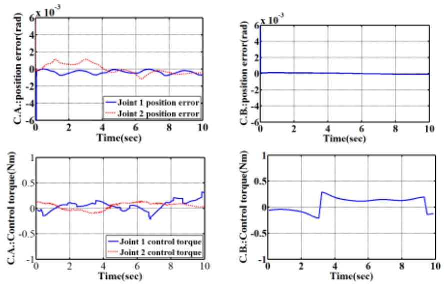

Fig. 2. Position error and control torque curves of configurable A and B under INSMC

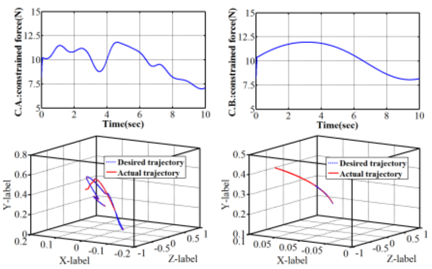

Fig. 3. Constrained force and trajectory tracking curves of end-effector

## 5. Conclusion

This paper studies on constrained reconfigurable manipulator with harmonic drive transmission, and addresses the problems of trajectory tracking control without using force/torque sensor. The dynamic model is formulated based on a nonlinear harmonic drive model. A decentralized INSMC method based on VGSTA is proposed to reduce the chattering effect and compensating the model uncertainties. Finally, simulations are performed to study the effectiveness of the proposed method.

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