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SPECIAL SECTION ON LEARNING SYSTEMS BASED CONTROL AND OPTIMIZATION OF COMPLEX NONLINEAR SYSTEMS

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Nonlinear Backstepping Tracking Control for a Vehicular Electronic Throttle With Input Saturation and External Disturbance

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ABSTRACT To achieve more precise positioning of the electronic throttle plate, a nonlinear backstepping tracking control strategy is presented in this paper. In contrast to the existing control schemes for electronic throttles, the input saturation and unknown external disturbances are explicitly considered in the tracking control design. The difficulties in controlling an electronic throttle include the strong nonlinearity of the spring and friction as well as the unknown external disturbance. In particular, the valve plate angle is adjusted by the control input voltage of the driving motor, and the input voltage is limited to a certain range. Therefore, input saturation problems exist in the control system for an electronic throttle. To overcome the abovementioned difficulties, an auxiliary design system is presented to handle the input saturation, and its state is applied in the proposed control design. A sliding-mode control term is also utilized in the tracking controller to counteract the unknown external disturbance. The proof and analysis show that the satisfactory tracking performance of the valve plate angle can be achieved by using the designed control scheme for the electronic throttle system in the presence of input saturation and unknown external disturbances. Simulation studies and results are provided to illustrate the desired performance of the proposed nonlinear tracking controller.

INDEX TERMS Vehicle electronic throttle, backstepping control, tracking control method, input saturation, sliding-mode control.

I. INTRODUCTION

In a conventional vehicle, the accelerator pedal is mechanically linked to the engine throttle. This mechanical linkage can decrease the efficiency of the engine. In recent years, the mechanical linkage has been replaced in modern vehicles with an electronic connection, commonly known as an electronic throttle [1]–[3]. In an electronic throttle, the accelerator pedal is linked to the engine throttle using a DC servomotor, which can improve both the vehicle's drivability and fuel economy. Therefore, in recent years, the electronic throttle system has been widely used in vehicle engines.

An electronic throttle is a DC-motor-driven valve. The air inflow into the combustion system of the engine can be regulated by the electronic throttle. The control objective of the electronic throttle system is to make the actual plate angle quickly and accurately track a given reference signal. Given the strong nonlinear characteristics of the return spring and friction as well as the external disturbance, it is difficult to design a control system using an electronic throttle with satisfactory performance [3]. In addition, the valve plate angle is adjusted by the input voltage of the driving motor, which has a limited range. Thus, input saturation also exists when controlling an electronic throttle.

There has been much research regarding the control of electronic throttle systems. In [3] and [4], the traditional proportional-integral derivative (PID) control method is utilized to control the electronic throttle, and the feedback/feedforward compensation for the friction and return spring in the main controller is applied in [3] and [4]. To improve the control strategy's robustness, robust nonlinear control, variable structure control, and adaptive control have been applied to control the electronic throttle [5]–[9]. A robust controller for motor-driven throttle is designed in [5], where a cascaded control structure is also presented

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to ensure high robustness at limited cost. In [6], a variable structure control strategy is introduced after the employment of feedback backstepping design technique in the intermediate stages. In [7], a high-order sliding-mode control concept is introduced into the tracking controller of an electronic throttle. In [8], an adaptive servo controller is designed to control the plate angle in an electronic throttle. The designed controller is composed of a feedback controller with an adaptive feedforward compensator, adaptive gain parameters, and adaptive nonlinearity compensators. In [9], a robust adaptive sliding mode control strategy is utilized to decrease the effects of the parameter uncertainties and nonlinearities including gear backlash, friction and return-spring limp-home. Currently, for the advantage of the intelligent control [10]–[13], intelligent control strategies are utilized in the electronic throttle system. In [14], in order to control the nonlinear hysteretic electronic throttle, a fuzzy logic control system is presented, and a new back-propagation tuning algorithm is designed to adjust the membership functions. In [15], a recurrent neural network identifier and a fuzzy neural network controller are presented to control the electronic throttle valves. In [16], based on the inverse model, an adaptive control method based on the RBF neural network is utilized to control the electronic throttle valves. In [17], based on the fuzzy neural network, a robust adaptive intelligent control method is designed to control the plate angle of the electronic throttle.

The acceptable control performance of an electronic throttle can be achieved by using the above mentioned control methods. However, there also exist some important issues that may be further improved especially the input saturation. In fact, by adjusting the input voltage of the driving motor, the valve plate angle can be regulated. The range of the input voltage of the driving motor is limited. Therefore, the issue of input saturation in the control system of an electronic throttle exists as an additional difficulty. Actually, input saturation usually appears in many industry cases, and is one of the most important non-smooth nonlinearities. The control performance of a closed-loop system will be severely decreased if the input saturation is ignored [18]. The analysis and design of control systems with input saturation constraints have been researched in many industry cases [18]–[21]. However, the problem of input saturation is rarely considered in the existing designs for the electronic throttle control system.

