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Robust Dynamic Event-triggered Control for Linear Uncertain System

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Abstract: Event-triggered control has a greater significance in networked control system (NCS) as it minimizes communication cost. The present paper introduces a novel event-based robust control framework for linear uncertain system. The robust control law is designed by solving an optimal control problem and realized thorough a dynamic event-triggering mechanism to reduce the communication traffic. A dynamic variable is used to generate the event-triggering law using Input-to-State Stability (ISS) criteria . Proposed control strategies ensure stability in the presence of bounded system uncertainties. Derivation of dynamic event-triggering rule with a non-zero positive inter-event time and corresponding stability criteria for uncertain system are the key contributions of this paper. The validation of proposed algorithm is carried out through a numerical simulation.

Keywords: Event-triggered control, robust control, dynamic event-triggered control, aperiodic control, input to state stability.

1. INTRODUCTION

Aperiodic sensing, communication and computation play a crucial role for controlling resource constrained Cyber-Physical Systems. It is shown in [Astrom et al. (2002); Heemels et al. (2012); Tabuada (2007); Marchand (2013)] that aperiodic sampling has more benefits over periodic sampling, which motivates control researchers towards event-triggered control. In event-triggered control, sensing, communication and computation happens only when any predefined event condition is violated. This control strategy finds application in different control problems like tracking [Tallapragada (2013)], estimation [Tallapragada (2012); Trimpe et al. (2012)] etc. Event-triggered system is modeled as a perturbed system in continuous and discrete time domain respectively [Tabuada (2007); Eqtami et al. (2010)]. Also the behaviour of such system is described by an impulsive dynamics in literature [Donkers et al. (2012); Sahoo et al. (2013)]. To achieve larger average inter-event time, [Girard (2015)] proposes a dynamic event-generating rule over the static approach [Tabuada (2007)]. The input to state stability (ISS) property [Sontag (2008); Nesic et al. (2004)] is exploited to prove the closed loop stability and to define triggering condition for event-triggered system. Sahoo et al. [Sahoo et al. (2013)] proposed an event based adaptive control approach for uncertain systems. A neural network is used to estimate the nonlinear function to generate the control law. In event based robust control problems, the uncertainty is mainly considered in the communication channel in the form of time-delay or data-packet loss [Garcia et al. (2013)]. The main shortcoming of the classical event-triggered system lies in the fact that one must know the exact model of the plant apriori. A plant with an uncertain (system) model is a more realistic scenario and has far greater significance. However, there are open problems of designing a control law and triggering conditions to deal with system uncertainties. These uncertainties mainly arise due to system parameter variations, unmodeled dynamics, disturbances etc. and necessitates the design of robust controller. To deal with uncertainties, an optimal control approach to robust controller design for the uncertain system has been reported in [Lin et al. (2000, 1998); Adhyaru et al. (2009)] and find applications in tracking problem of robot manipulator [Lin et al. (1998); Tripathy et al. (2014)], set-point regulation in CSTR system etc. To achieve an optimal solution to the robust control problem there is a need to minimize a cost functional. In this direction, a non-quadratic cost functional is utilized to solve robust control problem with input constraint [Adhyaru et al. (2009)]. In the above mentioned approach, event-trigger based implementation of robust control law is not considered which is essential in the context of NCS.

This paper considers a robust control strategy of linear uncertain system with limited state and input information. The limited state information is considered to address the channel unreliability or bandwidth constraint which is a very common phenomena in NCS. To capture the channel uncertainty, event-triggered control strategy is adopted in [Xia et al. (2013)] without considering system uncertainty explicitly. The primary motivation for this work is that with limited information, existing robust control results in [Lin et al. (2000, 1998); Kar (2002)] can not be simply extended to the event-triggered system. This paper proposes a novel event based robust control strategy for matched uncertain systems where it is assumed that the

