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CONGESTION TRACKING CONTROL FOR WIRELESS TCP/AQM NETWORK BASED ON ADAPTIVE DYNAMIC SURFACE SCHEME

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Abstract. *In order to address the Active Queue Management (AQM) issue in a wireless Transmission Control Protocol (TCP) network, the goal of this study is to develop an adaptive dynamic surface controller. This method enables the proposed control law to be applied to the nonlinear wireless network model's congestion tracking issue. A state-feedback congestion controller is additionally suggested to guarantee that the queue length can follow the target queue length despite unexpected changes and unknown parameters. The MATLAB environment is used to validate the developed control design. Simulated results are used to confirm the effectiveness of the suggested control, and it is contrasted with an adaptive integral backstepping scheme. The simulation results show that the proposed technique can not only give better transient performances, but also address the required congestion tracking control problem in spite of unknown parameters.*

Keywords: Congestion tracking control, Adaptive control, Wireless TCP/AQM network

1. **Introduction.** The Internet is currently undergoing tremendous development, which has created an inescapable network congestion control dilemma. It could also lead to network collapse, lock-out behavior, and a high probability of control-loop synchronization. As a result, there are numerous efforts to address this problem. The subject of controlling network congestion has received more and more attention recently. Thankfully, there is a significant and effective technique known as the Active Queue Management (AQM) scheme. It has been suggested to reduce the rate of packet loss, ensure the best-effort service with minimal packet drops, and enhance network usage. Following then, a number of AQM approaches with various design concepts have been reported. Random Early Detection (RED) [1] was the first AQM approach that was presented. The primary benefit of this method is the ability to determine the probability of dropped packets based on the average queue length. On the basis of an analytical fluid-flow model for TCP/AQM systems, a variety of strategies [2-11] for addressing network congestion issues were investigated. To guarantee the queue length stability and robustness against external disturbances and model perturbation using LMI technique, a combination of robust active queue management and $\mathcal{H}_\infty$ control theory [2] has been provided. To decrease packet loss and improve network utilization with input saturation, Mohammadi et al. [3] developed a fuzzy-based PID management of the AQM network for Internet routers. To counteract the effects of nonlinear disturbance uncertainties, time-varying delay, and input constraint through Lynpunov-Krasovskii functional, Han et al. [4] presented a nonlinear model prediction

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congestion management algorithm for networks. A minimax strategy was used to develop an adaptive backstepping congestion management control design [5] for TCP networks with User Datagram Protocol (UDP) flows. Since unknown UDP flows were considered to be external disturbances, the minimax UDP flow must be calculated. In addition, parameter estimation was implemented to limit parameter identification to a particular interval. To address the disturbances caused by UDP flows, a coordination of integral backstepping design and minimax technique of AQM for TCP networks was provided. Combining integral backstepping and $\mathcal{H}_\infty$ design, Liu et al. [6] proposed a congestion tracking control technique for uncertain TCP/AQM networks. The resulting control law can guarantee higher tracking performances of the queue despite the usage of a model with external disturbances and modeling uncertainties, and all trajectories are asymptotically stable. For TCP/AQM networks, an adaptive fuzzy funnel congestion controller [8] was reported to guarantee the tracking errors' required transient and steady-state performances. In [9], a nonlinear TCP network congestion system with unknown parameters and external disturbances is controlled by a backstepping sliding mode control law with the minimax in game theory. An adaptive neural network with practically finite-time congestion management [10] for TCP/AQM networks with the required performance control was proposed to guarantee that the queue length follows the intended queue length in finite-time. In TCP/AQM networks, sliding mode queue management [11] was created to guarantee parameter insensitivity to noise and variance.

All of the aforementioned systems were developed for wired networks, as can be seen. Because there are two key distinctions between a wired network and a wireless network, these strategies cannot be immediately applied to the wireless network. Firstly, because base stations and terminal devices have distinct capabilities, uplink and downlink are asymmetric. Secondly, there are two reasons resulting in packet loss. The first is network congestion in the router, and the second is poor wireless network performance during wireless link transmission. There are currently promising models [14-17] being developed to describe the dynamics of wireless networks. There have been numerous design strategies [14-18] for addressing the congestion control issue in wireless networks in recent years, all of which are based on the wireless model that was discussed earlier. An $\mathcal{H}_\infty$ control design [14] was developed for an AQM router that supports TCP flows using an LMI technique. In [15], Yang et al. designed a three-state mode model-based linear quadratic servo congestion controller for TCP/AQM systems. Using a parameterized set of linear matrix inequalities, a congestion management technique for wireless networks supporting TCP flows was presented to prevent severe congestion and improve resource utilization. It was demonstrated that a fractional-order proportional integral controller [18] for the AQM network was robust against system parameter variation and external disturbances.

According to the authors' knowledge, all known wireless congestion control algorithms were created using linearization approaches around the operational point. The described design method mainly utilized the input/output linearization approach directly and aimed to establish the connection between the desired controller u and the output $h(x)$ by calculating the time derivative of the output $y = h(x)$. Consequently, altering the chosen outputs influences the interaction between various types of controllers and outputs. Nevertheless, the nonlinear controllers for nonlinear wireless network system mentioned above possess notable disadvantages. However, the development of advanced nonlinear control approaches based on the nonlinear wireless network model has received very little attention. Ma et al. [19] presented an adaptive integral backstepping approach for resolving the congestion tracking issue in wireless TCP/AQM networks. The resulting controller's tracking performance was satisfactory. Also, adaptive update laws were developed to estimate the unknown uplink and downlink packet loss parameters. The adaptive integral backstepping strategy has a significant drawback despite being a potent control design technique that has been successfully used on a variety of real-world systems. The "explosion of complexity" problem, which is a drawback of the repeated differentiation of virtual control functions, is what causes it. It is difficult to compute the time derivative of the virtual control functions at each design method since it frequently happens in large-scale systems. This makes the ultimate control law more complicated. To alleviate this drawback, a concept of Dynamic Surface Control (DSC) design [21, 22] is developed to eliminate the problem of repeated differentiations of the virtual control variables. In order to circumvent this issue, these virtual control variables are passed through a low-pass filter at each design stage to prevent their derivatives.