Backstepping is a systematic and recursive design technique for controllers. By using the backstepping technique, a complex system is decomposed into multiple subsystems. A virtual controller is then designed for each subsystem, and the final control law can be obtained [22]–[28]. Due to the advantages of systematic design, the backstepping technique is easy to implement. Thus, the backstepping design method has been widely used in many industry control systems. In this paper, motivated by the advantage of the backstepping technique, a nonlinear backstepping tracking controller for an electronic throttle is proposed. In the proposed controller, the input saturation and external disturbance are considered. In this paper, the main control objective of the electronic throttle system is to track an appointed reference signal in the presence of input saturation and external disturbance. At first, the dynamic model of the electronic throttle is described. According to the dynamic model, the backstepping design technique is utilized to obtain the controller. Different from existing backstepping controllers, the proposed backstepping controller for the electronic throttle includes an auxiliary design system and sliding control term. To handle the input saturation, an auxiliary design system is presented to analyze the influence of input saturation. In the backstepping controller, an auxiliary design system is applied. The sliding control term is also utilized to overcome the external disturbance. Under the proposed backstepping controller, stability analysis of the closed-loop system is completed via Lyapunov function method.

The organization of this paper is as follows: the system description and the dynamic model of an electronic throttle are described in Section 2. The nonlinear backstepping controller for the electronic throttle is described in Section 3. In Section 4, simulation results and analysis are shown to prove the effectiveness of the proposed control method. Some conclusions are given in Section 5.

The following nomenclature is used throughout the paper:

NOMENCLATURE

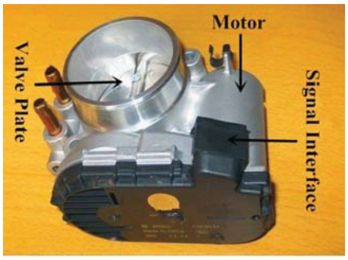
$\theta(t)$	Actual angle of the valve plate
θ_d	Set point of the valve plate angle
$\omega(t)$	Anglar speed of the valve plate
R_a	Armature resistance
i_a(t)	Armature current
L_a	Inductance of the armature loop
E_a(t)	Counter electromotive force
U_a(t)	Input voltage of the motor
T_f(t)	Friction torque
T_s(t)	Return spring torque
T_e(t)	Electromagnetism torque
K_a	Electromotive force constant
K_t	Torque constant
K_s	Elastic coefficient
K_m	Torque compensation coefficient
K_k	Coulomb friction coefficient
K_d	Sliding friction coefficient
j	Gear ratio
J_R	Equivalent moment of inertia.

II. DESCRIPTIONS AND THE DYNAMICAL MODEL OF THE ELECTRONIC THROTTLE

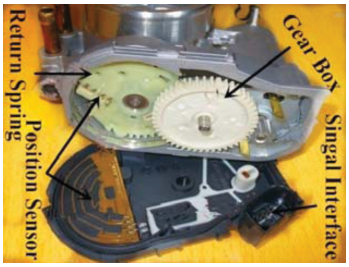
In the engine combustion system, the air flowrate is controlled by the opening angle of the valve plate in the electronic throttle. An actual electronic throttle is shown in Fig. 1, which consists of the external and internal view.

The block diagram of an electronic throttle control system is shown in Fig. 2.

The block diagram includes an electronic throttle body and a controller. The electronic throttle body is composed of a DC motor driven by the input voltage, a valve plate, a return



(a)



(b)

FIGURE 1. Actual electronic throttle. (a) External view of an electronic throttle. (b) Internal view of an electronic throttle.

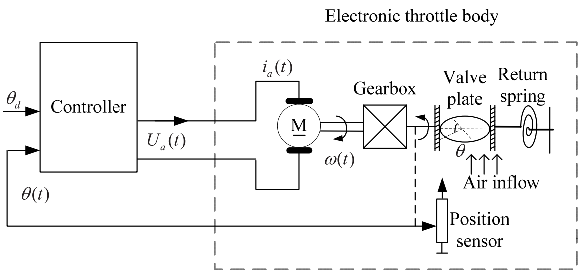


FIGURE 2. Block diagram of the electronic throttle control system.

spring, a position sensor, and a gearbox. All components in the throttle are assembled into an electronic throttle body. The control objective of the electronic throttle is to obtain a satisfactory tracking performance of the valve plate angle.

