Tension Networked Control Strategy for Carbon Fiber Multilayer Diagonal Loom

WEI LIU,1,2 XIAOYU WU,1 XIAOGANG DU,1 GUOWEI XU,3 AND SHUO WANG3

1School of Mechanical Engineering, Tiangong University, Tianjin 300387, China
2Advanced Mechatronics Equipment Technology Tianjin Area Major Laboratory, Tiangong University, Tianjin 300387, China
3School of Electrical Engineering and Automation, Tiangong University, Tianjin 300387, China

Corresponding author: Wei Liu (weiliu@tjpu.edu.cn)

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ABSTRACT With the aim of solving warp tension control problems in the let-off system and opening system in the carbon fiber multilayer diagonal loom, dynamic models of warp tension are established in this study based on dynamic analysis. Adaptive fuzzy PID control is applied to the tension-networked control, and an adaptive fuzzy PID controller is designed to solve the problems of network induced delay, packet loss, and network bandwidth occupancy. A TrueTime simulation structure of the tension control system is also built. Compared with PID control, adaptive fuzzy PID control exhibited the advantages of a small overshoot, small fluctuation of output tension, good tracking effect, and stability in simulations under different conditions, including a 30-ms network induced delay, 10% packet loss, and 30% network bandwidth occupancy. The results of the simulations show that adaptive fuzzy PID control has better control effect than PID control, and is more suitable for tension-networked control systems in the carbon fiber multilayer diagonal loom.

INDEX TERMS Carbon fiber multilayer diagonal loom, tension control, networked control systems, adaptive fuzzy PID control.

I. INTRODUCTION
Carbon fiber composites are widely used in the manufacturing industry because of their remarkable properties [1], [2]. Traditional looms cannot be used to braid carbon fibers, especially angular interlocking reinforced fabrics, as shown in Fig. 1.

Because of such characteristics of carbon fiber fabrics as thickness, poor wear resistance, and multiple layers, warp yarns are required to maintain tension during weaving [3], [4]. The let-off mechanism is an important part of the carbon fiber multilayer diagonal loom that provides warp yarns for the opening movement and keeps them stable. Therefore, an effective warp tension control strategy is important for the quality of the fabric.

With the rapid development of computer technology, advanced control methods have been used to maintain warp tension in looms [5]. Liu et al. [6] proposed a fast-discrete global sliding-mode control method, and the method, applied it to the tension control system of the carbon fiber multilayer diagonal loom with time delay, and verified its effectiveness.

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FIGURE 1. Structure of angle interlock-reinforced fabric.

Lu and Yang [7] proposed a fuzzy information fusion algorithm for neural networks based on tension control methods. This method improves the control accuracy of warp tension. Wang Junke designed a DSP digital controller [8] where, in addition to the real-time online adjustment of the let-off system, the system was calculated and corrected in the PID controller according to the deviation of the magnitude of let-off. This lent such excellent characteristics to the system as high accuracy, fast response, and stability. Many control methods have been applied to yarn tension control in looms, adaptive sliding-mode control, linear interpolation fuzzy control, and fuzzy PI control [9]–[11]. Moreover, many
research methods for networked control systems. Many methods are available to examine networked control systems, and to compensate for the impact of delay and packet loss on the system [12]–[15]. The considered system is intended to control complex nonlinear systems with unknown mathematical models. Some type-2 fuzzy systems, such as in [16]–[18], have a good control effect. However, few studies have considered the application of a networked control technology to looms, especially carbon fiber multilayer diagonal looms.

Compared with the traditional point-to-point control system, networked control systems have the advantages of sharing information resources, remote monitoring and control, reduced wiring, and improved flexibility and reliability [19]–[21]. However, when using the communication network, the system produces network induced delay, packet loss, and network bandwidth occupancy, which in turn affect tension in the yarn [22]. Network induced delay is inevitable in networked control systems, and is one of the main causes of degradation in network performance or instability. In the process of packet transmission, packet collision or node contention failure may result in the loss of data packets. When a packet loss occurs, the input to the controller or actuator is not updated in time, and leads to a degradation in system performance or even instability. Analyses of the problems caused by the network in the control system, including controller design and stability, have emerged as important aspects of research.

