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Supervisory hybrid control of piezoelectric actuators utilized in tracking piecewise continuous trajectories

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ABSTRACT

This article presents a supervisory hybrid control design for piezoelectric actuators utilized in tracking trajectories with intermittent jump discontinuities. We use a previously developed robust adaptive controller and a standard PID controller to construct this hybrid control strategy. We show that when the sub-controllers are used for step tracking, while primarily tuned for continuous trajectory tracking, large undesirable oscillations occur. Conversely, when the controllers are retuned for step tracking, their performance degrades in tracking high-frequency continuous trajectories. Thus, a supervisory hybrid controller is developed to track desired trajectories with occasional discontinuities, using both the robust adaptive and the PID controllers. The robust adaptive controller performs as the primary controller for tracking the continuous segments of the desired trajectory, while the PID controller is activated when the steps occur. Results indicate that the proposed supervisory hybrid controller outperforms both sub-controllers in tracking high-frequency trajectories with intermittent discontinuities.

1. Introduction

This paper examines the problem of supervisory hybrid control design for tracking piecewise continuous micro- and nano-scale trajectories using piezoelectric actuators. Particularly, we focus on trajectories that are dominantly continuous but suffer from occasional step-like discontinuities. The control architecture consists of a primary controller designed and tuned for tracking the continuous trajectory, and a secondary controller tuned for step tracking, which is activated when the desired trajectory experiences abrupt jumps. The ultimate goal of this effort is to improve the speed and the accuracy of piezoelectric actuators, through elaborate control design, in a variety of applications such as scanning probe microscopy (SPM) [1,2].

The feedforward and feedback control of piezoelectric actuators is subject to a number of limiting factors such as hysteresis and creep phenomena, parametric uncertainties, and external disturbances. Although hysteresis is known as the main limiting factor in feedforward control [3,4], the inclusion of a feedback loop along with a robust control design can effectively reduce this effect [5,6]. Parametric uncertainty, on the other hand, can significantly reduce the performance of tracking, particularly at high frequencies. To deal with this issue, adaptive control algorithms have been developed and implemented [7]. The combination of adaptive and robust control methods has therefore been adopted to effectively control piezoelectric actuators despite parametric uncertainties and unknown hysteresis nonlinearity [8,9]. In this paper, we will use a previously developed robust adaptive control law [9] as the primary controller.

Most of the sophisticated control algorithms developed for piezoelectric actuators assume that the desired trajectories (the trajectories to be tracked) are either standard step signals, or smooth and differentiable trajectories, such as sinusoids. Although these assumptions are widely used in control theory, and are legitimate in general, there are real situations where these assumptions cannot be fully satisfied. For example, in a standard SPM device the real-time command signal applied to the vertical actuator is the variation of surface topography, which can contain both smoothly varying regions as well as abrupt jumps (see Fig. 1). Thus, the controllers designed for solely continuous or solely step trajectories cannot be effectively used for such system.

To resolve this issue, at least three remedies can be considered: first, we can compromise control performance by tuning the gains so as to follow both high-frequency continuous and step trajectories smoothly. Second, we can filter out the discontinuities from the command signal. This also degrades the control performance because of introducing a delay to the real-time feedback loop. Third

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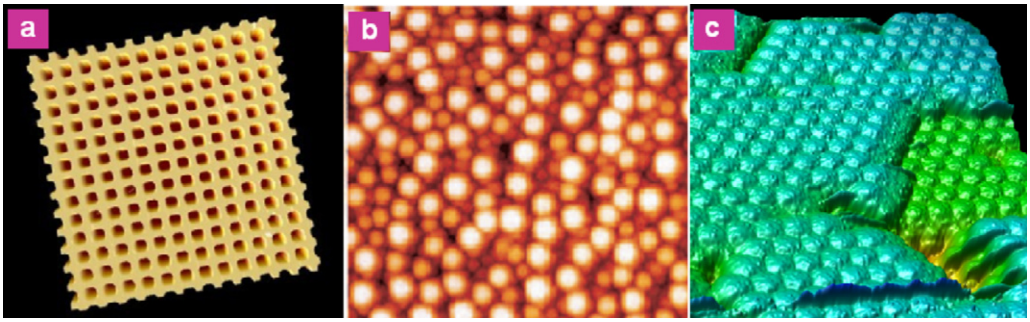

Fig. 1. Examples of different SPM sample topographies: (a) a SPM calibration sample [10] (example of a stepped topography), (b) a surface of positively charged polymer latex particles adsorbed to mica in water [11] (example of a smooth topography), and (c) a crystal of satellite tobacco mosaic virus particles [12] (example of combined stepped and smooth topographies).