The dynamics of the DC motor in Fig. 2 are described in (1):

$$T_e(t) - \frac{1}{j}\left[T_s(t) + T_f(t)\right] = J_R \frac{d\omega(t)}{dt}. \quad (1)$$

The electrical balance equations of the armature loop are:

$$i_a(t)R_a + L_a \frac{di_a(t)}{dt} + E_a(t) = U_a(t), \quad (2)$$

$$E_a(t) = K_a \times j \times \omega(t). \quad (3)$$

According to (2-3) and ignoring the inductance L_a, we have

$$i_a(t) = \frac{U_a(t) - K_a \times j \times \omega(t)}{R_a}. \quad (4)$$

The electromagnetic torque is

$$T_e(t) = K_t i_a(t). \quad (5)$$

Substituting (4) into (5), the electromagnetic torque is described by

$$T_e(t) = K_t \frac{U_a(t) - K_a \times j \times \omega(t)}{R_a}. \quad (6)$$

In the electronic throttle, the nonlinear characteristics are mainly caused by the return springs and friction. The nonlinear characteristic of the return spring is modeled as [5]

$$T_s(t) = K_s\left(\theta(t) - \theta_0\right) + K_m \mathrm{sgn}(\theta(t) - \theta_0), \quad (7)$$

where θ_0 is the default position of the electronic valve, called the limp-home position.

The nonlinear friction torque, including the viscous and Coulomb parts, is modeled as [8]

$$T_f(t) = K_d\omega(t) + K_k \mathrm{sgn}\left(\omega(t)\right). \quad (8)$$

Substituting (6-8) into (1), we have

$$\begin{aligned} \frac{d\omega(t)}{dt} &= \frac{K_t \times U_a(t)}{J_R \times R_a} - \left(\frac{j \times K_a \times K_t}{J_R R_a} + \frac{K_d}{jJ_R}\right)\omega(t) \\ &\quad - \frac{K_s}{jJ_R} \times (\theta(t) - \theta_0) - \frac{K_m}{jJ_R} sgn\left(\theta(t) - \theta_0\right) \\ &\quad - \frac{K_k}{jJ_R} \mathrm{sgn}\left(\omega(t)\right) \end{aligned} \quad (9)$$

Let $u(t) = U_a(t)$, $\mu_0 = \frac{K_t}{J_R \times R_a}$, $\mu_1 = \frac{K_s}{jJ_R}$, $\mu_2 = \frac{j \times K_a \times K_t}{J_R R_a} + \frac{K_d}{jJ_R}$, $\mu_3 = \frac{K_m}{jJ_R}$, $\mu_4 = \frac{K_k}{jJ_R}$.

The dynamic model of the electronic throttle considering the unknown external disturbance is

$$\begin{cases} \dot{\theta}(t) = \omega(t), \\ \dfrac{d\omega(t)}{dt} = \mu_0 u(t) - \mu_1 \times \theta(t) - \mu_2\omega(t) \\ \qquad - \mu_3 \mathrm{sgn}\left(\theta(t)\right) - \mu_4 \mathrm{sgn}\left(\omega(t)\right) + d(t), \end{cases} \quad (10)$$

where $d(t)$ is the unknown external disturbance, and satisfies the following restriction:

$$|d(t)| \leq D, \quad (11)$$

where D is a known constant that indicates the maximum value of the external disturbance.

Remark 1: In the control system of the electronic throttle, the unknown external disturbance mainly includes the fluctuation of the air flowrate and pressure ratio, and so on. The major control difficulties of an electronic throttle are discussed as follows:

- The strong nonlinear dynamics caused by the return spring and friction in the electronic throttle.
- The unknown external disturbance such as the fluctuation of the air flowrate and pressure ratio in the electronic throttle.
- Input saturation exists in the electronic throttle system because of input voltage of the driving motor has a limited range.

III. NONLINEAR BACKSTEPPING TRACKING CONTROL DESIGN

The control objective for the electronic throttle is to make the actual angle $\theta(t)$ quickly and accurately track its set point θ_d.

A nonlinear backstepping tracking controller is designed for the electronic throttle. In the tracking controller design, an auxiliary system is introduced to compensate for the effect of input saturation. A sliding-mode control term is also utilized in the tracking controller to compensate for the unknown external disturbance. By using the backstepping technique, the proposed tracking controller is designed as follows.

Step 1: According to the control objective, the tracking error $z_1(t)$ is defined as

$$z_1(t) = \theta(t) - \theta_d. \tag{12}$$

In this step, a virtual control function is defined as $\alpha(t)$. We define

$$z_2(t) = \omega(t) - \alpha(t). \tag{13}$$

The Lyapunov function candidate is considered as follows

$$V_1(t) = \frac{1}{2}z_1^2(t). \tag{14}$$

From (12)-(13), the time derivative of $V_1(t)$ is shown as

$$\begin{aligned}\dot{V}_1(t) &= z_1(t)\dot{z}_1(t) = z_1(t)\left[\omega(t) - \dot{\theta}_d(t)\right]\\ &= z_1(t)\left[z_2(t) + \alpha_1(t) - \dot{\theta}_d(t)\right].\end{aligned} \tag{15}$$

