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Event-Triggered Adaptive Control for Tank Gun Control Systems

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ABSTRACT In this paper, an event-triggered adaptive control scheme is proposed for the gun control system of a tank subject to not only external disturbances but also uncertain modeling errors and unknown parameters. Compared with the existing results, the upper bound function of modeling errors is unknown. Therefore, the traditional event-triggered control method cannot be applied directly to handle the effect caused by the modeling errors. To solve this problem, a smooth function $sg(\cdot)$ is introduced to estimate the bound of modeling errors, such that their effects on system stability are successfully compensated. The simulation results are provided to illustrate the effectiveness of the proposed control scheme.

INDEX TERMS Gun control system, adaptive control, event-trigger control, modeling error.

I. INTRODUCTION

For practical systems, due to various uncertainties including unknown failures [1]–[6], input and state delays [7]–[12] and unknown actuator nonlinearities [13]–[16], it is essentially important yet challenging to guarantee the desired system performance. The control of weapons, which is a decisive factor of winning or losing wars, has been widely investigated. With the development of advanced control technologies, many methods, including variable structure control, sliding mode control, adaptive control and robust control, have been used in controlling the gun system of tank [17]–[19]. The variable structure control method for tank gun control system was reported in [17]; An adaptive control scheme was proposed with nonlinear friction, backlash and external disturbance in [18]; [19] studied the same tank gun control system as in [18] and a new adaptive sliding mode control method was presented. Specifically, the proposed method can deal with the structure perturbation and external disturbance.

In this paper, we consider a class of tank gun control system with unknown parameters, external disturbance and modeling errors. An event-triggered adaptive control scheme is proposed which includes designing both the event-triggering mechanism and the updating laws for unknown parameters. Different from the existing results, the upper bound of the unknown term $\eta(t)$ is unknown due to the unknown constant l in function $\sigma_1(\xi, t)$. This makes it harder to compensate the effects of the unknown modeling error $\eta(t)$. To the best of our knowledge, there is still no result available to compensate such uncertainty $\eta(t)$ in existing event trigger control results [2], [20]–[25]. To solve this problem, $\eta(t)$ is divided into two parts. The first part contains an unknown parameter l and an adaptive law of l will be designed in the controller. The estimation error of the updating law can be handled by the property of $sg(\chi)$ based on Lemma 1. The remaining part of $\eta(t)$ is handled directly in the similar way.

The main contributions of this paper can be summarized as follows: (I) The control problem is investigated for gun control systems with uncertain external disturbance, unknown modeling errors and parameters. An event-triggered control scheme is proposed to guarantee desired system performance which can save the network resources such as communication bandwidth and computation abilities; (II) In contrast to existing results, we consider all sorts of uncertainties denoted by $\eta(t)$. The upper bound function of $\eta(t)$ is unknown due to the unknown constant l and a proper adaptive law is designed accordingly; (III) To improve system performance, we introduce $sg(\chi)$ in controller design which helps to compensate the effects caused by $\eta(t)$.

The rest of the paper is outlined as follows: In section 2, we formulate the gun control system with unknown parameters, unknown external disturbance and modeling errors. In section 3, an event-triggered adaptive control scheme

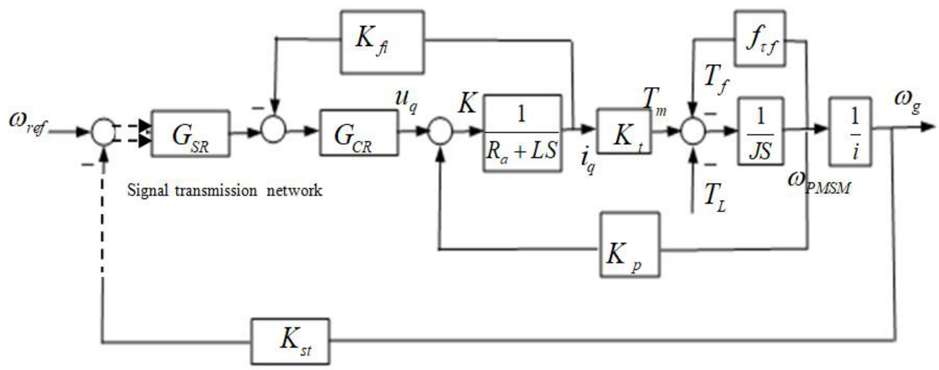

FIGURE 1. Structure of gun control system of tank.

is proposed. Main results including Lemma 1 and the stability analysis are shown in section 4. Some simulation results are shown in detail in section 5. Finally, the paper is concluded in section 6.

