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Switching event-triggered control of a ball and beam system based on $\alpha\epsilon$-mapping method

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Abstract

We propose an event-triggered control method to a ball and beam system with a switching logic based on $\alpha\epsilon$-mapping. Our proposed controller has two scaling factors - α and ϵ. We analytically show that there is a trade-off relation between the output convergence speed to a reference point and interexcecution times, and this relation is characterized by using α and ϵ factors. This characterized feature is called $\alpha\epsilon$-mapping. Then, based on the $\alpha\epsilon$-mapping, we present a switching algorithm for balanced control performance in terms of the convergence speed and interexecution times. The validity of our control method is demonstrated through the experimental results.

Key words : Ball and beam system, Event-triggered control, Switching control, $\alpha\epsilon$-mapping method, Gain Switching algorithm

Ⅰ. Introduction

A ball and beam system is mainly consists of a chrome beam and a steel ball and the actuator is a DC motor. Its main control objective is to control the position of a steel ball on a beam by a voltage control through a DC motor and it has been one of popular benchmark systems in control literature, and many related control results have been reported[1, 2, 3, 4].

Here, we address a few related results. In [1], they control a ball and beam system with a switching controller using partial state feedback. In [2], they use the flatness property of the system for a state feedback linear quadratic regulator. Also, with Kalman filter, state estimation is carried out. In [3], they present a state-disturbance observer-based adaptive fuzzy sliding mode control to control a ball and beam system. In [4], they provide a position control of the ball in the ball and beam system by adopting an active disturbance rejection control. It is noted that all aforementioned results are commonly time-triggered control methods, whether they are either continuous time or discrete time control methods.

On the other hand, as it can be seen in many recently published control papers, the event-triggered control method is one of popular control methods in these days. The main advantage of the event-triggered control is the less frequent updates of control input, which leads to some saves of communication/network resources [5].

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Some of recent event-triggered control results are stated as follows. In [6], they propose an adaptive event-triggered controller for uncertain nonlinear systems without the ISS assumption. In [7], they propose a high-gain type event-triggered controller for robust control of nonlinear systems. In [8], they propose an event-triggered controller coupled with parameter estimator. In [9], they propose an adaptive backstepping control method with event-sampled state and input vectors. In [10], they proposes a composed of the fixed-time disturbance observer and event-triggered based fixed-time controller. Note that all these previous results do not clearly address the relation between control performance such as the speed of the system state convergence and number of control input updates, I.e., number of triggers or the size of lower bounds of interexecution times.

In this paper, we aim to tackle a position control problem for a ball and beam system by event-triggered control. We propose a new event-triggered controller with two scaling factors, that is, α and ϵ factors.

These factors are incorporated into our proposed controller as parts of triggering condition and controller gain. First, we provide a system analysis to show the system stability and positive lower bounds of interexecution times. Then, we express the system output speed to a reference point and the positive lower bounds of interexecution times as functions of α and ϵ. Moreover, hinted by [1, 11], we show that there is a somewhat trade-off relation between system output speed to a reference point and the positive lower bounds of interexecution times by merging two functions of α and ϵ into a single map, and we call it $\alpha\epsilon$-mapping. Finally, the developed $\alpha\epsilon$-mapping is utilized to generate a balanced control input in terms of the output convergence speed and the interexecution times. To our best knowledge, our control problem has not been addressed in the existing results yet. The novelties of our method are summarized as follows: (i) We propose a new type of an event-triggered controller with two scaling factors; (ii) We develop a $\alpha\epsilon$-mapping based on the system stability and inter-execution times analyses; (iii) We propose a new control parameter selection algorithm based on the developed $\alpha\epsilon$-mapping to generate a balanced control input which improves both output regulation speed and interexecution times together. (iv) We perform an experiment which agrees with our analysis and design principle.

II. Ball and beam system and problem formulation

Our considered ball and beam system by Quanser is shown in Fig. 1.