The virtual control function $\alpha(t)$ is written as

$$\alpha_1(t) = -c_1 z_1(t) + \dot{\theta}_d(t). \tag{16}$$

By substituting (16) into (15), we know

$$\dot{V}_1(t) = -c_1 {z_1}^2(t) + z_1(t)z_2(t). \tag{17}$$

Step 2: In this step, the input saturation constraint for the control signal u is considered. The control signal u is shown as follows

$$-U_{\min} \le u(t) \le U_{\max}, \tag{18}$$

where $U_{\max}$ and $U_{\min}$ are the known maximum and minimum limits of the input saturation constraint, respectively. For the constraint, the control input u can be described as

$$u = \begin{cases} U_{\max}, & if\ v \ge U_{\max} \\ v, & if\ -U_{\min} \le v \le U_{\max} \\ -U_{\min}, & if\ v < -U_{\min}, \end{cases} \tag{19}$$

where v is the control command, which will be described in following steps.

To analyze the constraint effect of the input saturation, an auxiliary design system is introduced as follows [14], [15]:

$$\dot{\zeta} = \begin{cases} -k\zeta - \dfrac{|z_2\Delta u| + \frac{1}{2}\Delta u^2}{\zeta^2}\zeta + \Delta u, & |\zeta| \ge \varepsilon \\ 0, & |\zeta| < \varepsilon, \end{cases} \tag{20}$$

where $\Delta u = u - v$. ε is a small positive design parameter and ζ is the state of the auxiliary design system.

Considering the following Lyapunov function candidate as

$$V_2(t) = V_1(t) + \frac{1}{2}z_2^2(t) + \frac{1}{2}\xi^2. \tag{21}$$

Therefore, the time derivative of $V_2(t)$ is

$$\begin{aligned}\dot{V}_2(t) &= \dot{V}_1(t) + z_2(t)\dot{z}_2(t) + \xi\dot{\xi}\\ &= -c_1 z_1^2(t) + z_1(t)z_2(t) + z_2(t)\dot{z}_2(t) + \xi\dot{\xi}\end{aligned} \tag{22}$$

The time derivative of $\alpha_1(t)$ is

$$\dot{\alpha}_1(t) = -c_1\dot{z}_1(t) + \ddot{\theta}_d(t). \tag{23}$$

According to (10, 13, 16), the time derivative of $\dot{z}_2(t)$ is

$$\begin{aligned}\dot{z}_2(t) &= \dot{\omega}(t) - \dot{\alpha}(t)\\ &= \mu_0 v(t) - \mu_1 \times \theta(t) - \mu_2\omega(t)\\ &\quad - \mu_3 \mathrm{sgn}(\theta(t)) - \mu_4 \mathrm{sgn}(\omega(t)) + d(t) - \dot{\alpha}(t)\\ &= \mu_0 v(t) - \mu_1 \times \theta(t) - \mu_2\omega(t)\\ &\quad - \mu_3 \mathrm{sgn}(\theta(t)) - \mu_4 \mathrm{sgn}(\omega(t)) + d(t)\\ &\quad + c_1\omega(t) - c_1\dot{\theta}_d(t) - \ddot{\theta}_d(t)\end{aligned} \tag{24}$$

Noting the following fact:

$$\zeta\Delta u \le \frac{1}{2}\zeta^2 + \frac{1}{2}\Delta u^2. \tag{25}$$

Thus, from (20) and (25), we have

$$\begin{aligned}\zeta\dot{\zeta} &= -k\zeta^2 - \frac{|z_2\Delta u| + \frac{1}{2}\Delta u^2}{\zeta^2}\zeta^2 + \zeta\Delta u\\ &\le -k\zeta^2 - |z_2\Delta u| - \frac{1}{2}\Delta u^2 + \frac{1}{2}\zeta^2 + \frac{1}{2}\Delta u^2\\ &\le -[k - 0.5]\zeta^2\end{aligned} \tag{26}$$

By substituting (24) into (22), the time derivative of $V_2(t)$ is

$$\begin{aligned}\dot{V}_2(t) &= -c_1 z_1^2(t) + z_1(t)z_2(t) + \xi\dot{\xi}\\ &\quad + z_2(t)[\mu_0 v(t) - \mu_1\theta(t) - \mu_2\omega(t)\\ &\quad - \mu_3 \mathrm{sgn}(\theta(t)) - \mu_4 \mathrm{sgn}(\omega(t)) + d(t)\\ &\quad + c_1\omega(t) - c_1\dot{\theta}_d(t) - \ddot{\theta}_d(t)]\end{aligned} \tag{27}$$

According to (26), the time derivative of $V_2(t)$ can satisfy the following inequality:

$$\begin{aligned}\dot{V}_2(t) &\le -c_1 z_1^2(t) + z_1(t)z_2(t) - [k - 0.5]\zeta^2\\ &\quad + z_2(t)[\mu_0 v(t) - \mu_1\theta(t) - \mu_2\omega(t)\\ &\quad - \mu_3 \mathrm{sgn}(\theta(t)) - \mu_4 \mathrm{sgn}(\omega(t)) + d(t)\\ &\quad + c_1\omega(t) - c_1\dot{\theta}_d(t) - \ddot{\theta}_d(t)].\end{aligned} \tag{28}$$