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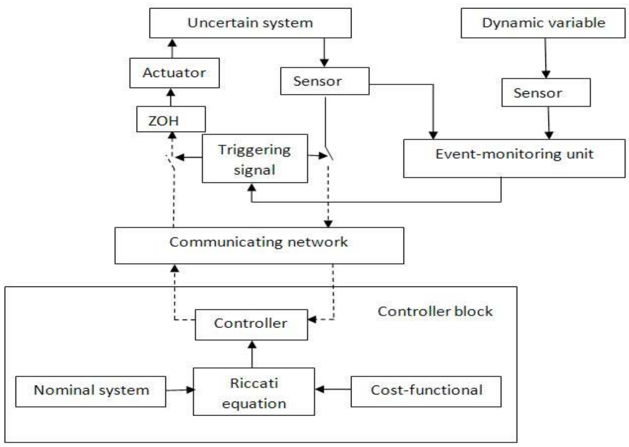


Fig. 1. Conceptual Block diagram of proposed event-trigger based robust control. Dotted line represents the aperiodic information transmission through the communication channel.

unknown uncertainty is in the range space of control input matrix. A conceptual block diagram of the proposed event-trigger based robust control framework is illustrated in Figure 1. Here the system, sensor and actuator are co-located but the controller is connected thorough a communication network. A dedicated computing unit monitors the event condition at the sensor end. The control input is computed and updated only when an event is generated. A zero-order-hold (ZOH) at the actuation end holds the last transmitted control input until the transmission of next input. The aperiodic state transmission to controller and control input update instant $\{t_k\}_{k\in I}$ over the network is decided by the same event-triggering law. For simplification, it is assumed that there is no communication, computation and actuation delay in the system. To design robust control law, an equivalent optimal control problem is formulated with an appropriate cost functional which takes care of the upper bound of system uncertainty. The nominal system dynamics is used to compute the optimal controller gain which minimizes the cost-functional. The analysis of this system is done in continuous time domain. The proposed method is also extended to design dynamic event-triggering rule in order to increase inter-event time. The corresponding triggering rule and their stability criteria for matched uncertain system have been derived. The advantage of the proposed control strategy is that it significantly reduces the number of control input transmission and computation in spite of system uncertainties.

Summary of contribution: The main contributions of this paper are summarized as follows.

- Defining an optimal control problem to design a robust control law for matched uncertain system.
- Deriving a dynamic event-triggering rule for uncertain system using the upper bound of system uncertainty.
- Ensuring stability of closed loop system using ISS Lyapunov function.
- Deriving a positive non-zero lower bound of inter-execution time. Results are verified through simulation studies.

Organization of paper The paper is organized as follows. In Section 2, we briefly review an optimal approach to robust control design for uncertain system. Section 3 discuss the optimal control approach to solve the robust stabilization problem for event-triggered system with system uncertainty. A dynamic event triggering conditions is stated in the form of theorems and their corresponding proofs are reported. Also the expressions of the minimum positive inter-event time is defined in Section 3. An academic example with simulation results is discussed in Section 4 to validate the proposed control algorithm. Section 5 concludes the paper.

Notation The notation $\|x\|$ is used to denote the Euclidean norm of a vector $x \in \mathbb{R}^n$. Here $\mathbb{R}^n$ denotes the n dimensional Euclidean real space and $\mathbb{R}^{n\times m}$ is a set of all $(n \times m)$ real matrices. $\mathbb{R}_0^+$ and $\mathbb{I}$ denote the all possible set of positive real numbers and non-negative integers. $X \leq 0$, X^T and X^{-1} represent the negative definiteness, transpose and inverse of matrix X, respectively. Symbol I represents an identity matrix with appropriate dimensions and time t_∞ implies $+\infty$. Symbols $\lambda_{min}(P)$ and $\lambda_{max}(P)$ denote the minimum and maximum eigenvalue of symmetric matrix $P \in \mathbb{R}^{n\times n}$ respectively. A function f: $\mathbb{R}_{\geq 0} \to \mathbb{R}_{\geq 0}$ is K_∞ if it is continuous and strictly increasing and it satisfies $f(0) = 0$ and $f(s) \to \infty$ as $s \to \infty$.