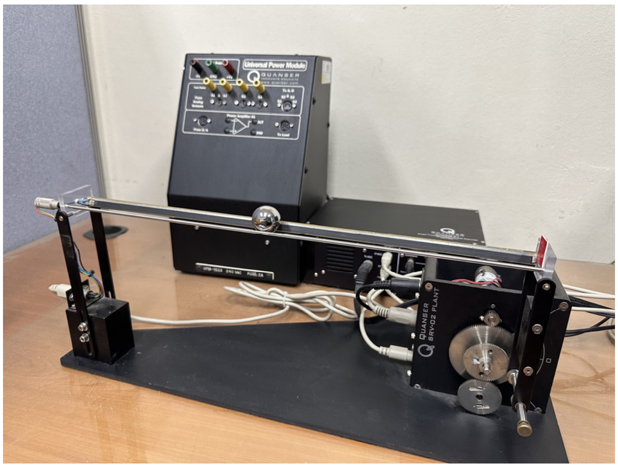


Fig. 1. Ball and beam system.

The state equation of the ball and beam system can be expressed as follows [2]

$$\begin{aligned} \dot{x}_1 &= x_2 \\ \dot{x}_2 &= K_{bb}\sin x_3 \\ \dot{x}_3 &= x_4 \\ \dot{x}_4 &= -\frac{1}{\tau}x_4 + \frac{\kappa}{\tau}u \\ y &= x_1 \end{aligned} \tag{1}$$

where x_1 is the ball position, x_2 is the velocity of the ball, x_3 is the angle of the beam, x_4 is the angular velocity of the beam, $K_{bb}(=41.8\,cm/rad \cdot s^2)$ is system model gain value, $\tau(=0.0211s)$ is time constant, and $\kappa(=1.53rad/V\cdot s)$ is state gain.

The system (1) can be rewritten as follows after Jacobian linearization is applied.

$$\dot{x}_2 = K_{bb}x_3 \tag{2}$$

Letting $u=\frac{\tau}{\kappa}v$, the system (2) is transformed into

$$\begin{aligned}\dot{x} &= \begin{bmatrix}0&1&0&0\\0&0&K_{bb}&0\\0&0&0&1\\0&0&0&0\end{bmatrix}x+\begin{bmatrix}0\\0\\0\\1\end{bmatrix}v+\begin{bmatrix}0\\0\\0\\-\frac{1}{\tau}x_4\end{bmatrix}\\ &= Ax+Bv+\delta(x)\\ y &= [1\,0\,0\,0]x = Cx\end{aligned} \tag{3}$$

Our main control goal is to develop an event-triggered controller for our considered ball and beam system. In achieving our goal, we propose an event-triggered controller containing two scaling factors - α and ϵ. Then, we necessarily provide a system analysis which results in the development of $\alpha\epsilon$-mapping, which in turn, is utilized in the completion of our switching event-triggered controller. Experimental results are followed, which agrees with our systematic analysis and design principle.

Ⅲ. Event-triggered controller with scaling factors and system analysis

3.1 Mathematical notations

Some notations to be used are listed as follows.

- $|x|$ denotes the Euclidean norm and I is an $n\times n$ identity matrix.
- $O(\epsilon)$ denotes that its magnitude is less than $\eta\epsilon$ for some positive constant η that is independent of ϵ [12].'
- $K(\epsilon)=[k_1/\epsilon^4,\cdots,k_4/\epsilon]$, $K=K(1)=[k_1,\cdots,k_4]$, $A_{K(\epsilon)}=A+BK(\epsilon)$, $A_K=A+BK$, and $E_\epsilon = diag[1,\epsilon,\epsilon^2,\epsilon^3]$.

3.2 Proposed controller and system stability analysis

In this section, we propose an $\alpha\epsilon$ event-triggered state feedback controller

$$v=K(\epsilon)x(t_k)+x_4(t_k)/\tau, \quad \forall t\in[t_k,t_{k+1}) \tag{4}$$

where $t_0=0$ with an event-triggering condition of

$$t_{k+1}=\inf\{t>t_k:||E_\epsilon e(t)||>\alpha||E_\epsilon x(t)||\} \tag{5}$$

where $\epsilon>0$ and $0<\alpha<1$ are to be selected and $e(t)=x(t_k)-x(t)$.