In this step, the control command $v(t)$ is given by

$$\begin{aligned}v(t) &= \frac{1}{\mu_0}[\mu_1\theta(t) + \mu_2\omega(t) + \mu_3 \mathrm{sgn}(\theta(t)) + \mu_4 \mathrm{sgn}(\omega(t))\\ &\quad - c_1\omega(t) + c_1\dot{\theta}_d(t) + \theta_d(t)] + v_s + v_a.\end{aligned} \tag{29}$$

In (29), $v_s(t)$ is the sliding-mode control term, and $v_a(t)$ is the control term where the state of the auxiliary system is introduced.

$v_s(t)$ and $v_a(t)$ are designed as follows:

$$v_s(t) = \frac{1}{\mu_0}\left[-\eta \mathrm{sgn}(z_2)\right], \ \eta > D. \tag{30}$$

$$v_a(t) = \frac{1}{\mu_0}\left[-c_2\left(z_2(t) - \zeta\right) - z_1(t)\right]. \tag{31}$$

By substituting (29)-(31) into (28), we have

$$\begin{aligned}\dot{V}_2(t) \le & -c_1 z_1^2(t) + z_1(t)z_2(t) + z_2(t)d(t) \\ & - \eta z_2(t)\mathrm{sgn}\left(z_2(t)\right) \\ & + z_2(t)\left[-c_2\left(z_2(t) - \zeta\right) - z_1(t)\right] - [k - 0.5]\,\zeta^2 \\ \le & -c_1 z_1^2(t) + z_1(t)z_2(t) + z_2(t)d(t) \\ & - \eta\left|z_2(t)\right| + z_2(t)\left[-c_2\left(z_2(t) - \zeta\right) - z_1(t)\right] \\ & - [k - 0.5]\,\zeta^2. \end{aligned} \tag{32}$$

From (11) and (30), we have

$$z_2(t)d(t) - \eta\left|z_2(t)\right| \le 0. \tag{33}$$

According to (32) and (33), the time derivative of $V_2(t)$ can satisfy the following inequality:

$$\dot{V}_2(t) \le -c_1 z_1^2(t) - c_2 z_2(t)\left(z_2(t) - \zeta\right) - [k - 0.5]\,\zeta^2. \tag{34}$$

Noting the fact as follows:

$$z_2\zeta \le \frac{1}{2}z_2^2 + \frac{1}{2}\zeta^2. \tag{35}$$

By substituting (35) into (34), we have

$$\dot{V}_2(t) \le -c_1 z_1^2(t) - 0.5c_2 {z_2}^2(t) - [k - 0.5 - 0.5c_2]\,\zeta^2. \tag{36}$$

Then, the design parameters c_1 and c_2 are designed to satisfy the following inequality

$$(k - 0.5 - 0.5c_2) > 0. \tag{37}$$

Based on (36) and (37), we have

$$\dot{V}_2(t) \le -c_1 z_1^2(t) - 0.5c_2 {z_2}^2(t) \le 0. \tag{38}$$

According to (38), if the control command v is described in (29) and the controller u is described in (19), $z_1(t)$ and $z_2(t)$ will be convergent variables. That is, the actual angle $\theta(t)$ of the electronic throttle can be controlled to track its set point θ_d.

Remark 2: It should be noted that the proposed control command $v(t)$ includes $v_s(t)$ and $v_a(t)$. The main function $v_s(t)$ is used to overcome the unknown external disturbance. The main function of $v_a(t)$ is to handle the input saturation, which includes the state ζ of auxiliary design system.

IV. SIMULATION

A simulation study is implemented to prove the effectiveness and feasibility of the proposed control strategy. In the simulation, some main parameters are shown in Tab. 1.

TABLE 1. Parameter values.

$j = 17$	$J_R = 4 \times 10^{-6} Kg\ m^2$
$R_a = 4.2\Omega$	$K_a = 0.016N\ m/A$
$K_t = 0.016N\ m/A$	$K_s = 0.107N\ m$
$K_m = 0.024N\ m/rad$	$K_d = 4 \times 10^{-6} N\ m\ s/rad$
$K_k = 4.8 \times 10^{-3} N\ m\ s/rad$	

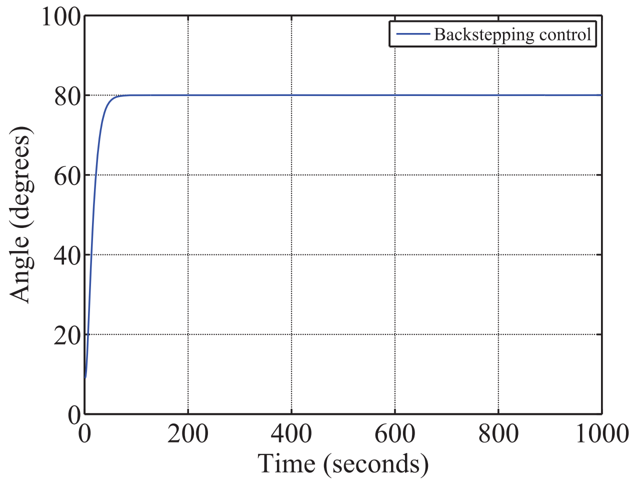


FIGURE 3. Actual angular $\theta(t)$.

