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Output Feedback Control for Pneumatic Muscle Joint System With Saturation Input

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ABSTRACT Pneumatic muscle as a relatively new pneumatic component is often applied to some precise and flexible control systems. The precise control accuracy puts forward higher requirements for the controller design of the pneumatic muscle system. To guarantee good performance, unknown input saturation which seems inevitable must be fully considered in the controller design. In this paper, such a control problem is investigated for a pneumatic muscle joint system with input saturation and external disturbance. The auxiliary signals are introduced to compensate for the effect caused by unknown saturation. Furthermore, a filter is constructed to estimate unmeasured system states. Then an output feedback control scheme has been proposed by these auxiliary signals and states filter. Finally, simulation studies are used to verify the effectiveness of the proposed control scheme.

INDEX TERMS Pneumatic muscle joint system, external disturbance, output feedback control, backstepping, input saturation.

I. INTRODUCTION

Pneumatic muscle [1], [2] is a new pneumatic component and has been used in precise and flexible control systems due to its good characteristics, for example, light-weight, low cost, high power-weight ratio, and high power volume ratio. Especially in the fields of rehabilitation medicine, virtual reality, and bionic robot and so on, production efficiency has been improved by using pneumatic muscle which seems similar to human skeletal muscle. However, the pneumatic muscle has uncertainties caused by strong nonlinear and gas compressibility [1], which leads to its controlling becoming more complicated. So it is difficult to achieve higher control accuracy. To improve the performance of the pneumatic muscle system, modern control theory has been used in the controller design and system analysis in recent twenty years. Several results which mainly aim to the estimation of unknown system parameters by using state feedback technique has been obtained. But the control schemes based on output feedback approach are always every limited due to the complexity of the practical system.

Uncertainties [3]–[20] which may affect the system performance heavily seem inevitable in practical systems. Such uncertainties may be caused by unknown parameters [3]–[7], [11]–[20], external disturbance [3], [4], [7], [8], modelling errors [5], [6], unknown actuator failures [9]–[20] and unknown strong nonlinear input including hysteresis, dead-zone and saturation. Different methods and techniques are used to deal with different uncertainties. Adaptive estimation by designing update law is utilized to estimate linearized parameters while unknown modelling errors are handled by some inequalities when its upper bound being a known function. To compensate for the uncertainties caused by external disturbance, we usually assume that such disturbance is bounded by an unknown positive constant. By estimating this upper bound, the disturbance can be restrained effectively. Dead-zone and backlash hysteresis are usually approximated by a linear function. The approximation error is assumed bounded by an unknown constant. Then it will be treated as an external disturbance.

Compared with these above uncertainties, saturation is a potential problem for actuators of control systems. It often severely limits system performance, giving rise to undesirable inaccuracy or leading instability. Input saturation [3] is inevitable in a pneumatic muscle joint system due to the physical limitations of components. Because parameter in the saturation model is usually unknown and such uncertainties caused by unknown saturation can not be estimated

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by constructing online estimator, the controller design of systems with input saturation become more and more difficult. To solve such a problem, we consider the control for pneumatic muscle joint system with input saturation and external disturbances in this paper. At the same time, considering system states are difficult to measure in practice, the proposed control scheme is an output feedback control scheme. The auxiliary signals are introduced to reduce the influence of unknown saturation input nonlinearity and filters are designed to estimate the unknown system states. The main contributions of this paper can be summarized as follows: (I) The control problem is investigated for pneumatic muscle joint systems with input saturation and external disturbance; (II) Filters are constructed to estimate the unknown system states and an output feedback control scheme is proposed to guarantee the stability of systems; (III) In contrast to existing results, the auxiliary signals r_1, r_2 are introduced to deal with the unknown saturation. The uncertainties caused by unknown saturation can be compensated successfully.

The paper is organized as follows: Section II describes a controlled system model with unknown saturation and unknown external disturbance. Section III presents the designed output feedback control law and analysis of the closed-loop system. Simulation results are given in Section IV to verify the effectiveness of the proposed control scheme. Finally, the paper is concluded in Section V.

