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FINITE TIME CONTROL FOR UNCERTAIN ELECTROSTATIC MICRO-ACTUATORS WITH TERMINAL SLIDING MODE CONTROL

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Abstract. *This paper is concerned with the stabilization problem for uncertain electrostatic micro-actuators. A terminal sliding mode control scheme is proposed such that the output tracking error of electrostatic micro-actuators will converge to zero quickly. The finite time control theory is used to ensure the reaching and sustaining of sliding mode and stability of the controlled system. The performance of the proposed controller is compared with the conventional backstepping controller. Finally, simulation results show the effectiveness and robustness of the proposed method.*
Keywords: Electrostatic micro-actuator, Sliding mode control, Finite time control, Stabilization

1. **Introduction.** Micro Electromechanical System (MEMS) is a semiconductor technology integrating mechanism and electronics, which generally requires very precise position control and accurate speed control [1-3]. Electrostatic micro-actuators have gained widespread acceptance in MEMS applications, due to the simplicity of structure, ease of fabrication, and favorable scaling of electrostatic forces into the micro domain. For example, the parallel-plate electrostatic actuator is often used in MEMS systems such as micro-mirrors, variable capacitors, and accelerometers. Since these systems contain several hundred thousands of micro-actuators, robust and accurate control of the system is of significant importance in order to achieve the required performance.

One of the main problems associated with open loop voltage control of MEMS is pull-in instability. To overcome this problem, closed loop voltage control with position feedback was proposed to stabilize any point in the gap [4]. Based on the use of current pulses injecting the required amount of charge to fix the position of the movable plate, full range of travel can be achieved without voltage penalty [5,6]. Closed-loop control is able to provide stable and controllable deflection and many linear approaches have been tried. For example, the advantages and disadvantages of simple open-loop and closed-loop control strategies for electrostatic comb actuators with bi-directional drive were studied in [7], respectively. Recently, different nonlinear control techniques have been extended to the control of electrostatic micro-actuator. In [8-10], different static and dynamic output feedback controls were investigated and compared, such as input-output linearization, feedback passivation, and charge feedback schemes. However, the finite time control problem for electrostatic micro-actuator has not been discussed in these papers. Recently, terminal sliding mode control (TSMC) has been developed [11-14]. Different from conventional sliding mode control, TSMC is a finite-time control method with nonlinear terminal sliding surface. In [13], TSMC is used for designing a finite-time control law for robotic manipulators, which is extended to several kinds of systems. These results provide a basic tool for designing continuous finite-time control laws. Therefore, how to investigate the control problem of micro-actuators system under the condition of uncertainty and modelling errors, is the behind motivation of this work.

As we all know, fuzzy control schemes have been found to be particularly useful to model unknown functions in nonlinear systems rather that only unknown parameters. Fuzzy logic systems (FLSs) are employed to approximate the unknown nonlinear uncertain ties due to their universal approximation property, and many stable adaptive fuzzy control design schemes have been developed using the backstepping adaptive design technique, see [15] and the references. The backstepping design method is a constructive tool which is often used in nonlinear control [16-19]. However, the traditional backstepping algorithm requires repetitive differentiations for the nonlinear components of the model. As a consequence, many controllers are very difficult to be implemented in practice. Compared with related works, there are two main contributions that are worth to be emphasized:

i) We propose a backstepping robust tracking control scheme to deal with the uncertainties. The complexity of the designed controller is reduced and the design procedure is much simpler than that of traditional backstepping control.

ii) Based on the terminal sliding mode control and the fuzzy control scheme, we achieve the finite time control for uncertain electrostatic micro-actuators.

The organization of this paper is described as follows. In the next section, system model is derived, and the assumptions are also given. In Section 3, the design of the proposed control strategies is discussed. The simulation results are presented to demonstrate the effectiveness of proposed control scheme in Section 4. Conclusion is presented in Section 5.

