Robust adaptive control approach for pneumatic artificial muscle system with actuator faults

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ABSTRACT

In this work, the angle tracking algorithm for a pneumatic artificial muscle-actuated mechanism is studied. The control system is subject to both multiplicative and additive actuator faults. Lyapunov synthesis is used to design controller. The uncertainties and external disturbances are dealt with according to robust adaptive strategy. The filtering error of closed-loop system may converge to the small neighour of origin even if both multiplicative and additive actuator faults happen.

Keywords: Adaptive control, pneumatic artificial muscle, actuator faults

1. INTRODUCTION

Pneumatic artificial muscle (PAM) is a special actuator with a tube shape. By inflating/deflating compressed air, it can mimic human muscles' functions to some extent[1,2]. PAM actuator has some prominent advantages, inclusive of rapid response, low cost and high power weight ratio, so that it can be seen as one of the most promising actuator at present. On the other hand, there exist some complicated inherent characteristics in PAM systems, such that achieving high-precision control is not an easy job for PAM systems.

To get good performances of PAM systems, scholars have taken advantage of numerous control technique in PAM control system design over the past two decades. In Reference[3], PID control algorithm for PAM systems is discussed. In Reference[4], the tracking control of PAM actuators is solved by employing sliding mode control and disturbance observer. In Reference[5], Cai et al. investigated output-feedback adaptive control for PAM systems with saturation input. In Reference[6], Xie et al. proposed iterative fuzzy control for pneumatic muscle driven rehabilitation robot. In Reference[7], Guo et al. present an adaptive learning control algorithm for a PAM actuated mechanism. None of above results has considered the controller design while there exist potential system faults. Obviously, the performance degradation of PAM systems must arise if no proper action is taken once the system faults occur[8,9].

Motivated by the above discussion, we study the angle tracking control design for a PAM-actuated mechanism， whose actuator is subject to both multiplicative and additive actuator faults. Robust adaptive control approach is adopted to compensate for uncertainties and external disturbances. The filtering error of closed-loop system may converge to the small neighour of origin even if both multiplicative and additive actuator faults happen.

2. PROBLEM FORMULATION

The control system structure of a PAM-actuated mechanism is shown in Figure 1.

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Third International Conference on Computer Science and Communication Technology (ICCSCT 2022)
edited by Yingfa Lu, Changbo Cheng, Proc. of SPIE Vol. 12506, 125065G
 · doi: 10.1117/12.2661954

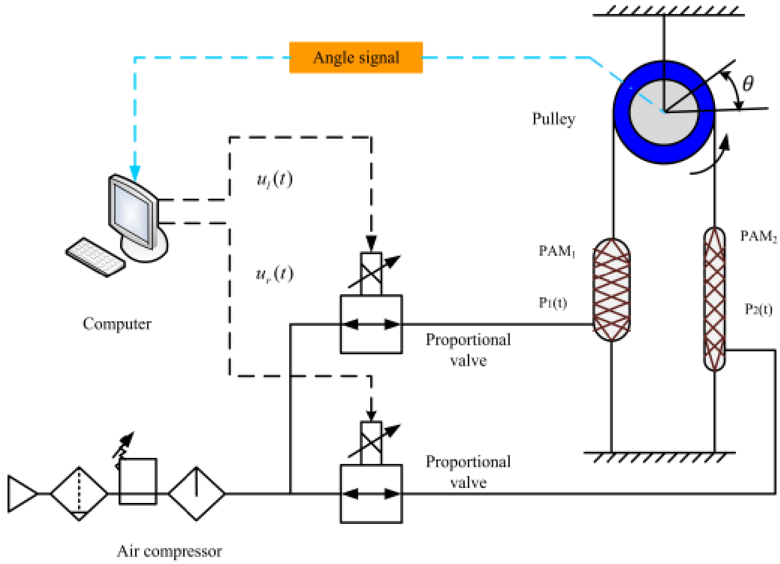

Figure 1. Control system structure of the PAM-actuated mechanism.

