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Analysis and synthesis of networked control systems: A survey of recent advances and challenges ☆

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ABSTRACT

A networked control system (NCS) is a control system which involves a communication network. In NCSs, the continuous-time measurement is usually sampled and quantized before transmission. Then, the measurement is transmitted to the remote controller via the communication channel, during which the signal may be delayed, lost or even sometimes not allowed for transmission due to the communication or energy constraints. In recent years, the modeling, analysis and synthesis of networked control systems (NCSs) have received great attention, which leads to a large number of publications. This paper attempts to present an overview of recent advances and unify them in a framework of network-induced issues such as signal sampling, data quantization, communication delay, packet dropouts, medium access constraints, channel fading and power constraint, and present respective solution approaches to each of these issues. We draw some conclusions and highlight future research directions in end.

1. Introduction

In the last decades, the rapid development on communication, control and computer technologies has a vital impact on the control system structure. In traditional control systems, the connection among the sensors, controllers and actuators are usually realized by the port to port wiring, which may cause many problems such as the difficulties in wiring, maintenance and the low flexibility. Such drawbacks appear in many automation systems due to the increasing complexity of controlled plants. In this scenario, networked control systems (NCSs) have attracted much more and more attention. The utilization of a multi-purpose shared network to connect spatially distributed elements results in flexible architectures and generally reduces installation and maintenance costs. Nowadays, NCSs have been extensively applied in many practical systems such as the car automation [1], intelligent building [2], transportation networks [3], haptics collaboration over the Internet [4], and unmanned aerial vehicles [5]. A typical structure of NCS is shown in Fig. 1, in which the network could be a wired or wireless communication network.

The conventional control theory focuses on the study of dynamical systems and each component is connected through "ideal channels", whereas the insertion of communication networks into control systems results in the control over network through "non-ideal channels". This is the main difference between the traditional control systems and NCSs. In NCSs, phenomena such as the communication delays, data dropouts, packet disorder, quantization errors and congestions may occur due to the usage of communication channel. These imperfections would significantly degrade the system performance or even destabilize the control systems. The new challenge, identified by Murray et al. [6], has been listed as one of the key future directions for control community. In recent years, much research effort has been devoted onto this area, and issues such as the stability analysis, state estimation, controller design and fault detection problems for

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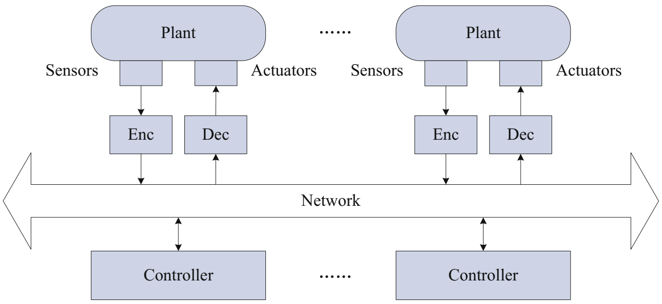

Fig. 1. A typical structure of NCS.

NCSs have been addressed. Nevertheless, it has been well recognized that theoretical development is still far behind the practical applications of NCSs. The difficulties in the analysis lie in that no single analysis and synthesis method can be applied to handle all the network-induced problems. The research is ongoing, more and more researchers are devoted onto this area, and clarification and discussion on the recent results seem to be necessary.

It is noted that some reviews on the advances have been made in NCSs. In the survey by Tipsuwan and Chow in 2003 [7], their main concern is the time-delay problem, Hespanha et al. in 2007 [8] addressed different types of imperfections in NCSs, such as packet losses, time-varying sampling intervals, and competition of multiple packet transmissions. Gupta and Chow in 2010 [9] paid their attention on network security and other realistic considerations. Recently, Zhang et al. in 2013 [10] discussed various network-induced constraints in NCSs, while Qiu et al. in 2016 [11] focused on the fuzzy-model-based NCSs and their main concerns are time delays, packet dropouts and signal quantization. Compared with these reviews, this work aims to classify the recent papers on the NCSs and then different modeling approaches are presented and discussed in a more precise way. The classification is performed according to the scenario whether the occurrence of these uncertainties are deterministic or stochastic. Modeling and analysis methods are presented from various perspectives, and finally some discussions and future directions are given.

