

Yun-Bo Zhao · Guo-Ping Liu
Yu Kang · Li Yu

Packet-Based Control for Networked Control Systems

A Co-Design Approach



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Preface

Networked control systems (NCSs) are control systems whose control links are closed via some form of communication networks. It has become a useful control system model in recent years due to the fast development of the embedded computational devices and the communication technology. These developments have made it possible that a large number of sensors, actuators and controllers can be interconnected over the communication network to interact with the physical environment. This remote and distributed control system structure is the basis of a great many of future applications in information technology, including Internet of Things, cyber-physical systems, smart home.

NCSs can contain a large number of control devices interconnected, and data is exchanged through communication networks which inevitably introduces communication constraints to the control system, e.g. network-induced delay, data packet dropout, data packet disorder, data rate constraint. These communication constraints in NCSs present great challenges for conventional control theory.

The study of NCSs therefore requires multi-field knowledge, and consequently the integration of control, communication and computations, i.e. the “co-design” approach. In this book, we report a class of co-design approach to NCSs—the “packet-based control” approach—which is achieved by taking advantage of the packet-based transmission of the communication network in NCSs, one primary feature distinct from conventional control systems.

For completeness, an introductory chapter is first included which provides a brief tutorial of NCSs, and then the remainder of the book is organized into three parts, covering the design, analysis and extension of the packet-based control approach, respectively.

These studies have shown that the packet-based control approach is both unified and flexible: on the one hand, the approach can stand on its own as a novel class of design and analysis methods different from existing ones; on the other, existing

control methods can also be fitted into the packet-based control approach for a better system performance. A unique co-design framework, i.e. packet-based networked control systems, is thus finally constructed.

We hope the reader will find this book useful for their understanding of and research on networked control systems.

Hangzhou, China
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Yun-Bo Zhao

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Acronyms

CARIMA	C ontrolled A uto R egressive I ntegrated M oving A verage
CAS	C ontrol A ction S elector
CTR	C ontroller T ransmission R ule
DCDD	D ifferent- C hannel- D elay- D ependent
DCDI	D ifferent- C hannel- D elay- I ndependent
DFS	D ynamic F eedback S cheduling
EBS	E rror B ounded S ensing
FCIS	F orward C ontrol I ncrement S equence
FCS	F orward C ontrol S equence
FFG	F ixed F eedback G ain
GPC	G eneralized P redictive C ontrol
LGPC	L inear G eneralized P redictive C ontrol
LQR	L inear Q uadratic O ptimal
LTI	L inear T ime- I nvariant
MPC	M odel P redictive C ontrol
NCS(s)	N etworked C ontrol S ystem(s)
PBNCS(s)	P acket- B ased N etworked C ontrol S ystem(s)
QoP	Q uality o f P erformance
RM	R ate M onotonic
RHC	R eceding H orizon C ontrol
STR	S ensor T ransmission R ule
SISO	S ingle- I nput- S ingle- O utput
SSRTD	S tability-guaranteed S upremum of R ound T rip D elay
TCP	T ransmission C ontrol P rotocol
TDS(s)	T ime D elay S ystem(s)
UDP	U ser D atagram P rotocol
VFG	V arying F eedback G ain

Chapter 1

A Brief Tutorial of Networked Control Systems

A brief tutorial of NCSs is provided in this introductory chapter. The tutorial first introduces the unique characteristics of NCSs and then reviews the research in this field. The former is explored from a perspective that emphasizes the differences between NCSs and conventional control systems, and thus the role played by the computation network in NCSs is extensively examined, including, e.g., the network topology, the packet-based transmission and the limited communication resources, etc. Among all these characteristics, the packet-based transmission will be highlighted as this is the basis of the so-called “packet-based control” for NCSs, the principal theme of the book. The second part of the tutorial covers the state-of-the-art research on NCSs. We particularly make the comparison between conventional studies and the so-called “co-design” approach to NCSs, to which the packet-based control approach belongs.

1.1 Introduction

“Networked control systems” refers to a general class of control systems whose control loop is closed via some form of communication network [1–6]. Interest in such a system configuration can date back to as early as 1980s’, when the so-called “Integrated Communication and Control Networks” attracted much attention from the control community [7]. From that time on, other alias such as “Network-based Control Systems” and “Control over (through) Networks” have also been used to describe the similar system configuration as NCSs but are not often used today [8–13].