The relationship between the driving moment of this mechanism and the pulling forces is described as follows:

$$T(t) = J\ddot{\theta} + b_v\dot{\theta} + F_1(t)r - F_2(t)r + d \quad (1)$$

The internal pressures of two pneumatic muscles can be determined by the control input according to equations (2) and (3).

$$P_1(t) = c_0 u_l(t), u_l(t) = u_0 + c_u u(t) \quad (2)$$

$$P_2(t) = c_0 u_r(t), u_r(t) = u_0 - c_u u(t) \quad (3)$$

The pulling forces $F_1(t)$ and $F_2(t)$ are caused by the internal pressures $P_1(t)$ and $P_2(t)$ as follows:

$$F_1(t) = P_1(t)(c_1\varepsilon_1^2(t) + c_2\varepsilon_1 + c_3) + \varepsilon_4 \text{ and } F_2(t) = P_2(t)(c_1\varepsilon_2^2(t) + c_2\varepsilon_2 + c_3) + \varepsilon_4, \quad (4)$$

where $\varepsilon_1(t) = \varepsilon_0 + rl_0^{-1}\theta(t)$ and $\varepsilon_2(t) = \varepsilon_0 - rl_0^{-1}\theta(t)$. The representations of such variables and parameters are given in Table 1.

From equations (1)-(4), we have

$$\begin{aligned}\ddot{\theta}(t) &= -\frac{b_v}{J}\dot{\theta}(t) + \frac{2k_0u_0r^2(2c_1\varepsilon_0 + c_2)l_0^{-1}}{J}\theta(t) + \frac{2k_0u_0r(c_1\varepsilon_0^2 + c_2\varepsilon_0 + c_3)}{J}u(t) + d(t) \\ &= \omega_1\theta(t) + \omega_2 u(t) + d_s(t)\end{aligned} \quad (5)$$

where $\omega_1 = \frac{2k_0u_0r^2(2c_1\varepsilon_0 + c_2)l_0^{-1}}{J}, \omega_2 = \frac{2k_0u_0r(c_1\varepsilon_0^2 + c_2\varepsilon_0 + c_3)}{J}$, $d_s(t) = -\frac{b_v}{J}\dot{\theta}(t) + d(t)$. In this work, the control input of pneumatic muscle joint is subject to actuator faults, which are formulated by

$$u(t) = \rho v(t) + \phi \quad (6)$$

where $v(t)$ is the real control input signal to be designed. ρ represents the multiplicative actuator fault, and

ϕ represents the additive actuator fault. We assume $\rho \geq \rho_{\min} > 0$, where $\rho_{\min}$ is an unknown positive constant.

By letting $x_1(t) = \theta(t), x_2(t) = \dot{\theta}(t), y(t) = x_1(t)$, we have

$$\begin{cases} \dot{x}_1(t) = x_2(t), \\ \dot{x}_2(t) = \omega_1 x_1(t) + \rho\omega_2 v(t) + \phi\omega_2 + d_s(t), \\ \text{y(t)}=x_1(t), \end{cases} \tag{7}$$

The control task of our work is to derive the precise trajectory tracking from y to desired trajectory y_d.

Table 1. The representations of parameters.

Symbol	Definition
T	Driving moment of mechanism
J	Moment of inertia
θ	Rotation angle of pneumatic muscle joint
b_v	Damping coefficient
d	External disturbance
r	Radius of pneumatic muscle joint
F_1 , F_2	Pulling forces
c_1 - c_4	Parameters in mathematical model of aerodynamic muscle
ε_1 , ε_2	Contraction rate of pneumatic muscle
P_1 , P_2	Pressure value of pneumatic muscle
ε_0	Initial contraction rate of pneumatic muscle
l_0	Initial length of pneumatic muscle
c_0	Proportionality factor
c_u	Voltage coefficient
u_0	Initial voltage
u_l , u_r	Input control voltages of pressure proportional valves
u	Control input

3. CONTROLLER DESIGN

Let $x_{1,d} = y_d, x_{2,d} = \dot{y}_d, e_1 = x_1 - x_{1,d}, e_2 = x_2 - x_{2,d}$. According to equations (6) and (7), we have

$$\begin{cases} \dot{e}_1 = e_2, \\ \dot{e}_2 = \omega_1 x_1(t) + \rho\omega_2 v(t) + \phi\omega_2 + d_s(t) - \dot{x}_{2,d} \end{cases} \tag{8}$$

Let us define $s = \lambda_s e_1 + e_2$, with $\lambda > 0$.

$$\dot{s} = \lambda_s e_2 + \omega_1 x_1(t) + \rho\omega_2 v(t) + \phi\omega_2 + d_s(t) - \dot{x}_{2,d} \tag{9}$$