2. PRELIMINARIES & PROBLEM STATEMENT

2.1 Preliminaries

Input to state stability In state space form, a linear system with external disturbance $d(t) \in \mathbb{R}^n$ is expressed as

$$\dot{x}(t) = Ax(t) + Bu(t) + d(t) \tag{1}$$

where $x(t) \in R^n$, $u(t) \in R^m$ are system's state and control input respectively. For simplification from now onwards, $x(t)$ and $u(t)$ are denoted by x and u respectively. Disturbance $d(t)$ is assumed to be bounded by a known function $d_m(t)$ i.e. $\|d(t)\| \leqslant d_m(t)$. The above system (1) is said to be ISS with respect to $d(t)$ if there exist an ISS Lyapunov function. To analyze the ISS of system (1) with respect to $d(t)$, following definition is introduced [Sontag (2008); Nesic et al. (2004)].

Definition 1. A continuous function $V(x) : \mathbb{R}^n \to \mathbb{R}$ is an ISS Lyapunov function for system (1) if there exist class k_∞ functions $\alpha_1, \alpha_2, \alpha_3$ and γ for all $x, d \in \mathbb{R}^n$ and it satisfy

$$\alpha_1(\|x(t)\|) \leq V(x(t)) \leq \alpha_2(\|x(t)\|) \tag{2}$$

$$\nabla V(x)\dot{x} \leq -\alpha_3(\|x(t)\|) + \gamma(\|d(t)\|) \tag{3}$$

System with matched uncertainty: A linear system having system-uncertainty is described as

$$\dot{x} = A(p)x + Bu \tag{4}$$

where $p \in P$ is an uncertain parameter vector. In general system uncertainty is classified in two categories namely matched and mismatched uncertainty [Lin et al. (2000); Kar (2002)]. The system (4) has matched uncertainty if there exists a bounded uncertain matrix $\phi(p) \in \mathbb{R}^{m\times n}$ such that

$$A(p) - A(p_0) = B\phi(p) \tag{5}$$

for any $p \in P$, where p_0 is known nominal parameters and $A(p_0)$ is nominal system matrix. In other words system uncertainty is assumed to be in the range space of input matrix B. The condition (5) is made to simplify the derivation of stability results. It is assumed that there exits a positive semi-definite matrix F to represent the upper bound of the uncertainty i.e.,

$$\phi(p)^T\phi(p) \leq F \tag{6}$$

for all $p \in P$. This assumption dose not hold in case of the mismatched system.

Robust control problem: Find a state feedback control law $u = Kx$ such that the uncertain system (4) is stable in the presence of matched uncertainty (5) for any $p \in P$. To solve the above mentioned robust control problem, this paper has adopted an optimal control approach. The essential idea is to compute the optimal control input for the nominal system which minimizes the modified cost functional. The cost functional is called modified cost functional as it depends on the upper bound of system uncertainty. The obtained optimal control input for nominal system is shown to be a robust control input for the actual uncertain system. For matched system (4) the corresponding nominal dynamics and cost functional are considered as follows:

$$\dot{x} = A(p_0)x + Bu \tag{7}$$

$$J = \int_0^\infty (x^TFx + x^TQx + u^TRu)dt \tag{8}$$

with $Q \geq 0$ and $R > 0$. The matrix $F \geq 0$ is the upper bound of matched uncertainty (6). The state feedback control input $u = Kx$ is used to stabilize (7). Now to design a robust control law using optimal control approach, following lemma is introduced [Lin et al. (2000, 1998)].

Lemma 1. Let there exists an optimal control solution for nominal system (7) with a modified cost functional (8). Then the optimal control law for the nominal system will be the robust control solution of the original system (4) for all bounded system uncertainty (5), (6).

