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Communication and control methodologies in networked control systems: A review

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Abstract

In recent years, networked control systems have grown in importance and received increased interest as a new research subject. The process of integration of control and communication in networked control systems has posed a significant theoretical challenge for traditional control theory in terms of system design and analysis. The installation of networked control systems becomes an essential intermediate step toward the final convergence of control, communication, and computing as a result of this integration. We begin by covering the fundamentals of networked control systems, followed by an overview of current research in the subject. We hope that this brief lesson will serve as a catalyst for further research and development of networked control systems, both theoretically and in terms of practical applications.

Keywords: Networked Control Systems; Communication Network; Data Transmission; Codesign

1. Introduction

Networked control systems" (NCSs) are control systems in which "the control loop is closed via a serial communication network" [1]. Interest in such a system architecture can be traced all the way back to the 1980s, when "Integrated Communication and Control Networks" received a lot of press [2]. Since then, aliases like "Network-Based Control Systems" and "Control over (through) Networks" have been used to refer to similar, if not identical, system setups as NCSs, albeit they are no longer widely used. as NCSs since then, although they are no longer commonly used.

The usage of communication networks in the control loop is the main distinguishing aspect of NCSs, as suggested by their name [3, 4]. Previously, control oriented communication networks such as the Control Area Network and DeviceNet were the first choice of communication networks in NCSs; however, with the rapid advancement of communication technology and the growing needs of large-scale systems, the Internet has become an overwhelmingly appealing alternative. We can develop a huge control system with the Internet at a considerably cheaper cost and with better maintenance, as well as more flexible reconfiguration. In recent years, we have witnessed several developments, like the smart home, smart transportation, remote surgery, and the Internet of Things, built on such fundamental theoretical advancements in NCSs [5–8].

However, the benefits that NCSs provide are not free. The lossless data transfers among the control components are a crucial foundation of traditional control systems. The data in NCSs must be communicated across a communication network, and the nature of the Internet and other types of data networks makes ideal data exchanges between control components nearly impossible. As a result of the imperfect data translation in NCSs, the control system is subjected to so-called communication constraints, such as network-induced delay (delays in transmitting sensing and control data), data packet dropout (data packets may go missing during transmission), and time synchronization issues (different control components may work on different clocks) [9]. In a networked control environment, simple extensions of standard control procedures cannot be acquired easily, which might drastically decrease system performance or

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potentially destabilize the system under certain situations [10–16]. These limitations provide significant challenges for the control and communication communities, and significant work has been done at the intersection of control theory and communication technology to [17–19] a better understanding and design of such systems

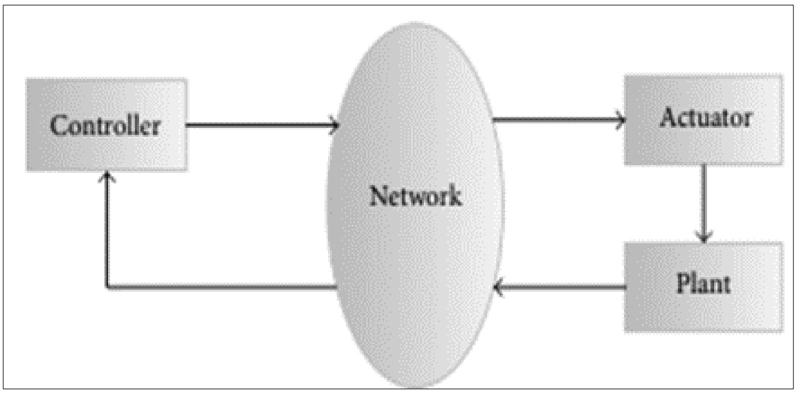

Figure 1 Networked control systems in the direct structure

There are two components to this. We begin by providing a thorough overview of communication networks in NCSs, including their fundamental properties and, more crucially, their interactions with the control system. Because of the increased usage and more intricate communication aspects of the former, we focus on data networks such as the Internet rather than control-oriented networks. The state-of-the-art research on NCSs is then reviewed, focusing on control but also emphasizing the codesign approach, which incorporates both control and communication. This tutorial is not intended to be comprehensive or exhaustive. Rather, our primary goal is to teach new scholars the fundamentals of NCSs.