PID control is among the earliest control strategies. It has been widely used in industrial process control because of its simple algorithm, robustness, and reliability. However, traditional PID control is not adaptive. Once the controller’s parameters have been set, they can be fixedly applied to only one operating condition. A fixed set of parameters cannot satisfy the need for change [23]–[25]. Parameters of the network in the network control system change in real time. Therefore, a single set of parameters cannot meet system requirements, and the controller should be adaptable to this dynamism. To achieve better control effects, the controller needs to adjust the control parameters according to the performance of the system. The characteristics of fuzzy control are the representation of the control experience, and knowledge of the operator or expert of control rules that are used to control the system, especially complex nonlinear systems with unknown mathematical models [26]. Controlled objects in automatic control systems have become increasingly complex over the years. The system thus has more stringent requirements, and the fuzzy controller exhibits unique advantages in complex system control.

An adaptive fuzzy PID controller is designed here to reduce the influence of network induced delay, packet loss and network bandwidth occupancy in a yarn tension control system.

II. WORKING PRINCIPLE OF CARBON FIBER MULTILAYER DIAGONAL LOOM

The carbon fiber multilayer diagonal loom is a new kind of weaving machine that is more complicated than the traditional loom in terms of its weaving process and mechanism. It can solve the technical problems in one-step, forming and wefting insertion layer by layer in a multilayer fabric [27]. The system principle is shown in Fig. 2 where the warp unwinds from the driving shaft through the tension compensation device, collects yarn, and passes it through the hole of the heddle. The warp shed is formed through the up-and-down movement of the heddle. The weft yarn clamped by the wefting insertion device is used to create fabric at the woven mouth. The final fabric is taken up to form the cloth roll.

III. DYNAMIC MODEL OF CONTROLLED OBJECT

In the carbon fiber multilayer diagonal loom, the let-off mechanism is one of five kernel components that can provide constant yarn storage for the opening action [28]. It plays an important role in ensuring constant tension and guaranteeing no damage during braiding.

A. THE LET-OFF MECHANISM

Assuming that the warp beam rotates clockwise, the corresponding parameters and their directions are shown in Fig. 3.

Notes: $T$ is the tension of the carbon fiber warp, $r_1$ is the radius of the warp beam, $r_0$ is the radius of the empty shaft, $v_1$ is warp speed, $M_D$ is the electromagnetic torque of the warping motor, and $i$ is the speed reduction ratio.

By setting the time-varying warp radius of loom to $r_1(t)$,

$$r_1(t) = r_m - n(t)\delta = r_m - \frac{\varphi(t)}{2\pi}\delta$$

(1)

where, $r_m$ is the radius of the full warp beam of the loom, $n(t)$ is the number of layers of unwinding on the warp beam, $\delta$ is the angular displacement of the warp beam.
The moment of inertia \( J(t) \) of the warp beam with time is:

\[
J(t) = \frac{1}{2} m[r_1'(t) + r_2'(t)] = \frac{1}{2} \rho \pi [r_1'(t) - r_0'(t)] \omega \cdot [r_1'(t) + r_0'(t)] = \frac{\pi \rho b}{2} [r_1'(t) - r_0'(t)]
\]

where, \( \rho \) is the mass density of the warp yarn, and \( b \) is the winding width of the woven shaft.

Substituting equation (1) into (2),

\[
J(t) = \frac{\pi \rho b}{2} \left[ \left( r_m - \frac{\phi(t)}{2\pi} \right)^4 - r_0^4 \right]
\]

The tensile torque \( M_T \) of the warp yarn is expressed as:

\[
M_T = T r_1
\]

and the frictional torque \( M_s \) is:

\[
M_s = C_s \omega
\]

where, \( C_s \) is the coefficient of viscous friction of the main warp beam and \( \omega \) its rotational angular velocity.

The force analysis of the let-off beam is shown in Fig. 4.

The dynamic for the warp spindle can be written as:

\[
i M_D - M_s + M_T = J_s(t) \frac{d\omega}{dt} = \left( J_0 + J(t) + i^2 J_D \right) \frac{d\omega}{dt}
\]

where, \( J_s(t) \) is the moment of inertia of the warp beam, \( J_0 \) is the moment of inertia of the empty warp beam, and \( J_D \) is the moment of inertia of the motor shaft [29].

