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Practice Article

High precision tracking control of a servo gantry with dynamic friction compensation ☆

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ABSTRACT

This paper is concerned with the tracking control problem of a voice coil motor (VCM) actuated servo gantry system. By utilizing an adaptive control technique combined with a sliding mode approach, an adaptive sliding mode control (ASMC) law with friction compensation scheme is proposed in presence of both frictions and external disturbances. Based on the LuGre dynamic friction model, a dual-observer structure is used to estimate the unmeasurable friction state, and an adaptive control law is synthesized to effectively handle the unknown friction model parameters as well as the bound of the disturbances. Moreover, the proposed control law is also implemented on a VCM servo gantry system for motion tracking. Simulations and experimental results demonstrate good tracking performance, which outperform traditional control approaches.

1. Introduction

Over the past several decades, high precision mechatronics has received considerable attention due to the wide applications in various important areas such as semiconductor manufacturing equipment [1], ultra precision machine tools [2], atomic force microscopy [3], three dimension printing [4], and hard disk drives (HDDs) [5]. The performance of such applications are usually dependent on their dynamical behaviors (e.g. stability, accuracy, response time and robustness). Hence, it is critically important to meet the increasing demands of such applications from control theoretic perspectives.

One of the central topics of high precision servo control systems is the tracking control problem, which represents a large class of motion control tasks, such as drilling, assembly, track seeking of HDDs [6]. However, the nonlinear phenomenon complicates the control design process and deteriorates the tracking accuracy [7]. In recent years, significant research efforts have been devoted to tracking control of various mechatronics applications. A robust neural network motion tracking control approach was employed for micro/nanomanipulations in [8]. In [9], a backstepping motion controller with disturbance observer was proposed for nonlinear mechanical systems. To reduce the effect of disturbances and parameter variations, a discontinuous adaptive robust controller was constructed for the control of linear motors [10]. In order to solve the actuator saturation problem, a saturated adaptive robust control strategy was proposed and applied to a linear motor based positioning system [11]. Meanwhile robust controllers with friction compensators were designed based on the static nonlinear friction model for high-speed/high-accuracy motion control systems [12–14]. Note that the impact of friction cannot be fully addressed by a static nonlinear function of velocity alone [15]. Therefore, the above results have limitations in high precision motion applications and low speed applications, due to the fact that dynamical friction compensations are not considered.

During the past decade, significant studies have been devoted to the problem of modeling and compensating dynamical frictions with various model representations. A LuGre dynamic model for friction was proposed in [16], where Stribeck effect, hysteresis, spring-like characteristics for stiction and varying break-away force were all included. A new modification of the Leuven model was also presented in [17]. In [18], Dupont et al. proposed a new class of single state models in which presliding is assumed to be elastoplastic. Among the above friction models, LuGre model is easier to use for real time controls due to its simpler form and its ability to capture major dynamic friction behaviors

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[15]. Therefore, the LuGre model has been widely employed in high precision servo control systems with dynamic friction compensations. In [19], LuGre model was used for an adaptive friction compensation on a servo motor system. By using LuGre model, a feedback controller with observer-based compensator was given in [20]. Based on LuGre model, a PD control method with an adaptive estimation of the friction force was proposed in [21]. Along the same line of research, Tan et al. presented an adaptive backstepping control scheme with friction compensation strategy [22]. Although LuGre model and various compensation schemes have been studied with significant efforts, most of the existing results focused on the stability and asymptotical behaviors of the control systems, without considering the performance requirements of high precision servo systems on finite time response and convergence speed.

Motivated by the above discussions and the recent finite time control techniques reported in [23–25], we investigate LuGre model based nonlinear friction compensation and propose an ASMC (adaptive sliding mode control) algorithm to deal with disturbances and dynamic frictions in a VCM-actuated linear servo stage. For the proposed control scheme, we introduce an adaptive control technique to estimate the unknown parameters of the friction model and the bounds of disturbances, and develop a new finite time sliding mode control method with a fractional power term to achieve fast convergence and good transient response.

The rest of this paper is organized as follows. In Section 2, the mathematical models for VCM servo systems and friction force variations are presented, where the formulation of tracking control problem is also given. The main results of this paper are given in Section 3. In Section 4, some simulations are provided to illustrate the effectiveness of the proposed algorithm. Real time experiments are deployed on a customize-designed two-axis VCM servo gantry and comparative studies are also provided in Section 5, followed by concluding remarks in Section 6.

2. Problem formulation

Many advanced applications of high precision mechatronics, such as laser beam direct writing (LBDW) systems, require high performance tracking or contouring of desired trajectories. The working principle of an LBDW machine can be illustrated in Fig. 1, where the key element to be controlled is an $X-Y$ precision servo gantry. In the case of semiconductor fabrication or material processing, the machining of the workpiece is determined by the motion trajectories of the servo gantry. In the present paper, high performance tracking control problem is investigated for a VCM driven two-axis servo stage, where system uncertainties, external disturbances, as well as nonlinear mechanical frictions are taken into consideration.