Proof : A detailed explanation is given in [Lin et al. (2000)]. □

2.2 Problem description and statement

The focus of this paper is to realize the robust control problem through an aperiodic state feedback control law. This formulation helps to realize such controller in the network control domain with limited state information. The aperiodic control input computation and actuation instant is determined through a predefined state-dependent event condition. This event condition is derived from ISS stability criteria. Suppose $\{t_k\}$ represents (aperiodic state transmission, control input computation and actuation instant) the event occurring instant. The event-based state feedback control input will be

$$u(t_k) = Kx(t_k), \tag{9}$$

which replaces the continuous time state feedback control law $u(t) = Kx(t)$. To solve the robust control problem through a aperiodic control law (9) the uncertain system (4) is rewritten as

$$\dot{x} = A(p)x(t) + Bu(t_k) \tag{10}$$

Adopting the concepts introduced in [Tabuada (2007)], the event-based closed loop system (10) reduces to

$$\dot{x} = A(p)x + BK(x + e) \tag{11}$$

The variable $e \in R^n$ is referred as measurement error and defined as

$$e(t) = x(t_k) - x(t), \forall t \in [t_k, t_{k+1}), k \in \mathbb{I} \tag{12}$$

Using (11) and (5) the event-triggered system with matched uncertainty is described as

$$\dot{x} = A(p_0)x + Bu + B(\phi(p)x + Ke) \tag{13}$$

Problem statement: Design of the controller gain K to stabilize an uncertain event-triggered system (13) such that the entire closed loop system is ISS with respect to its measurement error e.

We solve this problem in two steps. Firstly, we design a controller using Lemma 1 and then define an event-triggering rule such that the closed loop system (13) is ISS. These two steps are briefly discussed in next two subsections.

Controller design: The system (7) is the nominal dynamics of (13). Using Lemma 1, the optimal controller gain K of (7) which minimizes the cost functional (8) will be the robust solution of (13). For system (7), control input $u(t)$ is designed by minimizing J. Let $V(x)$ be a Lyapunov function for (13). Using optimal control results $V(x)$ should satisfy Hamilton Jacobi Bellman (HJB) equation [Naidu et al. (2009); Lin et al. (2000)]

$$min_{u \in R^m}(x^TFx + x^TQx + u^TRu$$
$$+ V_x^T(A(p_0)x + Bu) = 0 \tag{14}$$

where $V_x = \frac{\partial V}{\partial x}$ and $u = Kx$. Applying optimal u, the equation (14) reduces to

$$(x^TFx + x^TQx + u^TRu$$
$$+ V_x^T(A(p_0)x + Bu) = 0 \tag{15}$$

According to optimal control theory, the optimal input $u(t)$ should minimize the Hamiltonian [Naidu et al. (2009)]

$$H(x(t), u(t), V_x) = x^TFx + x^TQx + u^TRu$$
$$+ V_x^T(A(p_0)x + Bu) \tag{16}$$

which leads to

$$\frac{\partial H(x(t), u(t), V_x, t)}{\partial u(t)} = 2x^TK^TR + V_x^TB = 0 \tag{17}$$

For solving an infinite-time linear quadratic regulator (LQR) problem, a quadratic function $V(x) = x^TSx$ is defined, where matrix $S > 0$. With this choice, (14) reduces to the following algebraic Riccati equation (ARE)

$$SA(p_0) + A(p_0)^TS + F + Q - SBR^{-1}B^TS = 0 \tag{18}$$

Using the solution S of (18), the optimal control input u is computed as

$$u(t) = -R^{-1}B^TSx(t) = Kx(t) \tag{19}$$

Control gain K for (7) and aperiodic state information of original system $x(t_k)$ are used to realize the control law

$$u(t_k) = Kx(t_k) \tag{20}$$

The robust event-triggered control for (10) is written as

$$u(t_k) = Kx(t_k) \tag{21}$$

Now to realize (21), it is important to design the event triggering instant such that uncertain system (10) is ISS with a aperiodic control law (9). The approach for deriving the triggering law is discussed below.

Triggering condition design: Given an uncertain system (10) with a linear controller (9) there must have an event-triggering instant $t_{k\in\mathbb{I}}$ with a positive inter-execution time $(t_{k+1} - t_k = \tau > 0)$ such that the closed loop system (10) is ISS. To prove this there must have an ISS Lyapunov function with the time derivative in the form of (3). The ISS condition in the form of (3) helps to construct the event-triggering rule in-terms of measurement error norm $\|e(t)\|$ and the state norm $\|x(t)\|$. To design the event-triggering law for (13), the ISS Lyapunov functions are considered as follows:

$$V(x) = x^T Sx \tag{22}$$

where S is the solution of (18).