II. MODELS AND PROBLEM STATEMENT

The tank gun control system in [17] and [19] is considered in this paper. As shown in Fig.1, G_{SR} and G_{CR} are the speed regulator and current regulator, respectively; L is the inductance of motor, R_a is armature resistance, and J presents total load inertia; K_t and K_p are respectively the motor torque coefficient and back EMF(electromotive force) coefficient of motor; K_{cf} and K_{sf} are current feedback coefficient and rate feedback factor; i is reduction ratio, ω_{PMSM} is angular velocity of PMSM(permanent magnet synchronous motor), and ω_g is angular velocity of gun; ω_g is the reference angular velocity, $f_{\tau f}$ is ratio coefficient of viscous friction, T_f is disturbance torque of friction, and T_L is the load torque.

According to the above block diagram, the mathematical model of gun control system is given below:

$$\begin{aligned} \dot{i}_q &= -\frac{R_a}{L}i_q - \frac{K_p i}{L}w_g + \frac{K}{L}u_q \\ \dot{w}_g &= \frac{K_t}{J}i_q - \frac{1}{J}\bar{\eta}(t) \end{aligned} \tag{1}$$

where $\bar{\eta}(t)$ presents unknown modeling errors and external disturbance. The tank gun control system shown in Fig.1 and equation (1) had been constructed in [17]–[19]. In this paper, we will transform such gun control system model (1) into triangular form and design the event-triggered adaptive controller by backstepping.

By using Laplace transform, we have

$$i_q(s) = \frac{Ku_q - K_p i w_g}{LS + R_a} \tag{2}$$

With the second equation in (1), we have

$$\dot{w}_g = \frac{K_t}{J}\frac{Ku_q - K_p i w_g}{LS + R_a} - \frac{1}{J}\bar{\eta}(t) \tag{3}$$

Then we obtain

$$\ddot{w}_g = -\frac{R_a}{L}\dot{w}_g - \frac{K_p K_t i}{LJ}w_g + \frac{K_t K}{LJ}u_q - \frac{1}{J}(\dot{\bar{\eta}}(t) + \frac{R_a}{L}\bar{\eta}(t)) \tag{4}$$

Let

$$\xi_1 = \omega_g; \quad \xi_2 = \dot{\omega}_g \tag{5}$$

and

$$\begin{aligned} &\theta_1 = -\frac{K_p K_t i}{LJ}; \quad \theta_2 = -\frac{R_a}{L}; \; b = \frac{K_t K}{LJ} \\ &\eta(t) = -\frac{1}{J}(\dot{\bar{\eta}}(t) + \frac{R_a}{L}\bar{\eta}(t)) \end{aligned} \tag{6}$$

The mathematical model of the gun control system of tank can be transformed into

$$\begin{aligned} \dot{\xi}_1 &= \xi_2 \\ \dot{\xi}_2 &= \theta_1\xi_1 + \theta_2\xi_2 + bu_q + \eta(t) \\ y &= \xi_1 \end{aligned} \tag{7}$$

where $\xi = (\xi_1, \xi_2)$ is system state and y is the output. θ_1, θ_2, b are unknown constant parameters.

In the following, an event-trigger adaptive control scheme will be given. To this end, the following assumptions are needed.

Assumption 1: The unknown parameter $b \neq 0$ and $sign(b)$ is known. There exists a known constant $\bar{b}$ such that $|b| \leq \bar{b}$.

Assumption 2: Reference signal $\xi_r(t)$ and its derivative are known and bounded.

Assumption 3: The unknown term $\eta(t)$ satisfies

$$|\eta(t)| \leq l\sigma_1(\xi, t) + \sigma_2(\xi, t) \tag{8}$$

where l is an unknown positive parameter and $\sigma_1(\xi, t)$, $\sigma_2(\xi, t)$ are known positive functions.

Remark 1: $\eta(t)$ presents all external uncertainties caused by external disturbance, coulomb friction, eccentric moment and load moment. $l > 0$ is a positive parameter which will be estimated in the proposed event-triggered adaptive control law.

III. DESIGN OF EVENT-TRIGGERED CONTROLLER

The control objective is to design an event-triggered adaptive control scheme based on backstepping [26], [27] to guarantee that all signals of the closed-loop system are bounded while the expected precision of tracking error can be achieved.

To carry out the controller design, the following change of coordinates is introduced.

$$\begin{aligned} z_1 &= \xi_1 - \xi_r \\ z_2 &= \xi_2 - \alpha_1 - \xi_r^{(1)} \end{aligned} \tag{9}$$

where variable z_1 is the tracking error. α_1 is the virtual control and ξ_r is the reference signal. Below we will give the design details following the recursive backstepping procedure similar to [26] and [27].

