Robust Learning Tracking Control Design for Soft Actuators

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Abstract: This paper proposes a recursive sliding-mode control strategy for motion-tracking control of ionic polymer-metal composite soft actuator systems. The suggested controller is distinctive in that it can continuously modify the closed-loop response to maintain system stability. Accordingly, Lyapunov criteria have been used to establish the stability of the provided control technique. Additionally, since controller design does not require any prior knowledge of parameter uncertainties or system hysteresis, it is appropriate for ionic polymer-metal composites since its model changes depending on working conditions. Simulation investigations are conducted to validate the performance of the developed controller. The results demonstrate superior performance compared to the conventional sliding mode control approach.

Keywords: Sliding Mode Control; Ionic Polymer-metal Composites; Soft Actuator; Robust Learning Control; Tracking Control.

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1 Introduction

Ionic polymer-metal composites (IPMCs) are electro-catalyst polymers used as soft actuators which are essential components of mechatronic systems used in manufacturing processes and industrial systems. Additionally, IPMCs can be found in numerous applications, for instance, robotic systems, biomedical systems, nano-positioning devices, and micro-manipulator systems Khawwaf et al. (2020), Li et al. (2020), and Al-Ghanimi (2018). Despite the numerous benefits of IPMC actuators, such as their noiseless execution, minimal operating voltage, and capability for micro-machining, some of their inherent characteristics like aging, hysteresis, and sensitivity to environmental conditions make it challenging to control them accurately and consistently Aabloo et al. (2020). One of the implementations described by Khawwaf et al. (2019) was the underwater functioning of the IPMC actuator, which was built as an adaptive controller for a straightforward recognized transfer function that ignores hysteresis or other IPMC non-linearities. Researchers in Fang et al. (2007) employed a PID controller to monitor and control the bending angle of the IPMC actuator, which was custom-designed and produced for a disposable active cardiac catheter. The cutting force of a 1- degree of freedom (DOF) robotic surgical device controlled by IPMC was stabilized by the authors of Fu et al. (2013) utilizing the PI controller (adjusted using an experimental iteration technique) Tepljakov et al. (2019).

The idea behind inversion-based control is that a model's inverse acts as a controller. One of these controllers can operate in both open and closed loops. For control without sensors, the first choice is appealing. However, in this instance, feedback is not used to offset modeling uncertainties. Therefore, an extremely accurate model is required. Author of Dong & Tan (2012) employed an inversion-based open-loop control strategy to regulate a temperature-dependent variant of an IPMC actuator. They developed a third-order system model, in which the zeros and poles were represented as quadratic polynomial functions of the temperature. This model allowed for a more precise characterization of the system as a transfer function. By utilizing this approach, a single model encompassing the entire temperature range could be utilized to effectively operate the IPMC actuator, even when there were fluctuations in the ambient temperature. The difficulty with this method is that the transfer function is produced in a non-minimum phase, and as a result, its inverse is unstable. A stable but non-causal inversion approach is used to solve this issue, though it also required prior knowledge of the intended trajectories. Also, for optimal control and to eliminate the considerable overshoot and shorten the settling time of the IPMC actuator response to a step change in applied voltage, a linear quadratic regulator (LQR) was utilized. Using an observer, the LQR was used to regulate a three-finger IPMC clutch Yun & Kim (2006). Being an electrochemical sensor, the IPMC material's behavior is strongly reliant on the external environment, which in actuality is subject to unpredictable change. The controller's capacity for adaptation to such alterations is therefore of great value. The closed-loop tracking of the IPMC tip displacement was performed using model reference adaptive control (MRAC). To describe the hysteresis of IPMC, the Prandtl-Ishlinskii operator was added to the reference model Chen (2014). In addition, model free control techniques Mancisidor et al. (2019) have been also adopted for practical IPMC underwater application Khawwaf et al. (2020).

