Electronic Throttle Control Based on Fuzzy Self-adaptive Backstepping

Sheng Zhang , Xuejun Li, Haoyu Yu

***Abstract*—**Backstepping and other control methods based on model compensation have unique advantages in controlling nonlinear multivariable objects. However, the control performance will decrease dramatically when an inaccurate electronic throttle model is used. In order to reduce the difficulty of modeling without reducing the control performance, this technical note introduces a fuzzy self-adaptive backstepping control method. For electronic throttle control of inversion problem, using fuzzy self-adaptive method close to the throttle unknown parts, which can achieve system design requirements without precise model. The systerm simulation and physical experiments show that this method compared with backstepping can significantly reduce adjustment time of throttle, the steady-state error and other performance.

***Keywords*—**Backstepping, Electronic throttle, Fuzzy self-adaptation, Model compensation.

I. Introduction

It is very practical to study the control method of electronic throttle to reduce the emission of automobile pollutants and improve the vehicle dynamic characteristics. For those reasons, domestic and foreign scholars have carried out a lot of research on theoretical methods. In [1], feedforward linearization and fuzzy adaptive control are adopted. Both the step response test and tracking test of sine show that the designed electronic throttle control system has good stability and high precision. In [2], a physical platform by PID and sliding mode control methods is builded to control electronic throttle. The experimental results show that using sliding mode control compared with using the incremental PID almost have no overshoot and can track the accelerator pedal action instruction accurately and rapidly. According to the characteristics of nonlinear electronic throttle in [3], the control law of a nonlinear electronic throttle system is designed by using the inverse method. An output feedback control observer based on electronic throttle is presented. The electronic throttle dynamics model is derived in detail and is used to analyze the off-line simulation of the control object. The results show that the designed controller satisfies the predetermined control requirements of the electronic throttle. In [4], a model prediction controller based on FPGA hardware is implemented. The results show that the mpc-ipm controller based on FPGA can meet the needs of rapid and micro-control. In [5], the backstepping controller is designed with the disturbance of electronic throttle model. The stability and robustness of the control system are verified by the stability theory of ISS and the effectiveness of this method is verified by fast prototype dSPACE. In [6], the problem of variable structure nonlinearity in electronic throttle control is addressed. An improved variable-step-length integral PID control algorithm is designed, and the systerm is verified stabilization by finding a suitable Lyapunov function. In [7], in order to detect the malfunction of the electronic throttle, an electronic throttle fault detector based on STM32 is designed. Through experiments, the fault detector can detect the motor faults and the position sensor fails in line. In [8], in order to find the defult position of electronic throttle, an electronic throttle detector in line based on MCU controller was designed. The experiment shows that detector can find the defult position in line and control degree of electronic throttle. In [9], M.VASAK etc designed the optimal controller with constrained time. They have established the accurate electronic throttle model, so that the simulation control can achieve very good control effect. However, this control method is highly dependent on the accuracy of the model. When the parameters of the model are slightly perturbed, the control effect will decrease sharply.

Model-based control requires very precise mathematical model to achieve good control performance. There is always too much or too little of the model's compensation for physical objects. In fact, the mathematical model of nonlinear objects such as electronic throttle is difficult to model accurately. Therefore, in order to reduce difficulty of modeling under the condition of not reducing control performance, the fuzzy self-adaptive algorithm is used to realize the approximation of unknown throttle mathematic model. Then we can get better performance of electronic throttle systerm by backstepping method.

II. Electronic throttle modeling

A. The mathematical model of dc motor

The input $\bar{u}(V)$ of dc motor is the average voltage of PWM wave. Output is torque $T_m'(N \cdot m)$. By kirchhoff's laws, the motor

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loop equation is obtained:

$$R_a \cdot i_a + L_a \frac{di_a}{dt} = \bar{u} - k_v \frac{d\theta_m}{dt} \quad (1)$$

The torque equation:

$$T_m' = k_t \cdot i_a - T_{mf} - J_m \frac{d^2\theta_m}{dt^2} \quad (2)$$

where $R_a(\Omega)$ is the equivalent resistance of the armature circuit, $i_a(A)$ is the current flowing into the motor. $L_a(H)$ is the equivalent inductance of the loop. $k_v(V/rad/s)$ is back electromotive force constant. $T_m'(N\cdot \mathrm{m})$ is motor output torque. $T_{mf}(N\cdot m)$ is the torque caused by friction in the rotation of motor. $J_m(kg\cdot m^2)$ is moment of inertia of motor.

According to the research results in [10], dc motor is low-pass element; The effect of motor inductance can be ignored. The equation (1) is simplified as:

$$i_a = \frac{\bar{u} - k_t \frac{d\theta_m}{dt}}{R_a} \quad (3)$$

Considering the actuation of motor in actual circuit, we obtain:

$$\bar{u} = V_{bat} \cdot u \quad (4)$$

where u is the duty ratio of motor input and $V_{bat}(V)$ is the battery voltage on the car.