From (3), (4), and (5), we obtain the closed-loop system as

$$\begin{aligned}\dot{x} &= Ax+BKx(t_k)+Bx_4(t_k)/\tau+\delta(x)\\ &= \begin{bmatrix}0&1&0&0\\0&0&K_{bb}&0\\0&0&0&1\\\frac{k_1}{\epsilon^4}&\frac{k_2}{\epsilon^3}&\frac{k_3}{\epsilon^2}&\frac{k_4}{\epsilon^1}\end{bmatrix}x+BK(\epsilon)(x(t_k)-x(t))+\begin{bmatrix}0\\0\\0\\\frac{1}{\tau}(x_4(t_k)-x_4(t))\end{bmatrix}\\ &= A_{K(\epsilon)}x+BK(\epsilon)e+\overline{\delta}(x)\end{aligned} \tag{6}$$

In order to develop a proposed controller, we first let K be such that A_K is Hurwitz [13]. Since A_K is Hurwitz, there exists a Lyapunov equation as follows.

$$A_K^TP+PA_K=-I \tag{7}$$

where $P=P^T>0$.

Here, we note the relation between A_K and $A_{K(\epsilon)}$ as

$$E_\epsilon^{-1}A_KE_\epsilon=\epsilon A_{K(\epsilon)} \tag{8}$$

Then, we obtain a new Lyapunov equation by substituting (8) into (7) as

$$A_{K(\epsilon)}^TP_\epsilon+P_\epsilon A_{K(\epsilon)}=-\epsilon^{-1}E_\epsilon^2 \tag{9}$$

where $E_\epsilon PE_\epsilon=P_\epsilon$ and $P_\epsilon=P_\epsilon^{T>0}$.

Now, we set a Lyapunov function as $V(x)=x^TPx$. Then, along the trajectory of (6), using (7), we have, for $t\in[t_k,t_{k+1})$,

$$\dot{V}(x) = \dot{x}^T P x + x^T P \dot{x}$$
$$= x^T (A_{K(\epsilon)}^T P_\epsilon + P_\epsilon A_K(\epsilon))x + 2x^T P_\epsilon BK(\epsilon)e + 2x^T P_\epsilon \bar{\delta}(x) \quad (10)$$

Noting that $E_\epsilon BK(\epsilon)E_\epsilon^{-1} = \epsilon^{-1}BK$, we rewrite (10) as

$$\dot{V}(x) = x^T(-\epsilon^{-1}E_\epsilon^2)x + 2\epsilon^{-1}x^T E_\epsilon PBKE_\epsilon e + 2x^T E_\epsilon PE_\epsilon \bar{\delta}(x)$$
$$\leq -\epsilon^{-1}\| E_\epsilon x \|^2 + 2\epsilon^{-1}\| E_\epsilon x \| \| PBK \| \| E_\epsilon e \| + 2\| E_\epsilon x \| \| P \| \| E_\epsilon \bar{\delta}(x) \| \quad (11)$$

Under the event-triggering condition (5), the norm bounds of $\| E_\epsilon e \|$ and $\| E_\epsilon \bar{\delta}(x) \|$ from (11) are derived as

$$\| E_\epsilon e(t) \| \leq \alpha \| E_\epsilon x \| \quad (12)$$

$$\| E_\epsilon \bar{\delta}(x) \| = \sqrt{\left(\frac{\epsilon^3}{\tau}(x_4(t_k) - x_4(t))\right)^2}$$
$$\leq \frac{1}{\tau}\| E_\epsilon e \| \leq \frac{\alpha}{\tau}\| E_\epsilon x \| \quad (13)$$

Substituting (12) and (13) into (11), we have

$$\dot{V}(x) \leq -\epsilon^{-1}\| E_\epsilon x \|^2 + 2\epsilon^{-1}\alpha \| PBK \| \| E_\epsilon x \|^2 + \frac{2}{\tau}\alpha \| P \| \| E_\epsilon x \|^2$$
$$= -\epsilon^{-1}\left(1 - 2\alpha \| PBK \| - \frac{2}{\tau}\epsilon\alpha \| P \|\right) \| E_\epsilon x \|^2 \quad (14)$$

For $\dot{V}(x)$ to be negative definite, we select α and ϵ such that

$$1 - 2\alpha \| PBK \| - \frac{2}{\tau}\epsilon\alpha \| P \| =: \Delta(\epsilon,\alpha) > 0 \quad (15)$$

Thus, from (15), the stability of a ball and beam system is achieved by the proposed event-triggered controller.