Alternatively, for tracking applications, robust control would be an optimal choice Zaki et al. (2019). Specifically, the conventional sliding mode control (CSMC) method, has been thoroughly investigated and successfully used to manage both linear and nonlinear systems with unpredictable dynamics and external disturbances. The main issue with CSMC is the chattering phenomenon that is caused by the switching action Berrada & Boumhidi (2018). The solution to this issue is a soft control strategy. Using such a procedure, however, involves balancing tracking accuracy and robustness to uncertainty. In order to achieve the desired closed-loop dynamics with zero-error convergence, regardless of system uncertainties and external disturbances, researchers Man et al. (2012) proposed the utilization of sliding mode control (SMC). The SMC approach was employed to guide the closed-loop system towards the sliding mode surface and ensure its subsequent maintenance. Additionally, to address the chattering phenomenon commonly associated with SMC and achieve finite-time convergence, a higher-order terminal sliding mode control technique was developed Utkin et al. (2020).A successful application of a high order terminal SMC The piezoelectric nano-positioning system model has been presented by Al-Ghanimi et al. (2020) which can provide high tracking accuracy with chattering mitigation through the use of a second-order sliding surface with a toggle function. Another example of chattering free SMC is presented by Man et al. (2012) which is well known as a robust sliding mode-based learning control (SMLC). SMLC is an SMC based on the recursive learning technique that was created by utilizing real-time information on the system's closed-loop stability. With the suggested control strategy, the sliding variable and tracking error can be controlled to asymptotically converge to zero between the planned references and actual displacement Al-Ghanimi et al. (2021).

Motivated by the latter control strategy and to attain the required tracking accuracy in the presence of the IPMC actuator uncertainties, we employed the robust SMLC controller in this research to track the nonlinear motion of underwater IPMC soft actuators. The main contribution of this research is that a unique sliding-mode control strategy for motion-tracking of IPMC soft actuator systems is proposed. The proposed controller is distinctive in that it can continuously modify the closed-loop response to maintain system stability, making it appropriate for IPMC since its model changes depending on working conditions. As a result, precise tracking of different reference signals for IPMC actuators can be achieved without considering model uncertainties. Finally, this research aims to address the lack of a robust and adaptive control strategy for IPMC actuators that can handle parameter uncertainties and system hysteresis. The proposed SMLC controller addresses this gap by using a recursive algorithm to learn from past experiences and adjust the control parameters accordingly, without requiring any prior knowledge of parameter uncertainties or system hysteresis. This makes it suitable for real-world applications where the model changes depending on working conditions, and where precise tracking is essential.

The remainder of this research is structured as follows: The experimental configuration and modeling of the IPMC actuator are provided in Section 2. In Section 3, a robust SMLC controller is thoroughly studied for motion tracking of soft actuators for underwater applications. To demonstrate and validate the effectiveness of the suggested control mechanism, simulation studies are carried out under various conditions in Section 4. The conclusion and future work are done at the end of Section 5.

2 Modelling of the IPMC Actuator

Figure 1 depicts the experimental setup of a typical soft actuator, namely the IPMC actuator. As a highly nonlinear actuator, identifying the mathematical model would not be a simple task, especially for underwater applications, so the system has been fully immersed in being accurately identified. Our previous work has thoroughly discussed the system identification process Khawwaf et al. (2017). Therefore, the IPMC transfer function can be represented by a differential equation that involves the system uncertainties as follows:

$$m\ddot{y}(t) + b_0\dot{y}(t) + ky(t) = b_1\dot{u}(t) + b_2u(t) + \delta(t) + h(t) \tag{1}$$

Where m, b_0, k, and y represent the mass, damping coefficient, stiffness, and output displacements of the IPMC actuator respectively, $u(t)$ is the input voltage, and $h(t)$ is the hysteresis effect which can be lumped with other system uncertainties and $\delta(t)$ is the external disturbance. Following the general format of the second-order system, model (1) can be presented as follows:

$$\ddot{y} + a_1\dot{y} + a_2y = b_{11}\dot{u}(t) + b_{22}u(t) + d \tag{2}$$

Where d is the total system uncertainties that include nonlinear behavior, modeling error, parameter variations, and external disturbance. Meanwhile, $a_1 = \dfrac{b_0}{m}$, $a_2\dfrac{k}{m}$ and $b_{11} = \dfrac{b_1}{m}$ and $b_{22} = \dfrac{b_2}{m}$ are the system parameters which have been practically identified in Khawwaf et al. (2017) with $a_1 = 0.4357$, $a_2 = 0.1219$, $b_{11} = 0.0031$, and $b_{22} = 0.0146$ respectively. It should be noted that the IPMC model in (5) possesses a first-derivative represented by the $\dot{u}(t)$ term of the control input which implies it has a dynamic input. However, such a system must carefully process with discontinuous input, such as step input, which can lead to an impulse response. For underwater applications, the input is usually continuous, i.e., a sinusoidal signal, to mimic the fish fins' movement. To this end, we introduce the following virtual input:

$$v(t) = b_{11}\dot{u}(t) + b_{22}u(t). \tag{3}$$

It is obvious from equation (3) that the actual control signal will be filtered via a low pass filter before it is sent to the plant. Thus, the final form of the control signal can be achieved by performing the Laplace transform.

$$u(s) = \frac{1}{b_{11}s + b_{22}}V(s). \tag{4}$$

Since b_1 and b_2 are both positive, we can conclude that (4) is stable and therefore executable. In view of (3), the mathematical model (5) can be rewritten as follows

$$\ddot{y} + a_1\dot{y} + a_2y = v(t) + d \tag{5}$$

where $v(t)$ is the virtual control signal to be designed in the following section.