By equations (2)~(4), we can obtain

$$T_m' = -J_m \frac{d^2\theta_m}{dt^2} - T_{mf} + k_t \cdot i_a \quad (5)$$

$$\text{where } i_a = \frac{V_{bat}\cdot u - k_v \frac{d\theta_m}{dt}}{R_a} \quad (6)$$

B. Mathematical model of reduction gear group

Model input of the reduction gear group is the motor output torque T_m' ($\mathrm{N\cdot m}$) and the motor rotation Angle θ_m (rad). Output is the reduction gear set torque T_g' ($\mathrm{N\cdot m}$) and throttle angle θ (rad).

Ignore the effect of gear clearance and then we can obtain

$$T_g' = n\left(T_m' - T_{gf} - J_g \frac{d^2\theta_m}{dt^2}\right) \quad (7)$$

$$\theta = \frac{1}{n}\cdot\theta_m \quad (8)$$

Among them, n is from angle of motor to throttle gate angle ratio, $T_{gf}(N\cdot m)$ is the equivalent to the motor torque losses due to friction gear set, $J_g(kg\cdot m^2)$ is converted to the rotational inertia of motor side gears.

C. Mathematical model of reset spring

The torque characteristic of reset spring is equivalent to that in Fig. 1.

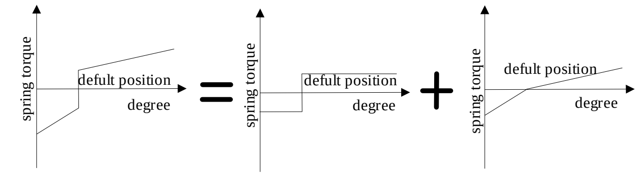

Fig. 1 the equivalent of the reset spring

The corresponding mathematical expression is:

$$T_s = k_{pre}\,\mathrm{sgn}(\theta-\theta_0) + k_s(\theta)(\theta-\theta_0) \quad (9)$$

$$\mathrm{sgn}(x) = \begin{cases} 1 & x>0 \\ -1 & x<0 \end{cases} \quad (10)$$

$$k_s(\theta) = \begin{cases} k_{sa} & \theta \ge \theta_0 \\ k_{sb} & \theta_0 > \theta \ge 0 \end{cases} \quad (11)$$

where $k_{pre}(N\cdot m)$ is the pre-tightening torque coefficient of the spring, $\theta_0(rad)$ is the degree of throttle that is no input signal. $k_{sa}(N\cdot m/rad)$ is elastic coefficient of spring when $\theta \ge \theta_0$, $k_{sb}(N\cdot m/rad)$ is elastic coefficient of spring when $\theta_0 > \theta \ge 0$.

D. Mathematical model of throttle valve.

The electronic throttle body is rotated in the deceleration gear group output torque, the reset spring output torque and so on. When the torque of reduction gear is equal to the turning torque and friction of the reset spring, the throttle body plate is stable at a certain degree of opening. At this point, the electronic throttle is in equilibrium. Thus there are:

$$J_t \frac{d^2\theta}{dt^2} = T_g' - T_s - T_{tf} \quad (12)$$

where $J_t(kg\cdot m^2)$ is the moment of inertia of throttle body, T_{tf} is the friction torque that the throttle valve loses during rotation. Formula (5, 7, 9) is brought into equation (12) :

$$\begin{aligned} J_t \frac{d^2\theta}{dt^2} &= nT_m' - nT_{gf} - nJ_g \frac{d^2\theta_m}{dt^2} - T_s - T_{tf} \\ &= -nJ_m \frac{d^2\theta_m}{dt^2} - nT_{mf} + nk_t\cdot i_a - nT_{gf} \\ &\quad -nJ_g \frac{d^2\theta_m}{dt^2} - T_s - T_{tf} \end{aligned} \quad (13)$$

then

$$\begin{aligned} J\frac{d^2\theta}{dt^2} &= \frac{k_t}{n}\cdot i_a - \frac{k_{pre}}{n^2}\mathrm{sgn}(\theta-\theta_0) \\ &\quad - \frac{k_s(\theta)}{n^2}(\theta-\theta_0) - \frac{T_f}{n} \end{aligned} \quad (14)$$

where $J = J_g + J_m + \frac{1}{n^2}J_t$ represents the moment of inertia that is converted to the motor side. $T_f = T_{mf} + T_{gf} + \frac{T_{tf}}{n}$ represents the friction torque converted to the motor side.

$c = \frac{180}{\pi} = 57.296(°)/rad$ is the coefficient of conversion from radian to degree.