3.2 Positive lower bounds for interexecution times

The next is to show that interexecution times $T_k := t_{k+1} - t_k$ have positive lower bounds to avoid the Zeno behavior [5]. We begin with a fact that $\| E_\epsilon e(t_k) \| = 0$. Suppose that $\| E_\epsilon e(t) \|$ stays at 0 after $t = t_k$. Then, by the triggering condition of (5), the next triggering does not occur, that is, $T_k = \infty$ [14]. Also, note that if $\| E_\epsilon x(t_k) \| = 0$, this means that all states are exactly at the equilibrium point at $t = t_k$, which simply means that all states remain at the origin and there is no triggering afterward. So, we only need to consider a case of $\| E_\epsilon e(t) \| > 0$ for $t \in [t_k, t_{k+1})$ and $\| E_\epsilon x(t_k) \| > 0$.

Using (5) and (13), we can derive,

$$\frac{d}{dt}\| E_\epsilon e(t) \|$$
$$\leq \left(\epsilon^{-1}\| A_K \| + \epsilon^{-1}\alpha\gamma(\epsilon) \| BK \| + \gamma(\epsilon)\right) \| E_\epsilon x(t) \|$$
$$\leq \left(\epsilon^{-1}\| A_K \| + \epsilon^{-1}\alpha\gamma(\epsilon) \| BK \| + \gamma(\epsilon)\right)\sqrt{\frac{M}{m}} \times \| E_\epsilon x(t_k) \| e^{-\frac{\epsilon^{-1}\Delta(\epsilon,\alpha)}{2M}(t-t_k)}$$
$$\leq \left(\epsilon^{-1}\| A_K \| + \epsilon^{-1}\alpha\gamma(\epsilon) \| BK \| + \gamma(\epsilon)\right) \times \sqrt{\frac{M}{m}} \| E_\epsilon x(t_k) \| \quad (16)$$

Since $\| E_\epsilon e(t_k) \| = 0$, by integrating (16), we have

$$\| E_\epsilon e(t) \| \leq \left(\epsilon^{-1}\| A_K \| + \epsilon^{-1}\alpha\gamma(\epsilon) \| BK \| + \gamma(\epsilon)\right)\backslash \times \sqrt{\frac{M}{m}} \| E_\epsilon x(t_k) \| (t - t_k) \quad (17)$$

We let the time instance t_{k+1}^- be a moment just before the next execution instance t_{k+1}. So, the following relation holds.

$$\| E_\epsilon e(t_{k+1}^-) \| = \alpha \| E_\epsilon x(t_{k+1}^-) \| \quad (18)$$

Then, at $t = t^{-\ k+1}$, using (17) and (18), we have

$$\| E_\epsilon x(t^{-\ k+1}) \| = \frac{1}{\alpha}\| E_\epsilon e(t^{-\ k+1}) \|$$
$$\leq \frac{1}{\alpha}\left(\epsilon^{-1}\| A_K \| + \epsilon^{-1}\alpha\gamma(\epsilon) \| BK \| + \gamma(\epsilon)\right) \times \sqrt{\frac{M}{m}} \| E_\epsilon x(t_k) \| (t - t_k) \quad (19)$$

which yields that

$$\mu(\epsilon,\alpha)\frac{\| E_\epsilon x(t_{k+1}^-) \|}{\| E_\epsilon x(t_k) \|} \leq t_{k+1}^- - t_k < T_k \quad (20)$$

where

$$\mu(\epsilon,\alpha) = \frac{\alpha}{\left(\epsilon^{-1}\|A_K\| + \epsilon^{-1}\alpha\gamma(\epsilon)\|BK\| + \gamma(\epsilon)\right)\sqrt{\frac{M}{m}}} \tag{21}$$

