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Robust Position Control of Electro-mechanical Systems

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Abstract

In this work, the robust position control scheme is proposed for the electro-mechanical system using the disturbance observer and backstepping control method. To the external unknown load of the electro-mechanical system, the nonlinear disturbance observer is given to estimate the external unknown load. Combining the output of the developed nonlinear disturbance observer with backstepping technology, the robust position control scheme is proposed for the electro-mechanical system. The stability of the closed-loop control system has been proved via the Lyapunov analysis technique. Simulation results are presented to demonstrate the feasibility of the proposed disturbance-observer-based position control scheme of the electro-mechanical system.

Keywords: *Electro-mechanical System, Position Control, Disturbance Observer, Backstepping Control*

1. Introduction

Electro-mechanical system (EMS) has been widely used in the sensor system of the agriculture mechanism. Thus, the position control of the mechanical system has been extensively studied by many researchers and various control results have been developed in the past several decades [1]. On the other hand, nonlinearities always ubiquitously exist in electro - mechanical systems such as nonlinear springs and damping mechanisms [2]. To achieve the good position control performance, the nonlinear control of EMS is a hot research topic in the nonlinear control area [3-9]. Friction characterization and compensation were studied for the electro-mechanical system [3]. Global chaos synchronization problem was investigated for electro-mechanical gyrostat systems via variable substitution control [4]. Robust adaptive vibration tracking control was developed for a micro-electro-mechanical system with bound estimation [5]. Rigorous hybrid systems simulation was studied for an electro-mechanical pointing system with discrete-time control [6]. However, the robust position control scheme of EMS need to be further developed. Specially, the suffering unknown external disturbance should be explicitly considered in the position control design stage to improve the control performance of EMS.

In most existing control technologies for the electro-mechanical system, the external disturbance has been strictly restricted with known upper boundary and then the position control scheme was developed based on this assumption. However, the upper boundary of the external disturbance is not exactly obtained in the practical engineering system. To eliminate the bounded requirement of the unknown external disturbance, the disturbance observer technique can be employed to estimate the unknown disturbance via using the good approximation performance of the disturbance observer. Recently, the disturbance observer technology has been extensively investigated and various results have been presented [10-17]. A robust tracking control was studied for an uncertain nonlinear system using disturbance observer. 10 A nonlinear disturbance observer was presented for robotic manipulators [11]. The disturbance attenuation and rejection technique was presented for systems with nonlinearity via Disturbance Observer Based Control (DOBC) approach [12]. Composite disturbance-observer-based control and H_∞ control were developed for complex continuous models [13]. Terminal sliding mode control was proposed for uncertain nonlinear systems using disturbance observer [14]. In this

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paper, the disturbance observer is developed for approximating the external unknown disturbance load of the electro-mechanical system.

On the other hand, the backstepping method has become one of the most popular control design methods for special classes of uncertain nonlinear systems and different backstepping control schemes have been developed [18-23]. Adaptive fuzzy output tracking control was proposed for a class of uncertain nonlinear systems.18 Using the backstepping method, adaptive tracking control was proposed for a class of uncertain multi-input and multi-output (MIMO) nonlinear systems with input saturation [19]. Robust adaptive neural network control was developed for a class of uncertain MIMO nonlinear systems with input nonlinearities via the backstepping technique [20]. Adaptive neural output feedback tracking control was studied for a class of uncertain discrete-time nonlinear systems [21]. A dynamical surface control (DSC) approach to robust adaptive neural network (NN) tracking control was presented for strict-feedback nonlinear systems [22]. Adaptive neural control was proposed for a class of perturbed strict-feedback nonlinear time-delay systems [23]. However, there are few disturbance-observer-based backstepping control results for electro-mechanical systems. Thus, the robust position control combining disturbance observer with backstepping technique needs to be further concerned for the electro-mechanical system to improve the control performance.

This work is motivated by the disturbance-observer-based robust position control of the electro-mechanical system with unknown load. The nonlinear disturbance observer is firstly developed to approximate the unknown load of the electro-mechanical system. Then, using the output of the developed disturbance observer, the robust position control is proposed for the electro-mechanical system. The organization of the paper is as follows. Section 2 details the problem formulation. Section 3 presents the design of nonlinear disturbance observer. Robust position control is investigated for electro-mechanical systems based on the disturbance observer in Section 4. In Section 5, simulation results are given to demonstrate the effectiveness of our proposed position approach, followed by concluding remarks in Section 6.

2. Problem Formulation

An electro-mechanical system with a nonlinear spring described as a controlled Duffing's equation can be expressed as [24]

$$m\ddot{x} + c\dot{x} + f_1 x + f_3 x^3 = k_t u + b \tag{1}$$

where x, u and b are displacement, controller force and disturbance, respectively. m, c and k_t are the mass, damping and the torque constant, respectively. f_1 and f_3 are nonlinear spring coefficient. b is the external disturbance which is an unknown time-varying load.