Substituting (3), (4), and (5) into (6),

\[
\frac{d\omega}{dt} = \frac{i M_D - C_s \omega + T \left( r_m - \frac{\phi(t)}{2\pi} \right)}{\pi \rho b \left[ \frac{r_1'(t)}{r_0^4} \right] + J_0 + i^2 J_D}
\]

The linear velocity of the unwinding yarn of the loom is \( v_1 \), and tension \( T \) of the warp yarn can be expressed as:

\[
T = K_f \int_{t_0}^{t} (v_2 - v_1) dt
\]

where, \( K_f \) is the tension coefficient of the yarn and \( v_2 \) is yarn speed in the hole of the heddle.

Suppose that \( v_2 \) is a constant, then

\[
\dot{T} = K_f \left[ v_2 - v_1(t) \right] = K_f \left[ v_2 - \omega \left( r_m - \frac{\phi(t)}{2\pi} \right) \right]
\]

B. THE OPENING MECHANISM

During the opening process, the warp yarn is divided into upper and lower layers to form a diamond-shaped space that is usually called the warp shed. The shape of the warp shed in the opening mechanism is shown in Fig. 5.

The tensile deformations \( \lambda_1 \) and \( \lambda_2 \) of the upper and lower warp yarns are, respectively, calculated as:

\[
\lambda_1 = AB_1 + B_1 C - AB - BC = \frac{2 l_1}{h^2} - \frac{2 l_2}{h^2}
\]

\[
\lambda_2 = AB_2 + B_2 C - AB - BC = \frac{h^2 + 2 b h - a}{2 l_1} + \frac{h^2 + 2 b h - c}{2 l_2}
\]

The change in warp tension can be described as:

\[
\Delta T_1 = K_f \lambda
\]

The law of opening action is approximately a sinusoidal curve, and the movement of the warp shed can be expressed as:

\[
\begin{cases}
   h = 0.5H \sin \omega t, & \omega t < 90^\circ, \omega t > 270^\circ \\
   h_{\text{max}} = 0.5H, & 90^\circ \leq \omega t \leq 270^\circ
\end{cases}
\]

where, \( H \) is the height of the warp shed, which is the maximum opening value.

Taking \( h = 0 \), and substituting (13) into the (10) and (11),

\[
\lambda_1 + \lambda_2 = \frac{H^2}{4} \left( \frac{1}{l_1} + \frac{1}{l_2} \right) \sin^2 \omega t
\]

By substituting (14) into (12), the change in tension during the opening process is:

\[
\Delta T_1 = K_f \left( \lambda_1 + \lambda_2 \right) = K_f H^2 \left( \frac{1}{l_1} + \frac{1}{l_2} \right) \sin^2 \omega t
\]

When \( \sin \omega t = 1 \), the change in tension is:

\[
\Delta T_1 = K_f H^2 \left( \frac{1}{l_1} + \frac{1}{l_2} \right)
\]

C. BUILDING THE DYNAMIC MODEL

Based on the working principle of the let-off and opening mechanisms, the rate of change in tension rate in the warp process is:

\[
\dot{T} = K_f H^2 \left( \frac{1}{l_1} + \frac{1}{l_2} \right) - K_f \omega r_1
\]
According to equation (17), we can get:

$$\dot{\omega} = -\frac{\ddot{T}}{K_fr_1}$$

(18)

Substituting (17) and (18) into (7),

$$\left[ \frac{\pi \rho b}{2} (r_1^4 - r_0^4) + J_0 + i^2 J_D \right] \ddot{T} + C_s \dot{T} + K_f r_1^2 T$$

$$= \frac{C_s K_f H^2}{4} \left( \frac{1}{l_1} + \frac{1}{l_2} \right) - i K_f r_1 M_D$$

(19)

Using the Laplace transforms on (19) with zero initial conditions, we can get:

$$G(s) = \frac{T(s)}{M_D(s)} = \frac{i K_f r_1}{J_s s^2 + C_s s + K_f r_1^2}$$

(20)

where, $J_s = \frac{\pi \rho b}{2} (r_1^4 - r_0^4) + J_0 + i^2 J_D$.

The system is connected through the network, and its transfer function can be described as:

$$G(s) = \frac{T(s)}{M_D(s)} = \frac{i K_f r_1}{J_s s^2 + C_s s + K_f r_1^2}$$

(21)

The mathematical model of tension control is obtained in the let-off process, where $T$ is the output and $M_D$ is the input. The parameters of the system are shown in Table 1.