According to the practice in [11] and [12], the friction is decomposed into coulomb friction and sliding friction.

$$T_f = k_f \operatorname{sgn}(\frac{d\theta_m}{dt}) + B\frac{d\theta_m}{dt} \tag{15}$$

k_f （N·m）is coulomb friction coefficient. B （N·m·s）is coefficient of sliding friction.

Order state variable $x_1 = \theta, x_2 = \frac{d\theta}{dt}$; The electronic throttle model is used in the formula (6, 14, 15) as follows:

$$\begin{cases} \dot{x}_1 = x_2 \\ \dot{x}_2 = \frac{k_t V_{bat}}{nJR_a}u - \frac{k_s(x_1)}{n^2 J}(x_1 - \theta_0) - \frac{k_{pre}}{n^2 J}\operatorname{sgn}(x_1 - \theta_0) \\ \quad -(\frac{B}{J} + \frac{k_t k_v}{JR_a})x_2 - \frac{k_f}{nJ}\operatorname{sgn}(x_2) \end{cases} \tag{16}$$

III. Design of electronic throttle controller

The electronic throttle model in （16） is follow:

$$\begin{cases} x_1 = \dot{x}_2 \\ \dot{x}_2 = \frac{k_t V_{bat}}{nJR_a}u(t) - \frac{k_s(x_1)}{n^2 J}(x_1 - \theta_0) - \frac{k_{pre}}{n^2 J}\operatorname{sgn}(x_1 - \theta_0) \\ \quad -(\frac{B}{J} + \frac{k_t k_v}{JR_a})x_2 - \frac{k_f}{nJ}\operatorname{sgn}(x_2) \\ y = x_1 \end{cases} \tag{17}$$

$x_1 = \theta$, $x_2 = \dot{\theta}$ θ is actual degree of electronic throttle. u(t) is input duty ratio and y is output of the controlled object.

In the above model, the gap of gears inside electronic throttle is neglected, and the impact of the air flow on the throttle plate is ignored. Therefore, there is some error in this model. And we're going to defined the function $f(x_1, x_2)$ as all relationship of x_1 and x_2. Error with time is defined to the function $\omega(t)$. We can change formula(1) into the following formula:

$$\begin{cases} \dot{x}_1 = b_1 x_2 \\ \dot{x}_2 = b_2 u(t) + f(x_1, x_2) + \omega(t) \\ y = x_1 \end{cases} \tag{18}$$

Where b_1=1, b_2=$\frac{k_t V_{bat}}{nJR_a}$ is a positive constant.

In order to control the electronic throttle, backstepping method is adopted. Definition $e_1 = y - y_d$, α_1 a virtual control signal and y_d is introduced for the desired tracking trajectory. Then

$$\dot{e}_1 = \dot{x}_1 - \dot{y}_d = x_2 - \alpha_1 + \alpha_1 - \dot{y}_d = e_2 + \alpha_1 - \dot{y}_d \tag{19}$$

Thereinto, $e_2 = x_2 - \alpha_1$ is defined. We obtain:

$$\dot{e}_2 = \dot{x}_2 - \dot{\alpha}_1 = b_2 u(t) + f(x_1, x_2) + \omega(t) - \dot{\alpha}_1 \tag{20}$$

Therefore, the formula (18) of throttle model can be converted into

$$\begin{cases} \dot{e}_1 = e_2 + \alpha_1 - \dot{\alpha}_0 \\ \dot{e}_2 = b_2 u(t) - \dot{\alpha}_1 + f(x_1, x_2) + \omega(t) \end{cases} \tag{21}$$

where $\alpha_0 = y_d$ is defined.

By determining the virtual control quantity α_1 and control quantity u (t), the electronic throttle system is stable and can track the desired trajectory y_d. When k=1, the Lyapunov function is chosen as:

$$V_1 = \frac{1}{2}e_1^2 \tag{22}$$

Then the derivative of V_1 is

$$\dot{V}_1 = e_1\dot{e}_1 = e_1(e_2 + \alpha_1 + \hat{f}_1) \tag{23}$$

where $\hat{f}_1 = -\dot{\alpha}_0$ is defined.

Make

$$\alpha_1 = -\lambda_1 e_1 - \varphi_1 \ (\lambda_1 > 0) \tag{24}$$

Then

$$\dot{V}_1 = -\lambda_1 e_1^2 + e_1 e_2 + e_1(\hat{f}_1 - \varphi_1) \tag{25}$$

For k=2, the Lyapunov function is designed as:

$$V_2 = V_1 + \frac{1}{2b}e_2^2 \tag{26}$$

Then

$$\begin{aligned} \dot{V}_2 &= -\lambda_1 e_1^2 + e_1 e_2 + e_1(\hat{f}_1 - \varphi_1) + e_2(u + \frac{1}{b_2}(f(x_1, x_2) - \dot{\alpha}_1)) \\ &\quad + \frac{1}{b_2}e_2\omega(t) \\ &= -\lambda_1 e_1^2 + e_1(\hat{f}_1 - \varphi_1) + e_2(u + e_1 + \frac{1}{b_2}(f(x_1, x_2) - \dot{\alpha}_1)) \\ &\quad + \frac{1}{b_2}e_2\omega(t) \\ &= -\lambda_1 e_1^2 + e_1(\hat{\hat{f}}_1 - \varphi_1) + e_2(u + e_1 + f_2) + \frac{1}{b_2}e_2\omega(t) \end{aligned} \tag{27}$$

where $\hat{f}_2 = \frac{1}{b_2}(f(x_1, x_2) - \dot{\alpha}_1)$ is defined.

