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Disturbance rejection-based robust control for micropositioning of piezoelectric actuators

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ABSTRACT

Precise control of piezoelectric actuators used in micropositioning applications is strongly under the effect of internal and external disturbances. Undesired external forces, unmodelled dynamics, parameter uncertainties, time variation of parameters and hysteresis are some sources of disturbances. These effects not only degrade the performance efficiency, but also may lead to closed-loop instability. Several works have investigated the positioning accuracy for constant and slow time-varying disturbances. The main concern is controlling performance and also the presence of time-varying perturbations. Considering unknown source and magnitude of disturbances, the estimation of the existing disturbances would be inevitable. In this paper, a compound disturbance observer-based robust control is developed to achieve precise positioning in the presence of time-varying disturbances. In addition, a modified disturbance observer is proposed to remedy the effect of switching behaviour in the case of slow time variations. A modified Prandtl–Ishlinskii (PI) operator and its inverse are utilized for both identification and real-time compensation of the hysteresis effect. Experimental results depict that the proposed approach achieves precise micropositioning in the presence of estimated disturbances.

1. Introduction

Internal and external disturbances are challenging issues in the control of dynamic systems, especially in micromanipulation applications. Disturbances include joint frictions, actuator perturbations, unmodelled dynamics, parameter uncertainties, undesired external forces and nonlinear behaviours such as hysteresis. As a result, the performance can strongly be degraded and may even lead to closed-loop instability. This problem is of serious concern in piezoelectric actuators, in particular in micromanipulation processes.

To deal with this issue, several robust control approaches such as sliding mode, adaptive and observer-based control have been presented for piezoelectric actuators [1–3]. However it has been assumed that the system deals with a known bounded disturbance which should be small enough. The assumptions are conservative for mechanical systems, especially when disturbance includes dynamic uncertainties. To eliminate the mentioned deficiencies, online disturbance estimation

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and feedforward compensation have been utilized as an alternative solution [4–7]. In such a case, the necessity of known boundedness assumption can be ignored.

Two control approaches have been generally considered, i.e. *Adaptive Perturbation Estimation Based Control* and *Disturbance Observer-Based Control* (*DOBC*). In the first approach, the perturbation could be adaptively estimated and compensated based on the closed-loop positioning error [1]. An adaptive perturbation estimation based on computed torque control for nonlinear systems has been presented in [4]. The proposed method guarantees asymptotic convergence for only slow varying disturbances. In addition, the convergence of perturbation to the real value could not be generally achieved. It would be achievable in special cases such as persistent excitation. In another works of the authors, a robust control combined with adaptive perturbation estimation has been developed for micropositioning actuators [5]. The major drawback has been the assumption of the separation of external force and perturbation. This issue is one of the points to be considered in this paper.

In the second approach, a disturbance observer coupled with different control approaches has been proposed [6–12]. In this method, the controller includes two separate parts: first, a conventional controller under the assumption that there is no disturbance or the disturbance is exactly known; second, the disturbance observer for the disturbance feedforward compensation [6,7]. Disturbance observers have many advantages as increasing the robustness of the closed-loop system [6]. It can be also utilized as an external force estimator in sensorless manipulations [8].

Several DOBC approaches have been proposed based on the linear system theories [9,10]. But the methods could not be effectively implemented for nonlinear systems. As a result, nonlinear disturbance observer-based control (NDOBC) has been of interest in the last decade. Robust motion control and output control based on a disturbance observer have been proposed for nonlinear systems [11,12]. The proposed observer does not have any analytical convergence. In addition, the low-frequency performance causes bounded tracking error in high-frequency applications. One of the most popular nonlinear disturbance observers with the analytical convergence has been introduced by Chen et al. for a two-link revolute manipulator [13]. The observer has also been improved for the general revolute manipulators [14]. Mohammadi et al. [15] has recently revised the observer for a general structure of manipulators. In this structure, the asymptotic convergence for slow time-varying disturbances has been deduced. In the case of fast time-varying disturbances, the convergence error would be ultimately bounded.