If the displacement is chosen as the output of the electro-mechanical system, i.e., $y = x$. Define $z_1 = x$ and $z_2 = \dot{x}$. Then, the electro-mechanical system (1) can be written as

$$\begin{aligned} \dot{z}_1 &= z_2 \\ \dot{z}_2 &= -\frac{c}{m} z_2 - \frac{f_1}{m} z_1 - \frac{f_3}{m} z_1^3 + \frac{k_t}{m} u + \frac{b}{m} \\ y &= z_1 \end{aligned} \tag{2}$$

The position control objective of this paper is that the displacement of the electro-mechanical system can track the given bonded desired position in the presence of external unknown load. For the desired position y_d, the proposed position control can make that all closed-loop signals are bounded, and the system output follows the desired signal y_d such that the tracking error converges to a very small neighbourhood of the origin.

Since the load b is unknown, it cannot be directly utilized to design the position control scheme for the electro-mechanical system. Thus, the disturbance observer is developed to efficiently estimate it in our paper. Before the design of disturbance observer, the following assumption is required:

Assumption 1: For all system states x, the unknown time-varying load b satisfies $|\dot{b}| \le \varepsilon$ with unknown positive constant $\varepsilon > 0$.

3. Nonlinear Disturbance Observer Design for Unknown Load

In this section, the nonlinear disturbance observer is developed to estimate the time-varying unknown load b [10, 25]. To design a nonlinear disturbance observer, the auxiliary design variable d is given by

$$d = -b + k_0 m z_2 \tag{3}$$

where $k_0 > 0$ is a design parameter of the nonlinear disturbance observer.

The time derivative of d can be written as

$$\dot{d} = -\dot{b} + k_0 m \dot{z}_2 = -\dot{b} - k_0 (c z_2 + f_1 z_1 + f_3 z_1^3 - k_t u - b) \tag{4}$$

Considering (3), we have

$$\dot{d} = -\dot{b} - k_0 (c z_2 + f_1 z_1 + f_3 z_1^3 - k_t u + d - k_0 m z_2) \tag{5}$$

On the basis of (5), the nonlinear disturbance observer is designed as

$$\dot{\hat{d}} = -k_0 (c z_2 + f_1 z_1 + f_3 z_1^3 - k_t u - \hat{d} + k_0 m z_2) \tag{6}$$

where $\hat{d}$ is the estimate value of the auxiliary design variable d.

Invoking (5) and (6), the estimate error of the disturbance observer can be described as

$$\dot{\tilde{d}} = \dot{d} - \dot{\hat{d}} = -\dot{b} - k_0 \tilde{d} \tag{7}$$

where $\tilde{d} = d - \hat{d}$ is the disturbance estimate error.

Using the estimate value of the auxiliary design variable and considering (3), the estimate of unknown time-varying load is given by

$$\hat{b} = k_0 m z_2 - \hat{d} \tag{8}$$

where $\hat{b}$ is the estimate value of unknown time-varying load b.

According to (3) and (8), the estimate error of unknown time-varying load b is written as

$$\tilde{b} = \hat{b} - b = d - \hat{d} = \tilde{d} \tag{9}$$

The design of nonlinear disturbance observer for the electro-mechanical system can be summarized in the following theorem.

Theorem 1: Considering the electro-mechanical system (1) with unknown time-delay load, the nonlinear disturbance observer is designed as (6) and (8). Then, the estimate error of the developed nonlinear disturbance observer for the unknown load is uniform asymptotically convergent.

Proof: To consider the convergent ability of estimate error $\tilde{b}$, the Lyapunov function candidate is given by

$$V_o = 0.5\tilde{b}^2 = 0.5\tilde{d}^2 \tag{10}$$

Invoking (7), the derivative of V_o is given by

$$\dot{V}_o = \tilde{d}(-\dot{b} - k_0\tilde{d}) = -\tilde{d}\dot{b} - k_0\tilde{d}^2 \tag{11}$$

Considering Assumption 1 and the following fact

$$-\tilde{d}\dot{b} \le 0.5(\tilde{d}^2 + \dot{b}^2) \le 0.5(\tilde{d}^2 + \varepsilon^2) \tag{12}$$

we have

$$\dot{V}_o \le -(k_0 - 0.5)\tilde{d}^2 + 0.5\varepsilon^2 \tag{13}$$

It is apparent that $\dot{V}_o < 0$ if the following inequality is satisfied:

$$\tilde{d}^2 > \frac{0.5}{k_0 - 0.5}\varepsilon^2 \tag{14}$$

Thus, we can choose proper design parameter k_0 obtain the satisfactory unknown load approximation performance.

