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Strategies for Optimal Control in Networked Systems under Limited Communication

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ABSTRACT: The optimal control of networked control systems (NCS) with limited communication channels poses significant challenges, such as delays, packet losses, and constrained data rates, which degrade system performance. Recent advancements propose strategies to address the delimitations by focusing on communication-control codesign, adaptive scheduling, and robust optimization. A deep reinforcement learning (DRL) algorithm demonstrates superior scheduling and control input performance for large-scale wireless NCS, efficiently handling timecorrelated channels (Pangetal.,2024). For connected vehicles, range-limited and time-delay communications are addressed through non-model-based control methods, ensuring system stability despite un- certainties(Wangetal.,2023). The presence of Markovian packet losses introduces complexity in the control problem, where stochastic difference equations are utilized to establish necessary conditions for stability and optimality (Han et al., 2023; Wang et al., 2023). Additionally, trade-offs in state estimation, balancing data rates and observability under dropout constraints, highlight the importance of tailored strategies for effective NCS performance (Liuetal.,2023). Despite the advances, computational complexity and real-time adaptability remain key areas for further research, particularly for dynamic environments where stringent response times are critical.

Keywords— NCS, DRL

1. Introduction

A networked control system (NCS) consists of control loops connected through communication networks, in which both the control signal and the feedback signal are exchanged between the system/plant and the controller. There are two types of approaches for design of NCSs, namely control of network approach and control over network approach. Only the control over network approach-based NCSs are considered in this review. A simple block diagram of this type of networked system is shown in Figure 1.

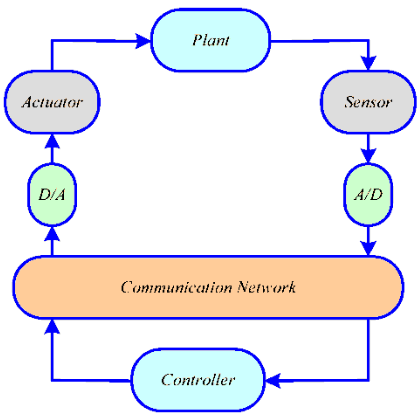

Figure 1. A simple block representation of a networked control system (NCS).

In an NCS, the plant output is measured using the sensors. These signals are converted into digital signals using the analog-digital (A/D) convertors, which are transmitted to the controller via a communication network. The controller determines the control signal based on the sensor output, which is transmitted back to the plant using same communication channel. The control signal before being fed to the actuator section of the plant, is converted from digital to analog signal using the digital-analog (D/A) convertor. In this manner, the plant dynamics can be controlled from a remote location.

1.1 Designing of Control System from Continuous Domain to Networked Control Domain

In the beginning, control signals were generated using analog computers. Frequency analysis and Laplace transform were the primary tools for analysis. The main drawbacks of this system are its limited accuracy, limited bandwidth, drift, noise, and limited capabilities to manage nonlinearities. Known delays could be handled at the time of control synthesis using the well-known Smith predictor.

Digital controllers replaced the analog technology with the advancement of processors. However, controlling an analog plant with a discrete electronic system inevitably introduces timing distortions. In particular, it will become necessary to sample and convert the sensor measurements to digital data and also convert them back to analog values. Sampling theory and z transform became the standard tools for the design and analysis of digital control systems analysis. For z transform, it is assumed that the sampling is uniform. Thus, for the design of digital controllers, periodic sampling became the standard. Note that, at the infancy of digital controls, as the computing power was poor and memory was expensive, it was vital to minimize the complexity of the controllers and the operating power. It is not obvious that the periodic sampling assumption is always the best choice. For example, adaptive sampling has been used in Reference [1], where the sampling frequency is changed based on the derivative of the error signal, and is far better than equidistant sampling in terms of computed samples (but possibly not in terms of disturbance rejection [2]). A summary of these efforts is provided in References [3,4]. However, with the decreasing computational costs, interest in adaptive sampling reduced, and the linearity preservation property of equidistant sampling has helped it to stay the undisputed standard.