### TABLE 1. The parameters of the system.

| Parameter | Value       | Parameter | Value       |
|-----------|-------------|-----------|-------------|
| $i$       | 8           | $J_D$     | 0.003 kg.m² |
| $K_f$     | 0.4         | $C_s$     | 0.0006024 Nm/rpm |
| $r_1$     | 0.5 m       | $r_0$     | 0.08 m      |
| $\rho$    | 1.76g/cm³   | $J_0$     | 0.506 kg.m² |
| $b$       | 0.8 m       |           |             |

Substituting the corresponding parameters,

$$G(s) = \frac{0.96}{183.1 s^2 + 1.65 s + 0.36}$$

(22)

**IV. CONTROLLER DESIGN**

Compared with traditional control methods, fuzzy control has many advantages. (1) Using the logical language, it becomes unnecessary to have a precise mathematical model of the object. Fuzzy control is thus often used for the control of complex systems that are difficult to model. (2) The dynamic response of the fuzzy control system is better than traditional control, and it is highly adaptable to changes in system parameters. (3) The fuzzy controller has a variety of structural forms that can be selected as needed to make the control more flexible. Fuzzy control is less sensitive to parametric changes. By Combining fuzzy control with traditional PID control, the system is highly adaptable, has high control precision, and can adjust the control parameters online [30]–[33].

In this paper, fuzzy control is introduced on the basis of PID control, and the parameters of the PID controller are adjusted by fuzzy logic to compensate for the influence of network induced delay in the system. The PID controller is designed according to the system without network induced delay. Fuzzy logic adjustment is to use the reference input signal and the error of the output of the controlled object to adjust the value of the gain factor and make it function with the output of the PID controller to compensate for the delay.

The one-dimensional (1D) fuzzy controller is poor in effect, and the 3D fuzzy controller has a complex structure and incurs a large amount of computation. The authors thus paper use a 2D fuzzy controller to reflect the dynamic characteristics of the output variables in the controlled process. It is the most widely used fuzzy controller [34]. A control block diagram is shown in Fig.6.

**FIGURE 6. Block diagram of adaptive fuzzy PID control.**

The adaptive fuzzy PID controller takes the deviation tension $e$ and the rate of change in $ec$ as inputs. The initial values of the controller parameters are $K_P$, $K_I$, and $K_D$. The fuzzy inference is made according to a predetermined fuzzy control rule, and the changes in $\Delta K_P$, $\Delta K_I$, and $\Delta K_D$ of the three PID parameters are the output. Thus, the corrected control parameter is

$$\begin{align*}
K_P (k) &= K_P (k - 1) + \Delta K_P \\
K_I (k) &= K_I (k - 1) + \Delta K_I \\
K_D (k) &= K_D (k - 1) + \Delta K_D
\end{align*}$$

(23)

Then, the control variable can be calculated as follows:

$$u (k) = K_P (k) e (k) + K_I (k) \sum_{i=0}^{k} e (i) + [e (k) - e (k - 1)]$$

(24)

In this way, by modifying the value of the PID parameter online, the requirements for the self-tuning of the PID parameters by $e$ and $ec$ can be met at different times. The process of modifying the parameter values online is shown in Fig. 7.

When designing an adaptive fuzzy PID controller, the initial values $K_P$, $K_I$, and $K_D$ are first determined. In this paper, the pidtool of the control system toolbox of MATLAB was used to adjust the parameters of the PID controller to enable dynamic performance index of the system to satisfy the following conditions: (1) The maximum overshoot is less than 10%. (2) The rise time is less than 0.5s. (3) The adjustment time is less than 2 s. The initial values of the controller parameters were set to $K_P = 1000$, $K_I = 10$, and $K_D = 450$. 

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To carry out the fuzzification process, the input variable must be converted from the basic domain to the corresponding domain of fuzzy sets, and the input variable needs to be multiplied by the corresponding quantization factor:

\[ E = e \times G_e, \quad EC = ec \times G_{ec} \]  

(25)

where, \( G_e \) and \( G_{ec} \) are input quantization factors.