3. DYNAMIC EVENT-TRIGGERED ROBUST CONTROL

In dynamic event-triggering mechanism, a variable $\eta(t) > 0$ is added to achieve larger inter-event time [Girard (2015)]. The time evolution of new dynamic variable $\eta(t)$ is expressed by the following general differential equation.

$$\dot{\eta}(t) = -\beta(\eta(t)) + \sigma\alpha(\|x(t)\|) - \gamma(\|e(t)\|) \tag{23}$$

Here β, α, γ are smooth class K_∞ functions and $\sigma \in (0, 1)$. The Lemma 1 of [Girard (2015)], ensures the positiveness of dynamic variable $\eta(t)$. In this section the dynamic event-triggering approach is adopted to solve the present robust control problem with limited state and input information. The dynamic event triggering instant generated for uncertain system is stated through the following theorem.

Theorem 1. Let the controller gain matrix K is designed for the nominal system (7) by minimizing the cost functional (8). The augmented matched system (13) and (23) with event-trigger based controller (20), is asymptotically stable if there exists a dynamic event occurring sequence $\{t_k\}_{k\in\mathbb{I}}$ given by

$$\begin{aligned} t_0 = 0,\ t_{k+1} = inf\{t \in \mathbb{R} | t > t_k \wedge \eta(t) \\ +\theta(\mu\|x\| - \|e\|) \le 0\} \end{aligned} \tag{24}$$

where μ is defined in (31) and the scalar θ is a design parameter.

Proof : As a special case of (23), the evolution of $\eta(t)$ with respect to time can be defined as

$$\dot{\eta}(t) = -\lambda\eta(t) + (\mu\|x\| - \|e\|) \tag{25}$$

Now select $W(x(t), \eta(t)) = V(x) + \eta(t)$ as a Lyapunov function for augmented systems (13), (25) where $V(x)$ is defined in (22).

$$\begin{aligned} \dot{V}(x) &= V_x^T \dot{x} \\ &= V_x^T (A(p_0)x + BKx + B\phi(p)x + BKe) \end{aligned} \tag{26}$$

Using (15) and substituting $V_x^T = 2x^T S$

$$\begin{aligned} \dot{V}(x) &= -x^T Fx - x^T Qx - u^T Ru \\ &\quad -2x^T K^T R\phi(p)x + 2x^T SBKe \\ &= -x^T((F - \phi(p)^T R\phi(p)) + Q \\ &\quad +(K + \phi(p))^T R(K + \phi(p)))x \\ &\quad +2x^T SBKe \end{aligned}$$

According to Definition 1, (3) holds if we select

$$\alpha(\|x\|) = \frac{\lambda_{min}(Q_1)}{2}\|x\|^2 \tag{27}$$

$$\gamma(\|e\|) = \frac{2\|SBKK^T B^T S\|}{\lambda_{min}(Q_1)}\|e\|^2 \tag{28}$$

In the above expressions,

$$\begin{aligned} Q_1 = (F - \phi(p)^T R\phi(p)) + Q \\ +(K + \phi(p))^T R(K + \phi(p)) \end{aligned} \tag{29}$$

From (3), (27) and (28), triggering law is derived as

$$\|e\| \le \mu\|x\| \tag{30}$$

where

$$\mu = \frac{\sigma^{1/2}\lambda_{min}(Q_1)}{2\|SBK\|} \tag{31}$$

Then using (26) and (25) the time derivative of $W(x)$ can be written as

$$\dot{W}(x) \le (\sigma - 1)\lambda_{min}(Q_1)\|x\|^2 - \lambda\eta(t) \tag{32}$$

Form (32), for any value of $\sigma \in (0, 1)$ and $\eta(t) > 0$ the closed loop system (13) is ISS by dynamic event-triggering rule (24). □