Let $V_1 = \frac{1}{2\eta} s^2$, where $\eta = \rho_{\min}\omega_2$. By taking the time derivative of V_2, we get

$$\begin{aligned}\dot{V}_1 &= s(\frac{1}{\eta}\lambda_s e_2 - \frac{\omega_1}{\eta}x_1(t) - \frac{1}{\eta}\dot{x}_{2,d}) + s(\frac{\phi}{\rho_{\min}} + \frac{d_s}{\eta}) + \frac{\rho}{\rho_{\min}}sv \\ &= sp^T\varphi + s(\frac{\phi}{\rho_{\min}} + \frac{d_s}{\eta}) + \frac{\rho}{\rho_{\min}}sv\end{aligned} \tag{13}$$

where $p = [\frac{1}{\eta}\lambda_s, -\frac{\omega_1}{\eta}, -\frac{1}{\eta}\dot{x}_{2,d}]^T, \varphi = [e_2, x_1(t), 1]^T$. Without loss of generality, we assume

$$|\frac{\phi}{\rho_{\min}} + \frac{d_s}{\eta}| \le \lambda_0 + \lambda_1 \| x \| + \lambda_2 \| x \|^2 \tag{14}$$

where λ_0, λ_1 and λ_2 are unknown positive constants.

$$\dot{V}_1 \le sp^T\varphi + |s|(\lambda_0 + \lambda_1 \| x \| + \lambda_1 \| x \|^2) + \frac{\rho}{\rho_{\min}}sv \tag{15}$$

Let $v_a = -\hat{p}^T\varphi$. Substituting $v = v_a + v_r$ into equation (15) yields

$$\begin{aligned}\dot{V}_1 &\le s(p^T\varphi + v_a) + s|(\lambda_0 + \lambda_1 \| x \| + \lambda_2 \| x \|^2) + \frac{\rho}{\rho_{\min}}sv_r + \frac{\rho - \rho_{\min}}{\rho_{\min}}sv_a \\ &\le s(p^T\varphi + v_a) + |s|(\lambda_0 + \lambda_1 \| x \| + \lambda_2 \| x \|^2) + \frac{\rho}{\rho_{\min}}sv_r + \beta |s| \cdot |v_a|\end{aligned} \tag{16}$$

where $\beta := \sup(\frac{\rho - \rho_{\min}}{\rho_{\min}})$. Let $\vartheta = \left[\lambda_0, \ \lambda_1, \ \lambda_2, \beta\right]^T$, $\mathrm{w}(x, v_p) = \left[1, \| x_k \|, \| x_k \|^2, | v_a |\right]^T$. It follows that

$$\dot{V}_1 \le s(p^T\varphi + v_a) + |s| \vartheta^T w(x, v_a) + \frac{\rho}{\rho_{\min}}sv_r \tag{17}$$

Then, we design the controller as

$$v = -\gamma_0 s + v_a + v_r, \tag{18}$$

$$v_a = -\hat{p}^T\varphi, \tag{19}$$

$$v_r = -\hat{\vartheta}^T w(x, v_a) \tan(\frac{s\hat{\vartheta}^T w(x, v_a)}{\varepsilon_v}) \tag{20}$$

$$\dot{\hat{p}} = \gamma_1 s\varphi - h_1\gamma_1\hat{p}, \tag{21}$$

$$\dot{\hat{\vartheta}} = \gamma_2 |s| w(x, v_a) - h_2\gamma_2\hat{\vartheta}, \tag{22}$$

where $\gamma_0 > 0, \gamma_1 > 0, \gamma_2 > 0, h_1 > 0, h_2 > 0, \varepsilon_v > 0.$

4. CONVERGENCE ANALYSIS

Theorem 1: For the closed-loop system comprised of equations (1), (18)-(22), all signals are bounded, and the system is stable in the meaning that

$$\lim_{t\to\infty} |s(t)| \leq \sqrt{\frac{2\eta\mu_2}{\mu_1}} \tag{23}$$

The definitions of μ_1 and μ_2 are available in (31).