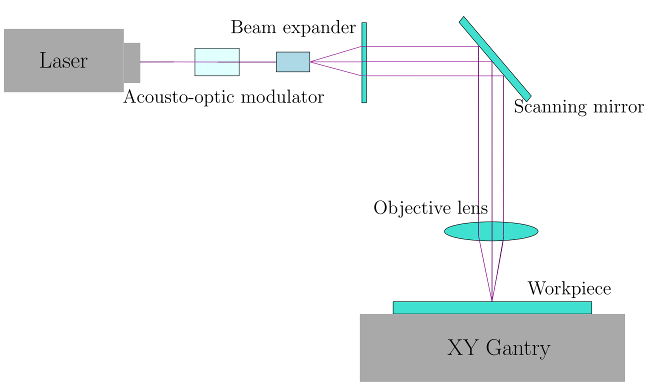

Fig. 1. Laser beam direct writing systems.

2.1. Dynamical model of the VCM servo system

We consider a customized designed high precision servo gantry depicted in Fig. 2, which is constructed by assembling two modular single-axis stages perpendicularly, with actuators of linear VCMs including cylindrical permanent magnet rotors and electromagnetic stators. Very high bandwidth current amplifiers are employed to drive the VCM actuators, such that the dynamics from the control voltage to the coil current can be simplified by a constant K_{u_i}.

The general form of the mechanical model for servo gantry systems can be referred to [15]. In this particular case, the dynamical model for one axis of the servo gantry, for example **x**-axis, can be represented by the following equation:

$$M_{\mathbf{x}}\ddot{y}+C_{\mathbf{x}}\dot{y}+K_{\mathbf{x}}y=F_{\mathbf{x}}-F_{f_{\mathbf{x}}}+d_{\mathbf{x}}, \tag{1}$$

where y denotes the displacement of a linear motor, with its velocity and acceleration represented as $\dot{y}$ and $\ddot{y}$. $M_{\mathbf{x}}$, $C_{\mathbf{x}}$, and $K_{\mathbf{x}}$ represent the moving mass, the equivalent viscous coefficient, and the stiffness constant in the **x**-axis respectively, and $F_{\mathbf{x}}$ is the driving force of the VCM. Meanwhile, $F_{f_{\mathbf{x}}}$ represents the unmeasurable friction, and $d_{\mathbf{x}}$ represents the disturbances including unmodeled lumped nonlinear dynamics such as magnetic lag and eddy current loss. Note that $F_{\mathbf{x}}=K_{F_{\mathbf{x}}}I_{\mathbf{x}}=K_{F_{\mathbf{x}}}K_{u_i}u_{\mathbf{x}}$, where $K_{F_{\mathbf{x}}}$ is the force constant, $I_{\mathbf{x}}$ is the coil current, $u_{\mathbf{x}}$ is the control input and K_{u_i} is the amplification gain discussed previously. Similarly **y**-axis dynamics can be written in the same fashion. Note that the coupling dynamics are not included in the model explicitly, but can be considered as part of the disturbances.

Choosing $x_1=y$ and $x_2=\dot{x_1}=\dot{y}$ as the system state variables, we have the state space representation of the system:

$$\begin{cases}\dot{x}_1=x_2,\\ \dot{x}_2=-a_2x_1-a_1x_2+bu-\dfrac{1}{M}F_f+\dfrac{1}{M}d,\end{cases} \tag{2}$$

$$y=x_1, \tag{3}$$

where $a_1=\frac{C}{M}$, $a_2=\frac{K}{M}$, and $b=\frac{K_FK_{u_i}}{M}$. As the dynamics of **x**-axis and **y**-axis have the same form, we remove the subscripts with respect to **x** or **y** for simplicity.

2.2. Friction model and problem formulation

Various friction models have been discussed in recent literatures such as [16,26]. In this paper, the friction model F_f in (2) is described by the LuGre model

$$\dot{z}=x_2-\sigma_0\frac{|x_2|}{g(x_2)}z, \tag{4}$$

$$F_f=\beta_0z+\beta_1\dot{z}, \tag{5}$$

where x_2 is the velocity defined in (2), z represents the internal friction state. Meanwhile, σ_0 is the nominal static friction parameter, and β_0, β_1 are friction force parameters that can be physically explained as the stiffness of bristles and damping coefficient. The function $g(x_2)$ is known and positive, and can be used to describe the Stribeck effect in the standard LuGre model [16,19]. In this paper, the function $g(x_2)$ is described in the following form:

$$g(x_2)=F_c+(F_s-F_c)\exp[-(x_2/v_s)^2], \tag{6}$$

where F_s is the level of the stiction force, F_c corresponds to the Coulomb friction level, and the Stribeck velocity v_s determines how quickly $g(x_2)$ approaches F_c. Now that the friction F_f can be written as