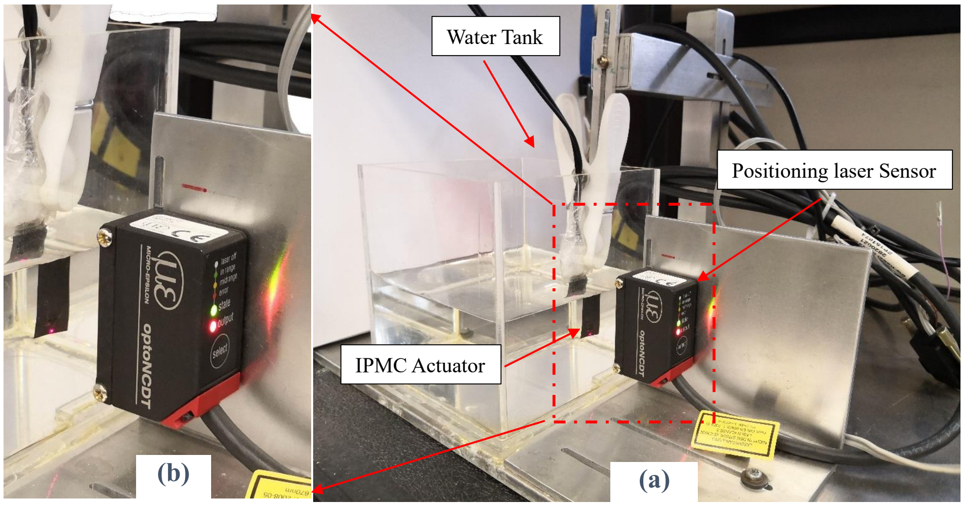

Figure 1 Experimental setup of the IPMC underwater actuator system. (a). experimental setup including the water tank, fully immersed IPMC underwater actuator and laser sensor. (b) zoomed section showed side view of laser sensor focusing laser beam at the end of IPMC actuator .

3 Learning-Based Control Design

The objective of this section is to design a robust SMLC controller for motion tracking of soft actuators for underwater applications. Soft actuators, specifically IPMC actuators, are highly nonlinear devices. In addition, working underwater would increase the system uncertainties, and hence adopting robust control is necessary. Therefore a formulation of robust SMLC for the IPMC actuator will be elaborated. The tracking error is defined as:

$$e(t) = y(t) - y_r(t) \tag{6}$$

where y is the actual displacement of the IPMC actuator, y_r indicates the tracking reference, we endeavor that the proposed controller enforces the IPMC actuator to track y_r accurately under variable working conditions. t indicates the time parameter. Furthermore, a sliding variable is defined as

$$s(t) = \dot{e}(t) + \lambda e(t) \tag{7}$$

where $\lambda > 0$, and $\lambda \in \mathbb{R}$. To achieve sliding mode condition. The derivative of the equation (7) concerning time is written as follows:

$$\dot{s}(t) = \Phi(t) + v(t) \tag{8}$$

Where

$$\Phi(t) = -(a_1\dot{y} + a_2 y) - \ddot{y}_r + d + \lambda\dot{e}(t) \tag{9}$$

As mentioned above, the actuator works in underwater conditions. Thus, using a conventional control design in such an environment is a challenging task. Therefore, adopting learning-based control does not require prior knowledge about the bounds of external disturbances, parameter variation, and many other uncertainties. This makes the learning-based control method outperforms the other conventional robust techniques. In this paper, we will adopt a learning base robust sliding mode controller which is proposed by Man et al. (2011), Man et al. (2012) and is given as follows:

$$v(t) = v(t - \tau) - \Delta v(t) \tag{10}$$

where $v(t - \tau)$ is the control signal from the previous sample and $\Delta v(t)$ indicates the iterative correcting term (learning term) which is written as follows:

$$\Delta v(t) = \begin{cases} \frac{1}{bs(t)}\left(\xi_1 \hat{\dot{\Lambda}}(t-\tau) + \xi_2 |\hat{\dot{\Lambda}}(t-\tau)|\right), & \text{for } s(t) \neq 0 \\ 0, & \text{for } s(t) = 0 \end{cases} \tag{11}$$

where ξ_1 and ξ_2 represent the controller parameters to be calculated. τ is the sampling period. $\hat{\dot{\Lambda}}(t - \tau)$ is the estimate of $\dot{\Lambda}(t - \tau)$, and is defined as

$$\hat{\dot{\Lambda}}(t - \tau) = \frac{\Lambda(t) - \Lambda(t - \tau)}{\tau} \tag{12}$$

where $\dot{\Lambda}(t - \tau)$ is the first derivative of the Lyapunov function candidate $\Lambda(t - \tau) = 0.5s^2(t - \tau)$. In the following, a simple investigation based on the previous work Man et al. (2011) and Man et al. (2012) is provided. The control signal can be considered to be made up of two different components. The first represents the contribution of the controller to compensate for the control signal when the sliding mode is incorrect ($s(t) \neq 0$). In other words, the iterative learning component $\Delta v(t)$ will interact to satisfy the sliding condition. On the other hand, the second component will consider the previous sample of the control signal. This action occurs when the sliding mode condition is correct ($s(t) = 0$). The aforementioned control strategies of the learning-based controller secure a continuous control signal. Consequently, the chattering phenomena will be significantly eliminated, thus a robust control design is achieved. Based on the characteristics of the above controller, it can be concluded that the proposed SMLC outperforms the CSMC in terms of performance enhancement as well as extending the lifespan of the IPMC actuator. In the subsequent section, we will discuss the stability of the system and the asymptotic convergence of the proposed SMLC. It has been demonstrated that when the parameter τ is set to be equal to the sampling time, the following inequality can be satisfied and maintained Man et al. (2011) and Man et al. (2012)

$$|\dot{\Lambda}(t - \tau) - \hat{\dot{\Lambda}}(t - \tau) < \epsilon|\hat{\dot{\Lambda}}(t - \tau)| \tag{13}$$

where $0 < \epsilon \ll 1$ This equality will be further explained and justified in the upcoming discussion.

4 System Stability and Convergence Analysis

Considering the candidate Lyapunov candidate $\Lambda(t) = 0.5s^2(t)$, then the time derivative of $\Lambda(t)$ is expressed as follows

$$\begin{aligned}\dot{\Lambda}(t) &= s\dot{s} \\ &= s\left[\,\Phi(t) + bu(t-\tau)\,\right] - s\,b\,\Delta v(t).\end{aligned} \tag{14}$$

In view of (11), the first order derivative of $\Lambda(t)$ can be rewritten as

$$\dot{\Lambda}(t) = \dot{\Lambda}(t, t-\tau) - \xi_1\hat{\dot{\Lambda}}(t-\tau) - \xi_2|\hat{\dot{\Lambda}}(t-\tau)| \tag{15}$$

suppose that the time interval τ is selected to be small enough with continuity of the $\dot{\Lambda}(t)$, then the following inequality can be held Man et al. (2011).

$$|\dot{\Lambda}(t, t-\tau) - \dot{\Lambda}(t-\tau)| < \frac{1}{\beta}|\hat{\dot{\Lambda}}(t-\tau)| \tag{16}$$

where $\beta > 0$ is a number chosen to satisfy specific conditions as will be illustrated late. The inequality represented by (16) in the literature Man et al. (2012, 2011) is commonly referred to as Lipschitz-like. To ensure compliance with (16), a large positive constant, denoted as β , needs to be carefully selected to fulfill specific criteria. Considering (16), the derivative of $\Lambda(t)$, denoted as $\dot{\Lambda}(t)$, can be expressed in the following form

$$\dot{\Lambda}(t) < \frac{1}{\beta}|\hat{\dot{\Lambda}}(t-\tau)| + \dot{\Lambda}(t-\tau) - \xi_1\hat{\dot{\Lambda}}(t-\tau) - \xi_2|\hat{\dot{\Lambda}}(t-\tau)|. \tag{17}$$