2. **Problem Formulation and Preliminaries.** The micro-actuator is modeled as a parallel-plate capacitor consisting of a movable top plate and a fixed bottom plate as shown in Figure 1. The motion equations of the micro-actuator are given by [1]:

$$m\ddot{G}(t) + b\dot{G}(t) + k(G(t) - G_0) = -\frac{Q_a^2(t)}{2\varepsilon A}. \quad (1)$$

The parameters in Figure 1 are given in Table 1.

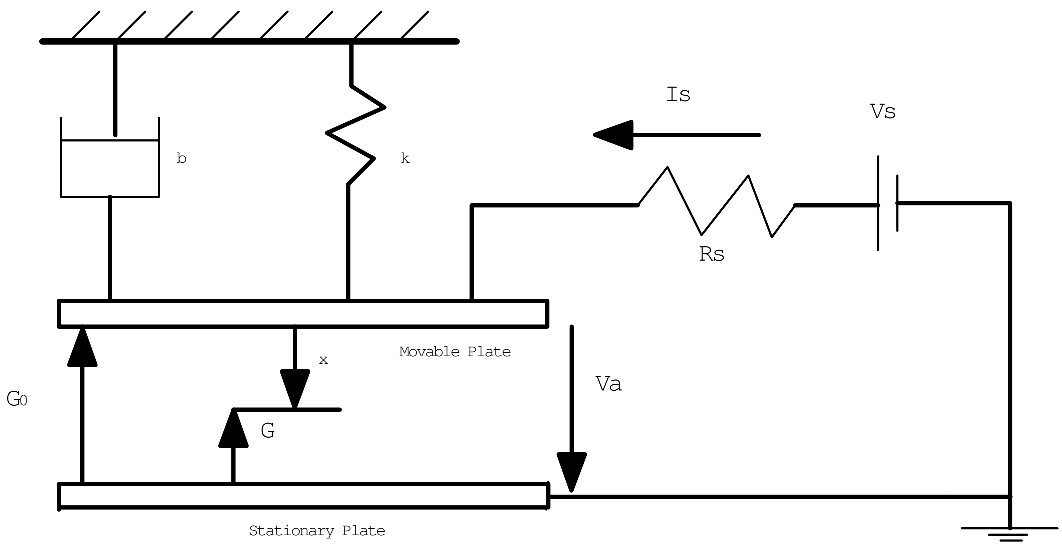

FIGURE 1. Parallel-plate electrostatic actuator

Table 1. Parameters of the micro-actuator

Parameter	Definition of the parameter
m	the mass of the moveable upper electrode
b	the damping coefficient
k	the elastic constant
V_a	the source internal resistance
R_s	the source current
I_s	the applied voltage
V_s	the actuation voltage
Q_a	the charge on the device
G	the air gap
G_0	the zero voltage gap
A	the plate area
ε	the permittivity in the gap

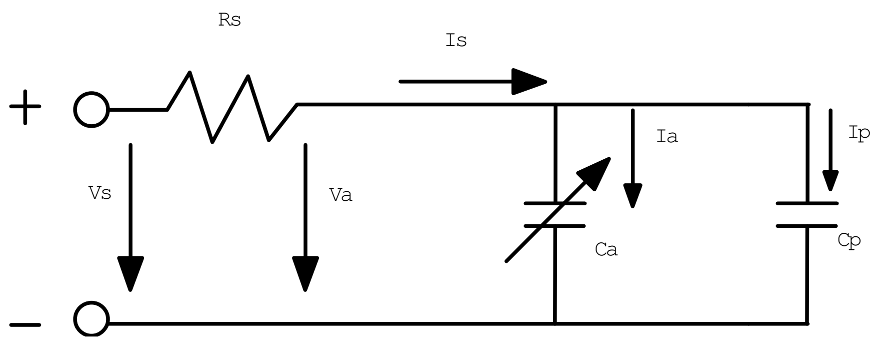

Figure 2. The equivalent circuit with parallel parasitic capacitance

The equivalent circuit of the micro-actuator device is shown in Figure 2, in which C_p denotes the parallel parasitic capacitance. In the presence of parasitics, the dynamic equation of the electrical subsystem is given by

$$\dot{Q}_a(t) = \frac{1}{R_s(1+\rho G/G_0)}\left\{V_s - \left\{\frac{G}{\varepsilon A} + R_s\rho\frac{\dot{G}}{G_0}\right\}Q_a\right\}, \tag{2}$$

where $\rho = \frac{C_p}{C_0}$ with $C_0 = \frac{\varepsilon A}{G_0}$ the capacitance of device at rest.

