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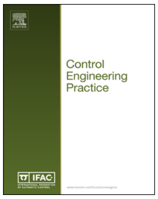

Reducing impact of network induced perturbations in remote control systems

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ABSTRACT

The practical realization of remote control systems enforces handling network-induced effects: information transfer and processing delay, delay variability, packet loss and reordering, etc. The paper presents a comparative study of algorithmic methods that assist the control law in achieving higher regulation quality by reducing the detrimental impact of network-related uncertainties. Three popular families of methods, encompassing dynamic delay compensators, multiple control loops, and adjustable sampling rate, are investigated in a common experimental framework that involves a benchmark plant – structurally unstable inverted pendulum-on-a-cart system – and commonly available modules and communication technologies. The method performance in relation to computational footprint and network load is discussed. For the delay with well-established trend of variation the dynamic compensator proves the most efficient option, while more sophisticated methods, involving the exchange of multiple pieces of information, are required under burst packet loss and in stochastic settings with aggravated randomness.

1. Introduction

While local plant control may nowadays be perceived well investigated, the problems of remote regulation and steering, or the control of distributed and networked control systems (NCSs) continue to attract significant attention of researchers and practitioners (Hokayem & Spong, 2006; Baillieul & Antsaklis, 2007; Hespanha, Naghshtabrizi & Xu, 2007; Gupta & Chow, 2010; Nuño, Basañez & Ortega, 2011; Postoyan, van de Wouw, Nešić & Heemels, 2014). Unlike local plant control, influencing the state of objects placed in separate locations requires signal exchange over a communication network, which is inherently uncertain. The information passed among the communicating parties may be lost, discarded as a result of errors, temporarily misplaced, and arrives with delay. Therefore, although gaining in popularity owing to the ease of installation, fault tolerance, economic benefits, or pure necessity (e.g. in hazardous environments), the remote control settings need extra measures to ensure consistency of the control process in the presence of network-induced perturbations (Dong & Kim, 2014; Heemels, Teel, van de Wouw & Nešić, 2010; Ignaciuk, 2015; Willig, 2008; Zhang, Gao & Kaynak, 2013).

A remote control system consists of at least two subsystems: a *local computer* that interacts with the plant through actuators, gathers sensor measurements, and provides a communication interface for the networked information exchange and a *remote computer* implementing the control logic and interacting with the plant via a data transmission network. Obviously, in order to elevate the quality of networked information exchange, e.g. in the effort to fulfill real-time requirements, robust communication media and high performance electronics can be used. However, the cost of such approach in terms of money and resources is prohibitive in many prospective applications, e.g. the systems of ambient intelligence (Acampora, Cook, Rashidi & Vasilakos, 2013). One would like to achieve similar control system performance using inexpensive devices and general-purpose networks rather than recur to large monolithic constructs with dedicated connectivity solutions. In addition to reducing costs, incorporating the modular designs with commonplace devices allows for providing the desirable active–active redundancy feature. The primary drawback of low-end solutions, in turn, is the increased level of system uncertainty related to the longer information transfer delays, larger delay variability (jitter), packet reordering, and higher loss rate. While in the circumstances of aggravated uncertainty the system stability can be preserved by implementing robust, sophisticated control laws (Ignaciuk & Bartoszewicz, 2011; Khanesar, Kaynak, Yin & Gao, 2015; Zhang & Lam, 2015), or throttling the responsiveness of linear controllers (Dasgupta, Halder, Banerjee & Gupta, 2015; Gao, Meng & Chen, 2008; Seuret & Gouaisbaut, 2014; Ignaciuk, 2016), the control quality cannot be improved unless the severity of perturbations themselves is mitigated. The objective of

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this work is to assess the performance of information processing algorithms and methods that alleviate the negative impact of network-induced perturbations in remote control systems. The control law is assumed already designed and the emphasis is placed on indicating a suitable method which by reducing the influence of inopportune networking phenomena (packet loss, communication jitter, etc.) will support the controller in achieving the desired regulation quality.

When handling the network-induced perturbations three classes of methods dominate the current literature (Zhang et al., 2013):