Step 1: From (7) and (9), we can obtain

$$\begin{aligned} \dot{z}_1 &= \dot{\xi}_1 - \xi_r^{(1)} \\ &= z_2 + \alpha_1 + \xi_r^{(1)} - \xi_r^{(1)} \\ &= z_2 + \alpha_1 \end{aligned} \tag{10}$$

Virtual control α_1 can be chosen as

$$\alpha_1 = -c_1 z_1 \tag{11}$$

where c_1 is a positive constant. We take the following Lyapunov function

$$V_1 = \frac{1}{2} z_1^2 \tag{12}$$

Then

$$\begin{aligned} \dot{V}_1 &= z_1 \dot{z}_1 \\ &= z_1(z_2 + \alpha_1) \\ &= -c_1 z_1^2 + z_1 z_2 \end{aligned} \tag{13}$$

Step 2: From (7) and (9), the derivative of z_2 is

$$\begin{aligned} \dot{z}_2 &= \dot{\xi}_2 - \dot{\alpha}_1 - \xi_r^{(2)} \\ &= \theta_1 \xi_1 + \theta_2 \xi_2 + b u_q + \eta(t) - \dot{\alpha}_1 - \xi_r^{(2)} \end{aligned} \tag{14}$$

We take

$$\begin{aligned} \alpha = &-\hat{\theta}_1 \xi_1 - \hat{\theta}_2 \xi_2 + \dot{\alpha}_1 + \xi_r^{(2)} - z_1 - c_2 z_2 \\ &- \hat{l} \sigma_1(\xi, t) sg(\frac{z_2 \sigma_1(\xi, t)}{\varepsilon}) \\ &- [\sigma_2(\xi, t) + \bar{m}] sg(\frac{z_2(\sigma_2(\xi, t) + \bar{m})}{\varepsilon}) \end{aligned} \tag{15}$$

where $c_2 > 0$ is a design parameter. $\bar{m}$ is a positive design parameter and will be detailed in the part of event design. $\hat{\theta}_1, \hat{\theta}_2, \hat{l}$ are estimators of unknown parameters θ_1, θ_2, l, respectively. The auxiliary function $sg(\cdot)$ is constructed as

$$sg(\chi) = \begin{cases} \dfrac{\chi}{|\chi|}, & |\chi| \geq \delta \\ \dfrac{\chi}{(\delta^2 - \chi^2)^2 + |\chi|}, & |\chi| < \delta \end{cases} \tag{16}$$

where δ is a positive design parameter. Then the event-triggered controller can be designed as

$$\begin{aligned} u_q(t) &= v_q(t_k), \quad \forall \in [t_k, t_{k+1}) \\ t_{k+1} &= inf\{t \in R, ||e(t)| \geq m\}, \quad t_1 = 0 \end{aligned} \tag{17}$$

Remark 2: From the event triggering mechanism given above, we know that the control signal holds as a constant $v_q(t_k)$ during the time $t \in [t_k, t_{k+1})$ which will be applied to the system till (17) is triggered. This means the signals transmitted by networks and control signals executed by actuators are simpler in the time interval $t \in [t_k, t_{k+1})$. This will lead to communication resources of network being saved by such discontinuous control gains.

Then we chose

$$v_q(t) = \hat{\upsilon} \alpha \tag{18}$$

where $\hat{\upsilon}$ is the estimation of $\upsilon = \frac{1}{b}$, $e(t) = v_q - u_q$ is the measurement error. Update laws of unknown parameters are

$$\begin{aligned} \dot{\hat{\theta}}_1 &= \gamma_1 z_2 \xi_1 - \gamma_1 \kappa_1 (\hat{\theta}_1 - \theta_{10}); \\ \dot{\hat{\theta}}_2 &= \gamma_2 z_2 \xi_2 - \gamma_2 \kappa_2 (\hat{\theta}_2 - \theta_{20}); \\ \dot{\hat{\upsilon}} &= -sign(b) \gamma_\upsilon z_2 \alpha - \gamma_\upsilon \kappa_\upsilon (\hat{\upsilon} - \upsilon_0); \\ \dot{\hat{l}} &= \gamma_l z_2 \sigma_1(\xi, t) sg(\frac{z_2 \sigma_1(\xi, t)}{\varepsilon}) - \gamma_l \kappa_l (\hat{l} - l_0) \end{aligned} \tag{19}$$

where $\gamma_1, \gamma_2, \gamma_l, \gamma_\upsilon, \kappa_1, \kappa_2, \kappa_l, \kappa_\upsilon$ are positive design parameters. $\theta_{10}, \theta_{20}, \upsilon_0, l_0$ are initial estimations of parameters $\theta_1, \theta_2, \upsilon, l$, respectively. Compared with the traditional adaptive control law for common triangular nonlinear systems, design parameters $\kappa_1, \kappa_2, \kappa_l, \kappa_\upsilon, \theta_{10}, \theta_{20}, \upsilon_0, l_0$ are introduced in the proposed adaptive control law (17)-(18) and update laws (19). The values of these parameters are chosen freely if we only consider the stability of systems. However, the different choosing will lead to the different control performance. It will be discussed in detail in the following section.

IV. MAIN RESULTS

We now establish the boundedness of all signals in the closed loop system. The following theorem about event-trigger control law of gun control system of tank can be achieved.