II. PROBLEM STATEMENT

Based on the dynamic model of the Lagrangian form of the pneumatic muscle joint [2], we have

$$\begin{aligned} T(t) &= J\ddot{\theta}(t) + b_v\dot{\theta}(t) \\ &= F_1(t)b_1 - F_2(t)b_2 + \vartheta(t) \end{aligned} \quad (1)$$

where J is the moment of inertia of the pneumatic muscle joint. θ is the rotation angle of the pneumatic muscle joint. b_v is the damping coefficient of the pneumatic muscle joint system. $\vartheta(t)$ represents external disturbances. b_1, b_2 represents the radius of the pneumatic muscle joint. F_1, F_2 are the pulling force on two pneumatic muscles and can be described by

$$\begin{aligned} F_1(t) &= P_1(t)(C_1\varepsilon_1(t)^2 + C_2\varepsilon_1(t) + C_3) + C_4 \\ F_2(t) &= P_2(t)(C_1\varepsilon_2(t)^2 + C_2\varepsilon_2(t) + C_3) + C_4 \end{aligned} \quad (2)$$

where C_1, C_2, C_3, C_4 represent parameters in the mathematical model of aerodynamic muscles. ε_1, ε_2 are the contraction rate of the pneumatic muscle and given as

$$\begin{aligned} \varepsilon_1(t) &= \varepsilon_0 + rl_0^{-1}\theta(t) \\ \varepsilon_2(t) &= \varepsilon_0 - rl_0^{-1}\theta(t) \end{aligned} \quad (3)$$

where ε_0 and l_0 represent the initial contraction rate and initial length of the pneumatic muscle, respectively. In equation (2), $P_1(t)$ and $P_2(t)$ are the pressure value of the pneumatic muscle. They are described by

$$\begin{aligned} P_1(t) &= P_0 + \triangle P(t) = k_0u_0 + k_uu(t) \\ P_2(t) &= P_0 - \triangle P(t) = k_0u_0 - k_uu(t) \end{aligned} \quad (4)$$

where k_0 is the proportionality factor. k_u is the voltage coefficient. u_0 is the initial voltage. P_0 is the initial pressure of the pneumatic muscle. $\triangle P(t)$ is the pressure change of the pneumatic muscle.

We suppose that the joint radius is the gear radius of the joint. Then we have $b_1 = b_2 = r$. With (1) (2) (3) and (4), the mathematical model of the pneumatic muscle joint system can be rewritten as

$$\begin{aligned} \ddot{\theta}(t) = &-\frac{b_v}{J}\dot{\theta}(t) + \frac{2k_0u_0r^2(2C_1\varepsilon_0 + C_2)l_0^{-1}}{J}\theta(t) \\ &+ \frac{2k_0k_ur(C_1\varepsilon_0^2 + C_2\varepsilon_0 + C_3)}{J}u(t) + \vartheta(t) \end{aligned} \quad (5)$$

We let $d(t) = \vartheta(t) - \frac{b_v}{J}\dot{\theta}(t)$. Because $\frac{b_v}{J}$ is small and $\dot{\theta}(t)$ is bounded in the practice, $d(t)$ is bounded by an unknown constant. Therefore we have

$$\begin{aligned} \ddot{\theta}(t) = &\frac{2k_0u_0r^2(2C_1\varepsilon_0 + C_2)l_0^{-1}}{J}\theta(t) \\ &+ \frac{2k_0k_ur(C_1\varepsilon_0^2 + C_2\varepsilon_0 + C_3)}{J}u(t) + d(t) \end{aligned}$$

Let

$$\begin{cases} x_1(t) = \theta(t) \\ x_2(t) = \dot{\theta}(t) \end{cases} \quad (6)$$

Then the system model can be rewritten as

$$\begin{aligned} \dot{x}_1(t) &= x_2(t) \\ \dot{x}_2(t) &= d_1x_1(t) + d(t) + b_0u(t) \\ y &= x_1 \end{aligned} \quad (7)$$

where y is the output signal and

$$\begin{aligned} b_0 &= \frac{2k_0k_ur(C_1\varepsilon_0^2 + C_2\varepsilon_0 + C_3)}{J}; \\ d_1 &= \frac{2k_0u_0r^2(2C_1\varepsilon_0 + C_2)l_0^{-1}}{J} \end{aligned} \quad (8)$$

where x_1, x_2, y and u are system states, output and input. d_1, b_0 are known constants.