This research continues this line of investigation and extends all currently available wireless congestion controllers based on the nonlinear wireless network model in the presence of unknown parameters. It does so by using an advanced control strategy known as an adaptive dynamic surface control technique. The controller proposed in this study can address the "explosion of complexity" problem brought on by backstepping and has a step-by-step design procedure. Another benefit of employing DSC is that it significantly relaxes the requirements for the desired signal and the smoothness of plant functions. As a result, simplified nonlinear feedback stabilizing as well as adaptive controllers for uncertain nonlinear systems have been synthesized using the DSC technique. Additionally, a variety of practical systems [23-25] have successfully used the DSC control concept. The proposed method's control goal is to determine an adaptive feedback controller that not only ensures all signals of the closed-loop system are semi-global uniformly and ultimately bounded, but also achieves the desired closed-loop system performance in the presence of unknown parameters.

As mentioned above, the following are the primary contributions of this work: (i) The congestion tracking control problem for wireless TCP/AQM networks, which has not before been studied, is proposed using an adaptive control approach based on a nonlinear wireless TCP/AQM dynamic model in the presence of unknown parameters; (ii) Despite having sudden changed parameters, all trajectories of the closed-loop dynamics are semi-global uniformly and ultimately bounded in spite of having sudden changes; (iii) The developed design process is less complex but still efficient when compared to the adaptive integral backstepping method. Additionally, the controller displays excellent dynamic performance, including small overshoot and rapid oscillation reduction.

The rest of this paper is organized as follows. Section 2 gives a brief presentation of dynamic model of wireless TCP/AQM network and the problem statement. Section 3 introduces adaptive dynamic surface control design. Simulation results are discussed in Section 4 and finally the paper is concluded in Section 5.

2. **System Model for Wireless Access Networks.** A dynamic model used in this paper is based on the fluid-flow model of TCP congestion-avoidance method and stochastic differential equation analysis presented in [12, 13]. Further, this model was confirmed via simulation results and can capture accurately the dynamics of TCP. The model is described by the following coupled, nonlinear differential equations:

$$\dot{W}(t) = \frac{1}{R(t)} - \frac{W(t)}{2}\frac{W(t-R(t))}{R(t-R(t))}p(t-R(t)) \tag{1}$$

$$\dot{q} = \begin{cases} -C + \dfrac{1}{R(t)}W(t), & q > 0 \\ \max 0, -C + \dfrac{1}{R(t)}W(t), & q = 0 \end{cases} \tag{2}$$

with $R(t) = T_p + \frac{q(t)}{C(t)}$, where $W(t) \in [W_{\min}, W_{\max}]$ denotes the TCP window size, $R(t)$ represents the round-trip delay, $p(t)$ denotes the ratio of packets marked as dropping in the queue that satisfies $0 \leq p(t) \leq 1$, $q(t) \in [q_{\min}, q_{\max}]$ denotes the queue length, $C(t)$ represents the link capacity, and T_p denotes the propagation delay. Note that the first differential equation in (1) relates to the TCP window control dynamics. In particular, the $1/R$ term in (1) models the window's additive increase, and the $W/2$ term models the window's multiplicative decrease in response to packet marking p. Further, the second differential equation in (2) represents the queue dynamics which models the bottleneck queue length as simply an accumulated difference between packet arrival rate W/R and the link capacity $C(t)$. Although the fluid-flow model in (1) and (2) was effective, the approach reported in [14] has indicated that the model above was not suitable to be used as the wireless network model.

Therefore, this model must be expanded in order to account for the wireless network, which creates an inescapable issue. When the model is used, for instance, the router detects packet losses. Congestion would be considered to exist. The router will then drop certain packets to lessen the impact of congestion. However, it is possible that the wireless link could have packet losses. Practically speaking, the router does not have to drop the packet. Due to the packet losses in wireless uplink and wireless downlink, the dynamic model is further enhanced. The model for wireless networks is more accurate than in [12] due to the addition of uplink and downlink packet losses.

According to the result presented in [14, 19], a nonlinear wireless TCP/AQM model can be expressed as

$$\begin{cases} \dot{W}(t) = \dfrac{1}{R(t)}(1 - p_{dl}(t)) - (1 - p_{dl}(t))\dfrac{W(t)}{2}\dfrac{W(t - R(t))}{R(t - R(t))}p(t - R(t)) \\ \qquad\qquad - p_{dl}(t)(W(t) - 1)\dfrac{W(t - R(t))}{R(t - R(t))}p(t) \\ \dot{q}(t) = \dfrac{W(t)}{R(t)}(1 - p_{ul}(t)) - C(t) \\ R(t) = T_p + \dfrac{q(t)}{C(t)} \end{cases} \tag{3}$$

where $p_{dl} \in [0, 1]$ is the packet loss of downlink while $p_{ul} \in [0, 1]$ is the packet loss of uplink. For this work, we assume that $C(t)$ is assumed as the constant, denoted by C. Further, both p_{dl} and p_{ul} are considered as the constants.

In order to simplify the state-space equation of the system (3), let us introduce the following state variables: $x_1 = q - q_r$, $x_2 = W$. Additionally, to ensure that the queue length q can track the desired queue length q_r, let us define another state variable to guarantee the zero error between the queue length and the desired queue length as $x_0 = \int_0^t (q(\tau) - q_r(\tau))d\tau$. Therefore, we have the vector of the state variables used in this design procedure as $x = [x_0, x_1, x_2]^T = \left[\int_0^t (q(\tau) - q_r(\tau))d\tau, q - q_r, W\right]^T$. By neglecting system delay and differentiating the state variables above, the dynamic model of the nonlinear wireless TCP/AQM model can be expressed as an affine nonlinear system as follows:

$$\begin{aligned} \dot{x}_0 &= x_1 \\ \dot{x}_1 &= f_1(x_1) + [g_{10}(x_1) + g_{11}(x_1)\theta_1]x_2 \\ \dot{x}_2 &= f_2(x_1, x_2) + [g_{20}(x_1, x_2) + g_{21}(x_1, x_2)\theta_2]u \end{aligned} \tag{4}$$

with

$$\begin{aligned} &f_1(x_1) = -C,\ g_{10}(x_1) = \frac{NC}{x_1 + q_r + CT_p},\ g_{11}(x_1) = \frac{-NC}{x_1 + q_r + CT_p} \\ &f_2(x_1, x_2) = \frac{C}{x_1 + q_r + CT_p} \\ &g_{20}(x_1, x_2) = -\frac{C}{x_1 + q_r + CT_p}\left(\frac{x_2^2}{2}\right),\ g_{21}(x_1, x_2) = -\frac{C}{x_1 + q_r + CT_p}\left(\frac{x_2^2}{2} - x_2\right) \\ &u = p(t),\ \theta_1 = p_{ul},\ \theta_2 = p_{dl}. \end{aligned}$$

The following assumption, definition, and lemmas are established in order to satisfy these required objectives above.