The design control law φ_2 is closed to the uncertain system $\hat{f}_2$ and control input $u(t)$ is chosen as:

$$u(t) = -\lambda_2 e_2 - e_1 - \varphi_2 (\lambda_2 > 0) \tag{28}$$

Then

$$\dot{V}_2 = -\lambda_1 e_1^2 - \lambda_2 e_2^2 + \sum_{i=1}^{2} e_i(\hat{f}_i - \varphi_i) + \frac{1}{b_2}e_2\omega(t) \tag{29}$$

With $\varphi_i = \theta_i^T \xi(\overline{x}_i)$ approximating unknown function $\hat{f}_i$, the optimal approximation vector θ_i^* exists for any given small constant $\varepsilon_i > 0$ as follow:

$$\left| \hat{f}_i - \theta_i^{*T}\xi(\overline{x}_i) \right| \le \varepsilon_i \quad (i=1, 2) \tag{30}$$

Taking the control law $\tilde{\theta}_i = \theta_i^* - \theta_i$, the self-adaptive law is designed.

$$\dot{\theta}_i = r_i e_i \xi_i(\overline{x}_i) - 2k_i\theta_i \quad (i=1, 2) \tag{31}$$

According to the method in [13], the Lyapunov function is chosen as:

$$V = V_2 + \sum_{i=1}^{2} \frac{1}{2r_i}\tilde{\theta}_i^T \tilde{\theta}_i \tag{32}$$

Then

$$
\begin{aligned}
\dot{V} &= \dot{V}_2 + \sum_{i=1}^{2}\frac{1}{r_i}\tilde{\theta}_i^T\dot{\tilde{\theta}}_i \\
&= -\sum_{i=1}^{2}\lambda_i e_i^2 + \sum_{i=1}^{2}e_i(\hat{f}_i - \varphi_i) + \frac{1}{b_2}e_2\omega(t) - \sum_{i=1}^{2}\frac{1}{r_i}\tilde{\theta}_i^T\dot{\theta}_i \\
&= -\sum_{i=1}^{2}\lambda_i e_i^2 + \sum_{i=1}^{2}e_i(\hat{f}_i - \theta_i^{*T}\xi_i(\overline{x}_i)) + \sum_{i=1}^{2}e_i(\theta_i^{*T}\xi_i(\overline{x}_i) - \theta_i^T\xi_i(\overline{x}_i)) \\
&\quad -\sum_{i=1}^{2}\frac{1}{r_i}\tilde{\theta}_i^T\dot{\theta}_i + \frac{1}{b_2}e_2\omega(t) \\
&= -\sum_{i=1}^{2}\lambda_i e_i^2 + \sum_{i=1}^{2}e_i(\hat{f}_i - \theta_i^{*T}\xi_i(\overline{x}_i)) + \sum_{i=1}^{2}e_i\tilde{\theta}_i^T\xi_i(\overline{x}_i) \\
&\quad -\sum_{i=1}^{2}\frac{1}{r_i}\tilde{\theta}_i^T\dot{\theta}_i + \frac{1}{b_2}e_2\omega(t) \\
&\le -\sum_{i=1}^{2}\lambda_i e_i^2 + \sum_{i=1}^{2}\left|e_i\varepsilon_i\right| + \sum_{i=1}^{2}\tilde{\theta}_i^T(e_i\xi_i(\overline{x}_i) - \frac{1}{r_i}\dot{\theta}_i) + \frac{1}{b_2}e_2\omega(t)
\end{aligned} \tag{33}
$$

Make

$$a_i = \lambda_i - \frac{1}{2} - \frac{1}{2\rho^2 b_i^2} \tag{34}$$

Then

$$\lambda_i = a_i + \frac{1}{2} + \frac{1}{2\rho^2 b_i^2} \tag{35}$$

We put the formula（35 ）into（33）.Then the derivative of V is

$$
\begin{aligned}
\dot{V} &\le -\sum_{i=1}^{2}a_i e_i^2 - \frac{1}{2}\sum_{i=1}^{2}e_i^2 - \sum_{i=1}^{2}\frac{1}{2\rho^2 b_i^2}e_i^2 + \sum_{i=1}^{2}\tilde{\theta}_i^T(e_i\xi_i(\overline{x}_i) - \frac{1}{r_i}\dot{\theta}_i) \\
&\quad + \sum_{i=1}^{2}\left|e_i\varepsilon_i\right| + \frac{1}{b_2}e_2\omega(t)
\end{aligned} \tag{36}
$$

