Review Article

Sampled-data control systems with non-uniform sampling: A survey of methods and trends

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ABSTRACT

The convergence of sensing, computing, communication and control elements drives the traditional point-to-point control systems towards networked control systems. Sampled-data control systems, which focus on the significant interplay between sampling and control, play a critical role in modern networked control systems, including intelligent transportation systems, smart grids, and advanced manufacturing systems. This paper presents a survey of methods and trends in non-uniform sampled-data control systems, where sampling and control actions are performed in an aperiodic manner. First, some fundamental issues of both continuous- and discrete-time sampled-data control systems are discussed. Next, main methods in both continuous-time and discrete-time domains are elaborated, respectively. Then, event-triggered sampling, under which sampling is executed only when the system needs attention, is examined. Typical triggering mechanisms in the existing literature are reviewed and classified into four types according to different threshold functions. Furthermore, two applications in terms of automated vehicle platoons and islanded microgrid are provided to demonstrate that sampled-data control methods are capable to support relevant practical application scenarios. Finally, several challenging issues are envisioned to direct future research.

1. Introduction

Sampled-data systems have been studied for over seven decades (Linvill, 1951). When sampling is periodic, there has been the mature theory for stability analysis and control design of sampled-data systems: see, e.g., Apkarian and Adams (1998), Chen and Francis (1995), Nesic and Teel (2001), Oishi (2001) and Yamamoto (2019). Undoubtedly, the mature theory has laid a solid foundation for networked control systems (NCSs). However, in practical scenarios, the sampling intervals between two consecutive sampling instants in an NCS are usually time-varying rather than constant (Gupta & Chow, 2010; Hespanha, 2014; Hu, Ren, Deng, & Li, 2022; Lu, Wen, Lu, Wang, & Zhang, 2022; Mahmoud & Hamdan, 2018). For example, when an NCS is subject to packet dropouts or denial-of-service (DoS) attacks, it can be modeled as a sampled-data system with non-uniform sampling (Heemels, Teel, van de Wouw, & Nesic, 2010; Hespanha, Naghshtabrizi, & Xu, 2007; Liu, Selivanov, & Fridman, 2019; Peng, Bai, Liu, Han, & Zhang, 2021; Zhang, Han, Ge, & Ding, 2020; Zhang, Han, Ge, et al., 2020), sometimes also known as aperiodic sampling and variable sampling.

The frequency of sampling actions for a sensor or sampler device should be proactively reduced due to the constrained resource budget. For example, real-world sensor and sampler devices are often battery-operated. Persistent or periodic sampling of the continuous-time signal of interest that has little fluctuation since the last sampling time inevitably causes unnecessary power consumption. In this case, event-triggered sampling is regarded as a promising sampling mechanism to reduce the potential resource consumption (Borgers & Heemels, 2014; Heemels, Sandee, & Van Den Bosch, 2008; Tabuada, 2007; Tiberi, Fischione, Johansson, & Benedetto, 2013). On the other hand, the core of NCSs is the communication network that enables data transmissions between networked sensors and controllers. However, communication resources such as bandwidth are often limited (Hespanha et al., 2007; Zhang, Han, & Ge, 2022). In this sense, the event-triggered sampling is prevalently employed to reduce the transmission frequency only when 'needed', e.g., when the current signal of interest suffers from a significant change from the last sampling and transmitting instant. The promising benefit of saving precious resources represents the primary

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Table of Contents Theory Of Sample Data Control Systems

1. Understanding the eBook Theory Of Sample Data Control Systems
    - The Rise of Digital Reading Theory Of Sample Data Control Systems
    - Advantages of eBooks Over Traditional Books
2. Identifying Theory Of Sample Data Control Systems
    - Exploring Different Genres
    - Considering Fiction vs. Non-Fiction
    - Determining Your Reading Goals
3. Choosing the Right eBook Platform
    - Popular eBook Platforms
    - Features to Look for in an Theory Of Sample Data Control Systems
    - User-Friendly Interface
4. Exploring eBook Recommendations from Theory Of Sample Data Control Systems
    - Personalized Recommendations
    - Theory Of Sample Data Control Systems User Reviews and Ratings
    - Theory Of Sample Data Control Systems and Bestseller Lists
5. Accessing Theory Of Sample Data Control Systems Free and Paid eBooks
    - Theory Of Sample Data Control Systems Public Domain eBooks
    - Theory Of Sample Data Control Systems eBook Subscription Services
    - Theory Of Sample Data Control Systems Budget-Friendly Options
6. Navigating Theory Of Sample Data Control Systems eBook Formats

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