In addition, the amount of control given by the fuzzy control algorithm for each sample must be converted into the basic domain required for the control object. The fuzzy output control quantities \( \Delta K_P, \Delta K_I, \) and \( \Delta K_D \) corresponding to the fuzzy control quantities \( K_P, K_I, \) and \( K_D \). Then,

\[
\begin{align*}
\Delta K_P &= K_P \times G_{KP} \\
\Delta K_I &= K_I \times G_{KI} \\
\Delta K_D &= K_D \times G_{KD}
\end{align*}
\]

(26)

where, \( G_{KP}, G_{KI}, \) and \( G_{KD} \) are output scale factors. Once the quantization factor and scale factor have been determined, the system can always be mapped to an element on the fuzzy domain.

\( E, \ EC, \ KP, \ KI, \) and \( KD \) all use triangular membership functions. The basic principle of fuzzy rules is that when the error is large, the extent of control is mainly used to eliminate error, and when the error is small, the quantity of control should prevent overshoot to satisfy the requirement of control accuracy. The domain of input and output is divided into seven fuzzy sets: NB (negative large), NM (negative medium), NS (negative small), Z (zero), PS (positive small), PM (positive median) and PB (positive large). Then, the fuzzy control rules of \( \Delta K_P, \Delta K_I, \) and \( \Delta K_D \) given in Table 2 are established according to the 49 fuzzy control rules between input and output. The corresponding inference rule surface is shown in Fig. 8.

Fuzzy inference based on control rules is a fuzzy set, and the magnitude of fuzziness can be made accurate to control the object. The method used in this paper is the minimum and maximum judgment method. The result of reasoning \( R_k (k = 1, 2, \ldots, n) \) obtained by the fuzzy rules is

\[
\mu_{R_k}(U) = \min \{ \mu_{E}(E), \mu_{EC}(EC), \mu_{U_k}(U) \}
\]

(27)

The final conclusion \( R \) obtained from the comprehensive result \( R_k \) is

\[
\mu_R(U) = \max \{ \mu_{U_k}(U) \}
\]

(28)

Then, the method of gravity is used to render each subset fuzzy. The output \( U \) of the adaptive fuzzy PID controllers with corresponding fuzzy inputs \( E \) and \( EC \) are:

\[
U = \frac{\sum_{\mu_R(U)} U \cdot \mu_R(U)}{\sum_{\mu_R(U)}}
\]

(29)

In this paper, the stability of the closed-loop control system is proved by the method of Routh criterion. The proof process is not described here.

V. SIMULATION EXPERIMENTS

The simulation of the tension control system was set-up based on the analysis in the previous section using MATLAB and
a True-time simulation environment, as shown in Fig. 9. Data that were sampled periodically by the sensor node were sent to the controller node through the network module. The controller node is designed to calculate the control data immediately after receiving them and to send the calculated control signal to the actuator node using the network module.

The network type was “Ethernet” and the sampling time was 1 ms. Five cases were examined for the parameters of the network environment:

1. Without network induced delay, packet loss, and network bandwidth occupancy. The system was regarded as a non-networked system without network modules and interfering nodes. The network induced delay, packet loss, and network bandwidth occupancy were all zero at the same time.

2. With network induced delay. The network induced delay was composed of the sensor-to-controller pre-delay. The controller calculated the pre-delay and the controller-to-actuator pre-delay. The delay was returned in the simulation program by assigning a value to the variable “exectime” in each program.

3. With packet loss. The packet loss rate was set by the “Loss probability (0-1)” in the Network module to simulate the effect of different packet loss rates on tension in the yarn.

4. With network bandwidth occupancy. In the interfering nodes, the network load was changed by changing the share of bandwidth occupancy that could create delay and packet loss by using conflicts in information transmission. The network bandwidth occupancy was determined by assigning a value to the variable “BW share”.

5. With network induced delay, packet loss, and network bandwidth occupancy. Considering conditions (2), (3), and (4), the corresponding parameters could be set to obtain the influence of the three conditions mentioned above.

According to the system’s tension model, the different control systems were simulated and the results were compared with the PID control method.

When the system did not have network induced delay, packet loss, and network bandwidth occupancy, and the expected tension was constantly 1 N, the control effect was as follows:

In Fig. 10, the results show that the overshoot of the PID control method and adaptive fuzzy PID control method were both below 10%, and the control effects were the same on the whole.