The rest of this paper is organized as follows: In Section 2, we address the NCSs with sampled-data measurement. The lifting approach, hybrid discrete/continuous approach, input delay approach, robust control approach switched system approach, and Markovian system approach are presented to model the NCSs with sampled-data measurement. Section 3 covers a collection of results on the NCSs with signal quantization, where the basis on the uniform quantization and logarithmic quantization is firstly presented and some modeling issues are then discussed. In Section 4, the results on the communication delay are given, modeling and analysis are also discussed. The NCSs with packet dropout issue are considered in Section 5, various modeling and analysis methods are presented. In Section 6, the results on the medium access constraints are presented from different perspectives. In Section 7, the recent advances on channel fading are discussed. Section 8 gives some interesting modeling methods on power constraint arising in the wireless networked control systems (WNCSs), and some discussions are also included. Finally, discussions and future directions are presented in Section 9.

Notation: R^n denotes the n-dimensional Euclidean space. We use A^T to represent the transpose of matrix A. I_n is the identity matrix with $n \times n$ dimension and I is introduced as an identity matrix with compatible dimension. The symbol diag$\{A\}$ indicates that A is a diagonal matrix. The symbol "$*$" is used to represent the symmetric terms. E$\{\cdot\}$ is the mathematical expectation, and Prob $\{\bullet\}$ is the occurrence probability of an event.

2. Signal sampling

NCS is a digital control system and continuous signal is usually sampled at a certain time instant, and then the sampled measurement is utilized for controller design. In the traditional digital control system, the sampling period is usually fixed. However, in NCSs, the sampled measurement may not be able for transmission since the sampled data is usually waiting in a queue, and recently it has been proved that a time-varying sampling period may achieve a better performance than the time-invariant one. Now many research papers are reported on the NCSs with time-varying sampling periods, where the deterministic sampling and stochastic sampling schemes have been investigated. We now discuss these results in the following.

2.1. Deterministic case

Assuming that the sampling period is time-invariant or time-varying, then the control, filtering and fault detection problems are investigated based on some appropriate modeling and analysis methods.

2.1.1. Lifting approach

A general framework for linear systems with periodical sampling were presented in [12,13] and the main tool is the lifting technique, which provides a strong correspondence between the continuous-time system and the discrete-time counterpart. Later in [14] a linear matrix inequality (LMI) based solution was derived for the sampled-data controller design when the sampling and holder are working under a commensurable rate. The main results were also extended to the multiple sensor case for the multi-rate sampling problem. This solution was computationally complicated because it includes the evaluation of the matrices of the lifted system. Related works can be found in [15–17]. The sampling period in the above results was time-invariant, which are discussed here as they have great impact on the study of NCSs with time-varying sampling periods, especially on the multi-rate sampling systems.

2.1.2. Hybrid discrete/continuous approach

This approach is based on the representation of a system in the form of hybrid discrete/continuous model, or more precisely, the impulsive system, and the solution was first obtained in terms of differential Riccati equations with jumps [18,19]. The hybrid system approach has been recently applied to robust H_∞ filtering with sampled-data measurements [20]. Sampling interval-independent LMI conditions have been derived there which were quite restrictive since the information of sampling period was not utilized in filter design. Recently, the impulsive system modeling of sampled data system was also used in [21], where a new Lyapunov function was introduced with discontinuities at the impulse time. To illustrate the main results in [21], we consider the following LTI system:

$$\dot{x}(t) = Ax(t) + B_u u(t), \tag{1}$$

where x and u are the state and the input of plant, respectively. Denote the sampling time instant by s_k, and let $\varepsilon \le s_k - s_{k-1} \le \tau_{\text{MATI}}$, where ε and τ_{MATI} are some positive scalars. Then, a linear state feedback control becomes $u(t) = Kx(s_k)$. Define a new state $\xi(t) = \left[x^T(t)\ z^T(t)\right]^T$, where $z(t) = x(s_k)$. The dynamics of system (1) can be written as

$$\dot{\xi}(t) = F\xi(t), \quad t \ne s_k,$$
$$\xi(s_k) = \begin{bmatrix} x(s_k^-) \\ x(s_k^-) \end{bmatrix}, \quad t = s_k, \tag{2}$$