Remark 1: As we all know, external disturbance as a common uncertainty is inevitable in practical systems. In the pneumatic muscle joint system, we use $d(t)$ representing external disturbance and such disturbance satisfies

$$|d(t)| \leq D_{max} \quad (9)$$

where $D_{max} > 0$ is an unknown constant.

According to the practical actuator of the pneumatic muscle joint system. The following saturation of actuator is considered.

$$u(v) = sat(v) = \begin{cases} u_M & v > u_M \\ v & -u_M \leq v \leq u_M \\ -u_M & v < -u_M \end{cases} \quad (10)$$

where $u_M > 0$ is an unknown constant. $u(v)$ and v are the output and input of actuator, respectively. With the saturation model (10), the controlled system is reorganized as

$$\begin{aligned}\dot{x}_1(t) &= x_2(t)\\ \dot{x}_2(t) &= d_1x_1(t) + b_0u(v) + d(t)\\ y(t) &= x_1(t)\end{aligned} \tag{11}$$

Remark 2: Saturation input is the most common strong nonlinearity of actuators in practical systems. In the pneumatic muscle joint system, the unknown saturation is inevitable due to the limitation of the inflation catheter. So it must be fully considered in the controller design and stability analysis.

To propose the controller design the following assumptions are made.

Assumption 1: The reference signal y_r and its i-$th(i = 1, 2)$ order derivatives are continuous and bounded.

III. DESIGN OF ADAPTIVE CONTROLLERS

In order to obtain the output feedback control law, we rewrite the system as

$$\dot{x} = Ax + \Phi_1\theta_1 + D(t) + \begin{bmatrix} 0 \\ b_0 \end{bmatrix} u \tag{12}$$

where

$$A = \begin{bmatrix} 0 & 1 \\ 0 & 0 \end{bmatrix}, \quad \Phi_1 = \begin{bmatrix} 0 \\ x_1 \end{bmatrix}$$
$$D(t) = \begin{bmatrix} 0 \\ d(t) \end{bmatrix}, \quad \theta_1 = d_1 \tag{13}$$

With (9), we have $||D(t)|| \le D_{max}$. Note that x is unavailable and only y is measured. So we design the filters to estimate x and generate available signals for controller design. The filters is constructed as

$$\begin{aligned}\dot{\xi} &= A_0\xi + ky\\ \dot{\Xi}_A^T &= A_0\Xi_A^T + \Phi_1(y)\\ \dot{\lambda} &= A_0\lambda + E_2u\\ \nu_0 &= A_0^0\lambda = \lambda\end{aligned} \tag{14}$$

where $k = [k_1, k_2]^T$ is a vector such that the matrix $A_0 = A - kE_1^T$ is Hurwitz. Namely, there exits a P such that $PA_0 + A_0^TP = -2I, P = P^T > 0$. By the filters, the x is estimated as

$$\hat{x}(t) = \xi + \Xi_A^T\theta_1 + b_0\nu_0 \tag{15}$$

The derivative of $\hat{x}(t)$ is

$$\begin{aligned}\dot{\hat{x}}(t) &= \dot{\xi} + \dot{\Xi}_A^T\theta_1 + b_0\dot{\nu}_0\\ &= A_0\xi + ky + (A_0\Xi_A^T + \Phi_1(y))\theta_1\\ &\quad + b_0(A_0\lambda + E_2u)\\ &= A_0(\xi + \Xi_A^T\theta_1 + b_0\nu_0) + ky\\ &\quad + \Phi_1(y)\theta_1 + b_0E_2u\\ &= A_0\hat{x} + ky + \Phi_1(y)\theta_1 + b_0E_2u\end{aligned} \tag{16}$$