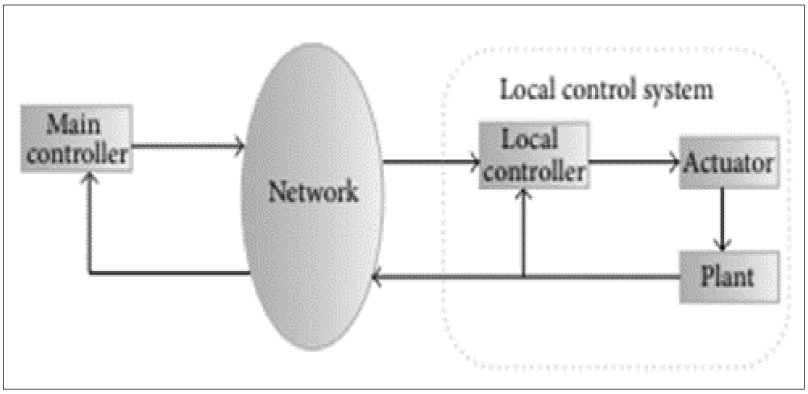

Figure 2 Networked control systems in the hierarchical structure

We concentrate on a more basic structure of NCSs. In reality, NCSs can have two distinct forms from a system structure standpoint [20]: the "direct structure" (Figure 1) and the "hierarchical structure" (Figure 2). The latter is distinguished from the former by the presence of a local controller and the usage of the communication network to close the loop between the main controller and the local system. This structural distinction may have theoretical as well as practical implications; however, because the latter can be viewed as a hierarchical combination of a direct structured NCS and a conventional local control system, it is not necessary to investigate the hierarchical structure as a separate type of NCS.

2. The Basics of Networked Control Systems

The principles of NCSs are covered in this part, with a focus on the differences between NCSs and traditional control systems, i.e., the distinct and distinctive qualities of NCSs caused by the added communication network.

2.1 Network Topology

In the existence of a communication network in the NCSs, traditional control components such as the sensor, controller, and actuator function as network nodes in terms of network topology. From this standpoint, the following two difficulties must be addressed:

2.1.1 Time-Synchronization

To function successfully, the control components must be time synced. This is a crucial foundation of traditional control systems, but owing to the usage of dispersed communication networks in NCSs, it is generally lacking [21]. If the network induced delay in the backward channel is not required for the computation of the control signals and/or the network induced delay in the forward channel is not required for the execution of the control actions, time-synchronization in NCSs may not be a necessary requirement. As discussed in [22, 23], time-synchronization in NCSs combined with the use of time stamps can provide an advantage over conventional time delay systems because the controller knows the backward channel delay and the actuator knows the forward channel delay (round trip delay as well). As shown in [22, 24], this advantage may be leveraged to build a better control structure for NCSs.

2.1.2 Drive Mechanism

Time or event can be used to control the sensor and actuator. The trigger technique that activates the control components is the distinction between the two driving systems. The control components of the time-driven mechanism are triggered to function at regular intervals, whereas the control components of the event-driven mechanism are only triggered by predetermined "events." Time-driven mechanisms can be thought of as a subset of event-driven mechanisms, in which the trigger events for the latter are chosen as the time. As a result, it's no surprise that event-driven processes are more complex and may necessitate the use of auxiliary devices. The sensor is typically timed, although the controller and actuator might be either timed or event driven. It's worth noting, however, that different driving methods yield distinct NCS system models, and event-driven control components typically result in higher system performance.

2.2 Packet-Based Data Transmission

The information in NCSs is encoded in data packets and subsequently sent across the communication network. Figure 3 depicts a typical data packet. One of the most fundamental properties of NCSs that separates it from conventional control systems is packet-based communication [16]. This characteristic might imply that NCSs lack the flawless data transfer that is required in traditional control systems, posing the most difficult component of NCSs. Network-induced latency, data packet dropout, and data packet disorder are examples of communication restrictions imposed by packet-based transmission in NCSs, and are discussed further below.