From the computing side, real-time scheduling modeling and analysis were introduced in Reference [5]. This scheduling was based on restrictive assumptions, one of them being the periodicity of the tasks. Even if more assumptions were progressively introduced to cope with the practical problems, the periodicity presumption remains popular [6]. Moreover, the topology of the network can vary with time, allowing the mobility of the control devices. Hence, the whole control system can be highly adaptive in a dynamic environment. In particular, wireless communications allow for the rapid deployment of networks for connecting remotely located devices. However, networking also has problems, such as variable delays, message de-sequencing, and periodic data loss. These timing uncertainties and disturbances are in addition to the problems introduced by the digital controllers. Figure 2 shows the trade-off between control performance and the sampling rate.

1.3. Co-Design Approach for the NCSs

The design of an NCS integrates the domains of control system, communication, and real-time computing. The increasing complexity of the computer systems, and their networks, requires advanced methods specifically suited for the NCS. The main issue to be addressed is the achievement of the control objective (i.e., a combination of security, performance, and reliability requirements), despite the disturbances. For instance, sharing of common computing resources and communication bandwidths by competing control loops, alongside the other functions, introduces random delays and data losses. Moreover, the use of heterogeneous computers and communication systems increases the complexity of the NCS.

Control plays a significant role in interconnected complex systems for their reliable performance [7]. The interconnection of elements and sub-systems, coming from different technologies, and which are subject to various constraints, calls for a design that can solve the conflicting constraints. Besides achieving the desired performance in normal situations, the reliability and safety-related problems are of concern for the system developers. A fundamental concept that is dependability, which is the device property that features various attributes, such as access, reliability, safety, confidentiality, integrity, and maintainability [8]. Being confronted with faults, errors, and failures, a system's dependability could be achieved in numerous ways, i.e., fault prevention, fault threshold, and fault forecasting [9].

Except in the event of failures due to hardware or software components, most procedures run with nominal behavior, but, neither the process nor the execution resource parameters are completely known or modeled. One method is to allocate the system resources conservatively, which results in the wastage of resources. From the control viewpoint, specific inadequacies to be considered include poor timing, delays, and data loss. Control usually deals with modeling uncertainty, powerful adaptation, and disturbance attenuation. More correctly, as shown with recent results obtained on NCS [10], control loops tend to be robust and can tolerate networking and computing disturbances, up to a certain level. Therefore, the timing deviations, such as jitter or data loss, as long as they remain within the bounds, may be viewed as the nominal features of the system, but not as exceptions. Robustness allows for provisioning the execution resources according to needs that are average than for worst cases, and to take into account system reconfiguration only once the failures surpass the abilities of the controller tolerance that is running.

Concluding Remarks and Future Potentials

The progress of NCSs can be termed as the steady progress which was based on evolution of computation and communication technology. The research of NCSs started with decentralized control systems, which later converged to several theories related to the stability analysis of NCSs. Then, many research papers discussed issues, such as sampling, quantization, and time delays. In a recent phase of NCSs development, some new topics, such as controller design for NCSs with event-triggered sampling and cyber-attacks, have received a lot of attention. NCSs have also been implemented for many practical systems, like UAVs, power systems and smart grids, robots, missiles, and manufacturing systems. At present, the components are distributed over long distances, such as in a smart grid, teleoperation control system, etc. Conventional control cannot satisfy the latest challenges, so novel control structures are needed to resolve the newly-presented complex control systems. Even though a lot of advancement has been made in NCSs, their practical applications are very limited. Most of the research works dealt with simple-nodes and simple-system. Multi-sensors (or multi-nodes) and multi-system, in addition to coupling of numerous nodes or subsystems, should be considered in the future research. In accordance with the undeniable fact that the complex NCSs have characteristics of wide area, wide selection, and big data, we ought to combine the network control technology with the computer technology, the cloud storage technology, the data mining technology, and the wide-area measurement techniques in such a way that more effective control algorithms are developed. The research in NCSs has come a long way since its inception, but, in terms of real-time implementation, there is still a lot of scope. This is definitely going to be taken into account in further research problems.

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