3.1 Selection of design parameters

The expression of inter-event time τ for dynamic event-triggered case is shown analytically in the nest subsection. The parameters θ, σ and λ are used in (24)-(32). These parameters mainly affect the lower bound of inter-event time and convergence rate of system state. This subsection introduces a possible selection guideline of such parameters. The convergence of closed loop system (13) is directly associated with σ as seen in (32). As $\sigma \to 0$ the convergence rate of (13) equivalent to the ideal closed loop system (4). The generated event number can also be controlled by varying the value of σ. similarly the parameter θ has contribution in the inter-event time τ. A possible selection procedure of parameter θ is carried out by deriving a lower bound on τ. The results are stated in form of a following lemma and its proof is reported in [Tripathy et al. (2016)].

Lemma 2. $\forall\ \sigma \in (0, 1)$, $\eta > 0$ and $\theta > 0$ the system (13), (25) with triggering law (24) has strictly positive lower bound of inter-event time $\tau > 0$ and it is expressed as

$$\tau = \int_0^\mu \frac{d\Gamma}{\frac{L_1}{\mu} + (L_2 + \lambda)\Gamma + (\frac{1}{\theta} + L_2\mu)\Gamma^2} \tag{33}$$

where $L_1 = \|(A(p_0) + B\phi(p) + BK)\|$, $L_2 = \|BK\|$ and $0 < \theta \le \frac{1}{L_1 - \lambda}$.

Remark 1. The existence of positive inter-event time (33) is guaranteed in the range of $0 < \theta \le \frac{1}{L_1 - \lambda}$ and it helps to select the parameter λ. The value of λ must satisfy $\lambda \leq L_1$ to make θ positive. Similarly, an analytical bound on τ can also be derived for $\theta > \frac{1}{L_1-\lambda}$. Note that the value of scalar L_1 depends on uncertainty $\phi(p)$. Hence, it is difficult to say the exact value of θ for which event-triggering law (24) have larger lower-bound τ. But it is possible to compute τ as the uncertain region is known apriori.

