Information Sciences xxx (2014) xxx–xxx

Contents lists available at ScienceDirect

Information Sciences

journal homepage: www.elsevier.com/locate/ins

Aperiodic triggering mechanisms for networked control systems

Q1 Magdi S. Mahmoud [a],*, Azhar M. Memon [b]

[a] Systems Engineering Department, King Fahd University of Petroleum and Minerals, Dhahran 31261, Saudi Arabia
[b] Center for Engineering Research, Research Institute (CER-RI), King Fahd University of Petroleum and Minerals, Dhahran 31261, Saudi Arabia

ARTICLE INFO

Article history:
Received 23 February 2014
Received in revised form 28 October 2014
Accepted 2 November 2014
Available online xxxx

Keywords:
Event-triggered
Networked control system
Periodic triggering
Self-triggered

ABSTRACT

A survey is presented on the triggering mechanisms in Networked Control Systems (NCSs). These mechanisms can be classified as periodic and aperiodic, where aperiodic mechanisms can be further divided into event- and self-triggered schemes. We focus on aperiodic triggering schemes and cover most of the work done with an emphasis on the theoretical results. A glance at the existing work shows a need to organize the scattered theoretical results on the subject, which will provide a basis for interested researchers and also facilitate to visualize open problems.

1. Introduction

With an increasing trend of wired and wireless networked control loops, the demand to address the issues of computational power, communication load, and energy consumption has also increased. The standard implementations of feedback control over a network or embedded platform use periodic schemes, whereby sensing and/or actuation is done at equidistant samples of time. Although a mature systems theory exists for such methodology which eases the design and implementation, it causes an enormous waste of energy and communication capabilities, especially when there is no need for a corrective feedback signal. This translates into considering alternates to the periodic implementation, namely, event- and self-triggered (ET and ST) mechanisms.

Both ET and ST schemes comprise two elements, a controller and a triggering mechanism. This mechanism determines the next update time of the control law based on the previously sampled state information. Particularly, in former, the sensor (or controller) node determines on the basis of a comparison between the present state and a threshold, if the information to the controller (or actuator) should be sent. As compared with the periodic setting, this significantly reduces the amount of required communication, however, computational cost at the sensing node increases due to continuous monitoring of the plant state which is not well-suited for the battery powered sensor nodes. Furthermore, it requires a dedicated hardware to check the event condition. ST mechanism was introduced as a remedy to this problem. This scheme does not require continuous checking of the state, rather it predicts update time on the basis of previously sampled state and plant dynamics. Hence, ET mechanism is reactive and ST is proactive.

In literature, ET scheme is referred using various terminologies such as, event-based sampling, event-driven sampling, Lebesgue sampling, dead-band sampling, send-on-delta sampling, level-crossing sampling, and state-triggered sampling.

Q2 * Corresponding author.
Q1 *E-mail addresses:* msmahmoud@kfupm.edu.sa (M.S. Mahmoud), azharmehmood@kfupm.edu.sa (A.M. Memon).

http://dx.doi.org/10.1016/j.ins.2014.11.004
0020-0255/© 2014 Published by Elsevier Inc.

Q1 Please cite this article in press as: M.S. Mahmoud, A.M. Memon, Aperiodic triggering mechanisms for networked control systems, Inform. Sci. (2014), http://dx.doi.org/10.1016/j.ins.2014.11.004

The survey is organized as follows. Section 2 gives some mathematical preliminaries and notations used in the paper. The literature for ET methodology is presented in Section 3, while that for ST scheme is given in Section 4. A comparison is presented between these two in Section 5 followed by the conclusion in Section 6. For the reader's ease, possible future directions are given as remarks, the advantages and disadvantages are pointed out in the discussion at the end of each subsection, and the table given in appendix lists the works which deal with time-delay.

2. Preliminaries and notations

A continuous function $\alpha : [0, a) \rightarrow [0, \infty)$ is said to belong to class $\mathcal{K}$ if it is strictly increasing and $\alpha(0) = 0$. It belongs to class $\mathcal{K}_\infty$, if $a = \infty$ and $\alpha(r) \rightarrow \infty$ as $r \rightarrow \infty$. Similarly, β is of class $\mathcal{L}$ if it is continuous and decreasing to zero. A function $\zeta : [0, \infty) \rightarrow [0, \infty)$ is said to be of class $\mathcal{G}$ if it is continuous and non-decreasing and $\zeta(0) = 0$. A continuous function $\gamma : [0, a) \times [0, \infty) \rightarrow [0, \infty)$ is said to belong to class $\mathcal{KL}$ if, for each fixed s, the mapping $\gamma(r, s)$ belongs to class $\mathcal{K}$ with respect to r and, for each fixed r, the mapping $\gamma(r, s)$ is decreasing with respect to s and $\gamma(r, s) \rightarrow 0$ as $s \rightarrow \infty$. Class $\mathcal{KK}$ functions are defined in the same fashion.