When $\dot{\Lambda}(t-\tau) > 0$, we may rewrite (18) in the following format

$$\dot{\Lambda}(t) < \dot{\Lambda}(t-\tau) + \big(\frac{1}{\beta} - \xi_1\big)|\hat{\dot{\Lambda}}(t-\tau)| - \xi_2|\hat{\dot{\Lambda}}(t-\tau)| \tag{18}$$

if the control parameters are chosen as follow:

$$\beta \gg 1 \text{ and } 1 - \epsilon - \frac{1}{\beta} > \xi_1 > \frac{1}{\beta}, \text{ yields} \tag{19}$$

$$\dot{\Lambda}(t) < \dot{\Lambda}(t-\tau) \tag{20}$$

The inequality (20) implies that the previous derivative of the Lyapunov function is always greater than the instantaneous value (i.e.,$\dot{\Lambda}(t)$). On the other hand, when $\dot{\Lambda}(t-\tau) < 0$, then (18) can be rewritten in view of (13) as

$$\begin{aligned}\dot{\Lambda}(t) &< \tfrac{1}{\beta}|\hat{\dot{\Lambda}}(t-\tau)| + \hat{\dot{\Lambda}}(t-\tau) + \epsilon|\hat{\dot{\Lambda}}(t-\tau)| \\ &\quad -\xi_1\hat{\dot{\Lambda}}(t-\tau) - \xi_2|\hat{\dot{\Lambda}}(t-\tau)| \\ &< \Big(\tfrac{1}{\beta} - 1 + \xi_1 + \epsilon\Big)|\hat{\dot{\Lambda}}(t-\tau)| - \xi_2|\hat{\dot{\Lambda}}(t-\tau)|\end{aligned} \tag{21}$$

based on (19) criteria, it can be deduced that inequality (21) implies $\dot{\Lambda}(t) < 0$. Hence, the asymptotic stability of the closed loop system is proved. Regarding the design of the CSMC controller and the stability analysis of the system, readers may refer to the work of Utkin et al. (2020) for a comprehensive and rigorously proven discussion.

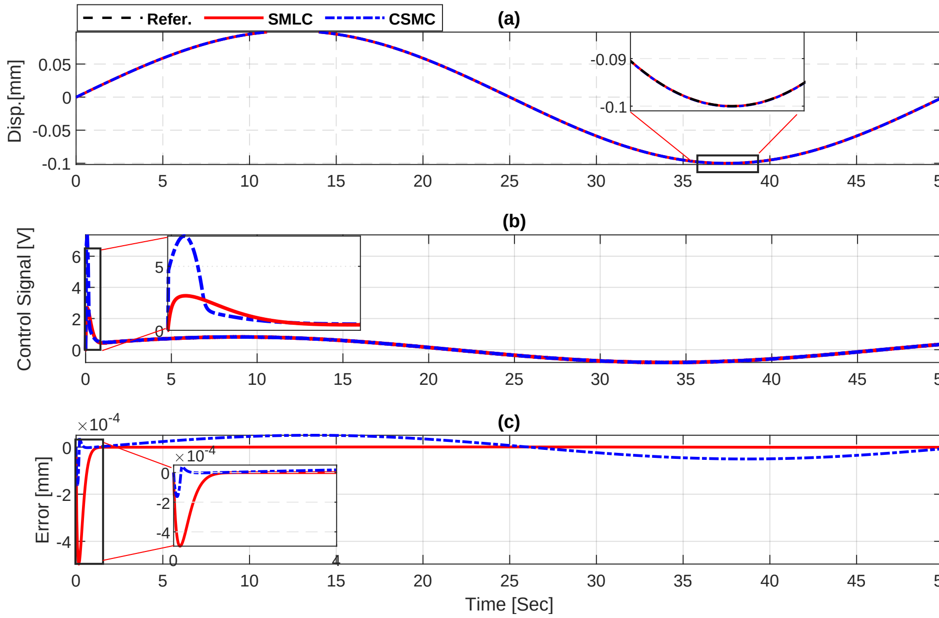

Figure 2 A tracking profile of IPMC system under a robust SMLC and CSMC for a dual-frequency sinusoidal signal with amplitude 0.1 mm and 0.02 (a) positioning tracking of the IPMC actuator (b) control signal (c) the tracking errors.

5 Results and Discussion

To display and validate the performance of the proposed control, simulation studies are performed under different circumstances. The tracking performance of the nominal system is tested for the first time. Then, in the event of system perturbation, the control robustness and tracking performance of the proposed controller are checked over a variable reference range of frequencies. Thus, these results are compared with CSMC performed at the same time under the same conditions to show the superiority of the proposed controller. Single and dual-tone sinusoidal signals used for tracking purposes are given by:

$$y_{r_1} = A\ sin(2\pi ft) \tag{22}$$

$$y_{r_2} = A_1 sin(2\pi f_1 t) + A_2 sin(2\pi f_2 t) \tag{23}$$

where A denotes the amplitude and f the frequency in Hertz. The list of the tests is tabulated in the table to summarize the conditions of each test.