Due to

$$-\frac{1}{2}\sum_{i=1}^{2}e_i^2 + \sum_{i=1}^{2}\left|e_i\varepsilon_i\right| \le \frac{1}{2}\sum_{i=1}^{2}\varepsilon_i^2 \text{ , } -\sum_{i=1}^{2}\frac{1}{2\rho^2 b_i^2}e_i^2 + \frac{1}{b_2}e_2\omega(t) \le \frac{1}{2}\rho^2\omega^2(t)$$

and self-adaptive law (31) we obtain:

$$
\begin{aligned}
\dot{V} &\le -\sum_{i=1}^{2}a_i e_i^2 + \sum_{i=1}^{2}\tilde{\theta}_i^T(e_i\xi_i(\overline{x}_i) - \frac{1}{r_i}(r_i e_i\xi_i(\overline{x}_i) - 2k_i\theta_i)) \\
&\quad + \frac{1}{2}\sum_{i=1}^{2}\varepsilon_i^2 + \frac{1}{2}\rho^2\omega^2(t) \\
&= -\sum_{i=1}^{2}a_i e_i^2 + \sum_{i=1}^{2}\frac{2k_i}{r_i}(\theta_i^* - \theta_i)^T\theta_i + \frac{1}{2}\sum_{i=1}^{2}\varepsilon_i^2 + \frac{1}{2}\rho^2\omega^2(t) \\
&= -\sum_{i=1}^{2}a_i e_i^2 + \sum_{i=1}^{2}\frac{k_i}{r_i}(2\theta_i^{*T}\theta_i - 2\theta_i^T\theta_i) + \frac{1}{2}\sum_{i=1}^{2}\varepsilon_i^2 + \frac{1}{2}\rho^2\omega^2(t)
\end{aligned} \tag{37}
$$

Due to $\theta_i^{*T}\theta_i^* + \theta_i^T\theta_i \ge 2\theta_i^{*T}\theta_i$, $2\theta_i^{*T}\theta_i\text{-}2\theta_i^T\theta_i \le \theta_i^{T*}\theta_i^* - \theta_i^T\theta_i$,we can obtain

$$
\begin{aligned}
\dot{V} &\le -\sum_{i=1}^{2}a_i e_i^2 + \sum_{i=1}^{2}\frac{k_i}{r_i}(-\theta_i^T\theta_i + \theta_i^{T*}\theta_i^*) + \frac{1}{2}\sum_{i=1}^{2}\varepsilon_i^2 + \frac{1}{2}\rho^2\omega^2(t) \\
&= -\sum_{i=1}^{2}a_i e_i^2 + \sum_{i=1}^{2}\frac{k_i}{r_i}(-\theta_i^T\theta_i - \theta_i^{T*}\theta_i^*) + \sum_{i=1}^{2}\frac{2k_i}{r_i}\theta_i^{T*}\theta_i^* \\
&\quad + \frac{1}{2}\sum_{i=1}^{2}\varepsilon_i^2 + \frac{1}{2}\rho^2\omega^2(t)
\end{aligned} \tag{38}
$$

$\tilde{\theta}_i^T\tilde{\theta}_i = (\theta_i^* - \theta_i)^T(\theta_i^* - \theta_i) = \theta_i^{*T}\theta_i^* - 2\theta_i^{*T}\theta_i + \theta_i^T\theta_i \le 2\theta_i^{*T}\theta_i^* + 2\theta_i^T\theta_i$, that is $-\frac{1}{2}\tilde{\theta}_i^T\tilde{\theta}_i \ge -\theta_i^{*T}\theta_i^*-\theta_i^T\theta_i$. Then

$$
\begin{aligned}
\dot{V} &\le -\sum_{i=1}^{2}a_i e_i^2 - \sum_{i=1}^{2}\frac{k_i}{2r_i}\tilde{\theta}_i^T\tilde{\theta}_i + \sum_{i=1}^{2}\frac{2k_i}{r_i}\theta_i^{T*}\theta_i^* + \frac{1}{2}\sum_{i=1}^{2}\varepsilon_i^2 + \frac{1}{2}\rho^2\omega^2(t) \\
&\le -\sum_{i=1}^{2}a_i\frac{2b_{i\min}}{2b_i}e_i^2 - \sum_{i=1}^{2}\frac{k_i}{2r_i}\tilde{\theta}_i^T\tilde{\theta}_i + \sum_{i=1}^{2}\frac{2k_i}{r_i}\theta_i^{T*}\theta_i^* + \frac{1}{2}\sum_{i=1}^{2}\varepsilon_i^2 \\
&\quad + \frac{1}{2}\rho^2\omega^2(t)
\end{aligned} \tag{39}
$$