4. Backstepping Position Control Design Using Disturbance Observer

In this section, the output of disturbance observer is used to replace the unknown load. And then, the robust position control is developed using backstepping method and disturbance observer technique. To design the backstepping position control, we define $e_1 = y - y_d$.

Step 1: Considering (2), the time derivative of e_1 can be written as

$$\dot{e}_1 = \dot{y} - \dot{y}_d = \dot{x} - \dot{y}_d = z_2 - \dot{y}_d \tag{15}$$

The virtual control law α_1 is designed as

$$\alpha_1 = -k_1 e_1 + \dot{y}_d \tag{16}$$

where $k_1 > 0$.

Define the new error variable as

$$e_2 = z_2 - \alpha_1 \tag{17}$$

Considering the following Lypunov function candidate

$$V_1 = 0.5e_1^{\ 2} \tag{18}$$

we have

$$\dot{V}_1 = e_1\dot{e}_1 = e_1(z_2 - \dot{y}_d) = e_1(e_2 + \alpha_1 - \dot{y}_d) \tag{19}$$

Substituting (16) into (19) yields

$$\dot{V}_1 = -k_1 e_1^2 + e_1 e_2 \tag{20}$$

Step 2: Consider the Lyapunov function candidate

$$V_2^* = V_1 + 0.5e_2^2 \tag{21}$$

The time derivative of e_2 is given by

$$\dot{e}_2 = \dot{z}_2 - \dot{\alpha}_1 = -\frac{c}{m}z_2 - \frac{f_1}{m}z_1 - \frac{f_3}{m}z_1^3 + \frac{k_t}{m}u + \frac{b}{m} - \dot{\alpha}_1 \tag{22}$$

where $\dot{\alpha}_1 = -k_1\dot{e}_1 + \ddot{y}_d$.

Invoking (21), we obtain

$$\dot{V}_2^* = -k_1 e_1^2 + e_1 e_2 - \frac{e_2 c}{m}z_2 - \frac{e_2 f_1}{m}z_1 - \frac{e_2 f_3}{m}z_1^3 + \frac{e_2 k_t}{m}u + \frac{e_2 b}{m} - e_2\dot{\alpha}_1 \tag{23}$$

To analyze the effect of disturbance estimate error, the Lyapunov function candidate is chosen as

$$V_2 = V_2^* + 0.5\tilde{b}^2 \tag{24}$$

Considering (18) and (22), we have

$$\dot{V}_2 \le -k_1 e_1^2 + e_1 e_2 - \frac{e_2 c}{m}z_2 - \frac{e_2 f_1}{m}z_1 - \frac{e_2 f_3}{m}z_1^3 + \frac{e_2 k_t}{m}u + \frac{e_2 b}{m} - e_2\dot{\alpha}_1 + \tilde{b}\dot{\tilde{b}} \tag{25}$$

The robust position control law is designed as

$$u = \frac{cz_2 + f_1 z_1 + f_3 z_1^3 - \hat{b} - me_1 - mk_2 e_2 + m\dot{\alpha}_1}{k_t} \tag{26}$$

where $k_2 > 0$ is the design parameter of the position control.

Substituting (26) into (25) yields

$$\dot{V}_2 \le -k_1 e_1^2 - k_2 e_2^2 + \frac{e_2 b}{m} - \frac{e_2 \hat{b}}{m} + \tilde{b}\dot{\tilde{b}} = -k_1 e_1^2 - k_2 e_2^2 - \frac{e_2 \tilde{b}}{m} + \tilde{b}\dot{\tilde{b}} \tag{27}$$

Considering (27) and the following fact

$$-e_2\tilde{b} \le 0.5e_2^2 + 0.5\tilde{b}^2 \tag{28}$$

we obtain

$$\dot{V}_2 \le -k_1e_1^2 - (k_2 + \frac{1}{2m})e_2^2 + \frac{1}{2m}\tilde{b}^2 + \tilde{b}\dot{\tilde{b}} \tag{29}$$

Considering (11) and (12), (29) can be written as

$$\dot{V}_2 \le -k_1e_1^2 - (k_2 - \frac{1}{2m})e_2^2 - (k_0 - \frac{1}{2m} - 0.5)\tilde{b}^2 + 0.5\varepsilon^2 \tag{30}$$

The design of robust position control using nonlinear disturbance observer and backstepping method for the electro-mechanical system can be summarized in the following theorem.