Lemma 1: For any positive constant ε, function $sg(\chi)$ given in (16) satisfies

$$|\chi| - \chi sg(\frac{\chi}{\varepsilon}) \leq \varepsilon \delta, \quad \forall \varepsilon > 0 \tag{20}$$

Proof: We consider the following two cases

1) When $\frac{|\chi|}{\varepsilon} \geq \delta$, we can easily get

$$|\chi| - \chi sg(\frac{\chi}{\varepsilon}) = 0 \leq \varepsilon \delta \tag{21}$$

2) When $\frac{|\chi|}{\varepsilon} < \delta$, we have

$$\begin{aligned} |\chi| - \chi sg(\frac{\chi}{\varepsilon}) &= |\chi| - \chi \frac{\chi}{(\delta^2 - \chi^2)^2 + |\chi|} \\ &= \frac{|\chi|(\delta^2 - \chi^2)^2}{(\delta^2 - \chi^2)^2 + |\chi|} \\ &\leq \frac{|\chi|(\delta^2 - \chi^2)^2}{(\delta^2 - \chi^2)^2} \\ &= |\chi| \\ &\leq \varepsilon \delta \end{aligned} \tag{22}$$

□□

Remark 4: $sg(\chi)$ is introduced in the design of the proposed adaptive event-triggered based controller. With Lemma 1 it is obtained that the error between $sg(\chi)$ and $sign(\chi)$ is zero when $\frac{\chi}{\varepsilon} \geq \delta$, while this error is smaller than $\varepsilon\delta$ when $\frac{\chi}{\varepsilon} < \delta$. Clearly $sg(\cdot)$ can realize more precise approximation than $sign(\cdot)$. Thus the performance of closed-loop systems can be improved.

Theorem 1: Consider gun control system of tank shown in (7), an event-trigger based adaptive controller with control law (17)-(18) and the update laws (19). Under Assumption 1-3, all signals of the closed-loop system are bounded. In addition, there exists a constant $T^* > 0$ such that $t_{k+1} - t_k \geq T^*$.

Proof: From (17), we have $|u_q(t) - v_q(t)| \leq m$ when $t \in [t_k, t_{k+1})$. So we can rewrite it as the following function

$$\begin{aligned} &u_q(t) = v_q(t) - \lambda(t)m \\ &|\lambda(t)| \leq 1, \quad \lambda(t_k) = 0, \ \lambda(t_{k+1}) = \pm 1, \ \forall t \in [t_k, t_{k+1}) \end{aligned} \tag{23}$$

where $\lambda(t)$ can be seen as a time varying unknown parameter. Note that

$$\begin{aligned} bu_q &= bv_q - \lambda(t)bm \\ bv_q &= b\hat{\upsilon}\alpha \\ &= b(\upsilon - \tilde{\upsilon})\alpha \\ &= \alpha - b\tilde{\upsilon}\alpha \end{aligned} \tag{24}$$

From (7) (9) and (15), we have

$$\begin{aligned} \dot{z}_2 &= \theta_1\xi_1 + \theta_2\xi_2 + \alpha - b\tilde{\upsilon}\alpha - \lambda(t)bm + \eta(t) \\ &\quad -\dot{\alpha}_1 - r^{(2)}(x) \\ &= \tilde{\theta}_1\xi_1 + \tilde{\theta}_2\xi_2 - z_1 - c_2z_2 + \eta(t) - \lambda(t)bm - b\tilde{\upsilon}\alpha \\ &\quad - (\sigma_2(\xi,t) + \bar{m})sg(\frac{z_2(\sigma_2(\xi,t) + \bar{m})}{\varepsilon}) \\ &\quad - \hat{l}\sigma_1(\xi,t)sg(\frac{z_2\sigma_1(\xi,t)}{\varepsilon}) \end{aligned} \tag{25}$$

Choose the Lyapunov function

$$V = V_1 + \frac{1}{2}z_2^2 + \frac{1}{2\gamma_1}\tilde{\theta}_1^2 + \frac{1}{2\gamma_2}\tilde{\theta}_2^2 + \frac{1}{2\gamma_l}\tilde{l}^2 + \frac{|b|}{2\gamma_\upsilon}\tilde{\upsilon}^2 \tag{26}$$

where $\tilde{\theta}_1 = \theta_1 - \hat{\theta}_1$, $\tilde{\theta}_2 = \theta_2 - \hat{\theta}_2$, $\tilde{l} = l - \hat{l}$, $\tilde{\upsilon} = \upsilon - \hat{\upsilon}$ denote estimation errors.