In order to make the system analysis and control design easier, (2) is normalized by changing the time scale $\tau = \omega_0 t$, $\omega_0 = \sqrt{k/m}$, and we redefine some new variables as follows [19]:

$$x_1 = 1 - \frac{G}{G_0},\ x_2 = \dot{x}_1,\ x_3 = \frac{Q_a^2}{Q_{pi}^2},\ u = \frac{V_s}{V_{pi}},\ r = \omega_0 C_0 R_s,\ \nu = \frac{b}{2m\omega_0},$$

where V_{pi} is the pull-in voltage, Q_{pi} is the pull-in charge. So, the systems (1) and (2) can be rewritten as follows:

$$\begin{cases} \dot{x}_1 = x_2, \\ \dot{x}_2 = 2\nu x_2 - x_1 + \frac{x_3}{3}, \\ \dot{x}_3 = f(x) + \frac{4\sqrt{x_3}}{3}\beta(x_1)u + d(t,x), \end{cases} \tag{3}$$

where $x = [x_1, x_2, x_3]^T$, $f(x) = -2x_3(1-x_1)\beta(x_1) + 2r\rho x_2 x_3 \beta(x_1)$, $\beta(x_1) = \frac{1}{r[1+\rho(1-x_1)]}$. Note that the state x in system (3) is defined on the state space: $\Omega = \left\{(x_1, x_2, x_3)|x_1 \in [0,l], x_3 > 0\right\}$, $d(t,x)$ contains both parametric uncertainties and external disturbance.

Also, we let the system output $y = x_1$. Besides, the following assumptions and lemmas are valid throughout this paper:

Assumption 2.1. *x_1, x_2 and x_3 are all measurable and bounded.*

Assumption 2.2. *The reference trajectory x_{1d} and its n-order derivatives is known and bounded, $n = 1, 2, \cdots$.*

Assumption 2.3. *$d(t,x)$ and $f(x)$ are assumed unknown, but bounded. Let $F(t,x) = f(x) + d(t,x)$ and $|F(t,x)| < \bar{F}$, $\bar{F}$ is satisfied with $\bar{F} - |F| > \varepsilon_0$ where $\varepsilon_0 > 0$.*

Assumption 2.4. *$F^* - \bar{F} = \varepsilon$ and $|\varepsilon| < \varepsilon_0$, $F^* = \theta^{*T}\psi(x)$, θ^* is the best estimated value and $||\theta^*|| \le \alpha$, the $\psi(x)$ is the fuzzy basis vector (see [16]), $\hat{\bar{F}} = \hat{\theta}^T\psi(x)$ is the estimate of $\bar{F}$, $\hat{\theta}$ is the adjustable parameter vectors of fuzzy system.*

Lemma 2.1. [15] *Assume that a continuous, positive-definite function $V(t)$ satisfies the following differential inequality:*

$$\dot{V}(t) \le -cV^{\eta}(t),\ t \ge t_0,\ V(t_0) \ge 0$$

where $c > 0$, $0 < \eta < 1$ are two constants. Then, for any given t_0, $V(t)$ satisfies the following inequality:

$$V^{(1-\eta)}(t) \le V^{(1-\eta)}(t_0) - c(1-\eta)(t - t_0),\ t_0 \le t \le t_1$$

and $V(t) \equiv 0$, $t \ge t_1$ with t_1 given by $t_1 = t_0 + \frac{V^{1-\eta}(t_0)}{c(1-\eta)}$.