Now we consider the state estimation error

$$\epsilon = x(t) - \hat{x}(t) \tag{17}$$

satisfies

$$\begin{aligned}\dot{\epsilon} &= \dot{x}(t) - \dot{\hat{x}}(t)\\ &= Ax + \Phi_1(y)\theta_1 + D(t) + \begin{bmatrix} 0 \\ b_0 \end{bmatrix} u\\ &\quad -(A_0\hat{x} + ky + \Phi_1(y)\theta_1 + b_0E_2u)\\ &= Ax - kE_1^Tx - A_0\hat{x} + D(t)\\ &= A_0\epsilon + D(t)\end{aligned} \tag{18}$$

Define the Lyapunov function V_ϵ

$$V_\epsilon = \epsilon^TP\epsilon \tag{19}$$

Then

$$\begin{aligned}\dot{V}_\epsilon &= \dot{\epsilon}^TP\epsilon + \epsilon^TP\dot{\epsilon}\\ &= \epsilon^T(P^TA_0 + PA_0)\epsilon + 2\epsilon^TPD(t)\\ &= -2\epsilon^T\epsilon + 2\epsilon^TPD(t)\\ &\le -2\epsilon^T\epsilon + \epsilon^T\epsilon + \|PD(t)\|^2\\ &= -\epsilon^T\epsilon + \|PD(t)\|^2\end{aligned} \tag{20}$$

Remark 3: Because P is a constant matrix and $D(t)$ is bounded by D_{max}, $\|PD(t)\|^2$ is bounded by a constant. Then from (20), we have the $\dot{V}_\epsilon$ being bounded by $-\epsilon^T\epsilon + \|PD(t)\|^2$. Although V_ϵ is not monotonically decrease, V_ϵ is bounded and its upper bound depends on $\|PD(t)\|$. Then we can get the estimation error $\epsilon = x(t) - \hat{x}(t)$ is bounded.

Note that y is the only available in the controller design. With (11), the derivative of y is

$$\dot{y} = \dot{x}_1$$

Note that $\epsilon_1 = x_1 - \hat{x}_1$ and from (14)-(16), we have

$$\begin{aligned}\dot{y} &= \dot{\hat{x}}_1 + \dot{\epsilon}\\ &= b_0\nu_{0,2} + \xi_2 + \bar{\omega}^T\Theta + \epsilon_2\\ \dot{\nu}_{0,2} &= -k_2\nu_{0,1} + u(v)\end{aligned} \tag{21}$$

where

$$\begin{aligned}\Theta &= [b_0, \theta_1^T]^T\\ \omega &= [\nu_{0,2}, \Xi_{A_2}]^T\\ \bar{\omega} &= [0, \Xi_{A_2}]^T\end{aligned} \tag{22}$$

In the above formula, $\nu_{0,2}, \xi_2, \epsilon_2$ denote the second entries of ν_0, ξ, ϵ. $\nu_{0,1}$ is the first entries of ν_0, $\nu_{0,2}$ is the second entries of $A\nu_0$. v is the control input signal which will be designed. Considering the saturation shown in (10), we know $u(v)$ can not be approximated by a linear function of v. Such an approximation is usually used in the dead-zone nonlinear input. To compensate for the uncertainties caused by unknown saturation input, the following auxiliary variables are introduced.

$$\begin{aligned}\dot{r}_1 &= r_2 - C_{k1}r_1\\ \dot{r}_2 &= -C_{k2}r_2 + b_0\triangle u\end{aligned} \tag{23}$$

where C_{k1}, C_{k2} are positive constants. $\triangle u = u(t) - v$ represents the input of the auxiliary system (23). By constructing this auxiliary system, the signals r_1 and r_2 are introduced to smooth the saturation function. Before designing the controller, we first perform the following coordinate transformations.

$$\begin{aligned} z_1 &= y - y_r - r_1 \\ z_2 &= v_{0,2} - \alpha_1 - \frac{1}{b_0}\dot{y}_r - \frac{1}{b_0}r_2 \end{aligned} \tag{24}$$