Proof:

By substituting equation (18) into equation (17), we have

$$\begin{aligned}
\dot{V}_1 &\leq -\gamma_0 s^2 + s\tilde{p}^T\varphi + |s|\,\vartheta^T w(x,v_a) - s\hat{\vartheta}^T w(x,v_a)\tan\left(\frac{s\hat{\vartheta}^T w(x,v_a)}{\varepsilon_v}\right) \\
&= -\gamma_0 s^2 + s\tilde{p}^T\varphi + |s|\,\vartheta^T w(x,v_a) - |s|\,\hat{\vartheta}^T w(x,v_a) + |s|\,\hat{\vartheta}^T w(x,v_a) - s\hat{\vartheta}^T w(x,v_a)\tan\left(\frac{s\hat{\vartheta}^T w(x,v_a)}{\varepsilon_v}\right) \\
&= -\gamma_0 s^2 + s\tilde{p}^T\varphi + |s|\,\tilde{\vartheta}^T w(x,v_a) + |s|\,\hat{\vartheta}^T w(x,v_a) - s\hat{\vartheta}^T w(x,v_a)\tan\left(\frac{s\hat{\vartheta}^T w(x,v_a)}{\varepsilon_v}\right)
\end{aligned} \tag{24}$$

By Lemma 1, we obtain

$$|s|\,\hat{\vartheta}^T w(x,v_a) - s\hat{\vartheta}^T w(x,v_a)\tan\left(\frac{s\hat{\vartheta}^T w(x,v_a)}{\varepsilon_v}\right) \leq |s\hat{\vartheta}^T w(x,v_a)| - s\hat{\vartheta}^T w(x,v_a)\tan\left(\frac{s\hat{\vartheta}^T w(x,v_a)}{\varepsilon_v}\right) \leq 0.2785\varepsilon_v \tag{25}$$

Then, combining equation (23) with equation (24) leads to

$$\dot{V}_1 \leq -\gamma_0 s^2 + s\tilde{p}^T\varphi + |s|\,\tilde{\vartheta}^T w(x,v_a) + 0.2785\varepsilon_v \tag{26}$$

Define a Lyapunov function as

$$V_2 = V_1 + \frac{\tilde{p}^T\tilde{p}}{2\gamma_1} + \frac{\tilde{\vartheta}^T\tilde{\vartheta}}{2\gamma_2},$$

A direct calculation gives

$$\begin{aligned}
\dot{V}_2 &\leq -\gamma_0 s^2 + s\tilde{p}^T\varphi + |s|\,\tilde{\vartheta}^T w(x,v_a) + 0.2785\varepsilon_v + \frac{1}{\gamma_1}\tilde{p}^T(-(\gamma_1 s\varphi - h_1\gamma_1\hat{p})) \\
&\quad + \frac{1}{\gamma_2}\tilde{\vartheta}^T(-(\gamma_2|s|\,w(x,v_a) - h_2\gamma_2\hat{\vartheta})) \\
&\leq -\gamma_0 s^2 + 0.2785\varepsilon_v + \tilde{p}^T h_1(p-\tilde{p}) + \tilde{\vartheta}^T h_2(\vartheta-\tilde{\vartheta})
\end{aligned} \tag{27}$$

Using basic algebra operations, we have

$$\begin{aligned}
&\tilde{p}^T h_1(p-\tilde{p}) \\
&= -h_1\tilde{p}^T\tilde{p} + h_1\tilde{p}^T p - h_1 p^T p + h_1 p^T p \\
&= -\frac{h_1}{2}\tilde{p}^T\tilde{p} - \frac{h_1}{2}(\tilde{p}-p)^T(\tilde{p}-p) + \frac{h_1}{2}p^T p
\end{aligned} \tag{28}$$

and

$$\begin{aligned}&\tilde{\vartheta}^T h_2(\vartheta-\tilde{\vartheta})\\&=-h_2\tilde{\vartheta}^T\tilde{\vartheta}+h_2\tilde{\vartheta}^T\vartheta-h_2\vartheta^T\vartheta+h_2\vartheta^T\vartheta\\&=-\frac{h_2}{2}\tilde{\vartheta}^T\tilde{\vartheta}-\frac{h_2}{2}(\tilde{\vartheta}-\vartheta)^T(\tilde{\vartheta}-\vartheta)+\frac{h_2}{2}\vartheta^T\vartheta\end{aligned} \tag{29}$$

