Precision Engineering 35 (2011) 309–317

Contents lists available at ScienceDirect

Precision Engineering

journal homepage: www.elsevier.com/locate/precision

Adaptive sliding mode control of a piezo-actuated bilateral teleoperated micromanipulation system

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ARTICLE INFO

Article history:
Received 21 May 2010
Received in revised form 1 November 2010
Accepted 17 November 2010
Available online 2 December 2010

Keywords:
Micro-telemanipulation
Adaptive sliding mode
Piezoelectric actuators
Unknown input observer

ABSTRACT

Piezoelectric actuators are widely used in micro manipulation applications. However, hysteresis nonlinearity limits the accuracy of these actuators. This paper presents a novel approach for utilizing a piezoelectric nano-stage as the slave manipulator of a teleoperation system based on a sliding mode controller. The Prandtl–Ishlinskii (PI) model is used to model actuator hysteresis in feedforward scheme to cancel out this nonlinearity. The presented approach requires full state and force measurements at both the master and slave sides. Such a system is costly and also difficult to implement. Therefore, sliding mode unknown input observer (UIO) is proposed for full state and force estimations. Furthermore, the effects of uncertainties in the constant parameters on the estimated external forces should be eliminated. So, a robust adaptive controller is proposed and its stability is guaranteed through the Lyapunov criterion. Performance of the proposed control architecture is verified through experiments.

1. Introduction

Telemanipulation defines the idea of a user interacting with and manipulating a remote environment and has led to applications ranging from space-based robotics to telesurgery [1]. Beside several applications of teleoperation systems, there is a new application area which is called macro–micro teleoperation. Man has restriction to sense or manipulate micro objects directly. Macro–micro teleoperation can enable human to manipulate tasks in micro world. Note that not all of these applications consider force feedback, though systems using force feedback are important in this work. In this paper, a piezoelectric-actuated stage was used as the slave manipulator of a macro–micro teleoperation system. A piezoelectric actuator is an excellent choice as a micro positioning actuator because of its high resolution, fast response and capability of producing high forces.

The hysteresis effect of piezoelectric actuators, which is revealed in their response to an applied electric field, is the main setback in precise position control [2]. In this study, a modified Prandtl–Ishlinskii (PI) model is applied and its inverse is used to cancel out the hysteresis effect in a feedforward scheme. Hysteresis-compensated model can be considered as a second order linear system [3].

One of the challenges associated with micro-teleoperation is the scaling between the human hand and micro parts. Fine motion control in teleoperation is generally achieved through position control with de-amplification from the master to the slave. Higher transparency is accomplished by tracking of scaled force of the slave on the master side. A method has been proposed to derive scaling factors based on Llewellyn's criterion [4]. However, it has been tested only on virtual environments and no method to tune the gains of the controller is provided.

The work presented here uses the position–force architecture, where the master sends its position and velocity to the slave side. The slave sends only the force exerted on it by the environment to the master. Comparing with the position–position architecture [5], this architecture provides perfect force tracking and avoids the reflection of large reaction forces, due to differences between the master and slave position in free motion, to the operator. Nevertheless, it requires force sensing at the slave side. From a performance point of view, the increased transparency of the position–force architecture motivates research into teleoperation systems where the forces are measured. However, force sensors are costly, can be unreliable, and provide noisy signals. Thus, this work develops an approach that has the benefits of a teleoperation architecture using force sensors, without the need to measure the forces. The unknown input observer for state estimation under unknown (non-white or non-Gaussian) inputs has been intensively studied recently [6,7]. Disturbance observers have been widely used for purposes such as improved tracking control [8,9], and fault detection [10].

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doi:10.1016/j.precisioneng.2010.11.006

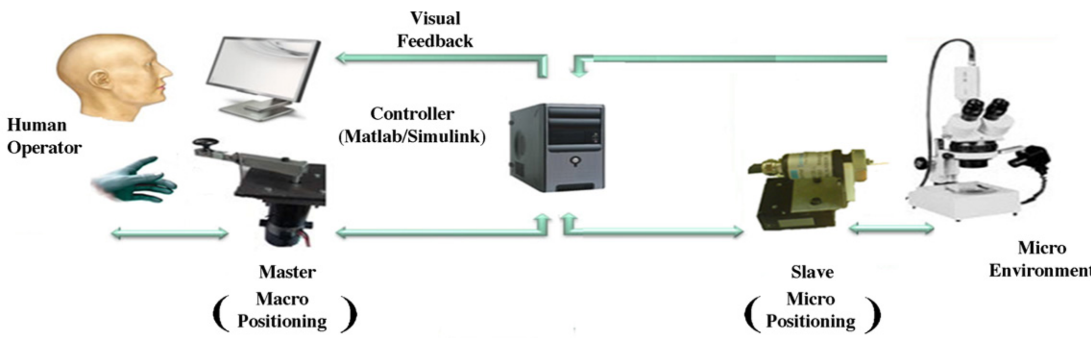

Fig. 1. Micro telemanipulation setup.