Step 1: Starting with the error z_1, we obtain

$$\begin{aligned} \dot{z}_1 &= \dot{y} - \dot{y}_r - \dot{r}_1 \\ &= b_0(z_2 + \alpha_1 + \frac{1}{b_0}\dot{y}_r + \frac{1}{b_0}r_2) + \xi_2 + \bar{\omega}^T\Theta \\ &\quad + \epsilon_2 - \dot{y}_r - r_2 + C_{k1}r_1 \\ &= b_0 z_2 + b_0\alpha_1 + \xi_2 + \bar{\omega}^T\Theta + \epsilon_2 + C_{k1}r_1 \end{aligned}$$

Then we chosen the α_1 is

$$\alpha_1 = \frac{1}{b_0}(-C_1 z_1 - e_1 z_1 - \xi_2 - \bar{\omega}^T\Theta - C_{k1}r_1) \tag{25}$$

Define the Lyapunov function V_1 as

$$V_1 = \frac{1}{2}z_1^2 + \frac{1}{2e_1}V_\epsilon \tag{26}$$

where C_1, e_1 are positive parameters. Then the derivative of V_1 is

$$\begin{aligned} \dot{V}_1 &= z_1\dot{z}_1 - \frac{1}{2e_1}\epsilon^T\epsilon + \frac{1}{2e_1}\|PD(t)\|^2 \\ &= z_1(b_0 z_2 + b_0\alpha_1 + \xi_2 + \bar{\omega}^T\Theta + \epsilon_2 + C_{k1}r_1) \\ &\quad - \frac{1}{2e_1}\epsilon^T\epsilon + \frac{1}{2e_1}\|PD(t)\|^2 \\ &= b_0 z_1 z_2 - C_1 z_1^2 - e_1 z_1^2 + z_1\epsilon_2 \\ &\quad - \frac{1}{2e_1}\epsilon^T\epsilon + \frac{1}{2e_1}\|PD(t)\|^2 \\ &\leq -C_1 z_1^2 + b_0 z_1 z_2 - \frac{1}{4e_1}\epsilon^T\epsilon + \frac{1}{2e_1}\|PD(t)\|^2 \end{aligned} \tag{27}$$

Step 2: We derive the error z_2

$$\begin{aligned} \dot{z}_2 &= \dot{v}_{0,2} - \dot{\alpha}_1 - \frac{1}{b_0}\ddot{y}_r - \frac{1}{b_0}\dot{r}_2 \\ &= v_{0,3} - k_2 v_{0,1} + u - \dot{\alpha}_1 - \frac{1}{b_0}\ddot{y}_r + \frac{C_{k2}}{b_0}r_2 - \triangle u \\ &= v + v_{0,3} - k_2 v_{0,1} - \dot{\alpha}_1 - \frac{1}{b_0}\ddot{y}_r + \frac{C_{k2}}{b_0}r_2 \end{aligned} \tag{28}$$

Choosing the control law v as

$$\begin{aligned} v &= -b_0 z_1 - C_2 z_2 - e_2(\frac{\partial\alpha_1}{\partial y})^2 z_2 - v_{0,3} \\ &\quad - \frac{C_{k2}}{b_0}r_2 + \frac{\partial\alpha_1}{\partial y}(b_0 v_{0,2} + \xi_2 + \bar{\omega}^T\Theta) \\ &\quad + \frac{\partial\alpha_1}{\partial\xi}(A_0\xi + ky) + \frac{\partial\alpha_1}{\partial r_1}(r_2 - C_{k1}r_1) \\ &\quad + \frac{\partial\alpha_1}{\partial\Xi_A^T}(A_0\Xi_A^T + \Phi_1(y)) \\ &\quad + k_2 v_{0,1} + \frac{1}{b_0}\ddot{y}_r + \frac{\partial\alpha_1}{\partial y_r}\dot{y}_r \end{aligned} \tag{29}$$

IV. STABILITY ANALYSIS

We now establish the boundedness of all signals in the closed loop system under the proposed output feedback control scheme. The following theorem about output feedback control of pneumatic muscle joint system with saturation input can be achieved.