Theorem 2: Considering the electro-mechanical system (1) with unknown time-delay load, the nonlinear disturbance observer is designed as (6) and (8), the robust position control is designed as (26). Then, the disturbance observer estimate error and the position tracking error are uniform asymptotically convergent.

Proof: From (30), we can know that all closed-loop system signals are convergent if all design parameters k_0, k_1 and k_2 are properly chosen.

Remark 1: Since the nonlinear disturbance observer is used to estimate the unknown load of EMS in this paper, the developed robust position control can also handle the parameter uncertainties of EMS. We need only treat the parameter uncertainties as a part of the unknown load and use the developed nonlinear disturbance observer to approximate it. On the hand, the exponential convergence of all closed-loop system signals can be guaranteed only if the unknown load is constant.

5. Simulation Study

In this section, the simulation results are presented to demonstrate the effectiveness of the proposed disturbance- observer-based robust position control for EMS.

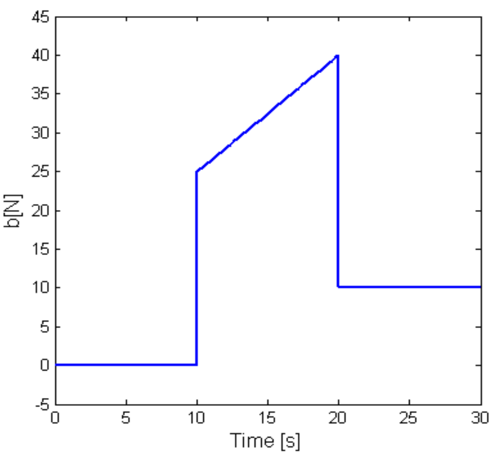

Figure 1. Time history of unknown load

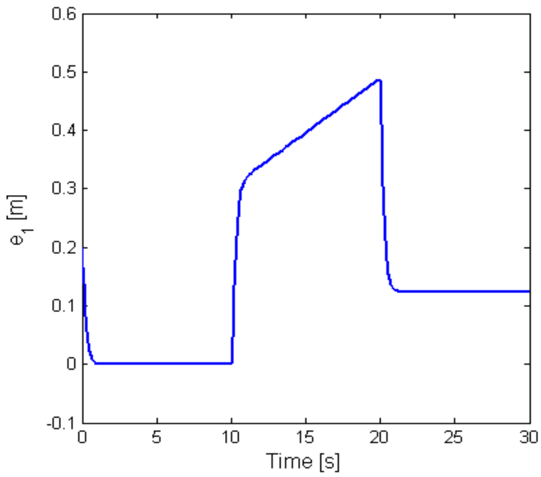

Figure 2. Position tracking error under the backstepping control

In the simulation, all simulation parameters of the electro- mechanical system are chosen as the following values: m = 1 kg, c = 5 Ns/m, f1 = 100 N/m, f3 = 500000 N/m3, kt=1N/v. All control design parameters are chosen as k0 = 20, k1= 5 and k2=16. 24 Consider the unknown load is applied on the electro-mechanical system. In the simulation, the load time history is given in Figure 1. The nonlinear disturbance observer is proposed as (6) and (8). The position controller is designed in accordance with (26). The position error under the design nonlinear control law is shown in Figure 2. The control output is shown in Figure 3.

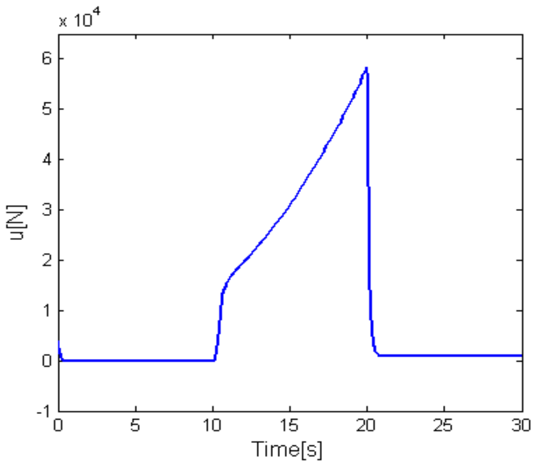

Figure 3. The control input

From these simulation results, we can see that the position tracking error is satisfactory under the designed robust position controller. On the other hand, the control input is convergent. Thus, the proposed robust position control scheme based on disturbance observer and backstepping method is valid for the electro-mechanical system.

6. Conclusion

Robust position control scheme has been studied for the electro-mechanical system with external time-varying unknown disturbance load in this paper. The nonlinear disturbance observer is developed to estimate the external disturbance load of the electro-mechanical system and the robust position control scheme combing the feedback control with the disturbance observer has been investigated based on the output of disturbance observer. Simulation results illustrate the effectiveness of the proposed robust position control scheme of the electro-mechanical system.

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