Local stability is defined when the initial state of the system lies close to the equilibrium point. When it can lie anywhere in the state space then the stability is defined as global. A system is said to be uniformly stable if its stability is independent of the initial time $t_0 \geqslant 0$. A system is said to be stable if for each $\epsilon > 0$, there exists a $\delta = \delta(\epsilon) > 0$ such that if $\|x(t_0)\| < \delta$ then $\|x(t)\| < \epsilon, \forall t \geqslant 0$. It is said to be asymptotically stable if it is stable and δ can be chosen such that if $\|x(t_0)\| < \delta$ then $\lim_{t \rightarrow \infty} x(t) = 0$. A system is said to be exponentially sable if there exists $\sigma, \lambda \in \mathbb{R}^+$ such that $\forall t \geqslant 0$ $\|x(t)\| \leqslant \sigma \|x(t_0)\| e^{-\lambda t}$. The state of a system is said to be ultimately bounded if there exist constants $\varepsilon, \varrho \in \mathbb{R}^+$ (ε defined as the bound) and for every $\eta \in (0, \varrho)$ there is a constant $T = T(\eta, \varepsilon) \in \mathbb{R}^+$ such that if $\|x(t_0)\| < \eta$ then $\|x(t)\| \leqslant \varepsilon, \forall t \geqslant t_0 + T$. A system is said to be Input-to-State Stable (ISS) if there exist a class $\mathcal{KL}$ function γ and a class $\mathcal{K}$ function α such that for any initial state $x(t_0)$ and any bounded input $u(t)$, state of the system satisfies $\forall t \geqslant t_0 \geqslant 0$ the following inequality,

$$\|x(t)\| \leqslant \gamma(\|x(t_0)\|, t - t_0) + \alpha\left(\sup_{t_0 \leqslant \tau \leqslant t} \|u(\tau)\|\right)$$

Consider a system with input–output relation given as $y = Hu$ for some mapping H. This mapping is said to be $\mathcal{L}_p$ stable if there exist a class $\mathcal{K}$ function α, defined on $[0, \infty)$ and a nonnegative constant μ such that,

$$\|(Hu)_\tau\|_{\mathcal{L}_p} \leqslant \alpha(\|u_\tau\|_{\mathcal{L}_p}) + \mu, \quad \forall \tau \in [0, \infty).$$

It is finite-gain $\mathcal{L}_p$ stable if there exist nonnegative constants ζ and μ such that,

$$\|(Hu)_\tau\|_{\mathcal{L}_p} \leqslant \zeta \|u_\tau\|_{\mathcal{L}_p} + \mu, \quad \forall \tau \in [0, \infty).$$

Here $\mathcal{L}_p$ denotes the p norm where $1 \leqslant p \leqslant \infty$.

Expectation operator and conditional expectation are denoted as $\mathrm{E}[.]$ and $\mathrm{E}[.|.]$, respectively.

3. Event-triggered network control

ET networked control (ETNC) or ET control (ETC) caught a great deal of attention by the end of last decade and plenty of work was done focusing the development of systems theory. A classification of this large number of control methods was presented by [54] and an appropriate generic model was introduced.

The general structure of ETNC system for sensor-controller communication is shown in Fig. 1. It consists of the plant, an event detector, an observer, and a control signal generator. When an event occurs, the event detector sends plant output to the observer. Here, an event refers to a situation whereby the output crosses a predefined threshold. The observer then computes state estimates and passes information to the control signal generator which generates the input signal for the process. The observer and control generator operate in open-loop between the events, therefore, the design of the generator is a central issue. In case all the states are available, full state vector is transmitted with the occurrence of an event. Also, controller and actuator can be connected over the network.

Fig. 2 shows the timing relationships for an ET scheme. The black rectangles on the timeline indicate when the control task is being executed. The time $\mathrm{T}_j = r_{j+1} - r_j$ is called the task period and it is the interval between any two consecutive invocations of the control task. D_j is the delay in jth job and it is the time between finishing and release time, i.e., $\mathrm{D}_j = f_j - r_j$.

We now present the survey for ETNC.

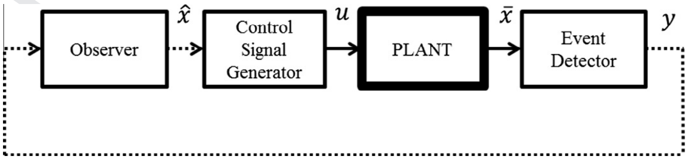

Fig. 1. Block diagram of event-triggered system. Solid lines denote continuous signal transmission and dotted lines show the event-based signals.

Q1 Please cite this article in press as: M.S. Mahmoud, A.M. Memon, Aperiodic triggering mechanisms for networked control systems, Inform. Sci. (2014), http://dx.doi.org/10.1016/j.ins.2014.11.004