A. SIMULATION STUDY I

In this section, the input saturation and external disturbance are not considered in the dynamical model of the electronic throttle.

The designed backstepping tracking controller for the electronic throttle in this simulation section is described as follows

$$\begin{aligned} v(t) = & \frac{1}{\mu_0}[\mu_1 x_1(t) + \mu_2 x_2(t) + \mu_3 \mathrm{sgn}\left(x_1(t)\right) \\ & + \mu_4 \mathrm{sgn}\left(x_2(t)\right) - c_1 x_2(t) + c_1 \dot{x}_d\left(t\right) + \ddot{x}_d\left(t\right)] \\ & + \frac{1}{\mu_0}\left[-c_2 z_2(t) - z_1(t)\right] \end{aligned} \tag{39}$$

Remark 3: In this section, we suppose that there is no external disturbance and input saturation in the electronic throttle. The controller (39) is designed by using the backstepping technique. Comparing with the controller (29), there is no $v_a(t)$ and $v_s(t)$ in the controller (39).

In this section, the set point θ_d is 80. Figs. 3-6 are the simulation results. According to Fig. 3, we know that $\theta(t)$ can track θ_d with the satisfactory performance. In Fig. 4, angle speed $\omega(t)$ is increased firstly. When $\omega(t)$ initially increases, the actual angle $\theta(t)$ will be increased to track θ_d. At the end of the dynamical adjustment process, the angle speed $\omega(t)$ converges to zero. As shown in Fig. 5, the control voltage $u(t)$ should be first increased in order to increase the actual angle $\theta(t)$. Thus, the actual angle $\theta(t)$ is controlled to track its set point θ_d. At the end of the dynamical adjustment process, the input voltage $u(t)$ reaches its stable state, and $\omega(t)$ is also controlled to zero.

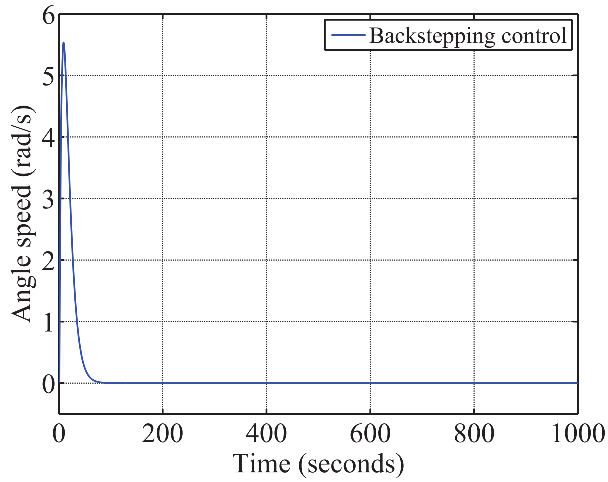


FIGURE 4. Angular speed $\omega(t)$.

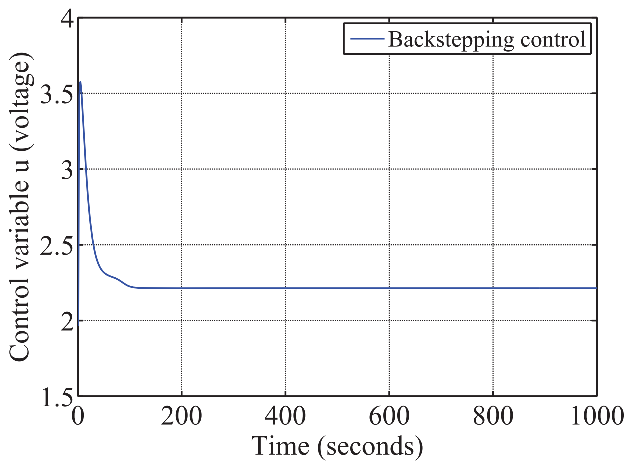


FIGURE 5. Control variable $u(t)$.