Lemma 2.2. [15] *For any real numbers $c_1 > 0$, $c_2 > 0$, $0 < \eta < 1$, an extended Lyapunov condition of finite-time stability can be given in the form as $\dot{V}(x) + c_1V(x) + c_2V^{\eta}(x) \le 0$, where the settling time satisfies $T \le \frac{1}{c_1(1-\eta)} \ln \frac{c_1V(0)^{1-\eta}+c_2}{c_2}$, $V(0)$ is the initial value of $V(x)$.*

Remark 2.1. *Unlike [1], $F(t,x)$ here is assumed unknown, we employ fuzzy systems to estimate the upper boundary $\bar{F}$.*

3. Main Results.

Let $e_1 = x_1 - x_{1d}$ and $e_2 = x_2 - \dot{x}_{1d}$, system (3) can be described as

$$\begin{cases} \dot{e}_1 = e_2, \\ \dot{e}_2 = 2\nu(e_2 + \dot{x}_{1d}) - (e_1 + x_{1d}) + \frac{x_3}{3} - \ddot{x}_{1d}, \\ \dot{x}_3 = f(x) + \frac{4\sqrt{x_3}}{3}\beta(x_1)u + d(t,x). \end{cases} \tag{4}$$

In the following, the backstepping design technique is applied to obtaining control law of system (4). The design procedure is divided into three steps shown as follows.

Step 1: From (4), treat the system state e_2 as an independent input and let

$$e_2 = g_1(e_1) = -k_1|e_1|^{\gamma_1}\text{sign}(e_1),\ k_1 > 0,\ 0 < \gamma_1 < 1, \tag{5}$$

where $g_1(e_1)$ is defined as a desired virtual stabilizing algorithm. Select a Lyapunov function $V_1 = \frac{1}{2}e_1^2$, and then

$$\dot{V}_1 = e_1\dot{e}_1 = -k_1|e_1|^{\gamma_1+1} = -2k_1V_1^{\frac{\gamma_1+1}{2}}. \tag{6}$$

According to Lemma 2.1, e_1 will converge to zero in finite time.

Step 2: In practice, e_2 may be different from $g_1(e_1)$ for all time. Therefore, define a new error variable $z_1 = e_2 - g_1(e_1)$. The derivative of z_1 is expressed as

$$\dot{z}_1 = 2\nu(e_2 + \dot{x}_{1d}) - (e_1 + x_{1d}) + \frac{x_3}{3} - \ddot{x}_{1d} - \dot{g}_1(e_1). \tag{7}$$

Take the state x_3 as an independent input of the form $g_2(e_2, z_1)$ as the following

$$x_3 = g_2(e_2, z_1) = -3(2\nu(e_2 + \dot{x}_{1d}) - (e_1 + x_{1d}) - \ddot{x}_{1d} - \dot{g}_1(e_1) + k_2|z_1|^{\gamma_2}\text{sign}(z_1)), \tag{8}$$

where $k_1 > 0$, $0 < \gamma_2 < 1$. Select a Lyapunov function $V_2 = \frac{1}{2}z_1^2$, and then

$$\dot{V}_2 = -2k_2 V_2^{\frac{\gamma_2+1}{2}}. \tag{9}$$

Similarly, according to Lemma 2.1, z_1 will converge to zero in finite time.

Step 3: Following Steps 1 and 2, we define a new error variable $z_2 = x_3 - g_2(e_2, z_1)$, the derivative of z_2 is expressed as

$$\dot{z}_2 = F(t,x) + \frac{4\sqrt{x_3}}{3}\beta(x_1)u - \dot{g}_2. \tag{10}$$

To obtain the finite-time convergence of the z_2 on the sliding surface, the sliding manifold is selected as follows

$$s = z_2 + k_3\int_0^t z_2 \mathrm{d}\tau + k_4\int_0^t |z_2|^{\gamma_3}\mathrm{sign}(z_2)\mathrm{d}\tau, \tag{11}$$

where $k_3, k_4 > 0$, $0 < \gamma_3 < 1$.