Theorem 1: Consider the pneumatic muscle joint system shown in (1), with saturation input (10), an output feedback controller (29). Under Assumption 1, all signals of the closed-loop system are bounded under the control of the proposed control scheme.

Proof: Firstly, defining the Lyapunov function V_2 as

$$V_2 = V_1 + \frac{1}{2}z_2^2 + \frac{1}{2e_2}V_\epsilon \tag{30}$$

The derivative of V_2 is

$$\begin{aligned} \dot{V}_2 &= -C_1 z_1^2 + b_0 z_1 z_2 - \frac{1}{4e_1}\epsilon^T\epsilon + \frac{1}{2e_1}\|PD(t)\|^2 \\ &\quad + z_2\dot{z}_2 - \frac{1}{2e_2}\epsilon^T\epsilon + \frac{1}{2e_2}\|PD(t)\|^2 \\ &= -C_1 z_1^2 + b_0 z_1 z_2 - \frac{1}{4e_1}\epsilon^T\epsilon + \frac{1}{2e_1}\|PD(t)\|^2 \\ &\quad + z_2(v + v_{0,3} - k_2 v_{0,1} - \dot{\alpha}_1 - \frac{1}{b_0}\ddot{y}_r + \frac{C_{k2}}{b_0}r_2) \\ &\quad - \frac{1}{2e_2}\epsilon^T\epsilon + \frac{1}{2e_2}\|PD(t)\|^2 \\ &= -C_1 z_1^2 - C_2 z_2^2 - \frac{1}{4e_1}\epsilon^T\epsilon + \frac{1}{2e_1}\|PD(t)\|^2 \\ &\quad - z_2\frac{\partial\alpha_1}{\partial y}\epsilon_2 - \frac{1}{2e_2}\epsilon^T\epsilon + \frac{1}{2e_2}\|PD(t)\|^2 \\ &\quad - e_2(\frac{\partial\alpha_1}{\partial y})^2 z_2^2 \end{aligned} \tag{31}$$

By using Young's inequality

$$ab \leq d_1 a^2 + \frac{1}{4d_1}b^2$$

where $d_1 > 0$ is a design parameter. Then the derivative of V_2 can be rewritten as

$$\begin{aligned} \dot{V}_2 &\leq -C_1 z_1^2 - C_2 z_2^2 - \frac{1}{4e_1}\epsilon^T\epsilon + \frac{1}{2e_1}\|PD(t)\|^2 \\ &\quad - \frac{1}{4e_2}\epsilon^T\epsilon + \frac{1}{2e_2}\|PD(t)\|^2 \\ &\leq -C_1 z_1^2 - C_2 z_2^2 - \frac{1}{4e_1}\epsilon^T\epsilon + \frac{1}{2e_1}\|P\|^2 D_{max}^2 \\ &\quad - \frac{1}{4e_2}\epsilon^T\epsilon + \frac{1}{2e_2}\|P\|^2 D_{max}^2 \end{aligned} \tag{32}$$

where D_{max} is bound of $D(t)$. Let

$$Y = \frac{1}{2e_1}\|P\|^2 D_{max}^2 + \frac{1}{2e_2}\|P\|^2 D_{max}^2 \tag{33}$$

Note that

$$-C_1 z_1^2 - C_2 z_2^2 - \frac{1}{4e_1}\epsilon^T\epsilon - \frac{1}{4e_2}\epsilon^T\epsilon \leq -f\_\bar{V}_2$$

$$\frac{1}{2}z_2^2 + \frac{1}{2e_2}V_\epsilon + \frac{1}{2}z_1^2 + \frac{1}{2e_1}V_\epsilon \leq f_+\bar{V}_2$$