The derivative of V is

$$\begin{aligned} \dot{V} &= \dot{V}_1 + z_2\dot{z}_2 - \frac{1}{\gamma_1}\tilde{\theta}_1\dot{\hat{\theta}}_1 - \frac{1}{\gamma_2}\tilde{\theta}_2\dot{\hat{\theta}}_2 \\ &\quad -\frac{1}{\gamma_l}\tilde{l}\dot{\hat{l}} - \frac{|b|}{\gamma_\upsilon}\tilde{\upsilon}\dot{\hat{\upsilon}} \end{aligned} \tag{27}$$

When we chose $\bar{m}$ such that $|\lambda(t)bm| \leq \bar{m}$, we can get

$$\begin{aligned} z_2(\eta(t) - \lambda(t)bm) &\leq |z_2|(l\sigma_1(\xi,t) + \sigma_2(\xi,t) + \bar{m}) \\ &= l|z_2|\sigma_1(\xi,t) + |z_2(\sigma_2(\xi,t) + \bar{m})| \end{aligned} \tag{28}$$

With (25) (27) and (28), we can get

$$\begin{aligned} \dot{V} &\leq -c_1z_1^2 - c_2z_2^2 + \tilde{\theta}_1z_2\xi_1 + \tilde{\theta}_2z_2\xi_2 \\ &\quad + |z_2(\sigma_2(\xi,t) + \bar{m})| - z_2(\sigma_2(\xi,t) + \bar{m}) \\ &\quad \times sg(\frac{z_2(\sigma_2(\xi,t) + \bar{m})}{\varepsilon}) + l|z_2|\sigma_1(\xi,t) \\ &\quad - \hat{l}z_2\sigma_1(\xi,t)sg(\frac{z_2\sigma_1(\xi,t)}{\varepsilon}) - \frac{1}{\gamma_1}\tilde{\theta}_1\dot{\hat{\theta}}_1 \\ &\quad - \frac{1}{\gamma_2}\tilde{\theta}_2\dot{\hat{\theta}}_2 - \frac{1}{\gamma_l}\tilde{l}\dot{\hat{l}} - \frac{|b|}{\gamma_\upsilon}\tilde{\upsilon}\dot{\hat{\upsilon}} - b\tilde{\upsilon}\alpha z_2 \end{aligned} \tag{29}$$

Note that

$$\hat{l}z_2\sigma_1sg(\frac{z_2\sigma_1}{\varepsilon}) = lz_2\sigma_1sg(\frac{z_2\sigma_1}{\varepsilon}) - \tilde{l}z_2\sigma_1sg(\frac{z_2\sigma_1}{\varepsilon}) \tag{30}$$

and

$$\begin{aligned} |z_2(\sigma_2 + \bar{m})| - z_2(\sigma_2 + \bar{m})sg(\frac{z_2(\sigma_2 + \bar{m})}{\varepsilon}) &\leq \varepsilon\delta \\ |z_2|\sigma_1(\xi,t) - z_2\sigma_1(\xi,t)sg(\frac{z_2\sigma_1(\xi,t)}{\varepsilon}) &\leq \varepsilon\delta \end{aligned} \tag{31}$$

So we have

$$\begin{aligned} \dot{V} &\leq -\sum_{i=1}^{2}c_iz_i^2 - \frac{1}{\gamma_1}\tilde{\theta}_1(\dot{\hat{\theta}}_1 - \gamma_1z_2\xi_1) \\ &\quad - \frac{1}{\gamma_2}\tilde{\theta}_2(\dot{\hat{\theta}}_2 - \gamma_2z_2\xi_2) - \frac{|b|}{\gamma_\upsilon}\tilde{\upsilon}(\dot{\hat{\upsilon}} + sign(b)\gamma_\upsilon z_2\alpha) \\ &\quad - \frac{1}{\gamma_l}\tilde{l}(\dot{\hat{l}} - \gamma_lz_2\sigma_1(\xi,t)sg(\frac{z_2\sigma_1(\xi,t)}{\varepsilon})) + (l+1)\varepsilon\delta \end{aligned} \tag{32}$$

With update laws (19), we have

$$\begin{aligned} \dot{V} &\leq -\sum_{i=1}^{2}c_iz_i^2 + \tilde{\theta}_1\kappa_1(\hat{\theta}_1 - \theta_{10}) + \tilde{\theta}_2\kappa_2(\hat{\theta}_2 - \theta_{20}) \\ &\quad + |b|\tilde{\upsilon}\kappa_\upsilon(\hat{\upsilon} - \upsilon_0) + \tilde{l}\kappa_l(\hat{l} - l_0) + (l+1)\varepsilon\delta \end{aligned} \tag{33}$$

With the following inequalities

$$\begin{aligned} \kappa_1\tilde{\theta}_1(\hat{\theta}_1 - \theta_{10}) &\leq -\frac{1}{2}\kappa_1\tilde{\theta}_1^2 + \frac{1}{2}\kappa_1(\theta_1 - \theta_{10})^2 \\ \kappa_2\tilde{\theta}_2(\hat{\theta}_2 - \theta_{20}) &\leq -\frac{1}{2}\kappa_2\tilde{\theta}_2^2 + \frac{1}{2}\kappa_2(\theta_2 - \theta_{20})^2 \end{aligned} \tag{34}$$

and

$$\begin{aligned} \kappa_\upsilon\tilde{\upsilon}(\hat{\upsilon} - \upsilon_0) &\leq -\frac{1}{2}\kappa_\upsilon\tilde{\upsilon}^2 + \frac{1}{2}\kappa_\upsilon(\upsilon - \upsilon_0)^2 \\ \kappa_l\tilde{l}(\hat{l} - l_0) &\leq -\frac{1}{2}\kappa_l\tilde{l}^2 + \frac{1}{2}\kappa_l(l - l_0)^2 \end{aligned} \tag{35}$$