5.1 Tracking performance of sinusoidal reference

Figure 2 shows the response of the IPMC actuator system to sinusoidal input signals of different frequencies. First, Fig. 2 depicts the results of 0.01 mm and the frequency of 0.02 Hz. Unsurprisingly, both controllers show distinct performance when running IPMC under nominal conditions. A slight improvement can be observed in terms of tracking errors and maximum control effort. Zoomed spots in Fig. 2 (b) and (c) are depicted the superiority of a robust SMLC over CSMC. It should be noted that the CSMC will perform better when

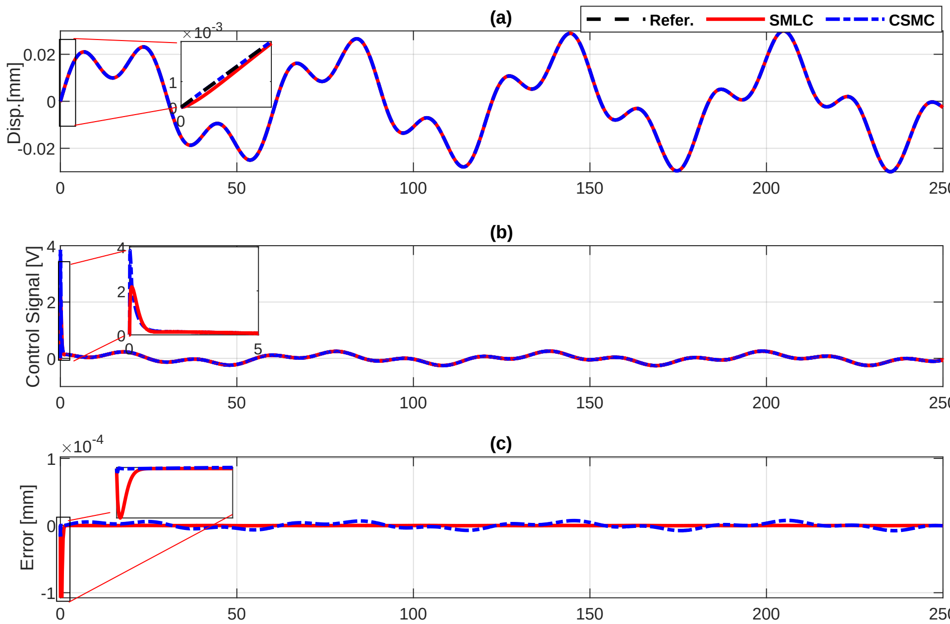

Figure 3 A tracking profile of IPMC system under a robust SMLC and CSMC to dual-frequency sinusoidal signal with amplitude 0.1 mm and 0.02 Hz (a) positioning tracking of the IPMC actuator (b) control signal (c) the tracking errors.

control gain is increased. However, a compromise between the level of control performance and robustness with the chattering effect will be the cost of such improvement.

5.2 Dual-frequency sinusoidal tracking

A dual-frequencies sinusoidal reference is examined to determine the complex frequency reference performance track. When two integrated sinusoidal signals are used to demonstrate the IPMC behavior for sophisticated reference tracking tasks, the signals have frequencies of 0.01 and 0.05 Hz. Figure 3 presents the tracking performance of both controllers for this test case. It can be seen that the control effort is further reduced by half under the proposed controller, which is also reflected in the study state error of the total tracking error. However, Figure 3. (c) shows that the maximum error is somewhat better in CSMC. This may be the result of the learning term in the SMLC's control structure needing time to adjust. Ultimately, it becomes evident that a robust SMLC outperforms CSMC in terms of tracking errors and energy conservation. As a result, this test illustrates the proposed SMLC's ability to precisely drive the IPMC actuator over a variety of frequencies when compared with the CSMC controller.

6 Conclusion

This paper presents the design, analysis, and validation of an SMLC for motion tracking control in systems. The key achievement of this study is the successful demonstration of the learning property of the proposed controller through theoretical analysis. The performance of the SMLC controller has been thoroughly evaluated through a series of simulation tests, confirming its convergence capability and superior performance compared to the CSMC for tracking different reference signals. Notably, the SMLC controller achieves precise tracking of the IPMC actuator without considering model uncertainties. This significant achievement highlights the potential of the proposed control system as an alternative methodology for controlling sophisticated IPMC systems, enabling rapid prototyping and advancing the field of IPMC control.

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