According to equations (28) and (29, we obtain

$$\begin{aligned}\dot{V}_2&\le -2\eta\gamma_0(\frac{1}{2\eta}s^2)-h_1\gamma_1\cdot\frac{1}{2\gamma_1}\tilde{p}^T\tilde{p}-h_2\gamma_2\cdot\frac{1}{2\gamma_2}\tilde{\vartheta}^T\tilde{\vartheta}+0.2785\varepsilon_v+\frac{h_1}{2}p^Tp+h_2\vartheta^T\vartheta\\&\le-\min(2\eta\gamma_0,h_1\gamma_1,h_2\gamma_2)\cdot V_2+0.2785\varepsilon_v+\frac{h_1}{2}p^Tp+h_2\vartheta^T\vartheta\\&=-\mu_1V_2+\mu_2\end{aligned} \tag{30}$$

where

$$\mu_1=\min(2\eta\gamma_0,h_1\gamma_1,h_2\gamma_2),\ \mu_2=0.2785\varepsilon_v+\frac{h_1}{2}p^Tp+h_2\vartheta^T\vartheta\,. \tag{31}$$

From equation (30), we have

$$V_2(t)\ \le \mathrm{e}^{-\mu_1 t}[V_2(0)-\frac{\mu_2}{\mu_1}]+\frac{\mu_2}{\mu_1},$$

which implies

$$\frac{1}{2\eta}s^2\le \mathrm{e}^{-\mu_1 t}[V_2(0)-\frac{\mu_2}{\mu_1}]+\frac{\mu_2}{\mu_1}\,.$$

Further, we obtain

$$\lim_{t\to\infty}|s(t)|\le\sqrt{\frac{2\eta\mu_2}{\mu_1}}\,.$$

Hence, we can get good control precision by choosing proper value of μ_1. On the other hand, from equation (30), we can see $V_2(t)$ is bounded. The boundedness of $\tilde{p},\tilde{\vartheta}$ and s may be obtained directly. Further, we can check all signals in the closed-loop system are bounded.

5. NUMERICAL SIMULATION

A numerical simulation was carried out to verify the effective of control algorithm for the controlled system (7), in which $d_v=0.5\sin(x_1)x_2+0.1\mathrm{sgn}(x_1x_2)$, $x_1(0)=3, x_2(0)=0$, $x_{1,d}(t)=\cos(0.4\pi t)$, $x_{2,d}(0)=-0.4\pi\sin(0.4\pi t)$, $c_0=0.9, c_1=1$, $c_2=1.5$, $c_3=4$, $c_u=1$, $b_v=2$, $J=10\mathrm{Kg.cm}$, $r=4\mathrm{cm}, u_0=0.5\mathrm{V}, l_0=20\mathrm{cm}$.

The control algorithm (17)-(19) is adopted for simulation with $\lambda_s=2$, $\gamma_0=10$, $\gamma_1=5, \gamma_2=5$, $h_1=2, h_2=2, \varepsilon_v=0.1$. The actuator fault is $\rho=0.6+0.4\mathrm{e}^{-0.5t}$, ϕ is a random number between -0.50 and 0.50. Figures 2 and 3 show both angle signal and angular velocity signal may asymptotically track their desired trajectories. The curves of angle tracking error and angular velocity tracking error are respectively shown in Figures 4 and 5, which converge to the neighbourhood of zero. The value of control input is illustrated in Figure 6. It can be seen that the signal of control input is smooth and continuous.

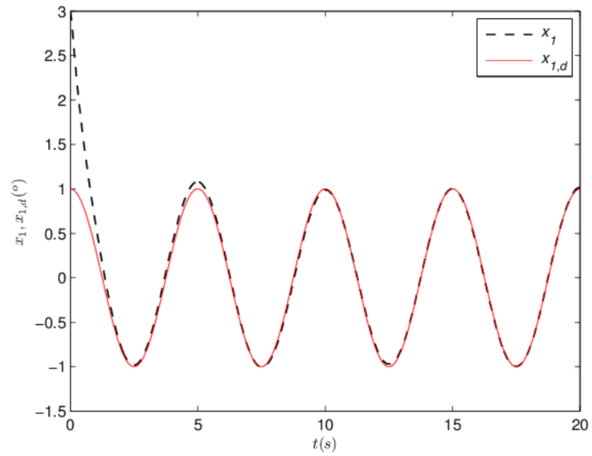

Figure 2. Angle trajectory x_1 .