we have

$$\dot{V} \leq -\sum_{i=1}^{2}c_iz_i^2 - \frac{1}{2}\Big(\kappa_1\tilde{\theta}_1^2 + \kappa_2\tilde{\theta}_2^2 + |b|\kappa_\upsilon\tilde{\upsilon}^2 + \kappa_l\tilde{l}^2\Big) + \Pi \tag{36}$$

where

$$\begin{aligned} \Pi = (l+1)\varepsilon\delta + \frac{1}{2}\Big(&\kappa_1(\theta_1 - \theta_{10})^2 + \kappa_2(\theta_2 - \theta_{20})^2 \\ &+ |b|\kappa_\upsilon(\upsilon - \upsilon_0)^2 + \kappa_l(l - l_0)^2\Big) \end{aligned} \tag{37}$$

Therefore, it has

$$\dot{V} \leq -\hbar_1\Big(\sum_{i=1}^{2}z_i^2 + \tilde{\theta}_1^2 + \tilde{\theta}_2^2 + \tilde{\upsilon}^2 + \tilde{l}^2\Big) + \Pi \tag{38}$$

where

$$\hbar_1 = min\Big\{c_1, c_2, \frac{\kappa_1}{2}, \frac{\kappa_2}{2}, \frac{|b|\kappa_\upsilon}{2}, \frac{\kappa_l}{2}\Big\} \tag{39}$$

Let

$$\hbar_2 = max\Big\{\frac{1}{2}, \frac{1}{2\gamma_1}, \frac{1}{2\gamma_2}, \frac{|b|}{2\gamma_\upsilon}, \frac{1}{2\gamma_l}\Big\} \tag{40}$$

Then it is obtained

$$V \leq \hbar_2\Big(\sum_{i=1}^{2} z_i^2 + \tilde{\theta}_1^2 + \tilde{\theta}_2^2 + \tilde{\upsilon}^2 + \tilde{l}^2\Big) \tag{41}$$

So we have

$$\dot{V} \leq -\frac{\hbar_1}{\hbar_2}V + \Pi \tag{42}$$

Clearly

$$V \leq V(0) + \frac{\hbar_2}{\hbar_1}\Pi \tag{43}$$

Hence we can conclude that all signals $z_1, z_2, \tilde{\theta}_1, \tilde{\theta}_2$ and $\tilde{\upsilon}, \tilde{l}$ are bounded. Since the virtual control α_1, α and states $\xi_i (i = 1, 2)$ are bounded, from the control laws (17) and (18), u_q and v_q are bounded.

Following we show that there exists a $T^* > 0$ such that $t_k + 1 - t_k \geq T^*$ for $\forall k \in Z^+$. Firstly we analysis the derivative of measurement error $e(t), t \in [t_k, t_{k+1})$ as follows. Because u_q is a constant, we can get

$$\frac{d}{dt}|e(t)| = sign(e)\dot{e} \leq |\dot{v}_q| \tag{44}$$

Note that $\dot{v}_q$ is the continuous function of $z_i, \xi_i, \hat{\theta}_i, \hat{\upsilon}, \hat{l}$ and these variables are bounded. So there exists a constant ϱ such that

$$|\dot{v}_q| \leq \varrho \tag{45}$$

Noting that

$$e(t_{k+1}) - e(t_k) = \dot{e}(t_k^0)(t_{k+1} - t_k), \quad \exists t_k^0 \in [t_k, t_{k+1}) \tag{46}$$

it has

$$t_{k+1} - t_k = \frac{e(t_{k+1}) - e(t_k)}{\dot{e}(t_k^0)} \geq \frac{m}{\varrho} \triangleq T^* \tag{47}$$

□□

Remark 3: From (37) and (42), we can find that the size of the bound of all signals depends on the design parameters $\kappa_1, \kappa_2, \kappa_l, \kappa_\upsilon, \theta_{10}, \theta_{20}, \upsilon_0, l_0$. Similar to [27], transient performance of tracking error can be systematically reduced by adjusting the design parameters $\kappa_1, \kappa_2, \kappa_l, \kappa_\upsilon$ and the initial estimation errors $\theta_1 - \theta_{10}, \theta_2 - \theta_{20}, \upsilon - \upsilon_0, l - l_0$ through choosing the values of $\theta_{10}, \theta_{20}, \upsilon_0, l_0$ properly.