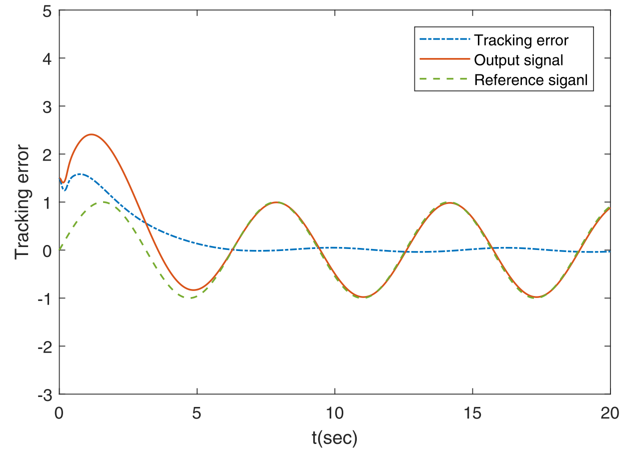

FIGURE 1. **Tracking.**

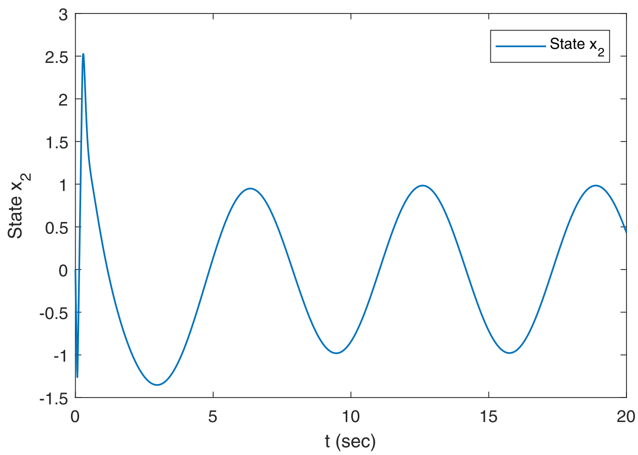

FIGURE 2. **State x_2.**

where

$$\bar{V}_2 = z_1^2 + z_2^2 + 2\epsilon^T \epsilon$$
$$f_- = min\{C_1, C_2, \frac{1}{4e_1}, \frac{1}{4e_1}\}$$
$$f_+ = max\{\frac{1}{2}, \frac{1}{2e_1}\lambda_{max}(P), \frac{1}{2e_2}\lambda_{max}(P)\} \quad (34)$$

Then we can get

$$\dot{V}_2 \leq -f * V_2 + Y \quad (35)$$

where $f = \frac{f_-}{f_+}$. Then we have

$$V_2 \leq V_2(0) + \frac{Y}{f}$$

So we can get all signals in closed-loop systems are all bounded.

V. SIMULATION STUDIES

We now apply the proposed control scheme to the following 2nd-order system described as

$$\begin{aligned} \dot{x}_1 &= x_2 \\ \dot{x}_2 &= d_1 x_1 + b_0 u(v) + d(x, t) \\ y &= x_1 \end{aligned} \quad (36)$$