Assumption 2.1. *All state variables $x_0, x_1, x_2 \in \mathbb{R}$, are assumed to be measurable.*

Remark 2.1. *In practice, Assumption 2.1 is unreasonable. For the purpose of simplicity in designing the adaptive DSC nonlinear controller in this paper, we made this assumption that all states are measured. In future work, we intend to introduce an output feedback controller through the adaptive DSC control design.*

Definition 2.1. *Consider the nonlinear system*

$$\dot{x}(t) = f(x, t)$$

where $x(t) \in R^n$ is the state vector. Its solution is said to be Semi-Global Uniformly and Ultimately Bounded (SGUUB) if, for $x(0) \in \Omega_x$ where is a compact set, there exist two constants σ and $T(\sigma, x(0))$, such that $\|x(t)\| \leq \sigma$ is held for all $t > t + T(\sigma, x(0))$.

Lemma 2.1. [20] *If the constants $p > 1$ and $q > 1$ are such that $(p-1)(q-1) = 1$, then for all $\epsilon > 0$ and all $(x, y) \in \mathbb{R}^2$ we have*

$$xy \leq \frac{\epsilon^p}{p}|x|^p + \frac{1}{q\epsilon^q}|y|^q \tag{5}$$

If choosing $p = q = 2$ and $\epsilon^2 = 2\kappa$, the inequality above becomes

$$xy \leq \kappa x^2 + \frac{1}{4\kappa}y^2 \tag{6}$$

For simplicity, provided that $\kappa = \frac{1}{2}$, it is straightforward to obtain the following inequality

$$xy \leq \frac{x^2}{2} + \frac{y^2}{2} \tag{7}$$

Lemma 2.2. [20] *Let $\mathcal{V}(t) \in R$ be a non-negative function of time on $[0, +\infty)$ which satisfies the differential inequality*

$$\dot{\mathcal{V}} \leq a\mathcal{V} + b \tag{8}$$

where $a \in R$ and $b \in R$ are positive constants. Then the function $\mathcal{V}(t)$ satisfies the following inequality:

$$\mathcal{V}(t) \leq e^{-at}\mathcal{V}(0) + \frac{b}{a}\left(1 - e^{-at}\right),\ \forall t \in [0, +\infty) \tag{9}$$

Additionally, when time approaches infinity, $\mathcal{V}(t)$ will become $\frac{b}{a}$.

Problem statement: The objective of this paper is to design an adaptive nonlinear controller capable of solving the queue tracking problem for wireless congestion control scheme with the help of dynamic surface method, which can be formulated as follows: an adaptive control law and a parameter update law in (4) are expressed in the following form:

$$u = \phi\left(x, \hat{\theta}\right), \; \dot{\hat{\theta}} = \varpi\left(x, \hat{\theta}\right) \tag{10}$$

where $\hat{\theta}$ is the estimate of $\theta = [\theta_1, \theta_2]^T$. The developed controller satisfies the followings: (i) the queue length q is able to track the desired queue length q_r; (ii) the window size W is stable and bounded; (iii) the ratio of packets marked as dropping in the queue is as small as possible; (iv) despite having unknown parameters, the overall closed-loop system is semi-global uniformly and ultimately bounded.

For the developed design procedure in the next section, the adaptive DSC control design will be developed to obtain a feedback stabilizing nonlinear control. In the following section, the developed control is designed step by step to achieve the desired performances.

3. **Adaptive Nonlinear Control Design.** This section introduces the ideas behind an adaptive dynamic surface control approach and the closed-loop system stability.

The proposed control procedure is developed as follows. In our design procedure, let us define the following error surfaces:

$$S_0 = x_0 \tag{11}$$

$$S_j = x_j - x_{jd}, \; j = 1, 2 \tag{12}$$

where x_{jd} denotes new state variables.

Additionally, let the virtual control function α_{j-1} pass through a first-order filter with a time constant τ_j to obtain the dynamics of x_{jd} as follows:

$$\tau_j \dot{x}_{jd} + x_{jd} = \alpha_{j-1}, \; x_{jd}(0) = \alpha_{j-1}(0) \Rightarrow \dot{x}_{jd} = -\frac{x_{jd} - \alpha_{j-1}}{\tau_j} \tag{13}$$

With the help of adaptive dynamic surface scheme, the virtual controller functions are designed as follows:

$$\alpha_0 = -k_0 S_0 \tag{14}$$

$$\begin{aligned} \alpha_1 &= \frac{1}{g_{10}(x_1) + g_{11}(x_1)\hat{\theta}_1}\left(-f_1(x_1) - k_1 S_1 - \frac{x_{1d} - \alpha_0}{\tau_1}\right) \\ &= \frac{x_1 + q_r + CT_p}{NC\left(1 - \hat{\theta}_1\right)}\left(C - k_1 S_1 - \frac{x_{1d} - \alpha_0}{\tau_1}\right) \end{aligned} \tag{15}$$

with k_{j-1} $(j = 1, 2)$ as positive design constants, and the proposed controller u and the update laws $\hat{\theta} = \left[\hat{\theta}_1, \hat{\theta}_2\right]^T$ are selected as

$$\begin{aligned} u &= \frac{1}{g_{20}(x_1, x_2) + g_{21}(x_1, x_2)\hat{\theta}_2}\left(-f_2(x_1, x_2) - k_2 S_2 - \frac{x_{2d} - \alpha_1}{\tau_2}\right) \\ &= -\frac{1}{C}\frac{x_1 + q_r + CT_p}{\left(\frac{x_2^2}{2} + \left(\frac{x_2^2}{2} - x_2\right)\hat{\theta}_2\right)}\left(-\frac{C}{x_1 + q_r + CT_p} - k_2 S_2 - \frac{x_{2d} - \alpha_1}{\tau_2}\right) \end{aligned} \tag{16}$$

$$\dot{\hat{\theta}}_1 = \gamma_1 g_{11}(x_1) S_1 = \frac{-\gamma_1 NCS_1}{x_1 + q_r + CT_p} \tag{17}$$

$$\dot{\hat{\theta}}_2 = \gamma_2 S_2 u \tag{18}$$

where k_2 is a positive design constant while γ_j denote positive constants.