V. SIMULATION STUDIES

In this section, the simulation results are presented to verify the effectiveness of the proposed event-trigger based adaptive control scheme. In the simulation, the values of system parameters will be taken in [15]–[17]. The inductance of motor $L = 2.097 \times 10^{-3}$, armature resistance $R_a = 0.036\Omega$, total load inertia $J = 0.0067\ kg \cdot m^2$, torque coefficient and back EMF(electromotive force) coefficient of motor $K_t = 0.097$, $K_p = 0.054$, reduction ratio $i = 1650$ and $K = 2$. Let the uncertain term $\eta(t)$ denote unknown modeling errors and external disturbance in the second equation of system model (7). Then system in simulation can be written as

$$\begin{aligned} \dot{\xi}_1 &= \xi_2 \\ \dot{\xi}_2 &= \theta_1\xi_1 + \theta_2\xi_2 + bu + \eta(t) \end{aligned} \tag{48}$$

where we can calculate system parameters $\theta_1 = -4.4374e+05$, $\theta_2 = -12.3839$, $b = 9.9605e+03$.

Then refer to the explanation on the choosing of design parameters bellow the equation (19), we choose $k_1 = 6$, $k_2 = 4$, $\epsilon = 1$, $\delta = 0.2$, $\gamma_1 = \gamma_2 = \gamma_v = \gamma_l = 0.001$, $\kappa_1 = \kappa_2 = \kappa_v = \kappa_l = 1$, $\theta_{10} = -4.0e+05$, $\theta_{20} = -12$, $v_0 = 0.5$, $l_0 = 1/(9.0e+3)$. For event-triggered controller (27), we set $m = 0.2$. The initial values are chosen as $x_1(0) = 0.5$, $x_2(0) = 0$, $\hat{\theta}_1(0) = 0$, $\hat{\theta}_2(0) = 0$, $\hat{l}(0) = \hat{v}(0) = 0$ and other initial values are also zero.

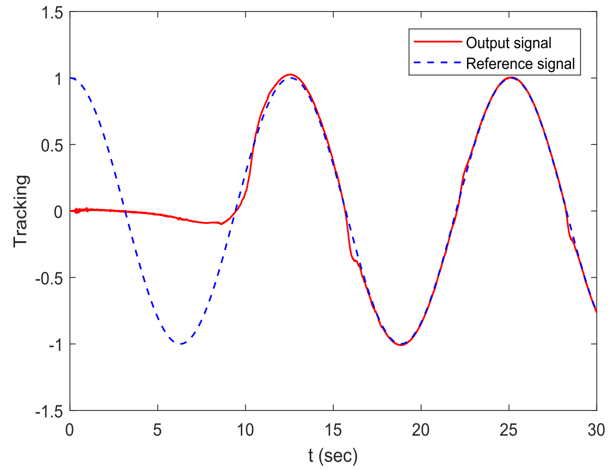

FIGURE 2. Tracking errors(no modeling error and disturbance).

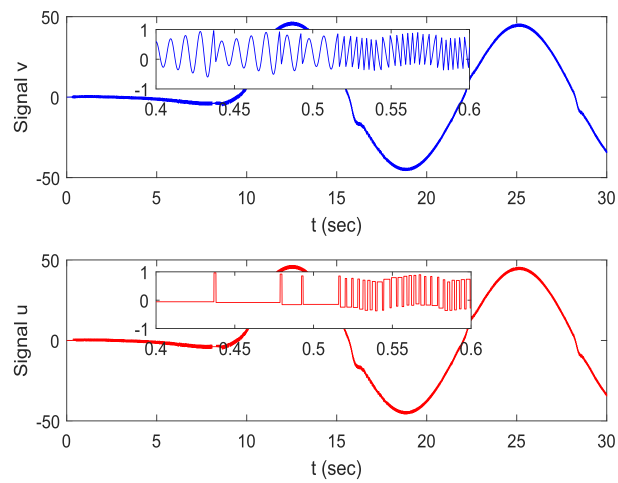

FIGURE 3. Input signals(no modeling error and disturbance).

Firstly, we consider that there are no modeling errors and external disturbance, namely $\eta(t) = 0$. Figure 2 and Figure3 show the tracking error and input signals including the discrete control signal (21) and continuous signal $v_q(t)$ under the reference signal $\xi_r = cos(0.5t)$, respectively. Then we consider $\eta(t) = 0.1 * (1 + (sin\xi_1)^2) + 0.1 * e^{-t}$.