Make $\lambda_i \ge \frac{1}{2} + \frac{1}{2\rho^2 b_i^2}$ for $a_i > 0$ and we define:

$$a_0 = \min\{2b_{i\min}a_i, k_i, i = 1, 2\}$$

$$b_0 = \sum_{i=1}^{2}\frac{2k_i}{r_i}\theta_i^{T*}\theta_i^* + \frac{1}{2}\sum_{i=1}^{2}\varepsilon_i^2$$

Then

$$
\begin{aligned}
\dot{V} &\le -a_0(\sum_{i=1}^{2}\frac{1}{2b_i}e_i^2 + \sum_{i=1}^{2}\frac{1}{2r_i}\tilde{\theta}_i^T\tilde{\theta}_i) + b_0 + \frac{1}{2}\rho^2\omega^2(t) \\
&= -a_0 V + b_0 + c_0
\end{aligned} \tag{40}
$$

There into $\omega^2(t) \le c_i$， $c_0 = \frac{1}{2}\rho^2\omega^2(t)$.

According to the solution of first order linear differential equation, the solution of equation (40) is:

$$
\begin{aligned}
V(t) &= (V(0) - \frac{b_0 + c_0}{a_0}\ \exp(-a_0 t) + \frac{b_0 + c_0}{a_0}\exp(-a_0 t)(1 - \exp(-a_0 t)) \\
&\le V(0)\exp(-a_0 t) + \frac{b_0 + \mathrm{c}_0}{a_0} \\
&\le V(0) + \frac{b_0 + c_0}{a_0} \qquad ,t \ge 0
\end{aligned} \tag{41}
$$

The definition of compact set as $\Omega_0 = \{\mathrm{X}\left|\mathrm{V(X)} \le \mathrm{C}_0\right.\}$, where the definition $C_0 = V(0) + \frac{b_0 + c_0}{a_0}$. From define of V in formula (6, 10, 16) we can concluded that all the signals of the closed loop system is bounded ,that is（e_1 , e_2 , $\tilde{\theta}_1$）$\tilde{\theta}_2$ $\tilde{\theta}_n$ $^T \in \Omega_0$. Order $d_0 = \min(a_i)$ and from (39) we can obtain :

$$
\begin{aligned}
\dot{V} &\le -\sum_{i=1}^{2}a_i e_i^2 - \sum_{i=1}^{2}\frac{k_i}{2r_i}\tilde{\theta}_i^T\tilde{\theta}_i + \sum_{i=1}^{2}\frac{2k_i}{r_i}\theta_i^{T*}\theta_i^* + \frac{1}{2}\sum_{i=1}^{2}\varepsilon_i^2 \\
&\quad + \frac{1}{2}\rho^2\omega^2(t) \\
&\le -\min(a_i)\sum_{i=1}^{2}e_i^2 + \sum_{i=1}^{2}\frac{2k_i}{r_i}\theta_i^{T*}\theta_i^* + \frac{1}{2}\sum_{i=1}^{2}\varepsilon_i^2 + \frac{1}{2}\rho^2\omega^2(t) \\
&= -d_0\sum_{i=1}^{2}e_i^2 + b_0 + \frac{1}{2}\rho^2\omega^2(t)
\end{aligned} \tag{42}
$$

We integrate the equation (42) among [0, T]. Then we obtain

$$\int_0^T \dot{V}dt \le -\int_0^T d_0\sum_{i=1}^{2}e_i^2(s)ds + Tb_0 + \int_0^T \frac{1}{2}\rho^2\omega^2(t)dt \tag{43}$$

Due to $\int_0^T \dot{V}dt = V(T) - V(0)$, we obtain

$$\sum_{i=1}^{2}\int_0^T e_i^2(s)ds \le \frac{1}{d_0}(V(0) - V(T) + Tb_0 + \int_0^T \frac{1}{2}\rho^2\omega^2(t)dt) \tag{44}$$

Due to $-\frac{1}{d_0}V(T) \le 0$, we obtain

$$\sum_{i=1}^{2}\int_0^T e_i^2(s)ds \le \frac{1}{d_0}V(0)+\frac{1}{d_0}Tb_0+\int_0^T \frac{1}{2d_0}\rho^2\omega^2(t)dt \qquad (45)$$

where $T\in[0,\infty]$. From (45) and the define of e_i, we can get conclusion that all the signals of the closed loop system is steady and convergence accuracy depends on $\omega(t)$ and the approximation error ρ.