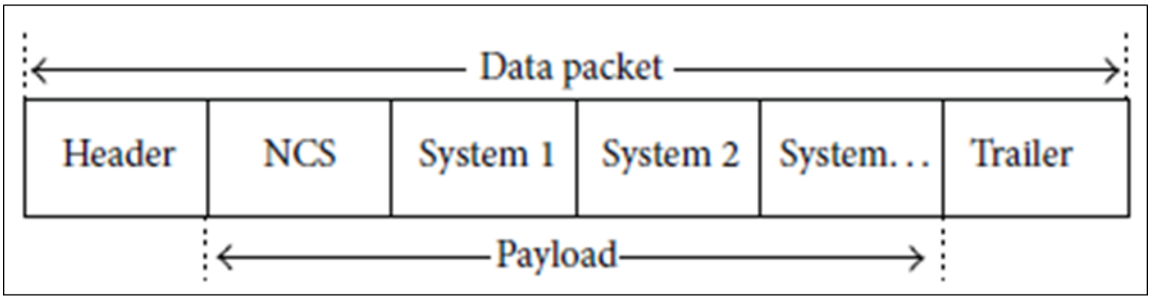

Figure 3 The typical data packet structure where NCS is sharing the data packet with other applications

2.2.1 Network-Induced Delay

The data packet transmission time causes network-induced delays to NCSs, which are well documented to affect control system performance. According to where they occur, network-induced delays are classified into two categories. The characteristics of the two forms of network-induced delays may differ [25]. However, in most circumstances, these delays are not evaluated independently, and just the round-trip time is considered [4, 22].

2.2.2 Data Packet Dropout

In communication networks, data transmission loss is unavoidable, resulting in a phenomenon known as "data packet dropout" in NCSs. Data packet dropout can occur in either the backward or forward channel, and it causes NCSs to lose access to either sensing data or control signals, resulting in considerable degradation of NCS performance.

2.2.3 Data Packet Disorder

Various data packets have different delays in most communication networks, resulting in a situation where a data packet supplied earlier may arrive at the destination later or vice versa; see Figure 4. Data packet disorder is the term for this occurrence. Because of data packet disorder, a recently received control signal in NCSs may not be the most recent, which does not happen in traditional control systems. If the control algorithm does not explicitly address the disordered data, the control performance will definitely suffer.