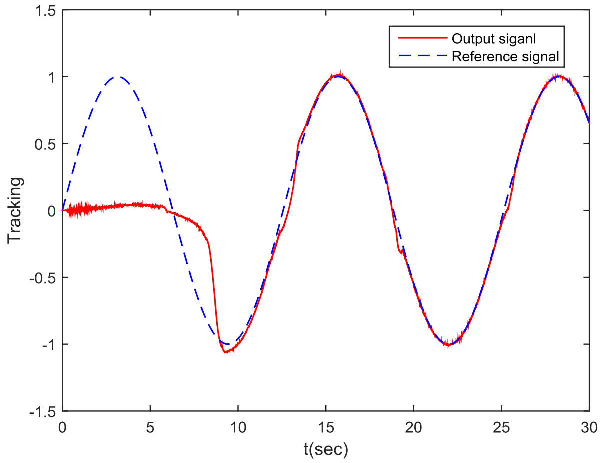

FIGURE 4. **Tracking errors.**

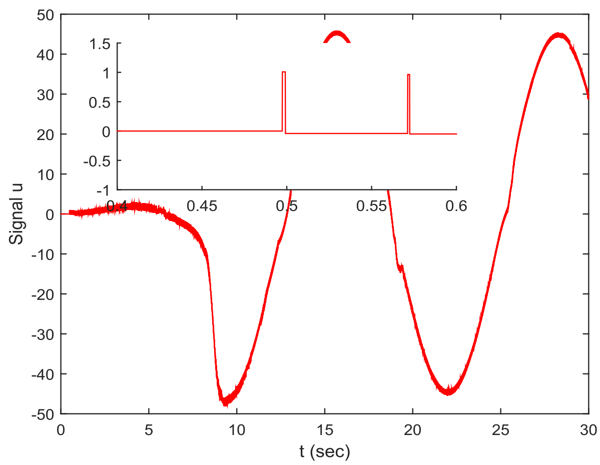

FIGURE 5. **Input $u_q(t)$.**

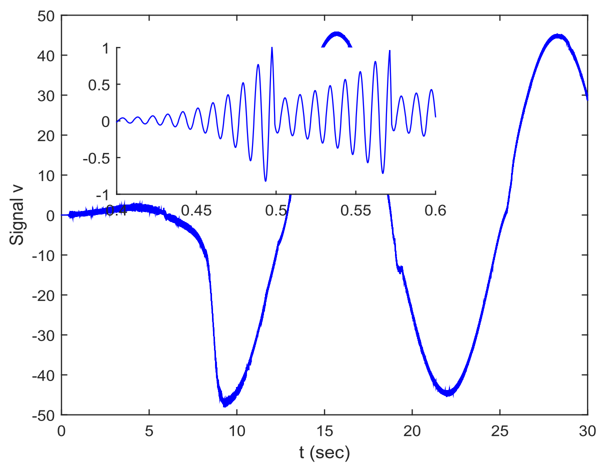

FIGURE 6. **Input $v_q(t)$.**

Figure 4-Figure 7 show the simulation results when reference signal is $sin(0.5t)$. Specifically, the tracking error is shown in Fig.4. It can seen that better tracking performance can be realized under the proposed event-triggered control law. The discrete control signal (21) is given in Fig.5, the continuous signal $v_q(t)$ is shown in Fig.6 and the comparison of these

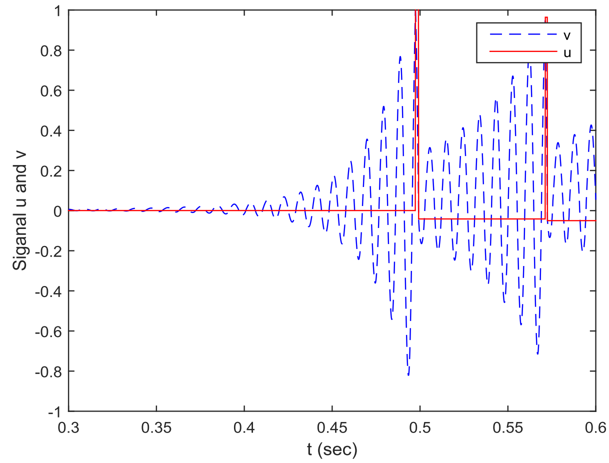

FIGURE 7. **Comparison of $u_q(t)$ and $v_q(t)$.**

two signals are shown in Fig.7. It is clear that the event-triggered control signal $v_q(t)$ is easy to execute. According to the simulation results, it can be seen that good tracking performance has been achieved under the different reference signals $\xi_r = sin(0.5t)$ and $\xi_r = cos(0.t)$. In addition, we know that the proposed event-trigger based adaptive controller is effective on the stability of tank gun control systems (1) no mater unknown modeling errors and disturbance exist or not.

VI. CONCLUSION

An event-triggered adaptive control scheme is proposed by using backstepping technique for gun control system of tank with unknown parameters and modeling errors. The unknown parameter l in the upper bound function of $\eta(t)$ is estimated in the proposed event-triggered adaptive controller. The boundedness of all signals of the closed-loop system and tracking performance are ensured by this proposed control law and corresponding update laws. Simulation results verify the effectiveness of the proposed control scheme.

A possible direction for future work is to investigate the mathematical model of tank gun control system. Based on the accurate model, more accurate and effective control law can be designed to improve system performance which satisfies the practical requirement.

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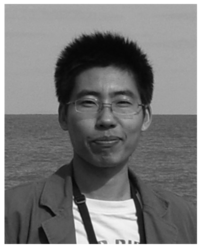

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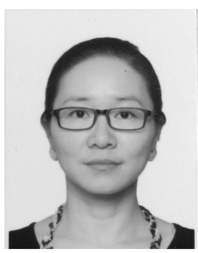

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