Now, at $t=t_{k+1}^{-}$, we have $\|E_\epsilon x(t_k)-E_\epsilon x(t_{k+1}^{-1})\| = \sigma\|E_\epsilon x(t_{k+1}^{-1})\|$. Using $|\|E_\epsilon x(t_k)\|-\|E_\epsilon x(t_{k+1}^{-1})\|| \le \|E_\epsilon x(t_k)-E_\epsilon x(t_{k+1}^{-1})\|$, we have $\|E_\epsilon x(t_k)\| \le (\sigma+1)\|E_\epsilon x(t_{k+1}^{-1})\|$. Inserting this inequality into (20), we finally obtain

$$\frac{\mu(\epsilon,\alpha)}{\sigma+1} \le t_{k+1}^{-}-t_k < T_k \tag{22}$$

Thus, there exists positive lower bounds which are independent of the time-interval and there is no Zeno behavior [14].

Ⅳ. $\alpha\epsilon$-mapping method and switching controller

In this section, we propose the $\alpha\epsilon$-mapping method and design a switching controller which provides a balanced performance between the output convergence speed and interexecution times.

From (15), we have an inequality as follows for $t\in[t_k,t_{k+1})$ [14],

$$y = x_1 \le \|E_\epsilon x\| \le \sqrt{\frac{M}{m}}\|E_\epsilon x(t_k)\| e^{-\frac{\epsilon^{-1}\Delta(\epsilon,\alpha)}{2\lambda_{\max}(P)}(t-t_k)} \tag{23}$$

From (20) and (23), we can observe the following key points:

(i) If the value of $\mu(\epsilon,\alpha)$ increases, the interexecution times increase as observed from (20), and vice versa.

(ii) If the value of $\epsilon^{-1}\Delta(\epsilon,\alpha)$ increases, the convergence speed of ball position increases as observed from (23), and vice versa.

4.1 $\alpha\epsilon$-mapping method

Fig. 2 shows two mappings regarding $\epsilon^{-1}\Delta(\epsilon,\alpha)$ and $\mu(\epsilon,\alpha)$ where I.P. denotes the initial position of the selected values of α and ϵ. Then, we can increase the convergence speed of ball position when we change the point from I.P. to Point 1(Pt. 1). Also, we can increase the lower bounds of interexecution times when we change the point from I.P. to Point 2(Pt. 2).

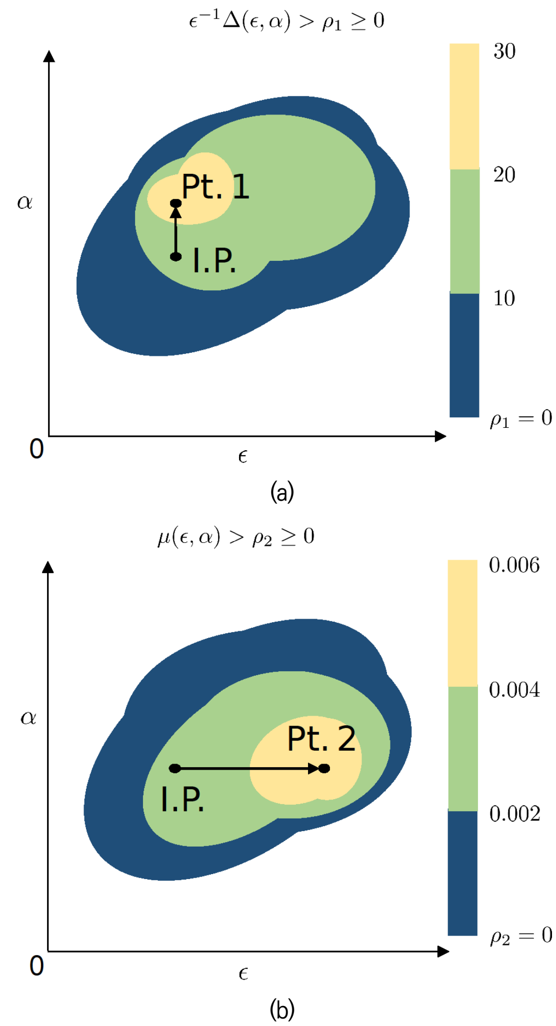


Fig. 2. $\alpha\epsilon$ mapping (a) : Pt. 1 for increaseing the convergence speed of ball position. (b) : Pt. 2 for increasing the interexecution times

The following Table 1 summarizes a trade-off relation between the output convergence speed and the size of interexecution times in general.