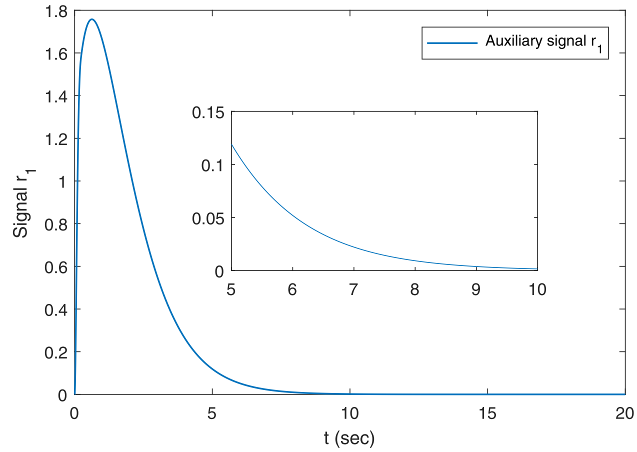

FIGURE 3. **Signal r_1.**

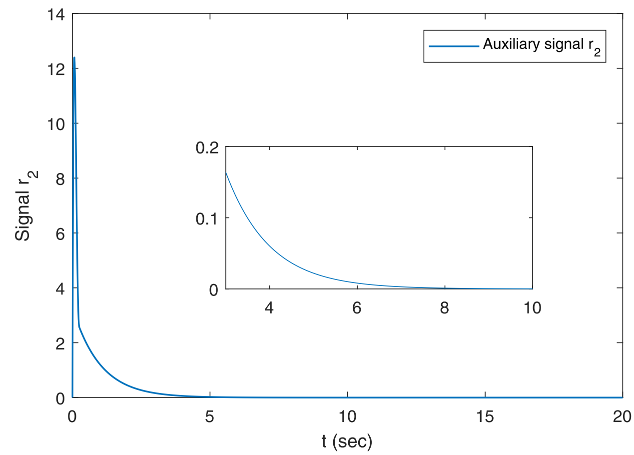

FIGURE 4. **Signal r_2.**

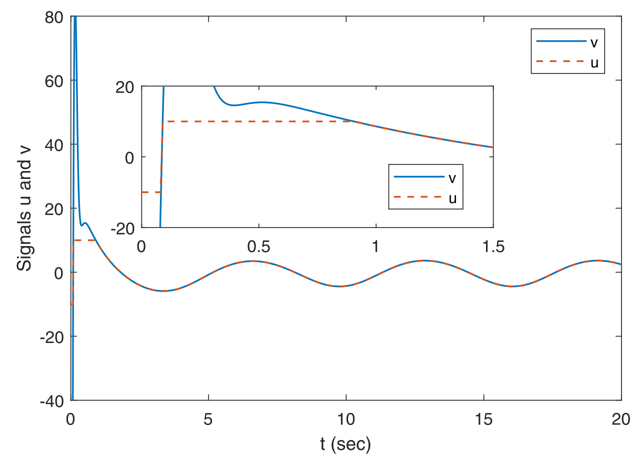

FIGURE 5. ***u* and *v*.**

where x_1, x_2 are system states, y is the output signal. u is the output of the saturation actuator while v is the input signal. d_1, b_0 are known parameter. $d(x, t)$ is an unknown nonlinear function and is taken as

$$d(x, t) = 0.1 sin(x_2) cost \quad (37)$$

In simulation, we take $d_1 = 0.2, b_0 = 2, u_M = 10$. The design parameters can be chosen as: $c_1 = c_2 = 15, c_{k1} = c_{k2} = 1, e_1 = e_2 = 0.1, k = (6, 8)^T$. The initial values are taken as: $x_1(0) = 1.5$, $x_2(0) = 0$, $r_1(0) = r_2(0) = 0$, $\xi(0) = 0$, $\Xi(0) = 0$, $\lambda(0) = 0$.

Fig.1 represents tracking error and the state x_2 is shown in Fig.2. Fig.3 and Fig.4 show the auxiliary signals r_1 and r_2. Fig.5 shows the signal v which is designed by the proposed control law (29) and the signal $u(t)$ given by changing of saturation (10). Clearly, we can get that all signals of the systems are bounded under the control of the proposed output feedback control scheme.

VI. CONCLUSION

The control problem is investigated for a pneumatic muscle joint system with unknown input saturation and external disturbance. With the auxiliary signals and states filter, an output feedback control scheme has been proposed by using backstepping. The uncertainties caused by unknown saturation and external disturbance can be compensated and the stability of closed-loop systems can be guaranteed by the proposed control scheme. Finally, simulation studies are used to verify the effectiveness of the proposed control scheme. In our future work, we will consider the estimation of unknown parameter and to obtain the adaptive control scheme.

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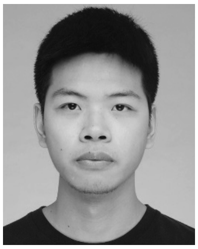

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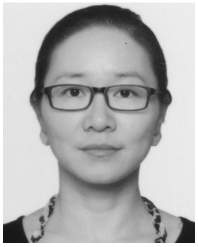

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