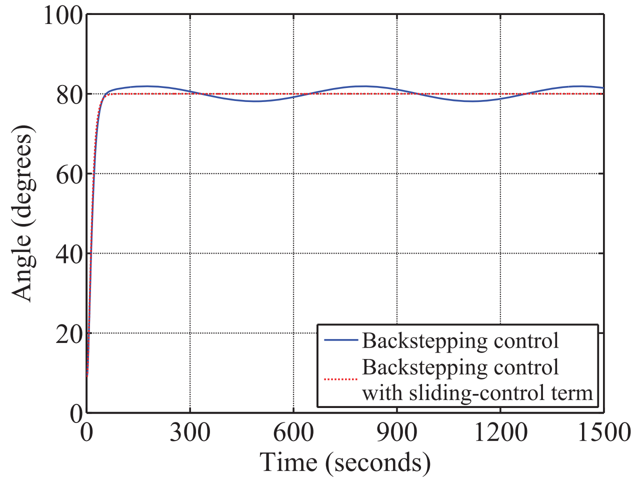


FIGURE 6. Actual angular $\theta(t)$.

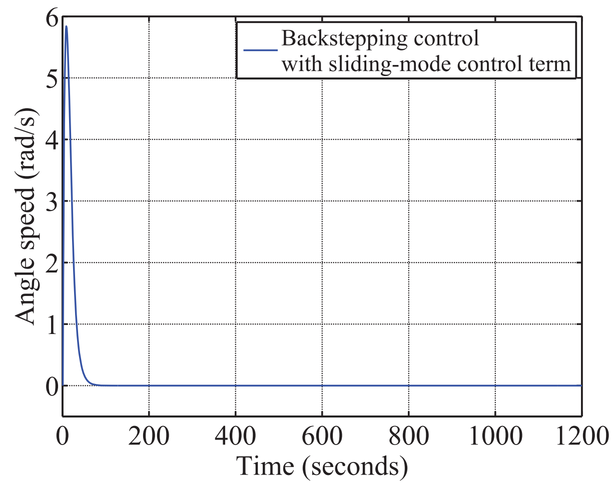


FIGURE 7. Angular speed $\omega(t)$.

B. SIMULATION STUDY II

In this section, only the external disturbance is considered. During this simulation study process, the external disturbance is assumed to be $d(t) = 5\sin(t)$.

The sliding-mode control term is utilized in the backstepping tracking controller to suppress the external disturbances. The backstepping tracking controller which contains the sliding-mode control term is determined as follows:

$$\begin{aligned} v(t) = &\frac{1}{\mu_0}[\mu_1 x_1(t) + \mu_2 x_2(t) + \mu_3 \text{sgn}\,(x_1(t)) \\ &+ \mu_4 \text{sgn}\,(x_2(t)) - c_1 x_2(t) + c_1 \dot{x}_d\,(t) + \ddot{x}_d\,(t)] \\ &+ \frac{1}{\mu_0}\,[-c_2 z_2(t) - z_1(t)] + v_s(t) \end{aligned} \tag{40}$$

When the external disturbance is considered, a comparison of the control performance between controller (39) and controller (40) is shown in Fig. 6. In Fig. 6, the dotted line is the control performance of controller (39), and the solid line is the control performance of controller (40).

As shown in Fig. 6, when the external disturbance is considered, the actual angle $\theta(t)$ cannot track the corresponding set point θ_d with satisfactory control performance by using the controller (39). The main reason is because the external disturbance is not considered during the controller (39) design process. However, the control performance of controller (40) is satisfactory. Therefore, the sliding-mode control term $v_s(t)$ can effectively overcome the external disturbance.

Fig. 7 and Fig. 8 show the simulation results using controller (40) for the angle speed $\omega(t)$ and control variable $u(t)$, respectively. According to Fig. 7, we know that the angle speed $\omega(t)$ is controlled to zero at the time that the dynamical regulation process is finished. According to Fig. 8, the control variable $u(t)$ is oscillatory even once the angle $\theta(t)$ is controlled to its stable state. This oscillation is caused by the action of the switching control in the sliding-mode control term $v_s(t)$.

C. SIMULATION STUDY III

In this section, the external disturbance and input saturation are considered during the control design process.

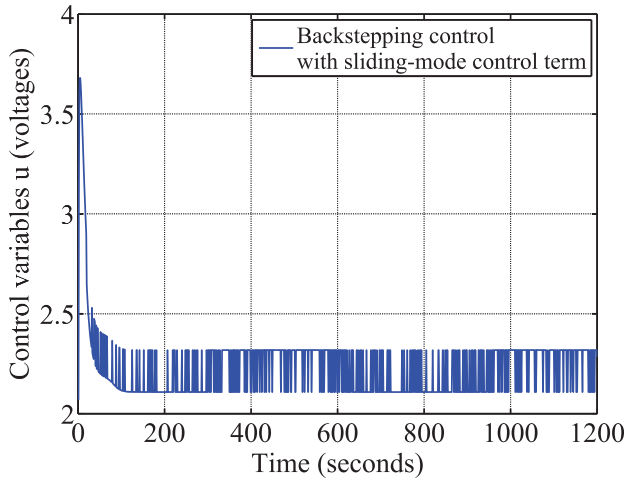


FIGURE 8. Control variable $u(t)$.