Table 1. $\alpha\epsilon$ mapping.

	Pt. 1	Pt. 2
Convergence speed of output	Relatively faster	Relatively slower
Interexecution times	Relatively smaller	Relatively larger

4.2 Switching algorithm

As observed previously, we may not be able to increase both output convergence speed and interexecution times at the same time by choosing a single set value of α and ϵ. So, in order to increase both, we suggest a switching algorithm as shown in Fig. 3.

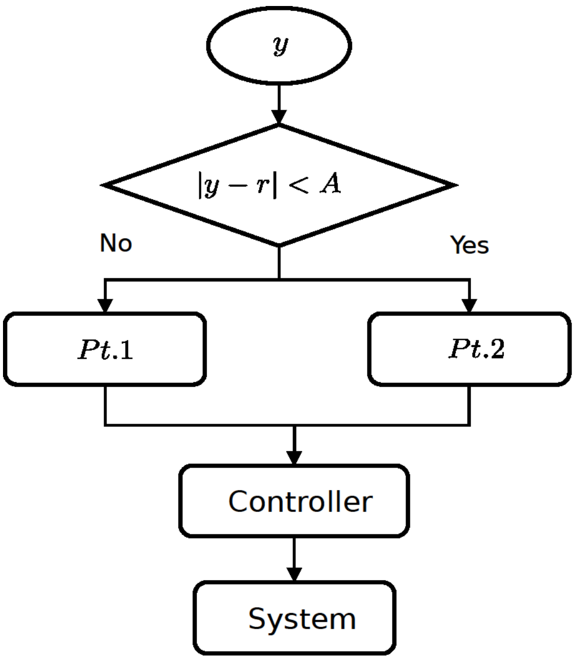


Fig. 3. Proposed switching algorithm

The basic idea of the proposed algorithm is that during the initial transient time period, we select Pt. 1 so that the output approaches the reference input relatively quickly. Then, once the output approaches the nearby value of the reference input, we switch the values of α, ϵ to Pt. 2 so that the output still converges to the reference input with relatively increased interexecution times. In this way, we can obtain the balanced control performance to improve both output convergence speed and interexecution times. Here, we suggest that the value of A is about , 10% of value of $|y(0)-r|$.

V. Experimental result

We carry out the actual experiment of a ball and beam system for the verification of our proposed control method. The control parameter K, is selected as $K=[-1,-3,-3,-1]$. With equation (20) and (23), we show the mappings of $\epsilon^{-1}\Delta(\epsilon,\alpha)$ and $\mu(\epsilon,\alpha)$ in Fig. 4.