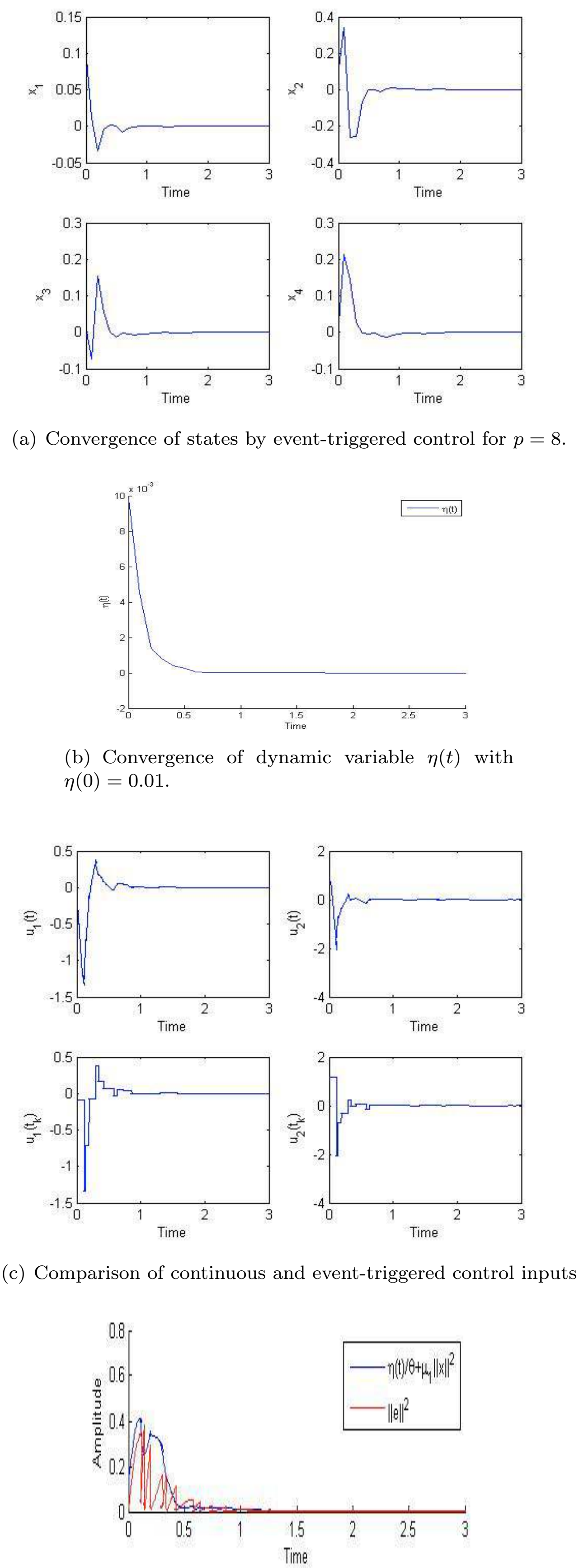
4. NUMERICAL RESULTS

In this section a benchmark example is used to validate the theoretical results. Here we consider a batch reactor as a coupled two input (u_1, u_2) and two output NCS with a matched uncertainty [D. Nesic et. al. (2004); G C Walsh et. al. (2014)] where $A = \begin{bmatrix} 1.38 & -0.20 & 6.71 & -5.67 \\ -0.58 & -4.29 & 0 & 0.675 \\ 1.06 & 4.27 & -6.65 & 5.89 \\ 0.04 & 4.27 & 1.34 & 2.10 \end{bmatrix}$, $B = \begin{bmatrix} 0 & 0 \\ 5.679 & 0 \\ 1.136 & -3.146 \\ 1.136 & 0 \end{bmatrix}$ and $\phi(p) = \begin{bmatrix} p & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix}$. The uncertain parameter p is assumed to vary from 0 to 10. To realize the event-triggered robust control law (21), the Riccati equation (18) is solved with the design parameters $Q = I, R = I, F = diag([100, 0, 0, 0])$. The parameters $\sigma = 0.6$, $\theta = 0.01$, $k = 0.48$ are selected to design the event-triggering law (21). The simulation is carried out for 3 seconds with the initial condition $[0.1, 0.1, 0.01, 0.01, 0.01]^T$. Figures 2(a) and 2(b) show the convergence of uncertain states $x(t)$ and the dynamic variable $\eta(t)$. It is observed that $\eta(t)$ is always remain positive for any non-zero positive initial condition but this condition may not hold for a zero initial condition. The evolution of control inputs, error norm $\|e\|^2$, state-dependent threshold with respect to time are shown through Figures 2(c) and 2(d) respectively. Figure 2(c) also compares the input variation in conventional continuous and event-triggered control. Through this figure it can be concluded that the variation of eventual inputs $u_1(t_k)$ and $u_2(t_k)$ is less. Also event has occurred only when $\|e\|^2$ exceeds the threshold $\eta(t) + \mu_1\|x\|^2$ which is shown in Figure 2(d).

5. CONCLUSION

This paper proposes a framework of event-triggered based robust control strategy for matched uncertain system. The proposed control law is valid for a wider class of linear systems in which event-triggering law is applicable. To design the event-triggering law, a dynamic event-triggering mechanisms is adopted. The stability of closed loop event-triggering system is proved to be ISS for bounded variation of parameters. The lower bound of inter-event time for dynamic event-triggered control under presence of uncertainty is also derived. It is observed that the total number of control input computation and information transmission are very less in an event-based mechanism over conventional time-triggered system. The detailed analysis of design parameters, like θ, σ and λ are addressed to evaluate their effects on system performance.

As a future work, the self-triggered approach [Anta et al. (2010); Santos et al. (2012)] can be considered to solve the robust control problem. The discrete-time version of



(a) Convergence of states by event-triggered control for $p = 8$.

(b) Convergence of dynamic variable $\eta(t)$ with $\eta(0) = 0.01$.

(c) Comparison of continuous and event-triggered control inputs

(d) Evolution of error norm and state-dependent threshold.

Fig. 2. Results of robust dynamic event-triggered control.

the proposed event-triggered approach is also a challenging future scope of this paper.

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