IV. System Simulation

For the model of electronic throttle, the fuzzy membership function is chosen as:

$$\mu_{F_i^j}(x_i)=\exp(-0.5(x_i+2-0.5(j-1))^2) \quad (j=1,2,3....,9) \qquad (46)$$

Single value fuzzy and product inference machine is chosen for $\xi_i(\bar{x}_i)$ in the self-adaptive law (31) as:

$$\xi_{1j}(\bar{x}_1)=\frac{\mu_{F_1^j}(x_1)}{\sum_{j=1}^{9}\mu_{F_1^j}(x_1)} \qquad \xi_{2j}(\bar{x}_1)=\frac{\mu_{F_1^j}(x_1)\mu_{F_2^j}(x_2)}{\sum_{j=1}^{9}\mu_{F_1^j}(x_1)\mu_{F_2^j}(x_2)} \qquad (47)$$

Therefore:

$$\xi_1(\bar{x}_1)=[\xi_{11}(\bar{x}_1),\xi_{12}(\bar{x}_1),\cdots,\xi_{19}(\bar{x}_1)]^T$$
$$\xi_2(\bar{x}_2)=[\xi_{21}(\bar{x}_2),\xi_{22}(\bar{x}_2),\cdots,\xi_{29}(\bar{x}_2)]^T \qquad (48)$$

The simulation results of membership with degree are shown in Fig. 2.

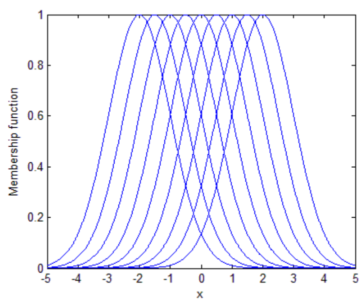

Fig. 2 Membership function

The control input is chosen as equation (28). α_1 is obtained by formula (24) and λ_i is chosen in equation (35). The self-adaptive law is adopted equation (31) among $k_1=k_2=1.5$, $r_1=r_2=2$. Attenuation coefficient is $\rho=0.16$. The parameters of electronic throttle are shown in table 1.

Table 1 model parameters

parameter	value	parameter	value
V_{bat}	$12V$	k_{pre}	$0.1393\ N\cdot m$
n	22.08	k_f	$4.8e\text{-}3\ N\cdot m$
θ_0	0.116rad	k_t	$0.016\ N\cdot m/rad$
R_a	$4.6\ \Omega$	k_v	$0.016\ N\cdot m/A$
K_{sa}	$3.89e\text{-}4\ N\cdot m/rad$	J	$4e\text{-}6\ kg\cdot m^2$
K_{sb}	$3.3e\text{-}4\ N\cdot m/rad$	B	$0\ N\cdot m/rad$

The simulation is shown in Fig 3.

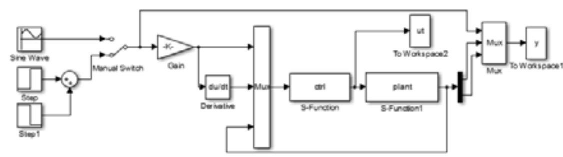

Fig. 3 Simulation of backstepping control system based on fuzzy self-adaptation.

The first experiment

The design tracking target is a positive and negative step signal(10°~60°)to check the adjusting time, overshoot and steady-state error performance indexes of electronic throttle. The simulation results are shown in Fig. 4.

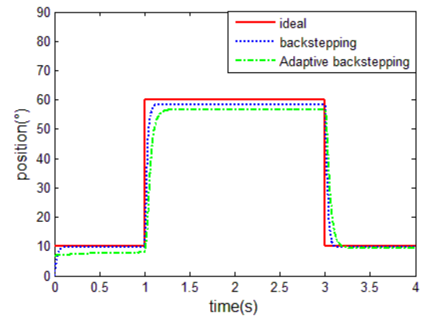

Fig. 4 10°~60° of positive and negative step responses

We can obtain the simulation results in Fig. 4 that the rising time based on the fuzzy self-adaptive backstepping is 55ms. The adjustment time is 100ms. Overshoot is zero and steady-state error is about 2.5%.

The second experiment

In order to check the angle resolution of the electronic throttle system, the initial value of step is set 10° and final signal value is set 10.2° . The simulation results are shown in Fig. 5.

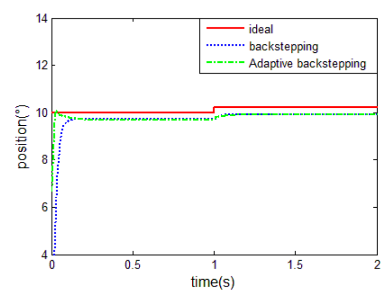

Fig. 5 Step response of 10°~10.2°

From the simulation results Fig. 5, we obtain that the fuzzy self-adaptive backstepping controller can recognize and control the throttle change in 0.2° .

