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Position control of piezoelectric actuator in robotic hand using extended state observer and sliding mode control

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1 Introduction

A piezoelectric actuator (PEA) is a type of smart material based actuator that converts electrical energy into mechanical displacement or force using the converse piezoelectric effect. PEAs are known for their high resolution and fast response, as well as their ability to generate significant force despite their small size and weight. PEAs have been commonly employed in applications that require precise motion control and force control, such as cell puncture mechanisms [1], scanning probe microscopy [2], smart microfinger [3], and microgripper [4]. However, they also have inherent nonlinear dynamics such as creep and hysteresis, and vibration dynamics that can limit their performance, with hysteresis being the primary obstacle to achieving good performance. It can cause a gap between the PEA output and the desired output, as well as output instability [5]. Hysteresis can be addressed through the use of appropriate control techniques and compensators.

One technique for compensating for hysteresis is open-loop control, which requires an accurate hysteresis model. In this approach, an inverse hysteresis model is cascaded with the PEA [6], making hysteresis modeling the primary step [7]. Various models, such as Bouc-Wen, Duhem, Maxwell-Slip, Prandtl-Ishlinskii, and Preisach, are well-known in the literature for hysteresis modeling. However, open-loop control has several drawbacks, including the time-consuming and cumbersome identification of the hysteresis model [7], the complexity of creating an inverse hysteresis model, and undesired control performance due to modeling errors and unknown disturbances [6]. To overcome these issues, feedback control patterns with or without feed-forward control have been investigated in the literature [6]. Some researchers have utilized feedback control along with a feed-forward compensator without the need to invert the hysteresis model, as was introduced in [8]. However, the feed-forward structure still depends on the hysteresis model, and identification of its parameters remains necessary.

The sliding mode control (SMC) is a systematic nonlinear control approach that is widely used to address uncertainties and disturbances, making it a valuable algorithm for improving the tracking performance of PEAs. In some research studies, SMC has been designed while taking hysteresis into consideration as an unknown disturbance. In such algorithms, a large upper bound is considered for the disturbance, making them conservative [9].

The extended state observer (ESO) is a widely-used tool to mitigate the impact of disturbances on the performance of control systems; it creates an additional state to account for internal uncertainty and external disturbance and then estimates this state in real-time [10]. To achieve high-quality estimation performance a fuzzy ESO (FESO) was introduced in [10].

2 Design of observer and controller

To achieve precise tracking performance of the PEA without the complexity of hysteresis modeling, we apply the FESO and SMC for PEA control. FESO is utilized to estimate unknown terms such as hysteresis nonlinearity, unmolded dynamics, uncertainties, and external disturbances. Then, based on the second-order dynamic model of the PEA, we design a robust SMC to achieve accurate tracking. Consider the classical Bouc-Wen model as

$$\begin{cases} m\ddot{y}(t) + b\dot{y}(t) + ky(t) = k(du(t) - h(t)) - f(y, w, t) \\ \dot{h}(t) = \alpha d\dot{u}(t) - \beta|\dot{u}(t)|h(t) - \gamma\dot{u}(t)|h(t)| \end{cases} \tag{1}$$

where u is the control signal, and y is the position of PEA. The linear part is described with m, b, k, and d, which are the mass, damping coefficient, stiffness coefficient, and piezoelectric coefficient, respectively. Also, $f(y, w, t)$ represents external disturbance, model uncertainty, and other unknown terms. Further, $h(t)$ represents the hysteresis state with α, β, and γ. By considering $h(.)$ and $f(.)$ as the total disturbance, the dynamical model (1) is rewritten as

$$\ddot{y}(t) + \frac{b}{m}\dot{y}(t) + \frac{k}{m}y(t) = \frac{kd}{m}u(t) + P(t) \tag{2}$$

This simplified model eliminates the requirement for the identification of parameters of hysteresis, as the FESO accurately estimates the disturbance term, $P(t)$. The design of the SMC control rule relies on the sliding surface $s = \dot{e} + \lambda e$.

$$u = \frac{m}{kd}(\ddot{y}_d + \lambda\dot{y}_d) + \frac{1}{d}y - \frac{m}{kd}z_3 + (\frac{b}{kd} - \lambda\frac{m}{kd})z_2 - k_{c1}s - k_{c2}\,\mathrm{sgn}(s) \tag{3}$$

where $e = y - y_d$, λ, k_{c1}, and k_{c2} are the design parameters, z_2 and z_3 are the estimation of $\dot{y}$ and the total disturbance, respectively.

3 Experimental results

This section presents experimental results to verify the performance of the FESO-SMC algorithm. Various reference trajectories, including sinusoidal and step waveforms, were considered for this purpose. To provide a comparison, the PI and the FESO-SMC algorithms were tested. The experimental setup consisted of a PEA (PZS001) with a 20μm motion range, a KPZ101 high-voltage amplifier, and signal conditioner circuit devices (AMP001 and KSG101). For communication between software and hardware, a PCI-1711 data acquisition module from Advantech was used. The experimental results show that the FESO-SMC controller has better performance than PI controller, see Fig. (1).

4 Conclusions and perspectives

The precision tracking of PEAs has become challenging due to hysteresis. In order to achieve the desired tracking, we developed a FESO-SMC controller. By using FESO, the need for hysteresis identification and inversion to compensate for its effect is eliminated. To assess the tracking performance of FESO-SMC algorithm, we evaluated its tracking ability for both continuous and discontinuous reference trajectories. Results demonstrate that the FESO-SMC algorithm performs satisfactorily in both the transient and steady-state phases.

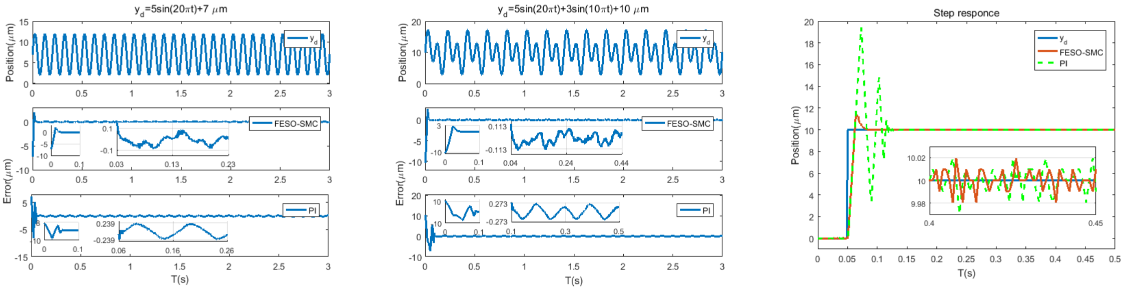

FIG. 1: Tracking performance of FESO-SMC and PI algorithems

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