Next, we propose the control law as

$$u = \frac{3}{4\sqrt{x_3}\beta(x_1)}(u_n + u_r), \tag{12}$$

where $u_n = \dot{g}_2 - \hat{\bar{F}}$, $u_r = -k_3 z_2 - k_4|z_2|^{\gamma_3}\mathrm{sign}(z_2) - k_5|s|^{\gamma_4}\mathrm{sign}(s) - \frac{k_6}{s}\left(||\hat{\theta}|| + \alpha\right)^{\gamma_4+1}$, where $0 < \gamma_4 < 1$, $k_5, k_6 > 0$. Letting $\tilde{\theta} = \theta^* - \hat{\theta}$, the parameter $\dot{\hat{\theta}}$ is updated by the following

$$\dot{\hat{\theta}} = s\psi(x). \tag{13}$$

Theorem 3.1. *By using the control law (12) with update law (13), the state z_2 will reach the sliding surface $s = 0$ in finite time.*

Proof: Select a Lyapunov function

$$V_3 = \frac{1}{2}s^2 + \frac{1}{2}\tilde{\theta}^T\tilde{\theta}. \tag{14}$$

Then we obtain $V_3 > 0$ and its derivative is expressed as

$$\begin{aligned}\dot{V}_3 &= s\left\{\dot{z}_2 + k_3 z_2 + k_4|z_2|^{\gamma_3}\mathrm{sign}(z_2)\right\} + \tilde{\theta}^T\dot{\tilde{\theta}} \\ &= s\left\{F(t,x) + \frac{4\sqrt{x_3}}{3}\beta(x_1)u - \dot{g}_2 + k_3 z_2 + k_4|z_2|^{\gamma_3}\mathrm{sign}(z_2)\right\} - \tilde{\theta}^T\dot{\hat{\theta}}.\end{aligned} \tag{15}$$

Substituting (12) into the above Equation (15), it yields

$$\begin{aligned}\dot{V}_3 &= s\left\{F(t,x) - \hat{\bar{F}} - k_5|s|^{\gamma_4}\mathrm{sign}(s) - \frac{k_6}{s}\left(||\hat{\theta}|| + \alpha\right)^{\gamma_4+1}\right\} + \tilde{\theta}^T\dot{\tilde{\theta}} \\ &= s\left\{F(t,x) + F^* - F^* - \hat{\bar{F}} + \bar{F} - \bar{F} - k_5|s|^{\gamma_4}\mathrm{sign}(s) - \frac{k_6}{s}\left(||\hat{\theta}|| + \alpha\right)^{\gamma_4+1}\right\} - \tilde{\theta}^T\dot{\hat{\theta}} \\ &\le s\left\{|F(t,x)| - \bar{F} + F^* - \hat{\bar{F}} - F^* + \bar{F} - k_5|s|^{\gamma_4}\mathrm{sign}(s) - \frac{k_6}{s}\left(||\hat{\theta}|| + \alpha\right)^{\gamma_4+1}\right\} - \tilde{\theta}^T\dot{\hat{\theta}} \\ &\le s\left\{-\varepsilon_0 - \varepsilon + \tilde{\theta}^T\psi(x) - k_5|s|^{\gamma_4}\mathrm{sign}(s) - \frac{k_6}{s}\left(||\hat{\theta}|| + \alpha\right)^{\gamma_4+1}\right\} - \tilde{\theta}^T\dot{\hat{\theta}} \\ &\le \tilde{\theta}^T\left(s\psi(x) - \dot{\hat{\theta}}\right) + s\left(|\varepsilon| - \varepsilon_0\right) - k_5|s|^{\gamma_4+1} - k_6\left(||\hat{\theta}|| + \alpha\right)^{\gamma_4+1}.\end{aligned}$$