As indicated by its name, the most distinct feature of NCSs is the use of communication networks in the control loop [14, 15]. Earlier days have witnessed the use of the control-oriented communication networks such as the Control Area Network (CAN), DeviceNet, etc., as the first choice of the communication networks in NCSs, the fast development of the communication technology as well as the increasing needs of large scale systems have now made the Internet or other forms of data networks an

attracting alternative. The Internet offers us the capability of building a large control system at much lower cost, easier maintenances, with also the more flexible reconfiguration capability. Built on the fundamental theoretical advances in NCSs, we have seen various innovations such as the smart home, smart transportation, remote surgery, Internet of Things, etc. in recent years [16–22].

The advantages brought by NCSs however do not come at no cost. A fundamental basis of conventional control systems is that the data exchanges among the control components are lossless. In NCSs, the data have to be transmitted through the communication network, and the nature of the Internet and other variations of data networks means that perfect data exchanges among the control components is essentially unavailable. The imperfect data translation in NCSs thus introduces the so-called communication constraints to the control system, which include, e.g., the network-induced delay (the delays occurred in transmitting the sensing and control data), the data packet dropout (the data packet may be missing during transmission), the time synchronization issue (different control components may work on different clocks), and so on [23]. These communication constraint can greatly degrade the system performance or even destabilize the system at certain conditions, while simple extensions of conventional control approaches can not be obtained directly in a networked control environment [24–29]. These difficulties thus pose great challenges for the control and communication communities and considerable works have been done to a better understanding and design of such systems at the boundary of control theory and communication technology [30–32].

We provide a brief tutorial on NCSs in this introductory chapter. This consists of two parts. We first give an extensive introduction of the communication networks in NCSs, including its basic characteristics and more importantly its interactions with the control system. Note that we focus on data networks such as the Internet but not the control-oriented networks, simply because of the increasing use and more complicated communication features of the former. We then survey the state-of-the-art research on NCSs, from mainly the control perspective with also an emphasis on the co-design approach which integrates both control and communication.

For simplicity in this tutorial we focus on a simple structure of NCSs. From a general perspective of system structure, NCSs may contain two different structures [33]: the “direct structure” in Fig. 1.1 and the “hierarchical structure” in Fig. 1.2. The latter is different from the former as a local controller is present and the communication network is used to close the loop between the main controller and the local system. This structural distinction may have some theoretical as well as practical values, the latter, however, may be regarded as a hierarchical combination of the direct structured NCS and a conventional local control system and therefore it is not absolutely necessary to investigate the hierarchical structure as a brand new type of NCSs. In fact, most available works on NCSs to date have focused on the direct structure, which is also the main focus of this brief tutorial and the book.

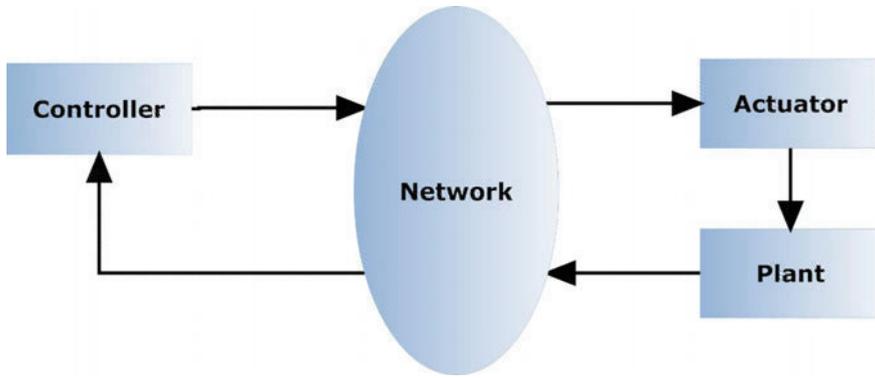


Fig. 1.1 Networked control systems in the direct structure

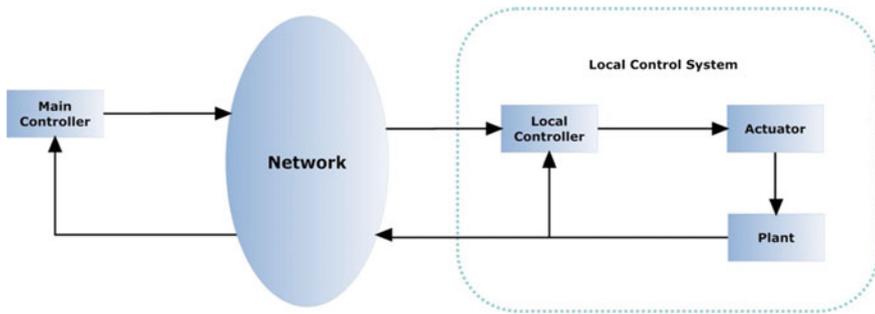


Fig. 1.2 Networked control systems in the hierarchical structure

1.2 Communicational Characteristics of NCSs

This section introduces the basics of NCSs, where the emphasis is on the differences between NCSs and conventional control systems, that is, the distinct and unique characteristics of NCSs that are brought by the inserted communication network.