When the system had 30 ms of network induced delay, the control effect was as follows:

In Fig. 11, the overshoot of the adaptive fuzzy PID control method was 40% whereas that of the PID control method was up to 78%. The adaptive fuzzy PID control method had low fluctuation in output tension, and was stable.
When the system had 10% packet loss, the control effect was as follows:

In Fig. 12, the overshoot of the adaptive fuzzy PID control method was 22% whereas that of the PID control method was up to 69%. Therefore, the adaptive fuzzy PID control method had a better effect.

The control effect when the system had 30% network bandwidth occupancy was as follows:

In Fig. 13, the overshoot of the adaptive fuzzy PID control method was 32% whereas that of the PID control method
When the system had network induced delay, packet loss, and network bandwidth occupancy, the control effect was as follows:

In Fig. 14, (a) and (b) show the results of the PID control method and the adaptive fuzzy PID control method, respectively, with a 10 ms delay, 10% packet loss rate, and 10% network bandwidth occupancy. (c) and (d) show the results of the PID control method and the adaptive fuzzy PID control method, respectively, with a 30 ms delay, 20% packet loss rate, and 20% network bandwidth occupancy. (a) and (b) show that the overshoot of the PID control method reached 82% while the overshoot of the adaptive fuzzy PID control method was 30%. The adaptive fuzzy PID control method had a lower overshoot and a better control effect. (c) and (d) show that the PID control method exhibited
a high fluctuation in output tension and the system was unstable, whereas the overshoot of the adaptive fuzzy PID control method was 68%, and it still achieved output tension stability in a short time.

In practice, tension cannot be a constant value owing to various factors. The desired tension value was changed to the dynamic value \( \sin \pi t \), and the results were as follows:

In Fig. 15, (a) and (b) show the results of the PID control method and the adaptive fuzzy PID control method, respectively, with a 10 ms delay, 10% packet loss rate and 10% network bandwidth occupancy. (c) and (d) show the results of the PID control method and the adaptive fuzzy PID control method, respectively, with a 30 ms delay, 20% packet loss rate, and 20% network bandwidth occupancy. The results show that the PID control method exhibited a large fluctuation in output tension, was unstable, and had a poor tracking effect while the adaptive fuzzy PID control method had a better effect.

VI. CONCLUSION
This paper examined the let-off system and opening system, and created dynamic models of warp tension in a carbon fiber multilayer diagonal loom. Based on the network-induced delay, packet loss, and network bandwidth occupancy, an adaptive fuzzy PID controller was designed. The proposed controller was compared with the PID control method through simulations. The results show that the adaptive fuzzy PID control method has many advantages, such as low overshoot, small output fluctuation, good tracking, and stability. It has a better control effect in the network control systems with network induced delay, packet loss, and network bandwidth occupancy. The control effects have a wide range of prospects for application to the warp tension network control system of the carbon fiber multilayer diagonal loom.

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**WEI LIU** received the M.Sc. degree in computer application technology and the Ph.D. degree in mechanical engineering from Tianjing University, Tianjin, China, in 2010 and 2018, respectively. She is currently an Associate Professor with the School of Mechanical Engineering, Tiangong University. Her research interests include detection technology, intelligent control, and computer applications of control methodologies.

**XIAOGANG DU** received the M.Sc. and Ph.D. degrees from Tianjin University, Tianjin, China, in 1990 and 2008, respectively. He is currently an Associate Professor with the School of Mechanical Engineering, Tiangong University. His research interests include electromechanical system optimization and air conditioning system technology.

**GUOWEI XU** received the M.Sc. degree in motor and electrical professional from the Shenyang University of Technology, Shenyang, China, in 2000, and Ph.D. degree in textile engineering from Tiangong University, Tianjin, China, in 2015. He is currently an Associate Professor with the School of Electrical Engineering and Automation, Tiangong University. His research interests include sliding mode control, neural networks, and artificial intelligent.

**XIAOYU WU** received the B.S. degree in mechanical design manufacture and automation from Northeast Petroleum University, Daqing, China, in 2017. He is currently pursuing the master’s degree with the School of Mechanical Engineering, Tiangong University. His research interests include intelligent control and networked control.

**SHUO WANG** received the B.S. degree from the College of Intelligence and Information Engineering, Tangshan University, Tangshan, China, in 2018. He is currently pursuing the master’s degree with the School of Electrical Engineering and Automation, Tiangong University. His research interests include sliding mode control and neural networks.

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