Due to $||\hat{\theta}-\theta^*|| \leq ||\hat{\theta}||+\alpha$, we have $-k_6\left(||\hat{\theta}||+\alpha\right)^{\gamma_4+1} \leq -k_6||\hat{\theta}-\theta^*||^{\gamma_4+1}$. Substituting (13) into above equation, we obtain

$$\begin{aligned}\dot{V}_3 \leq & -k_5|s|^{\gamma_4+1} - k_6||\hat{\theta}-\theta^*||^{\gamma_4+1} \leq -2\min\{k_5,k_6\}\left(\frac{(s^2)^{\frac{\gamma_4+1}{2}}}{2} + \frac{(\tilde{\theta}^T\tilde{\theta})^{\frac{\gamma_4+1}{2}}}{2}\right) \\ \leq & -2\min\{k_5,k_6\}\left(\frac{s^2}{2}+\frac{\tilde{\theta}^T\tilde{\theta}}{2}\right)^{\frac{\gamma_4+1}{2}} = -2\min\{k_5,k_6\}V_3^{\frac{\gamma_4+1}{2}}.\end{aligned}$$

Therefore, according to Lemma 2.1, the conclusion holds.

Theorem 3.2. *Tracking error z_2 on the surface $s=0$ can converge to equilibrium $z_2=0$ in finite time.*

Proof: When tracking error z_2 reaches the surface $s=0$, we obtain

$$\dot{s} = \dot{z}_2 + k_3 z_2 + k_4|z_2|^{\gamma_4}\text{sign}(z_2) = 0.$$

Defining Lyapunov function as $V_4 = \frac{z_2^2}{2}$, its derivative is expressed as

$$\dot{V}_4 = z_2\dot{z}_2 = -k_3 z_2^2 - k_4|z_2|^{\gamma_3+1} \leq -2\min\{k_3,k_4\}V_4 - 2^{\frac{\gamma_3+1}{2}}\min\{k_3,k_4\}V_4^{\frac{\gamma_3+1}{2}}.$$

According to Lemma 2.2, the conclusion holds.

Theorem 3.3. *The system (4) is controlled by the control law (12) with the adaptive law (13), the error state e_1 will converge to equilibrium point in finite time T, and T satisfies*

$$T \leq \frac{2V_5(0)^{\frac{1-\frac{\epsilon}{2}}{2}}}{\mu(2-\epsilon)},$$

where $\epsilon = \min\{1+\gamma_1, 1+\gamma_2, 1+\gamma_3, 1+\gamma_4\}$, $0<\epsilon<1$ *and*

$$\mu = \min\left\{2k_1, 2k_2, 2^{\frac{\gamma_3+1}{2}}\min\{k_3+k_4\}, 2\min\{k_5,k_6\}\right\}.$$

Proof: Define Lyapunov function as $V_5 = V_1+V_2+V_3+V_4$. Then

$$\begin{aligned}\dot{V}_5 \leq & -2k_1V_1^{\frac{\gamma_1+1}{2}} - 2k_1V_2^{\frac{\gamma_2+1}{2}} - 2\min\{k_5,k_6\}V_3^{\frac{\gamma_4+1}{2}} - 2^{\frac{\gamma_3+1}{2}}\min\{k_3+k_4\}V_4^{\frac{\gamma_3+1}{2}} \\ \leq & -\mu V_1^{\frac{\epsilon}{2}} - \mu V_2^{\frac{\epsilon}{2}} - \mu V_3^{\frac{\epsilon}{2}} - \mu V_4^{\frac{\epsilon}{2}} \leq -\mu\{V_1+V_2+V_3+V_4\}^{\frac{\epsilon}{2}} = -\mu V_5^{\frac{\epsilon}{2}}.\end{aligned}$$

According to Lemma 2.1, the conclusion holds.

Remark 3.1. *If $F(t,x)$ is known, we can design*

$$u = \frac{3}{4\sqrt{x_3}\beta(x_1)}(-F(t,x)+\dot{g}_2 - k_7|z_2|^{\gamma_5}\text{sign}(z_2))$$

to satisfy e_1 converge to zero in finite time.