Based on the aforementioned disturbance observer, different approaches such as sliding mode and computed torque controls have been proposed for uncertain nonlinear systems [16,17]. A modified disturbance observer-based feedback linearization has also been investigated for a teleoperation system [18]. In all the mentioned methods, the perfect convergence is derived for slow time-varying and constant disturbances. But the major challenge is the case of time-varying disturbances. The controller performance for time-varying disturbances has been investigated for special disturbances such as linear exogenous systems [19]. An integral based sliding mode control has also been proposed for time-varying disturbances [20]. Conservative assumptions such as boundedness of both first and second time derivatives of disturbances have been taken in this case. However, improper control gains may make a limit cycle in the closed-loop system.

In this paper, a compound disturbance observer-based robust control has been designed for time-varying disturbances. The necessity condition for the asymptotic convergence is boundedness of the disturbance variation. This point has been a common assumption in dynamic systems [7,15,20]. Based on the approach used by other researchers, a modified observer has also been developed to eliminate the switching behaviour of the controller for slow time-varying disturbances [18]. The proposed approach has been implemented for a precise micropositioning piezoelectric actuator. Therefore, a generalized Prandtl–Ishlinskii model and its inverse are utilized for the identification and online feedforward compensation of hysteresis. This leads to the elimination of the actuator's hysteretic behaviour. PI estimation errors, probably unmodelled dynamics and undesired external forces are the major parts of the disturbances. The experimental results demonstrate that the PI model has achieved hysteresis identification and compensation. In addition, the proposed controller tracks the desired trajectories precisely in the presence of disturbances.

2. General nonlinear dynamic modelling and control design

In this section, the control approaches will be designed for a general nth-order nonlinear dynamic system. Absolutely, the proposed approaches can be also utilized for linear dynamic systems. A general nonlinear dynamic system is represented as follows:

$$\boldsymbol{X}^{(n)} = \boldsymbol{F}\big(\boldsymbol{X}, \dot{\boldsymbol{X}}, \ldots, \boldsymbol{X}^{(n-1)}\big) + \boldsymbol{B}\big(\boldsymbol{X}, \dot{\boldsymbol{X}}, \ldots, \boldsymbol{X}^{(n-1)}\big)\boldsymbol{u}(\boldsymbol{t}) + \boldsymbol{d}_{\text{ext}}(\boldsymbol{t}) \tag{1}$$

where $\boldsymbol{X} = [x_1, x_2, \ldots, x_m]$ is the vector of m generalized coordinates. $\boldsymbol{X}^{(i)} = [x_1^{(i)}, x_2^{(i)}, \ldots, x_m^{(i)}]$ is the ith time derivative of the generalized coordinates. $\boldsymbol{u}(\boldsymbol{t})$ is the input and $\boldsymbol{d}_{\text{ext}}$ includes external disturbances such as joint frictions, actuator perturbations and undesired external forces.

Due to parametric uncertainties, unmodelled dynamics and identification errors, the dynamic is described as:

$$\begin{aligned}\boldsymbol{X}^{(n)} &= \boldsymbol{f} + \tilde{\boldsymbol{f}} + (\boldsymbol{b} + \tilde{\boldsymbol{b}})\boldsymbol{u}(\boldsymbol{t}) + \boldsymbol{d}_{\text{ext}}(\boldsymbol{t}) \\ &= \boldsymbol{f} + \boldsymbol{b}\boldsymbol{u}(\boldsymbol{t}) + \tilde{\boldsymbol{f}} + \tilde{\boldsymbol{b}}\boldsymbol{u}(\boldsymbol{t}) + \boldsymbol{d}_{\text{ext}}(\boldsymbol{t})\end{aligned} \tag{2}$$

$\boldsymbol{f}$, $\boldsymbol{b}$ are the known parts and $\tilde{\boldsymbol{f}}$, $\tilde{\boldsymbol{b}}$ are the unknown parts of $\boldsymbol{F}$ and $\boldsymbol{B}$, respectively [4]. The unknown part can be considered as the internal disturbances $\boldsymbol{d}_{\text{int}}(\boldsymbol{t}) = \tilde{\boldsymbol{f}} + \tilde{\boldsymbol{b}}\boldsymbol{u}(\boldsymbol{t})$. With regards to dynamic model (2), total uncertainties could be represented