Theorem 3.1. *Under Assumption 2.1, consider the closed-loop dynamics consisting of the wireless TCP/AQM network (4), the virtual control (14) and (15) and the control law (16), and the update laws (17) and (18) together with the following Lyaponov function candidate*

$$V = \sum_{i=0}^{2} \frac{1}{2} S_i^2 + \sum_{j=1}^{2} \frac{1}{2} y_j^2 + \sum_{j=1}^{2} \frac{1}{2\gamma_j} \tilde{\theta}_j^2, \ \gamma_j > 0 \tag{19}$$

Given a positive number p, for all initial conditions of V satisfying $V(0) \leq p$, if there exists a set of suitable design parameters k_j, c_k $(j = 0, 1, 2,\ k = 1, 2)$ satisfying

$$\bar{k}_0 = k_0 - 1 > 0,\ \bar{k}_1 = k_1 > 0,\ \bar{k}_2 = k_2,\ \bar{c}_1 = \frac{1}{\tau_1} - \frac{\bar{B}_1^2}{2\pi_1} - \frac{1}{2} > 0,\ \bar{c}_2 = \frac{1}{\tau_2} - \frac{\bar{B}_2^2}{2\pi_2} \tag{20}$$

such that all signals of the overall closed-loop dynamics are semi-globally uniformly and ultimately bounded. Additionally, the error surfaces S_i converge to a small residual set that can be made arbitrarily small by appropriate selecting of the above-mentioned design parameters.

Proof: The proof can be divided into two parts. One is the adaptive dynamic surface control scheme which is applied to finding out the control law and the update laws capable of accomplishing the control performances. The other is the closed-loop system stability analysis to ensure that the error surfaces S_i will converge into a small residual set and all trajectories are bounded. First, the proposed control procedure is developed step by step as follows.

Step 1: First, we focus on the first subsystem (4). In order to accomplish stability for the error surface S_0, differentiating S_0 with respect to time yields

$$\dot{S}_0 = \dot{x}_0 = x_1 \tag{21}$$

From (21), x_1 is viewed as a virtual control input; therefore, we have the desired feedback control α_0 as given in (14).

Step 2: Define the second error surface as given in (12), and then by calculating the derivative of S_1, we have

$$\begin{aligned} \dot{S}_1 &= f_1(x_1) + [g_{10}(x_1) + g_{11}(x_1)\theta_1]x_2 - \dot{x}_{1d} \\ &= f_1(x_1) + \left[g_{10}(x_1) + g_{11}(x_1)\left(\tilde{\theta}_1 + \hat{\theta}_1\right)\right] x_2 - \dot{x}_{1d} \\ &= f_1(x_1) + \left[g_{10}(x_1) + g_{11}(x_1)\hat{\theta}_1\right] x_2 - \dot{x}_{1d} + g_{11}(x_1)\tilde{\theta}_1 \end{aligned} \tag{22}$$

where $\hat{\theta}_1$ is an estimate of θ_1 and $\tilde{\theta}_1 = \theta_1 - \hat{\theta}_1$. Similarly, from (22), x_2 is viewed as a virtual control input; therefore, the virtual control law α_1 and the update law for $\hat{\theta}_1$ are given in (15) and (17).

Step 3: Finally, after defining the third surface as S_2, we have the following time derivative of S_2 along the system trajectories:

$$\begin{aligned} \dot{S}_2 &= f_2(x_1, x_2) + [g_{20}(x_1, x_2) + g_{21}(x_1, x_2)\theta_2]u - \dot{x}_{2d} \\ &= f_2(x_1, x_2) + \left[g_{20}(x_1, x_2) + g_{21}(x_1, x_2)\left(\tilde{\theta}_2 + \hat{\theta}_2\right)\right] u - \dot{x}_{2d} \\ &= f_2(x_1, x_2) + \left[g_{20}(x_1, x_2) + g_{21}(x_1, x_2)\hat{\theta}_2\right] u - \dot{x}_{2d} + g_{21}(x_1, x_2)\tilde{\theta}_2 u \end{aligned} \tag{23}$$

where $\hat{\theta}_2$ is an estimation of θ_2 and $\tilde{\theta}_2 = \theta_2 - \hat{\theta}_2$.

Therefore, a suitable selection of the control law $u = p$ and the update law θ_2 to achieve the closed-loop system stability is given as (16) and (18). In order to analyze the closed-loop stability of TCP/AQM system, let us consider the surface and boundary layer errors' time derivatives and the update laws as follows:

$$\begin{cases} \dot{S}_0 = -k_0 S_0 + S_1 + y_1 \\ \dot{S}_1 = -k_1 S_1 + g_{11}(x_1)\tilde{\theta}_1 \\ \dot{S}_2 = -k_2 S_2 + g_{21}(x_1, x_2)\tilde{\theta}_2 u \\ \dot{y}_j = -\dfrac{y_j}{\tau_j} + B_j(S_0, S_1, S_2, y_1, y_2),\ j = 1, 2 \\ \dot{\hat{\theta}}_1 = \gamma_1 g_{11}(x_1) S_1 \\ \dot{\hat{\theta}}_2 = \gamma_2 S_2 \left(\dfrac{1}{g_{20}(x_1, x_2) + g_{21}(x_1, x_2)\hat{\theta}_2} \left(-f_2(x_1, x_2) - k_2 S_2 - \dfrac{x_{2d} - \alpha_1}{\tau_2} \right) \right) \end{cases} \tag{24}$$

where $y_j = x_{jd} - \alpha_{j-1}$ denotes the boundary layer error. $B_j(\cdot)$ is a continuous function defined as follows:

$$\begin{cases} B_1(\cdot) = -\dot{\alpha}_0 = -\dfrac{\partial \alpha_0}{\partial x_1}\dot{x}_1 - \dfrac{\partial \alpha_0}{\partial x_{1d}}\dot{x}_{1d} \\ B_2(\cdot) = -\dot{\alpha}_1 = -\dfrac{\partial \alpha_1}{\partial x_1}\dot{x}_1 - \dfrac{\partial \alpha_1}{\partial x_{1d}}\dot{x}_{1d} - \dfrac{\partial \alpha_1}{\partial \hat{\theta}_1}\dot{\hat{\theta}}_1 \end{cases} \tag{25}$$