4. **Simulation Studies.** In this section, the proposed control scheme is applied to controling electrostatic micro-actuators system. The parameters of electrostatic micro-actuators system are given as $r=0.8$, $\rho=0.1$, $\nu=1$, $d(t,x)=0.1+\sin(2tx_1)$, $x(0)=[0.1,0.1,0.1]^T$, $x_d = 0.8+0.2\cos(2t)$. The main design parameters $k_i=3$, $\gamma_j=\frac{3}{5}$, $i=1,2,\cdots,6$, $j=1,2,3,4$. Firstly, we use the method of [18] to control electrostatic micro-actuators system, and the control law is designed as follows:

$$u = \frac{3}{4\sqrt{x_3}\beta(x_1)}\left(\dot{h}_2 - \hat{\bar{F}} - k_4\xi_2 - k_5 s_1\right), \quad (16)$$

where $h_2 = -3\left(2\nu(e_2+\dot{x}_{1d}) - (e_1+x_{1d}) - \ddot{x}_{1d} - \dot{h}_1 + k_2\xi_1\right)$, $h_1 = -k_1e_1$, $\xi_1 = e_1 - h_1$, $\xi_2 = e_2 - h_2$ and $s_1 = \xi_2 + k_3\int_0^t \xi_2(\tau)\mathrm{d}\tau$, $\dot{\hat{\theta}} = s\psi(x)$.

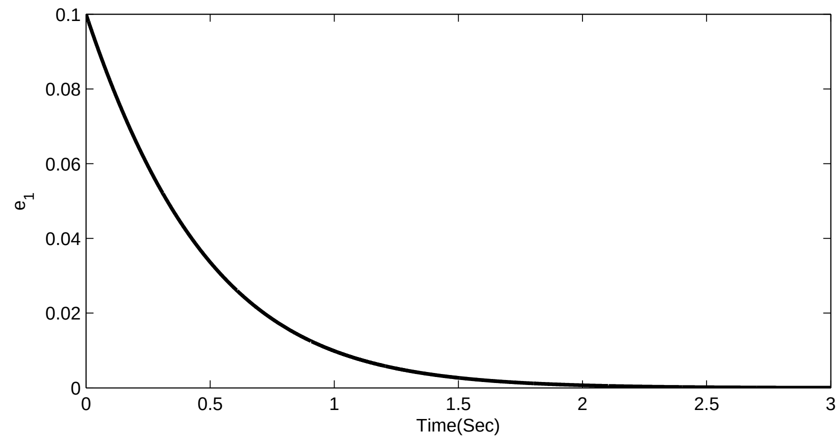

FIGURE 3. Time response of e_1 with the control scheme (16)

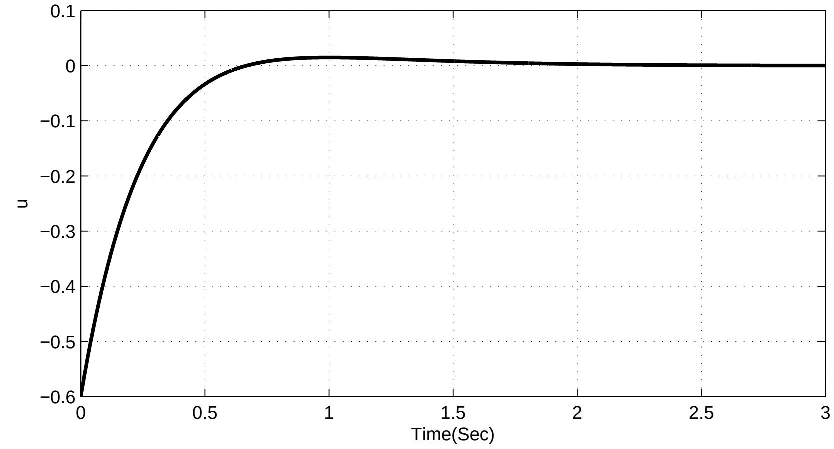

FIGURE 4. Time response of u with the control scheme (16)