In teleoperation systems, a robot has usually a control input and a force input applied to the robot by an external environment. The control input is clearly a known input, but without a force sensor, the external force input may be viewed as an unknown input. Thus, unknown input observers are used as external force estimators. As a result, force sensing in no longer required.

The disturbance identification algorithms are output feedback in nature and are based on the concept of inverse dynamics—which seems well motivated, because disturbance estimation is essentially a plant inversion problem. Since the inverse of physical systems is usually noncausal, derivatives of the output signal will help the reconstruction of the disturbance input [11,12]. If the output signals are contaminated by noise, accurate output derivatives may be difficult to obtain. This has been a common problem for many output feedback disturbance observers. However, in the approach proposed in this work, only the position needs to be measured and derivatives of the output signals are no longer required.

Another problem is that a robust controller suffers from disturbances originated from parametric uncertainties. Furthermore, without eliminating the effects of uncertainties in the constant parameters, the unknown input observers estimate the external forces and the disturbances caused by uncertainties altogether. As a result, the external forces cannot be estimated correctly. To remedy this problem, a Lyapunov-based robust adaptive controller is proposed in this article in order to adapt to system parameters, improve the tracking transparency, and estimate the external forces accurately.

This article consists of seven sections. Dynamic modeling for the teleoperation system is introduced in Section 2. Section 3 presents the sliding mode unknown input observer approach. In Section 4, the problem of parametric uncertainties' effect on force estimation accuracy is stated. Section 5 undertakes the derivation and implementation of an impedance controller for the master, a robust adaptive controller for the slave, and sliding mode unknown input observers to estimate the human and environmental forces. A condition for stability is then presented. Experimental results are given in Section 6 and conclusions are presented is Section 7.

2. Macro–micro telemanipulation system

Fig. 1 shows the master–slave system for a micro telemanipulation setup. To design an efficient controller for this system the dynamics equations of motion of the teleoperation system are first derived.

2.1. Dynamic modeling for the master robot

In this research the master is a 1-DOF manipulator which utilizes a DC servo motor. A load cell is installed on the shaft of the motor to measure the force exerted on the master. Dynamic model of the motor can be considered as follows:

$$j_m\ddot{x}_m(t) + b_m\dot{x}_m(t) + k_m x_m(t) = u_m(t) + L_m F_h(t) \quad (1)$$

where x_m denotes the rotation angle. j_m, b_m and k_m are moment of inertia, damping constant and spring constant, respectively. F_h is the force exerted by human operator and L_m is the effective length between the force and motor shaft. u_m is the control signal that is applied to the master robot.

2.2. Dynamic modeling for the slave robot

The slave manipulator consists of a 1-DOF stage actuated by a piezo stack actuator. Hysteresis effect of piezoelectric actuators which is revealed in their response to an applied electric field is the main drawback in precise positioning. Therefore, the development of a dynamic model which describes the hysteresis behavior is very important. This is for the improvement of the control performance of the piezo-positioning mechanism. In many investigations, a second-order linear dynamics has been utilized for describing the system dynamics. As shown in Fig. 2, this model combines mass–spring–damper ratio with a nonlinear hysteresis function appearing in the input excitation to the system. The following equation defines the model:

$$m_s\ddot{x}_s(t) + b_s\dot{x}(t) + k_s x_s(t) = H_F(v(t)) \quad (2)$$

where $x_s(t)$ is the salve position. m_s, b_s and k_s are the mass, damping constant and spring constant, respectively.

$H_F(v(t))$ denotes the hysteretic relation between input voltage and excitation force. Piezoelectric actuators have very high stiffness, and consequently, possess very high natural frequencies. In low-frequency operations, the effects of actuator damping and inertia could be safely neglected. Hence, the governing equation of motion is reduced to the following static hysteresis relation between the input voltage and actuator displacement:

$$x_s(t) = \frac{1}{k_s} H_F(v(t)) = H_x(v(t)) \qquad \{m_s\ddot{x}_s(t) \ll b_s\dot{x}_s(t) \ll k_s x_s(t)\} \quad (3)$$

Eq. (3) facilitates the identification of the hysteresis function $H_F(v(t))$ between the input voltage and the excitation force. This is performed by first identifying the hysteresis map between the input voltage and the actuator displacement, $H_x(v(t))$. It is then scaled up to k_s to obtain $H_F(v(t))$. To consider interaction with environment, the force F_e exerted by the environment is inserted into the model. Therefore, dynamics of the slave manipulator can be written as follows:

$$m_s\ddot{x}_s(t) + b_s\dot{x}_s(t) + k_s x_s(t) = k_s H_x(v(t)) - F_e \quad (4)$$