Based on the Lyapunov direct method, the time derivative of V along trajectories (24) is as follows:

$$\begin{aligned} \dot{V} &= \sum_{i=0}^{2} S_i \dot{S}_i + \sum_{j=1}^{2} y_j \dot{y}_j - \sum_{j=1}^{2} \frac{1}{\gamma_j}\tilde{\theta}_j \dot{\hat{\theta}}_j \\ &= S_0(-k_0 S_0 + S_1 + y_1) - k_1 S_1^2 - k_2 S_2^2 + \sum_{j=1}^{2} y_j \left(-\frac{y_j}{\tau_j} + B_j \right) \\ &\quad + \tilde{\theta}_1 \left(S_1 g_{11}(x_1) - \frac{1}{\gamma_1}\dot{\hat{\theta}}_1 \right) + \tilde{\theta}_2 \left(S_2 g_{21}(x_1, x_2) u - \frac{1}{\gamma_2}\dot{\hat{\theta}}_2 \right) \end{aligned} \tag{26}$$

For $i = 0, 1, 2$, $j = 1, 2$ and $p > 0$, the set $\Omega := \sum_{i=0}^{2} S_i^2 + \sum_{j=1}^{2} y_j^2 + \sum_{j=1}^{2} \frac{1}{\gamma_j}\tilde{\theta}_j^2 \leq 2p$ is compact set in R^7. According to the property of continuous function, we know that $B_j(\cdot)$ has a bound on Ω, such that $|B_j(\cdot)| \leq \bar{B}_j$. Based on the Young's inequality (Lemma 2.1), we have the following inequalities:

$$\begin{cases} S_0 S_1 \leq \dfrac{S_0^2}{2} + \dfrac{S_1^2}{2} \\ S_0 y_1 \leq \dfrac{S_0^2}{2} + \dfrac{y_1^2}{2} \\ y_j \left(-\dfrac{y_j}{\tau_j} + B_j \right) \leq -\left(\dfrac{1}{\tau_j} - \dfrac{\bar{B}_j^2}{2\pi_j} \right) y_j^2 + \dfrac{\pi_j}{2} \end{cases} \tag{27}$$

From the inequalities above, one has

$$\dot{V} \leq -(k_0 - 1)S_0^2 - k_1 S_1^2 - k_2 S_2^2 + \left(\frac{1}{\tau_1} - \frac{\bar{B}_1^2}{2\pi_1} - \frac{1}{2} \right) y_1^2 - \left(\frac{1}{\tau_2} - \frac{\bar{B}_2^2}{2\pi_2} \right) y_2^2 + \sum_{j=1}^{2} \frac{\pi_j}{2} \tag{28}$$

After selecting $\bar{k}_0 = k_0 - 1 > 0$, $\bar{k}_1 = k_2 > 0$, $\bar{k}_2 = k_2 > 0$, $\bar{c}_1 = \frac{1}{\tau_1} - \frac{\bar{B}_1^2}{2\pi_1} - \frac{1}{2} > 0$, $\bar{c}_2 = \frac{1}{\tau_2} - \frac{\bar{B}_2^2}{2\pi_2} > 0$, we obtain

$$k = \min\left\{\bar{k}_0, \bar{k}_1, \bar{k}_2, \bar{c}_1, \bar{c}_2\right\} > 0 \tag{29}$$

After that, the following inequalities hold.

$$\dot{V} \leq -kV + \Pi \tag{30}$$

where $\Pi = \sum_{j=1}^{2} \frac{\pi_j}{2}$. After solving Inequality (30) and using Lemma 2.2, we obtain

$$0 \leq V(t) \leq \left(V(0) - \frac{\Pi}{c}\right) e^{-ct} + \frac{\Pi}{c} \tag{31}$$

From (31), it can be inferred that $\lim_{t\to+\infty} V(t) \leq \frac{\Pi}{c}$. This means that the error surface S_i can converge to an arbitrarily small residual set by selecting c sufficiently large. Similarly, it can be also concluded that all the trajectories of the closed-loop dynamics are semi-globally uniformly ultimately bounded. In particular, it implies that S_i and y_j are all semi-globally uniformly ultimately bounded. This completes the proof.

Remark 3.1. *The incremental contribution discussed in Section 3 focuses on the developed design procedure and presents the distinctions between our research and the existing controllers of literature. Specifically, we highlight our innovative method of developing a congestion tracking controller for wireless TCP/AQM networks using an adaptive dynamic surface strategy, a novel approach that has not been explored before. Moreover, our study introduces a new technique for handling the unknown parameters that arise in the wireless TCP/AQM model. It is worth noting that, unlike the adaptive integral backstepping control mentioned in prior works* [19, 20]*, our proposed control law does not require the use of analytical differentiators.*

4. Simulation Results.

In this section, the effectiveness of the proposed controller is evaluated and verified in MATLAB environment under the following parameters of the networks.

$$C = 1750 \text{ packets/s},\ T_p = 0.1 \text{ s},\ q_r = 100 \text{ packets}$$

Further, both uplink and downlink packet loss ratios are as follows:

$$\theta_1 = \begin{cases} 0.005, & \text{if } 0 \leq t \leq 4, \\ 0.001, & \text{else if } 4 < t \leq 10 \\ 0.01, & \text{else if } 10 < t \leq 16 \\ 0.05, & \text{else if } 16 < t \leq 22 \\ 0.01, & \text{else if } 22 < t \leq 28 \\ 0.05, & \text{else} \end{cases}, \quad \theta_2 = \begin{cases} 0.008, & \text{if } 0 \leq t \leq 4, \\ 0.002, & \text{else if } 4 < t \leq 10 \\ 0.02, & \text{else if } 10 < t \leq 16 \\ 0.06, & \text{else if } 16 < t \leq 22 \\ 0.01, & \text{else if } 22 < t \leq 28 \\ 0.05, & \text{else} \end{cases}$$

The tuning parameters of the proposed controller are $c_0 = c_1 = c_2 = 10$, $\tau_1 = \tau_2 = 0.001$, $\gamma_1 = \gamma_2 = 0.0000001$.

Remark 4.1. *According to the tuning parameters of the suggested control law above, using the trial-and-error method in this work, it is discovered that selecting such control parameters that are too large or too small may result in unsatisfactory transient responses. As a result, it is difficult to determine which design parameters are optimal for achieving asymptotic tracking and good dynamic performance. However, an optimization strategy is likely to be an effective means of addressing this issue.*

The time domain simulations are carried out via the computer simulation. To investigate the system dynamic performance of the designed controller, as given in (16)-(18), in the system under study, the performance of the proposed controller (adaptive dynamic surface controller) is compared with that of adaptive integral backstepping controller [19, 20], as follows.