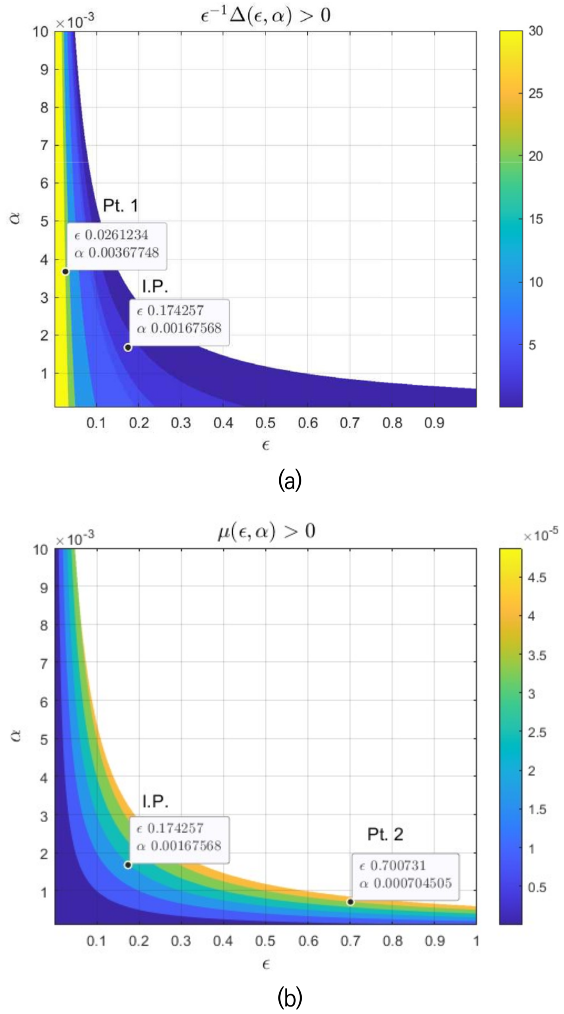
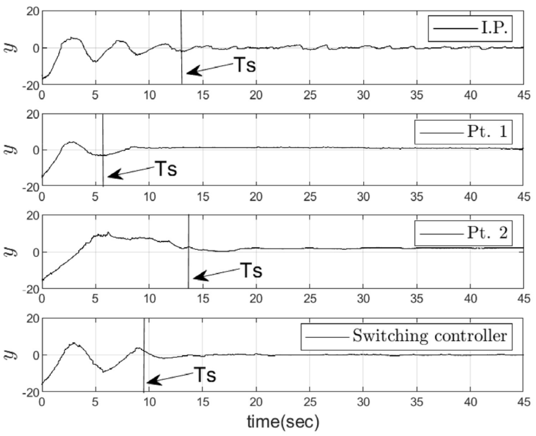
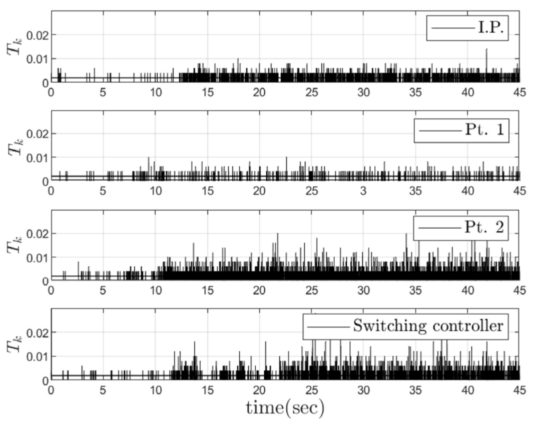


Fig. 4. $\alpha\epsilon$ mapping (a) : Pt. 1 (b) : Pt. 2

The initial condition is set as $y(0)=-15$[cm] and $r=0$[cm]. As explained before, Pt. 1($\epsilon=0.2$, $\alpha=0.0009$) is for the relatively faster output convergence speed to I.P. and Pt. 2($\epsilon=0.07$, $\alpha=0.0007$) is for the relatively larger interexecution times to I.P. As proposed, our switching controller is employed by switching between Pt. 1 and Pt. 2 with $A=1.5$. In Fig. 5, we show the four control results for comparison where T_s denotes the settling time. We can see that Pt. 1 yields the increased output convergence speed at the cost of reduced interexecution times over I.P., Pt. 2 yields the increased interexecution times at the cost of slowed output convergence speed over I.P., and finally our switching controller provides both increased performances over I.P. at the same time. The numerical results regarding the settling time and interecexecution times for cases are summarized in Table 2. Thus, the experimental results validate our control method.



(a)



(b)

Fig. 5. (a) : Trajectory of ball position.
(b) : Interexecution times

Table 2. Settling time and number of triggering.

	I.P.	Pt. 1	Pt. 2	Switching
Settling time(sec)	13.74	5.33	14.08	9.68
Number of triggering	23466	24522	21065	22758

Ⅵ. Conclusions

We have proposed a new switching event-triggered controller for the control of a ball and beam system. We have developed an $\alpha\epsilon$-mapping method based on the system analysis, then have suggested a switching algorithm by utilizing the $\alpha\epsilon$-mapping method. As a result, our proposed controller can yield a balanced performance between the output convergence speed and interexecution times. Via experiment, we have shown the validity of our proposed control method.

Ⅶ. Acknowledgement

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〈A field of interest〉
Feedback Linearization Techniques for Nonlinear Systems, Time delay system, Time optimal control etc.