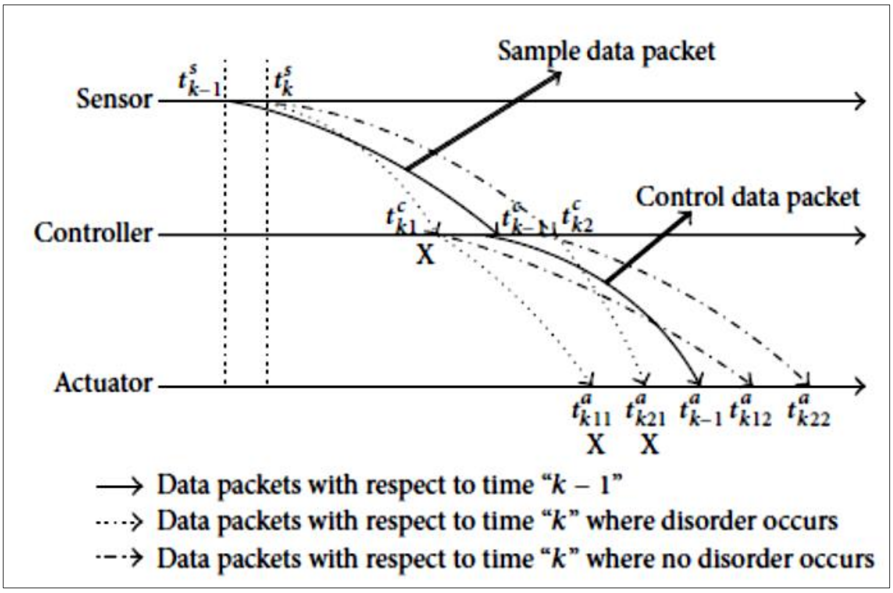

Figure 4 Data packet disorder in NCSs

2.2.4 Single and Multipacket

If, for example, multiple sensors are used in NCSs and are geographically distributed, and each sensor sends its sensing data to the controller separately over the network, the controller may have to wait for all of the sensing data packets to arrive before it can calculate the control actions, and if just one sensing data packet is lost, all of the control actions are lost. This is referred to as "multipacket" data transfer in NCSs. Another circumstance in NCSs is when the control signals or sensing data from many stages are delivered over the network in a single data packet, because the packet size utilized in NCSs can be quite big in comparison to the data size necessary to encode a single step of sensing data or control signal. The essential premise of the so-called packet-based control technique [24] is the "single packet" transfer of data in NCSs.

2.3 Limited Network Resources

The constraint of network resources in NCSs is principally caused by the communication network's restricted capacity, which results in the three circumstances in NCSs that differ from traditional control systems.

2.3.1 Sampling Period, Network Loads, and System Performance

Because of the digital transfer of data through communication networks, NCSs are a subset of sampled data systems. However, because of the restricted bandwidth of the network in NCSs, a shorter sampling time may not result in greater system performance, as is generally true for sampled data systems [14]. This occurs because a too short sample interval generates too much sensor data, overloading the network and producing congestion, resulting in more data packet failures and longer delays, and ultimately reducing system performance. Figure 5 depicts the link between the sample time, network loads, and system performance in NCSs. For example, when the sampling period decreases from the value corresponding to points "a" to "b," the system performance improves as in conventional sampled data systems because network congestion does not appear until point "b"; however, when the sampling period decreases even further from the value corresponding to points "b" to "c," the system performance is likely to deteriorate due to network congestion. As a result, the connection depicted in Figure 5 shows that there is a trade-off between the period of sampling of plant data and system performance in NCSs; that is, an ideal sampling period exists in NCSs that provides the highest system performance (point "b" in Figure 5).

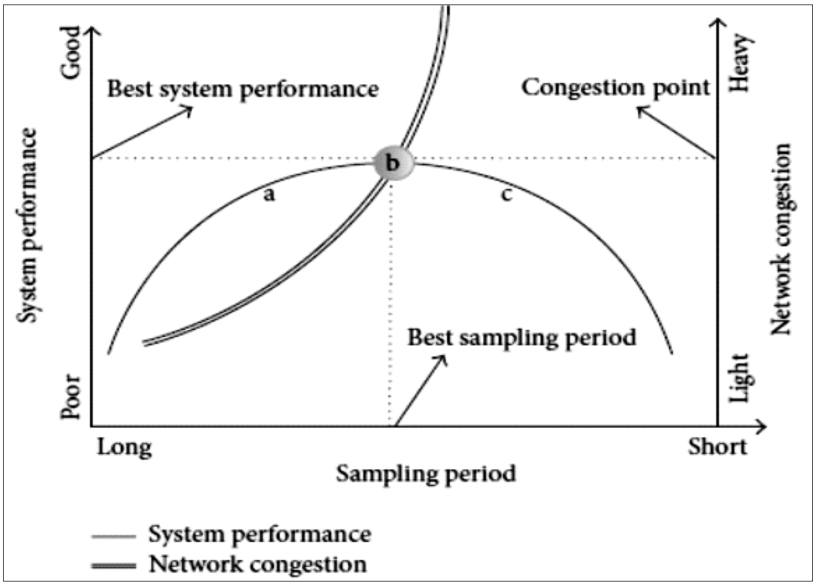

Figure 5 Relationship between the sampling period, network loads and system performance in NCSs

2.3.2 *Quantization*

Signal quantization is unavoidable in NCSs due to the usage of data networks with restricted capacity, which has a substantial influence on system performance. Meanwhile, quantization is a viable approach for reducing bandwidth utilization, making it an efficient tool for avoiding network congestion in NCSs and therefore improving NCS system performance. The reader is referred to [16,23] and the references therein for further information on the quantization effects in NCSs.