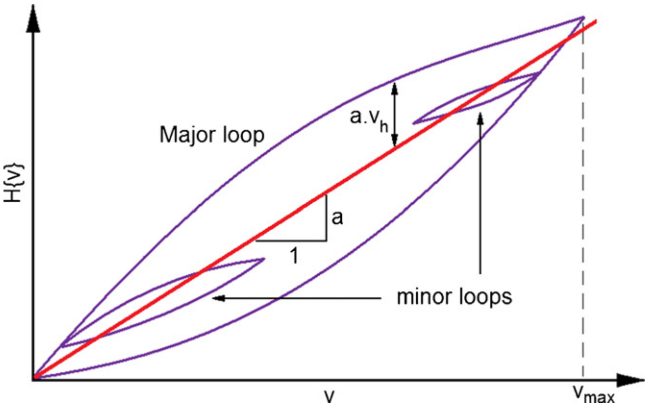

Fig. 2. Approximation of hysteresis loops by a line and a bounded time-varying disturbance term.

and last, we can divide the desired trajectory into segments of continuous and stepped sub-trajectories, and implement two controllers, one in charge of the continuous segments, and the other responsible for the discontinuities. This way, the control structure becomes more sophisticated, but the accuracy can be largely preserved. In this article, we adopt the latter solution and develop a supervisory hybrid controller for piezoelectric actuators.

Currently, there is a lack of literature developing supervisory hybrid control schemes for piezoelectric nanopositioning systems. Although simpler switching strategies, such as sliding mode control (SMC), have been developed for piezoelectric actuators [6], the purpose of switching in such methods is to achieve robustness with respect to system uncertainties. This is why the goal of supervisory hybrid control design is to maintain control performance in the presence of trajectory jumps.

In this paper, we develop, analyze, and experimentally validate a supervisory hybrid controller for piezoelectric actuators. We use a previously developed robust adaptive controller [9] and a PID controller to build the supervisory control strategy. We define the switching laws that coordinate between the sub-controllers, and derive the necessary conditions on the control signals to assure the continuity of the system input and states. We provide experimental results throughout the paper to clarify the problem and justify the proposed approach. Finally, we show that the proposed supervisory control strategy provides more precise tracking of piecewise-continuous trajectories.

2. Feedback control of piezoelectric actuators

To effectively track time-varying continuous trajectories in the presence of parametric uncertainties, unmodeled dynamics, and external disturbances, we adopt a previously developed robust adaptive controller [9]. Here, we briefly review this approach before discussing the supervisory hybrid control design.

2.1. System modeling

A widely used model for piezoelectric actuators is a second order linear time-invariant system subject to a hysteretic input excitation, as follows:

$$\ddot{x}(t)+2\xi\omega_n\dot{x}(t)+\omega_n^2x(t)=\omega_n^2H\{v(t)\} \tag{1}$$

where $x(t)$ and $v(t)$ respectively stand for the system displacement and applied voltage, ξ and ω_n are the system damping ratio and natural frequency, and $H\{v(t)\}$ represents the hysteretic excitation between the applied voltage and the force generated through the piezoelectric stack. The hysteresis operator H is assumed to yield bounded output for bounded inputs, and thus can be divided into a linear segment and a bounded variation:

$$H\{v(t)\}\equiv a(v(t)+v_h(t)); \qquad a|v_h(t)|\le M \tag{2}$$

where a is the average slope of the hysteresis trajectory and M is the finite bound of its variation from the linear approximation (see Fig. 2). Hence, Eq. (1) can be recast as:

$$m\ddot{x}(t)+c\dot{x}(t)+kx(t)=v(t)+v_h(t), \qquad m=\frac{1}{a\omega_n^2}, \qquad c=\frac{2\xi}{a\omega_n},$$
$$k=\frac{1}{a}, \qquad r=\frac{b}{a} \tag{3}$$

Assuming that the collective effects of the system unknown disturbances, including $v_h(t)$, form a static and a dynamic disturbance input leads to:

$$m\ddot{x}(t)+c\dot{x}(t)+kx(t)=v(t)+(d_c+d(t)), \qquad |d(t)|\le N \tag{4}$$

with d_c and $d(t)$ being respectively the static (constant) and dynamic disturbance terms, and N being the finite bound of the dynamic disturbance.

2.2. Robust adaptive control

Here, we briefly review the robust adaptive control strategy developed in Ref. [9] for piezoelectric actuators whose salient dynamic is governed by Eq. (4). The tracking error is defined as $e(t)=x_d(t)-x(t)$, with $x_d(t)$ being a two times continuously differentiable desired trajectory. The control law proposed in [9] for the robust adaptive tracking control of piezoelectric actuators is given by:

$$v(t)=\hat{m}(t)(\ddot{x}_d(t)+\sigma\dot{e}(t))+\hat{c}(t)\dot{x}(t)+\hat{k}(t)x(t)-\hat{d}_c(t)+\eta_1 s(t)$$
$$+\eta_2 sat\left(\frac{s(t)}{\varepsilon}\right); \qquad s(t)=\dot{e}(t)+\sigma e(t) \tag{5}$$