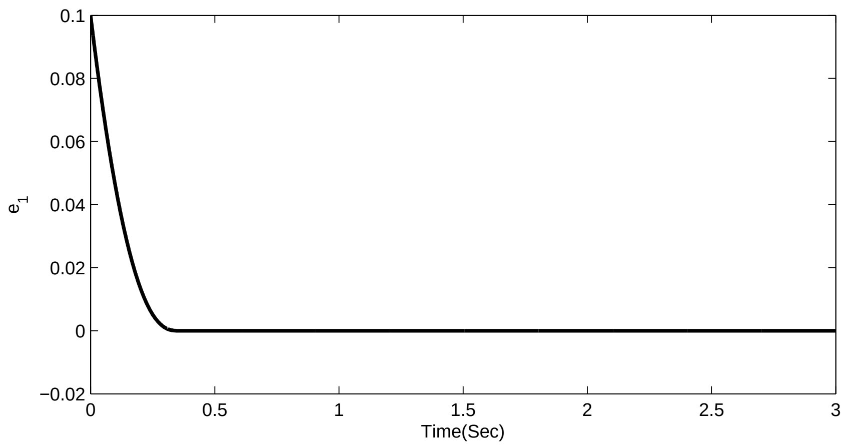

FIGURE 5. Time response of e_1 with the control scheme (12)

The Gaussian membership functions are assigned to x_i over interval $[-3, 3]$, and each of the fuzzy systems use 7^2 fuzzy rules to model $\hat{F}(x, \theta)$:
$\mu_{A_i^1} = \exp\left[\frac{-(x+3)^2}{2}\right]$, $\mu_{A_i^2} = \exp\left[\frac{-(x+2)^2}{2}\right]$, $\mu_{A_i^3} = \exp\left[\frac{-(x+1)^2}{2}\right]$, $\mu_{A_i^4} = \exp\left[\frac{-(x+0)^2}{2}\right]$, $\mu_{A_i^5} = \exp\left[\frac{-(x-1)^2}{2}\right]$, $\mu_{A_i^6} = \exp\left[\frac{-(x-2)^2}{2}\right]$, $\mu_{A_i^7} = \exp\left[\frac{-(x-3)^2}{2}\right]$. Under the same system's

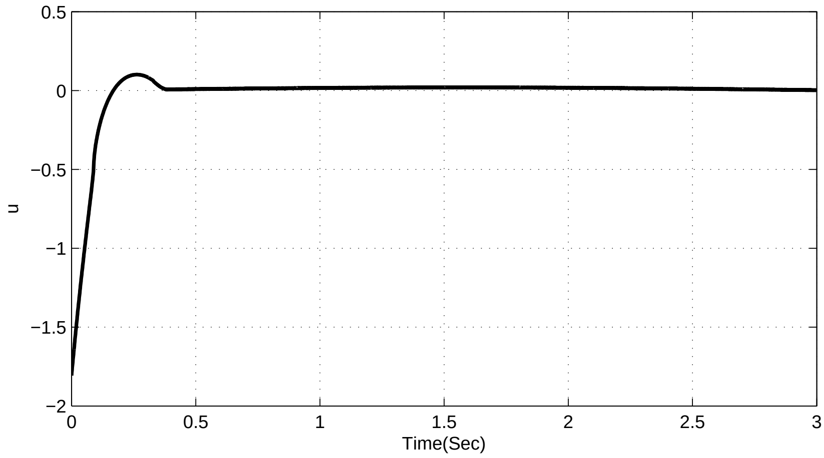

Figure 6. Time response of u with the control scheme (12)

parameters, the time response of e_1 and u with the control scheme (16) are shown in Figures 3 and 4.

Now, by using the present control scheme (12), the time responses of the error state e_1 and controller u are shown in Figure 5 and Figure 6, respectively. Obviously, the effectiveness of the present control scheme (12) is better than the control law (16). Thus, the numerical simulations verify theoretical analysis.

5. **Conclusion.** In this paper, the robust control scheme for controlling uncertain electrostatic micro-actuators is proposed. Based on the rigorous mathematical analysis and finite time control theory, the controller design was integrated with the TSMC via backstepping design such that the uncertain electrostatic micro-actuators state is driven to a reference trajectory. Simulation results demonstrate that the proposed controller is able to stabilize the uncertain electrostatic micro-actuators in finite time. Fuzzy adaptive prescribed performance control for uncertain electrostatic micro-actuators is our next research direction.

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