2.3.3 *Network Access Constraints and Scheduling*

As seen in Figure 3, an NCS may only use a portion of the payload and share the data packet with other applications. Figure 6 shows that the other apps can also be NCSs, implying that many NCSs share the same communication network. Due to resource rivalry, subsystems may not be able to access network resources at all times in this situation due to the network's restricted capacity. To arrange the timeline of when and how long a certain subsystem can utilize the network resource, a scheduling algorithm is required. Simultaneously, under the suitable control performance limitation, the less bandwidth an NCS requires, the better it performs in comparison to other applications.

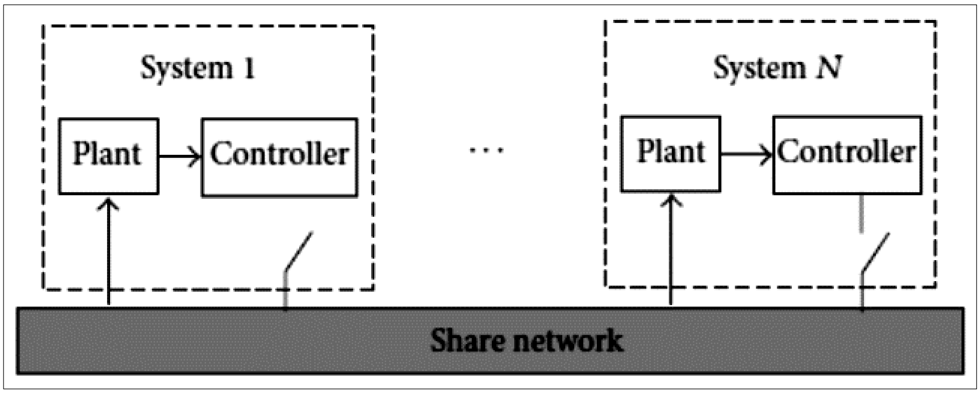

Figure 6 Multiple NCSs can share the communication network

3. The Codesign Research Approach to Networked Control Systems

The communication network substitutes the direct connections between control components in traditional control systems in Codesign approach for NCSs. As a result, the so-called codesign approach to NCSs, which incorporates both control and communication, has emerged as a new trend. Communication limitations are no longer regarded to be predetermined parameters, but rather serve as designable elements, and higher performance may be anticipated by making optimal use of these factors. [23, 25]. We provide two instances of the codesign approach to NCSs.

3.1 Packet-Based Control Approach

As previously stated, one of the most distinguishing features of NCSs is packet-based communication. This property may be exploited to develop the packet-based control framework, a codesign control structure for NCSs, as described in [18]. The packet-based control methodology has its roots in [19], where the packet-based structure of data transmission was efficiently exploited to actively adjust for communication restrictions in NCSs using the generalized predictive control method.

Control and Scheduling Codesign: Multiple control components sharing a network with limited bandwidth may arise in NCSs. In such a case, network resource allocation among control components is required. [1] introduced a dynamic scheduling technique known as "try-once-discard" (TOD), which allocates network resources so that the node with the biggest error in the most recently reported period obtains access to the network resource. Reference [10] introduced a TOD-based Lyapunov uniformly globally asymptotically stable (UGAS) protocol, which is enhanced in [12]. To deal with the network access constraint for such a system configuration, the authors in [13] used the technique of "communication sequence" and modeled the subsystems as switched systems with two modes "open loop" and "closed loop" that switch depending on whether the current subsystem has access to the medium or not. The authors of [17] studied a specific instance of the arrangement presented in Figure 6 in which the channel from controller to actuator is directly connected and the rate monotonic scheduling technique is used to plan the transmissions of the subsystems' sensing data.

4. Conclusion

Despite all of the advances achieved in networked control systems over the last few decades, additional efforts are required in the future. The majority of these active studies use the codesign technique, and cooperation between the control and communication groups, as well as the computation community, are needed. These partnerships will then show the utility of networked control systems in larger contexts by investigating their tight interaction with other systems such as the Internet of Things, cyber-physical systems, and multiagent systems. All of this adds up to a bright future for networked intelligent automation.

Compliance with ethical standards

Disclosure of conflict of interest

No conflict of interest.

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