- Adaptive Integral Backstepping Control (AIBSC)

$$u(t) = \frac{1}{g_{20}(x_1,x_2)+g_{21}(x_1,x_2)\hat{\theta}_2}\Bigg(-c_2z_2 - z_1\left(g_{11}(x_1)+g_{11}(x_1)\hat{\theta}_1\right) - f_2(x_1,x_2) + \frac{\partial\alpha_1}{\partial z_0}\dot{z}_0 + \frac{\partial\alpha_1}{\partial z_1}\left[f_1(x_1)+\left(g_{10}(x_1)+g_{11}(x_1)\hat{\theta}_1\right)x_2 - \dot{\alpha}_0\right] + \frac{\partial\alpha_1}{\partial\hat{\theta}_1}\dot{\hat{\theta}}_1 + \frac{\partial\alpha_1}{\partial q_r}\dot{q}_r + \frac{\partial\alpha_1}{\partial\dot{q}_r}\ddot{q}_r\Bigg) \tag{32}$$

$$\dot{\hat{\theta}}_1 = \gamma_1\left(z_1 - \gamma_1^{-1}\frac{\partial\alpha_1}{\partial z_1}\right)g_{11}(x_1)x_2 \tag{33}$$

$$\dot{\hat{\theta}}_2 = \gamma_2 g_{21}(x_1,x_2)z_2 u \tag{34}$$

where $z_0 = x_0$, $z_1 = x_1 - \alpha_1$, $z_2 = x_2 - \alpha_2$, $\alpha_0 = -c_0z_0$, $\alpha_1 = -\frac{c_1z_1+z_1-f_1(x_1)+\dot{\alpha}_0}{g_{10}(x_1)+g_{11}(x_1)\hat{\theta}_1}$, $\dot{\alpha}_0 = -c_0\dot{z}_0 = -c_0x_1$. The controller parameters of the adaptive integral backstepping control law are chosen as follows: $c_i = 0.0001$, $i = 0,1,2$, $\gamma_1 = \gamma_2 = 0.0000001$.

- Adaptive Backstepping Control (ABSC)

$$u(t) = \frac{1}{g_{20}(x_1,x_2)+g_{21}(x_1,x_2)\hat{\theta}_2}\Bigg(-c_2z_2 - z_1\left(g_{11}(x_1)+g_{11}(x_1)\hat{\theta}_1\right) - f_2(x_1,x_2) + \frac{\partial\alpha_1}{\partial z_1}\left[f_1(x_1)+\left(g_{10}(x_1)+g_{11}(x_1)\hat{\theta}_1\right)x_2\right] + \frac{\partial\alpha_1}{\partial\hat{\theta}_1}\dot{\hat{\theta}}_1 + \frac{\partial\alpha_1}{\partial q_r}\dot{q}_r + \frac{\partial\alpha_1}{\partial\dot{q}_r}\ddot{q}_r\Bigg) \tag{35}$$

$$\dot{\hat{\theta}}_1 = \gamma_1 z_1 g_{11}(x_1)x_2 \tag{36}$$

$$\dot{\hat{\theta}}_2 = \gamma_2 g_{21}(x_1,x_2)z_2 u \tag{37}$$

where $z_1 = x_1$, $z_2 = x_2 - \alpha_1$, $\alpha_1 = \frac{(-c_1z_1-f_1(x_1))}{g_{10}(x_1)+g_{11}(x_1)\hat{\theta}_1}$. The controller parameters of the adaptive backstepping control law are chosen as follows: $c_i = 0.0001$, $i = 1,2$, $\gamma_1 = \gamma_2 = 0.0000001$.

Remark 4.2. *Observed from (32)-(37) is that the AIBSC and the ABSC and the update law $\hat{\theta}_1$ are significantly dependent on the time derivative of the virtual control function α_1, whereas the proposed control law is based on the linear filter $\dot{x}_{2d}$ with the constant τ_2. This makes the DSC design approach more efficient and straightforward.*

Based on the following issues, the simulation results are used to demonstrate the usefulness of the developed method: 1) the tracking error between the queue length and the desired queue length converges to zero; 2) despite unknown rapid changed parameters, the window size becomes stable and the packet loss ratio in the queue is small.

The findings of the simulation are shown and discussed below. Figures 1 and 2 illustrate the time histories of the integral of error between the queue length and desired queue length, the queue length, the window size, the estimation of θ_1 and θ_2, and the packet loss ratio under the proposed method and the AIBSC method and ABSC method.

It is clear that the designed control law outperforms the AIBSC law and the ABSC law in terms of better dynamic performances. In particular, it has been found that using the suggested strategy causes the tracking error to rapidly converge or the queue length to go closer to the desired queue length ($q_r = 100$). Furthermore, all trajectory rising and settling times are obviously shortened, which improves transient performances as well as

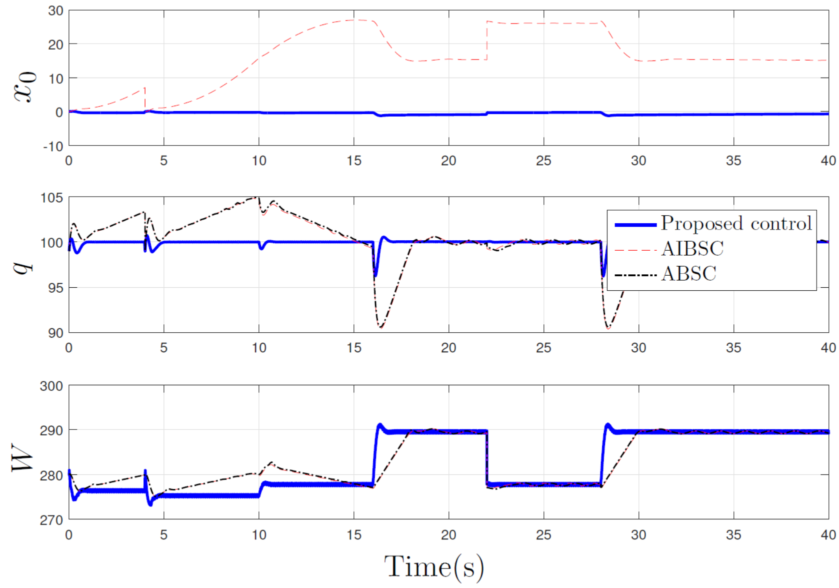

FIGURE 1. Controller performance – $x_0 = \int_0^t (q(\tau) - q_r)d\tau$, queue ($q$) and desired queue length ($q_r = 100$) and window size (W) (Solid: Proposed control (Adaptive dynamic surface control), Dashed: Adaptive integral backstepping control, Dash-dotted: Adaptive backstepping control)