1.2.1 Network Topology

In the presence of the communication network in the NCSs, the conventional control components including the sensor, the controller and the actuator work as network nodes. From this perspective, two issues need to be addressed, as follows.

1.2.1.1 Time-Synchronization

The control components need to be time synchronized to act properly. This is a fundamental basis of conventional control systems, but is usually missing in NCSs due to the use of the distributed communication networks [34]. Under certain conditions, time-synchronization in NCSs may not be a necessary condition if the network-induced delay in the backward channel is not required for the calculation of the control signals and/or the network-induced delay in the forward channel is not required for the implementation of the control actions. In some other cases, as discussed in [35, 36], time-synchronization together with the use of time stamps in NCSs can offer an advantage over conventional time delay systems since the backward channel delay is known by the controller and the forward channel delay (round trip delay as well) is known by the actuator. This advantage can then be used to derive a better control structure for NCSs as done in [35, 37].

1.2.1.2 Drive Mechanism

The sensor and the actuator can be driven either by time or event. The difference between the two drive mechanisms lies in the trigger method that initiates the control components. For the time-driven mechanism, the control components are triggered to work at regular intervals, while for the event-driven mechanism the control components are only triggered by predefined “events”. From a broad perspective time-driven can be regarded as a special case of event-driven, when the trigger events for the latter are chosen as the time. Therefore, it is no wonder why the event-driven mechanisms are more sophisticated and may require ancillary devices for it to work.

The sensor is usually time-driven, while the controller and the actuator can either be time-driven or event-driven. For more information on the drive mechanism for the control components, the reader is referred to [38–41] and the references therein. It is worth mentioning though, with different drive mechanisms different system models for NCSs are obtained and event-driven control components generally lead to a better system performance.

1.2.2 Packet-Based Data Transmission

The data in NCSs is encoded in the data packets and then transmitted through the communication network. A typical data packet is shown in Fig. 1.3. Packet-based transmission is one of the most important characteristics of NCSs that distinguishes it from conventional control systems [42–44]. This characteristic can mean that the perfect data transmission as assumed in conventional control systems is absent in NCSs, posing the most challenging aspect in NCSs. The communication constraints caused by the packet-based transmission in NCSs include the network-induced delay, data packet dropout, data packet disorder, etc., which are detailed in what follows.

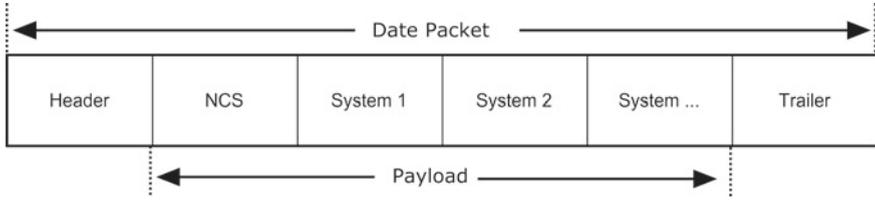


Fig. 1.3 The typical data packet structure where NCS is sharing the data packet with other applications

1.2.2.1 Network-Induced Delay

The transmission time for the data packets introduces network-induced delays to NCSs, which are well known to degrade the performance of the control systems.

There are two types of network-induced delays according to where they occur.

- τ_{sc} : Network-induced delay from the sensor to the controller, i.e., backward channel delay;
- τ_{ca} : Network-induced delay from the controller to the actuator, i.e., forward channel delay.

The two types of network-induced delays may have different characteristics [45]. In most cases, however, these delays are not treated separately and only the round trip delay is of interest [15, 46–48].

According to the types of the communication networks being used in NCSs, the characteristics of the network-induced delay vary, as follows [33, 49, 50].

- Cyclic service networks (e.g., Token-Ring, Token-Bus): Bounded delays which can be regarded as constant for most occasions;
- Random access networks (e.g., Ethernet, CAN): Random and unbounded delays;
- Priority order networks (e.g., DeviceNet): Bounded delays for the data packets with higher priority and unbounded delays for those with lower priority.

Network-induced delay is one of the most important characteristics of NCSs which has been widely addressed in the literature to date, see, e.g., [15, 46, 48, 51–60].

1.2.2.2 Data Packet Dropout

Data transmission error in communication networks is inevitable, which in the case of NCSs then produces a situation called “data packet dropout”. Data packet dropout can occur either in the backward or forward channel, and it makes either the sensing data or the control signals unavailable to NCSs, thus significantly degrading the performance of NCSs.