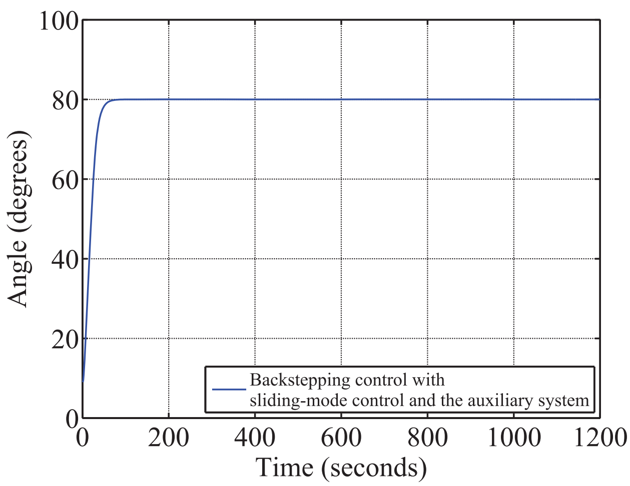


FIGURE 9. Actual angular $\theta(t)$.

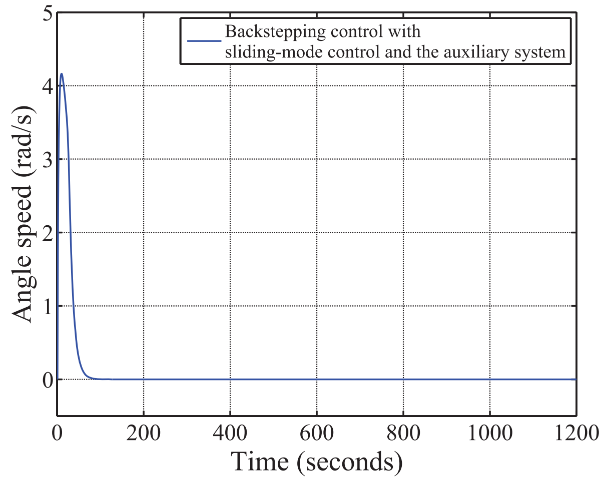


FIGURE 10. Angular speed $\omega(t)$.

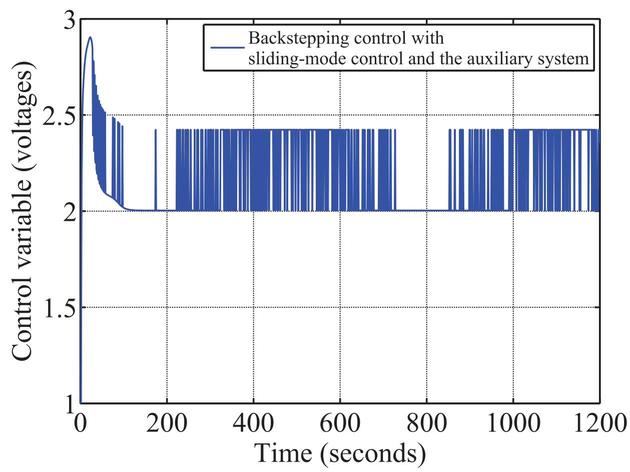


FIGURE 11. Control variable $u(t)$.

In the simulation study II, only the external disturbance is considered during the design process of the backstepping tracking controller. In the control system of the electronic throttle, the control variable is the input voltage of the driving motor. In fact, the input voltage of the driving motor is provided by the car battery. The car battery's output has a limited voltage range. Therefore, the input voltage of the driving motor also has a limited range. There exists an input saturation in the electronic throttle control system.

According to Fig. 8, we know that the control variable is more than three volts in the initial stage. In fact, the input voltage of the motor cannot exceed three volts due to its limited range. In this section, the external disturbance and input saturation are fully considered during the control design process. The state of the auxiliary design system and sliding-mode control term are utilized in the tracking controller, which is shown in (29).

Figs. 9-11 show the simulation results. According to Fig. 9, the actual angle $\theta(t)$ can track its set point θ_d with satisfactory performance by using the proposed controller (29). Fig. 11 shows the trajectory of $u(t)$; the figure shows that the maximum value of the control $u(t)$ is less than 3. It should be noted that the control variable $u(t)$ is in it range limit when using the proposed controller (29). Compared with Fig. 7, we can see that the maximum value of the angle speed is also decreased in Fig. 10, and the decrease of maximum angle speed is advantageous for the motor's operation.

V. CONCLUSION

Based on the dynamic model of the electronic throttle, a nonlinear backstepping tracking control method of for an electronic throttle has been proposed, and the input saturation and unknown external disturbances have been explicitly considered. The stability of the closed-loop system has been guaranteed via the Lyapunov function method. A simulation study and its result are implemented to illustrate the performance of the proposed throttle control method for tracking the reference signal.

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