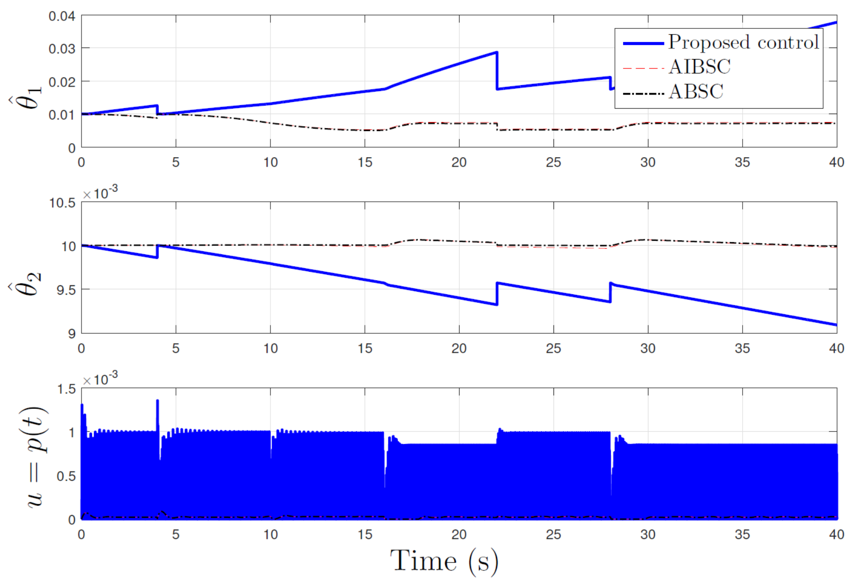

FIGURE 2. Controller performance – The estimation of θ_1 and θ_2 and the packet loss ratio $u = p(t)$ (Solid: Proposed control (Adaptive dynamic surface control), Dashed: Adaptive integral backstepping control, Dash-dotted: Adaptive backstepping control)

oscillation overshoot magnitude. Additionally, it has been found that while time responses under the AIBSC and ABSC schemes exhibit good dynamic performances, they perform worse than the developed one in transient situations.

The expected time responses of θ_1 and θ_2 estimation after unknown rapid changes in both the uplink and downlink packet loss parameters are also shown in Figure 2.

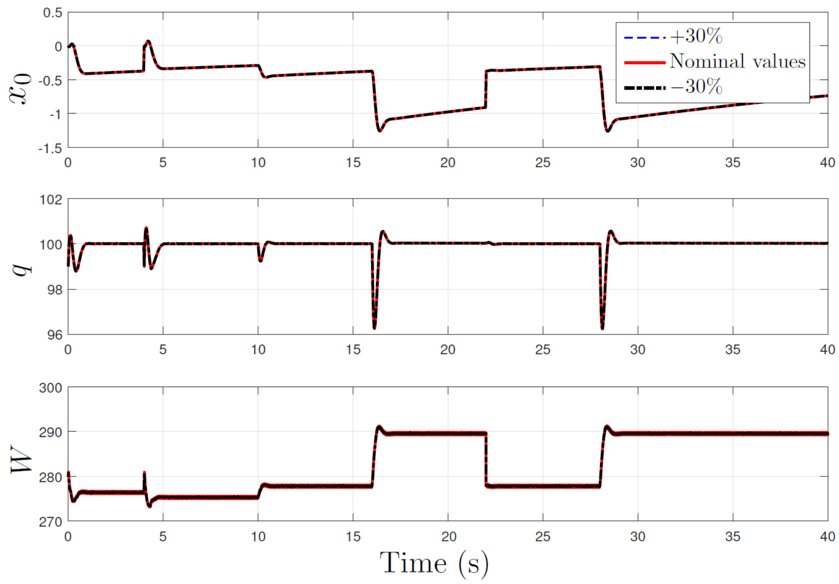

FIGURE 3. Time histories – x_0, queue length q and window size W under parameter variation of the link capacity C

Furthermore, it can be observed that the packet loss ratio $u = p(t)$ is seen to belong to the required interval $[0, 1]$.

In practical applications, obtaining accurate model parameters for the considered system is challenging. Hence, one of the key challenges that requires investigation is ensuring the robustness of the developed control law in the presence of parameter variations and uncertainties in the wireless TCP/AQM network. Subsequently, the performance of the developed control strategy is assessed with respect to uncertainties. Specifically, a system parameter, such as the link capacity C, is uncertain due to the difficulty in precisely estimating its value. Therefore, it is crucial to evaluate the robustness of the resulting controller against variations in the link capacity. To assess the system's performance under such circumstances, a robustness test was conducted by introducing a variation of $\pm 30\%$ in the value of C from its nominal value. Figure 3 clearly demonstrates that, despite the variation in the system parameter, the proposed design consistently delivers effective control performance. The tracking error converges to zero, and there is no degradation in the system's performance, indicating the robustness of the developed control method in the face of parameter variations. Additionally, the window size W remains stable as expected. Consequently, the resulting controller exhibits commendable tracking performance and a strong ability to handle parameter variations.

From the previously mentioned simulation findings, it is clear that when the devised system is used for the congestion tracking control for wireless TCP/AQM networks, the following improvements over the AIBSC method and the ABSC method are realized: (i) The proposed controller is synthesized to steer all the trajectories of the closed-loop dynamics to be semi-global uniformly and ultimately bounded; (ii) Despite unknown rapid changes in both the uplink and downlink packet loss parameters, the developed control technique can give clearly superior transient performances, as evidenced by the rapid suppression of system oscillations across all time trajectories, and the robustness against parameter variation.

5. **Conclusions.** The queue tracking problem for wireless congestion control is addressed in this study utilizing the adaptive dynamic surface control approach, despite the fact that

the parameters are unknown. The simulation results have demonstrated that the uplink and downlink packet loss ratios, which are unknown, are used to evaluate the developed control mechanism. It can cause the window size and all the trajectories of the closed-loop dynamics to be semi-global uniformly and ultimately bounded, in addition to making the tracking error between the queue and the target queue lengths quickly converge to zeros. It can enhance better transient control performance than the adaptive integral backstepping control and the adaptive backstepping control thanks to the created design technique. Additionally, the comparative results support the effectiveness of the proposed controller, which is capable of resolving the congestion tracking problem and enhancing transient performances in the closed-loop system dynamics, despite unknown uplink and downlink packet loss parameters. To validate the robustness of the proposed control method against parameter variations and uncertainties, the simulations have demonstrated that even with a 30% variation in the link capacity, the overall time trajectories remain insensitive to the parameter variation. The application of this strategy to a robust adaptive control scheme will be the subject of a subsequent investigation. Moreover, further studies will focus on how to extend the proposed approach to wireless TCP/AQM systems with event-triggered communications [26].