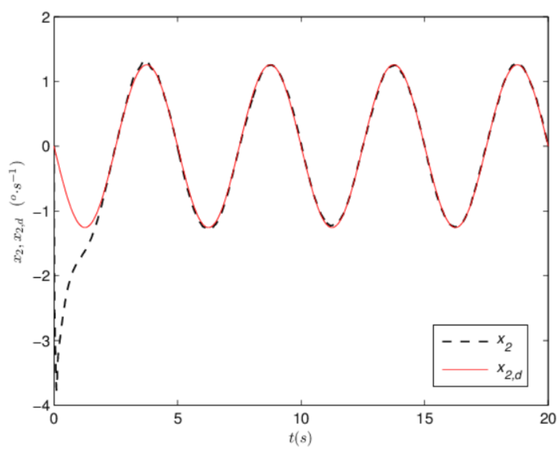

Figure 3. Angular velocity trajectory x_2 .

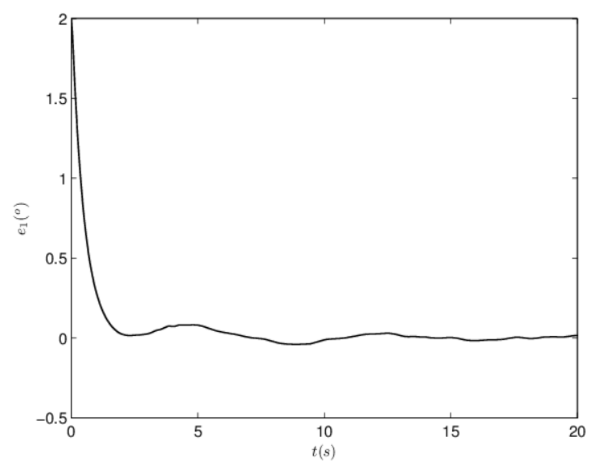

Figure 4. Angle tracking error.

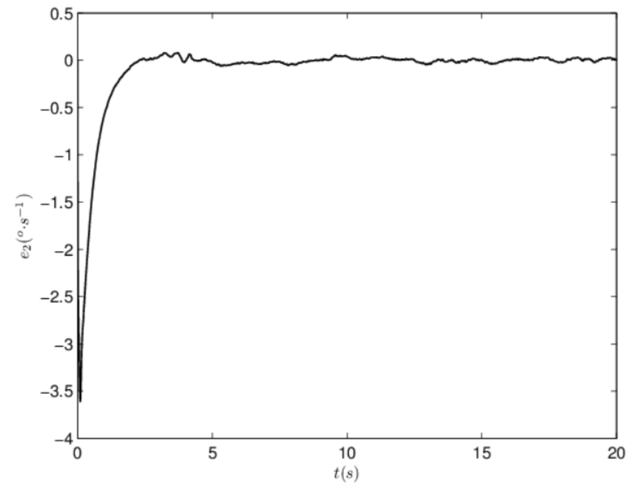

Figure 5. Angular velocity tracking error.

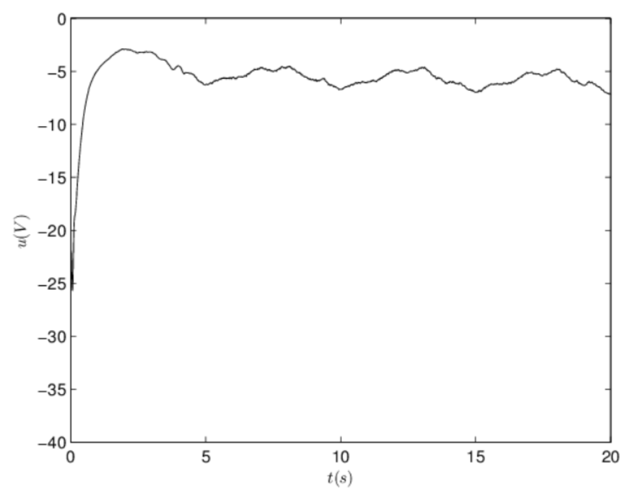

Figure 6. Control input.

6. CONCLUSION

A robust adaptive control approach is developed for a PAM actuated mechanism with both multiplicative and additive actuator faults. The unknown parameters are estimated by using adaptive learning strategy, and nonparametric uncertainties are compensated for according to robust adaptive strategy. The filtering error of the system asymptotically converges to the neighborhood of zero. The boundedness of all signals is guaranteed.

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