In communication networks, two different strategies are applied when a data packet is lost, that is, either to send the packet again or simply discard it. Using the

terms from communication networks, these two strategies are called Transmission Control Protocol (TCP) and User Datagram Protocol (UDP) respectively [34]. It is readily seen that with TCP, all the data packets will be received successfully, although it may take a considerably long time for some data packets; while with UDP, some data packets will be lost forever.

As far as NCSs is concerned, UDP is used in most applications due to the real-time requirement and the robustness of control systems. As a result, the effect of data packet dropout in NCSs has to be explicitly considered, as done in, e.g., [61–65].

1.2.2.3 Data Packet Disorder

In most communication networks, different data packets suffer different delays, which then produces a situation where a data packet sent earlier may arrive at the destination later, or vice versa, see Fig. 1.4. This phenomenon is referred to as data packet disorder. The existence of data packet disorder can mean that a newly arrived control signal in NCSs may not be the latest, which never occurs in conventional control systems. The control performance will be inevitably degraded if the control algorithm has not taken explicit consideration of the disordered data. Some preliminary works have been done, usually using an active compensation scheme [66–68].

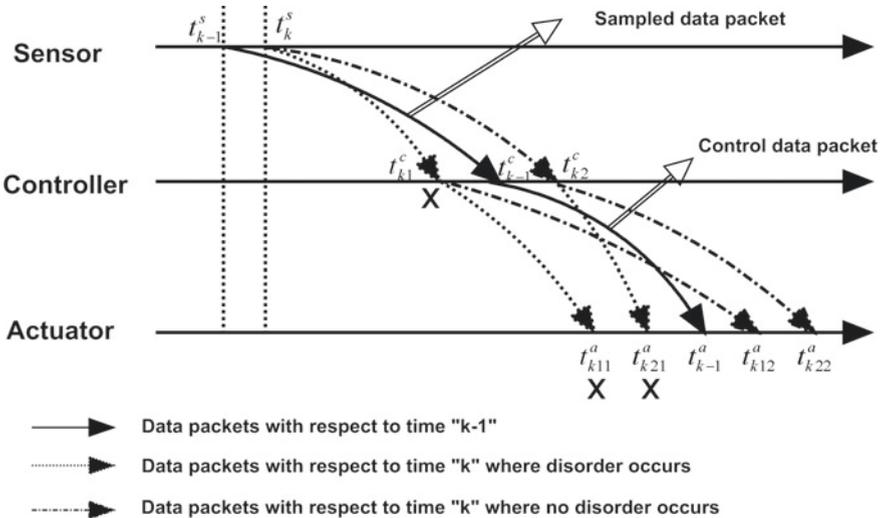


Fig. 1.4 Data packet disorder in NCSs

1.2.2.4 Single and Multi-packet Transmission

When the sensing data and the control signals are sent via data packets of the network, another situation occurs: in a case where, for example, multiple sensors are used and distributed geographically in NCSs and thus they send their sensing data separately to the controller over the network, the controller may have to wait for the arrival of all the sensing data packets before it is able to calculate the control actions, and if only one sensing data packet is lost, all the other sensing data packets have to be discarded due to incompleteness. We call this situation the “multi-packet” transmission of the data in NCSs.

Another situation in NCSs is where the sensing data or the control signals of multiple steps are sent via a single data packet over the network, since the packet size used in NCSs can be very large compared with the data size required to encode a single step of sensing data or control signal. This “single-packet” transmission of the data in NCSs is the fundamental basis of the so-called packet-based control approach [37].

1.2.3 Limited Network Resources

The limitation of the network resources in NCSs is primarily caused by the limited bandwidth of the communication network, which results in the following three situations in NCSs that are distinct from conventional control systems.

1.2.3.1 Sampling Period, Network Loads and System Performance

NCSs is a special class of sampled data systems due to the digital transmission of the data in communication networks. However, in NCSs, the limited bandwidth of the network produces a situation where, a smaller sampling period may not result in a better system performance which is normally true for sampled data systems [4, 25, 69–71].

This situation happens because, with too small a sampling period, too much sensing data will be produced; thus overloading the network and causing congestion, which will result in more data packet dropouts and longer delays, and then degrade the system performance. The relationship between the sampling period, network loads and system performance in NCSs is illustrated in Fig. 1.5. For example, when the sampling period decreases from the value corresponding to point “a” to “b”, the system performance is getting better as in conventional sampled data systems since the network congestion does not appear until point “b”; However, the system performance is likely to deteriorate due to the network congestion when the sampling period is getting even smaller from the value corresponding to point “b” to “c”. Therefore, the relationship shown in Fig. 1.5 implies that there is a trade-off between the period of sampling the plant data and the system performance in NCSs, that is, in