REFERENCES

[1] S. Floyd and V. Jacobson, Random early detection gateways for congestion avoidance, *IEEE/ACM Transactions on Networking*, vol.1, no.4, pp.397-413, 1993.
[2] C. Zhou, J. He and Q. Chen, A robust active queue management scheme for network congestion, *Computer & Electrical Engineering*, vol.39, no.2, pp.285-294, 2013.
[3] S. Mohammadi, H. M. Pour, M. Jafari and A. Javadi, Fuzzy-based PID active queue manager for TCP/IP networks, *Proc. of the 10th International Conference on Information Science, Signal Processing and Their Applications (ISSPA 2010)*, Kuala Lumpur, pp.434-439, 2010.
[4] C. Han, M. Li, Y. Jing, L. Lei, Z. Pang and D. Sun, Nonlinear model predictive congestion control for networks, *IFAC-Papers on Line*, vol.50, no.1, pp.552-557, 2017.
[5] Z. H. Li, Y. Liu and Y.-W. Jing, Design of adaptive backstepping congestion controller for TCP networks with UDP flows based on minimax, *ISA Transactions*, vol.95, pp.27-34, 2019.
[6] Z. H. Li, Y. Liu and Y.-W. Jing, Active queue management algorithm for TCP networks with integral backstepping and minimax, *International Journal of Control, Automation and Systems*, vol.17, no.4, pp.1059-1066, 2019.
[7] Y. Liu, X. Liu, Y. Jing, Z. Zhang and X. Chen, Congestion tracking control for uncertain TCP/AQM network based on integral backstepping, *ISA Transactions*, vol.89, pp.131-138, 2019.
[8] K. Wang, Y. Liu, X. Liu, Y. Jing and S. Zhang, Adaptive fuzzy funnel congestion control for TCP/AQM network, *ISA Transactions*, vol.95, pp.11-17, 2019.
[9] K. Wang, Y. Jing and S. Zhang, Minimax controller design based on backstepping sliding mode for TCP network systems, *Proc. of 2017 29th Chinese Control and Decision Conference (CCDC)*, Chongqing, China, pp.764-768, 2017.
[10] Y. Liu, Y. Jing and X. Chen, Adaptive neural practically finite-time congestion control for TCP/AQM network, *Neurocomputing*, vol.351, pp.26-32, 2019.
[11] M. Jalili-Kharaajoo, Sliding mode queue management in TCP/AQM networks, *Proc. of International Conference on Telecommunication (ICT 2004)*, pp.638-643, 2004.
[12] V. Misra, W.-B. Gong and D. Towsely, Fluid-based analysis of a network of AQM routers supporting TCP flows with an application to RED, *Proc. of ACM/SIGCOMM*, pp.151-160, 2000.
[13] C. V. Hollot, V. Misra, D. Towsley and W. Gong, Analysis and design of controllers for AQM routers supporting TCP flows, *IEEE Transactions on Automatic Control*, vol.47, no.6, pp.945-959, 2002.
[14] F. Zheng and J. Nelson, An $\mathcal{H}_\infty$ approach to congestion control design for AQM routers supporting TCP flows in wireless access networks, *Computer Networks*, vol.51, no.6, pp.1684-1704, 2007.
[15] J. Yang, D. Lim and W. Oh, LQ-servo congestion control for TCP/AQM system in wireless network environment, *International Journal of Control and Automation*, vol.6, 2013.
[16] H. Mukaidani, C. Lin and X. Shen, Stable queue management for supporting TCP flows over wireless networks, *Proc. of IEEE International Conference on Communications*, 2011.

[17] K. Chavan, R. G. Kumar, M. N. Belur and A. Karandikar, Robust active queue management for wireless networks, *IEEE Transactions on Control Systems Technology*, vol.19, no.6, pp.1630-1638, 2011.
[18] Y. Qian, W. Hu, X. Lin and B. Wang, Fractional order proportional integral controller for active queue management of wireless network, *Proc. of Control Conference*, 2011.
[19] L. Ma, X. Liu, H. Wang and Y. Zhou, Congestion tracking control for wireless TCP/AQM network based on adaptive integral backstepping, *International Journal of Control, Automation and Systems*, vol.18, pp.2289-2296, 2020.
[20] M. Krstic, I. Kanellakopoulos and P. Kokotivic, *Nonlinear and Adaptive Control Design*, John Wiley & Sons, New York, 1995.
[21] D. Swaroop, J. K. Hedrick, P. P. Yip and J. C. Gerdes, Dynamic surface control for a class of nonlinear systems, *IEEE Transactions on Automatic Control*, vol.45, no.10, pp.1893-1899, 2000.
[22] P. P. Yip and J. K. Hedrick, Adaptive dynamic surface control: A simplified algorithm for adaptive backstepping control of nonlinear systems, *International Journal of Control*, vol.71, no.5, pp.959-979, 1998.
[23] Z. J. Yang, K. Miyazaki, S. Kanae and K. Wada, Robust position control of a magnetic levitation system via dynamic surface control technique, *IEEE Transactions on Industrial Electronics*, vol.51, no.1, pp.26-34, 2004.
[24] J. Yu, P. Shi, W. Dong, B. Chen and C. Lin, Neural network-based adaptive dynamic surface control for permanent magnet synchronous motors, *IEEE Transactions on Control Systems Technology*, vol.23, no.6, pp.640-645, 2015.
[25] A. Kanchanaharuthai and E. Mujjalinvimut, Adaptive dynamic surface control for higher-order model of synchronous generators, *International Journal of Innovative Computing, Information and Control*, vol.16, no.2, pp.749-794, 2020.
[26] S. Wan, Y. Zhang, Z. He and L. Chen, Periodic event-triggered tracking control for nonholonomic wheeled mobile robots, *International Journal of Innovative Computing, Information and Control*, vol.18, no.5, pp.1507-1517, 2022.

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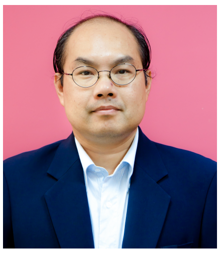

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