The Third experiment

The input frequency of the driver to the controller by accelerator pedal is within 0~3*HZ*. The input signal of 1.5*HZ* with average is chosen as the tracking signal to check the dynamic tracking index. The simulation results are shown in Fig. 6.

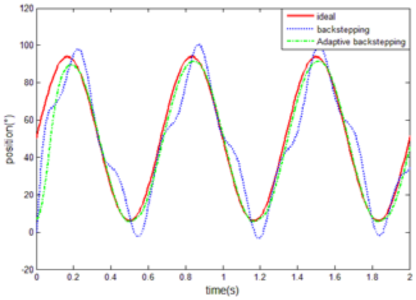

Fig. 6 1.5*HZ* sinusoidal response.

From the experimental results Fig. 6, we can conclude that backstepping controller based on the fuzzy self-adaptive has better steady control performance and good dynamic tracking performance. But the good performance rely on ideal model object. The actual electronic throttle is much more complicated and the parameters of model are changing, so it is necessary to investigate the practical application performance.

V. HARDWARE IN LOOP SIMULATION

Hardware in loop simulation (HIL) is a method to check the actual throttle performance [14]-[15]. Due to low cost, HIL can be reused and other features are favored by developers. The design of backstepping controller based on fuzzy self-adaptive is shown in Fig. 7.

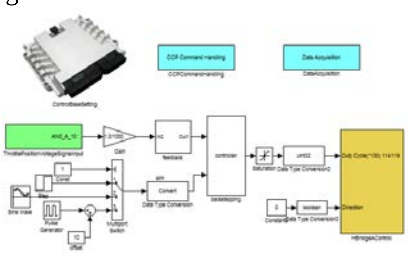

Fig. 7 Backstepping compilation model based on the fuzzy self-adaptive

Download to the electronic control unit (ECU) in the HIL cabinet. Open the monitoring interface and observe the starting process as shown in Fig. 8.

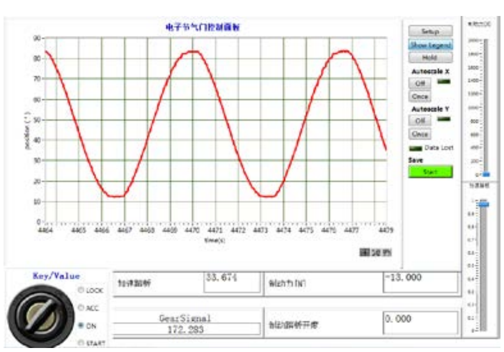

Fig. 8 Electronic throttle control panel

When setting position instruction is 10°~80° of the positive and negative step signal, the result is shown in Fig. 9.

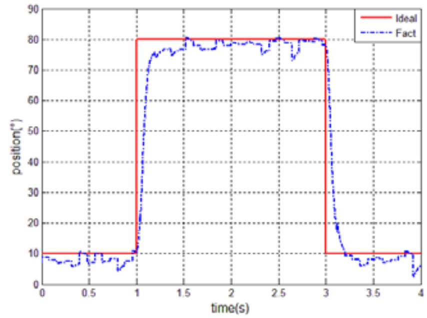

Fig. 9 10°~80° positive and negative step response

Fig. 9 shows that the rise time of the system for 56 ms, adjust the time of 102 ms, 0.1% of overshoot, steady-state error under 2.5%.

The simulation result with sine response of 3*HZ* are shown in Fig. 10.

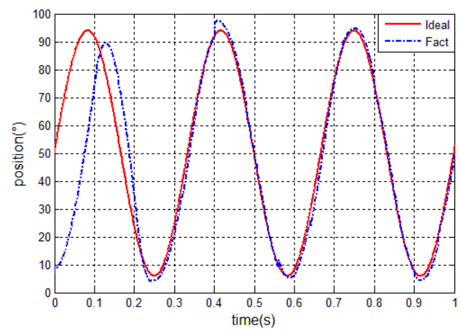

Fig. 10 Sine response of 3*HZ*.

From the experimental results Fig. 10, we can conclude that backstepping controller based on the fuzzy self-adaptive has good dynamic tracking performance in fact.

VI. CONCLUSION

Electronic throttle is a complex composed of throttle body, reset spring and reduction gear group. It is not easy to build accurate mathematical model. In this technical note, the fuzzy self-adaptive law is introduced into the electronic throttle control system to realize the approximation of unknown throttle mathematic model. The control systerm without precise model is designed by backstepping. By entering 10° to 80° of the positive and negative step signal, the rise time of the system is 56ms, adjustment time is within 105ms, steady-state error is under 2.5%. and contronller can identify changes of electronic throttle in 0.2° .By the sine response of 3*HZ*, it is found that the tracking perfomance of the control system is good. According to the conclusion in [16], as long as the throttle response speed and expected position tracking with same order is good work. Backstepping controller based on the fuzzy self-adaptive by experiment is proved to be satisfied those requirements.

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