1. *Dynamic compensators*. Since the remote control configuration constitutes a time-delay system, in order to ensure closed-loop stability without downgrading efficiency, a delay compensator can be applied (Normey-Rico & Camacho, 2008). However, the compensators are sensitive to modeling mismatch, in particular to the improperly estimated loop delay. In order to address this issue, instead of a fixed value of the delay between the controller and the plant measured at the connection setup, the compensator may work with continuous updates of the internal model (Hu, Liu & Rees, 2008; Ignaciuk, 2014; Natori, Tsuji, Ohnishi, Hace, & Jezernik, 2010; Vatanski, Georges, Aubrun, Rondeau & Jämsä-Jounela, 2009), thus reducing the influence of jitter. Hence, the first group of the investigated methods concentrates on dynamic adjustment of the compensator operation (through delay measurements) to current networking conditions.
2. *Multiple control loops*. The control law implementation in a network environment allows for communicating richer information than in the classical one-loop configuration. Various pieces of information can be placed in the packets exchanged between the controller and the plant, thus creating a system with multiple (virtual) control loops. The local computer selects the control input corresponding to the current conditions in the communication system (e.g. the loop delay) which allows one to relieve restrictions of the static, one-loop constructs (Ignaciuk & Morawski, 2015; Zhang, Xia & Shi, 2013; Zhao, Liu & Rees, 2010).
3. *Variable sampling rate*. In order to improve the accuracy in local control implementation one may decrease the system sampling time and in this way lower the error between the continuous-time model of the physical process and its discrete-time representation used for the digital control purposes. In remote control systems, however, such an approach is often counterproductive (Dong & Kim, 2014; Peng, Yue & Han, 2012). Sending packets more frequently, e.g. at each sampling instant, disrupts the energy budget in serving more intense communication process, requires higher throughput, increases delay variability, and may lead to network congestion. Since the controllers in remote control systems are implemented digitally, one may dynamically adjust the sampling time to the current channel capabilities thus obtaining a switched system (Jungers & Daafouz, 2013; Truong & Ahn, 2015) with reduced amount of network traffic, loss rate, and delay variability.

The dynamic compensators (method 1) examine the changes of communication delay (through timestamp comparison) and adjust the value in the internal loop so that the discrepancy between the internal estimate and real delay is reduced. In this way, a more precise model is employed to predict the system behavior and thus obtain higher control quality. However, although conceptually straightforward and efficient, they may fail in the practical settings if the trend of delay changes cannot be well identified. As an alternative, by exchanging more information placed in one or multiple packets, one can create a control system with multiple feedback loops (method 2). Since the input at the plant corresponds to the control value calculated for the current feedback delay the impact of its variability is relieved. Moreover, the exchange of extended information allows one to mitigate the influence of data loss, however, at the expense of increased traffic and implementation complexity. Finally, the third concept assumes extending or contracting the sampling period according to delay fluctuations so that it matches the current loop delay. In this way, the NCS approaches a retarded one with unity delay and the jitter “trapped” inside one period. A possible drawback, in addition to increased network and computational load, is the requirement of obtaining good modeling representation of the controlled process sampled at different rates.

Each method tackles the network-related uncertainty in a different way, though with a common goal of reducing its detrimental impact on the control system performance. The objective of this work is to discuss characteristics of the described methods and comment on their performance in relation to the computational complexity, resource consumption, network overhead, etc., in various networking conditions. In contrast to the earlier studies, primarily limited to the computer simulations, or experiments emphasizing the characteristics of one chosen method, e.g. (Li, Zhang & Li, 2014), all three methods are tested within a common experimental platform and with the same controller type. As a result, a consistent framework for practical evaluation of different perturbation reduction concepts in NCSs is provided. Since the tests involve a benchmark, structurally unstable plant (inverted pendulum-on-a-cart), low-end devices, and general-purpose networks, the conclusions are applicable not only to industrial solutions but also customary systems, e.g. encountered in automated buildings. In addition to the implementation guidelines, application areas with respect to the specifics and severity of network-originating perturbations are identified. The experimental studies indicate that all three methods do improve the control quality in perturbed networked environment. The dynamic compensators prove efficient under low loss rate and jitter with slowly-varying average. Under aggravated uncertainty, the multi-loop constructs demonstrate overall superior performance to the adjustable sampling rate mechanism owing to better robustness to plant-related uncertainty, in particular in the settings with longer delays and discretization periods.

The paper is organized in the following way. The considered class of systems is formally introduced in Section 2. The fundamental issues related to choosing the control law are addressed in Section 3. Section 4 contains a detailed description of methods selected for the comparative study. The results of the conducted experiments are presented in Section 5. Finally, Section 6 comprises the conclusions.

Notation. The set of real numbers is denoted by $\mathbb{R}$, the set of integers by $\mathbb{Z}$, and positive integers by $\mathbb{Z}_+$. The vector and matrix variables are given in bold face with vectors denoted by lower case and matrices by capital letters. $\mathbb{R}^n$ denotes the space of n-dimensional real vectors, and $\mathbb{R}^{n\times r}$ the space of $n \times r$ real matrices.

2. Remote control setting

Consider the system depicted in Fig. 1. The plant dynamics are modeled as

$$\dot{\mathbf{x}}_{\mathbf{p}}(t) = \mathbf{F_c}\mathbf{x}_{\mathbf{p}}(t) + \mathbf{G_c}\mathbf{u}_{\mathbf{p}}(t) + \mathbf{d}_{\mathbf{p}}(t), \tag{1}$$

where t is a continuous variable denoting the evolution of time, $\mathbf{x}_{\mathbf{p}}(t) \in \mathbb{R}^n$ is the plant state vector, $\mathbf{u}_{\mathbf{p}}(t) \in \mathbb{R}^r$ is the input applied at the plant, $\mathbf{F_c} \in \mathbb{R}^{n\times n}$ and $\mathbf{G_c} \in \mathbb{R}^{n\times r}$for r, n $\in\mathbb{Z}_+$, and $\mathbf{d}_{\mathbf{p}}(t) \in \mathbb{R}^n$ represents the cumulative impact of model uncertainty and external disturbances.