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Research Article

A normalized PID controller in networked control systems with varying time delays ☆

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ABSTRACT

It requires not only simplicity and flexibility but also high specified stability and robustness of system to design a PI/PID controller in such complicated networked control systems (NCSs) with delays. By gain and phase margins approach, this paper proposes a novel normalized PI/PID controller for NCSs based on analyzing the stability and robustness of system under the effect of network-induced delays. Specifically, We take into account the total measured network delays to formulate the gain and phase margins of the closed-loop system in the form of a set of equations. With pre-specified values of gain and phase margins, this set of equations is then solved for calculating the closed forms of control parameters which enable us to propose the normalized PI/PID controller simultaneously satisfying the following two requirements: (1) simplicity without re-solving the optimization problem for a new process, (2) high flexibility to cope with large scale of random delays and deal with many different processes in different conditions of network. Furthermore, in our method, the upper bound of random delay can be estimated to indicate the operating domain of proposed PI/PID controller. Finally, simulation results are shown to demonstrate the advantages of our proposed controller in many situations of network-induced delays.

1. Introduction

Control systems based communication networks have rapidly developed and given many challenges to science and technology. As a typically promising model with control loops closed via a network, networked control systems (NCSs) have been widely applied to many fields including automotive, aerospace, robotic, manufactured industry, etc. On one hand, NCSs reduce implementation cost, increase flexibility in system design, and ease diagnostics and maintenance. On the other hand, due to inherent problem of such communication networks, NCSs always get involved with delays which can be constant, time varying or almost random [1,2]. The network-induced delays of NCSs mainly cause the control systems less performance and even unstable state.

From the view point of communication networks, delays can be mitigated by developing protocols. However, in terms of control system design, many researches have focused on analyzing the stability and the performance of system under the effect of delays [3,4], and new methods to design the controllers have been proposed to cope with delays [1,2,5–7,19,20,13], etc. These methods are primarily based on modern control theories and their creative combinations. Practically, they have been applied to several fields, especially, to industrial process control where PID is the most popular controller. PID controller is still useful for industrial process controlled over network thanks to its simplicity, low cost, and feasibility. Therefore, in NCSs, many researchers have proposed intelligent PID controllers [8–12,14–16,20]. Two advanced approaches usually used to design the PID controller are optimization [8,9,14] and LMI (linear matrix inequality) techniques [10,11].

The optimization technique is a powerful tool and popular to design the optimal PID controller for NCSs. For instance, in [8], consider the worst effect of network-induced delays, Pohjola obtained the parameters of controller from minimizing the cost function using ITAE (Integral Time Absolute Error) criterion. The disadvantage of this method is that it uses many times step response test to find the worst situation of system when the delays are random. Thus, it is difficult to apply in practice. In the same way, Eriksson [9] studied PID tuning rules for first-order plus dead-time process (FOPDT) under varying time-delays. Based on optimizing multi-objective function including ITAE criterion and the inverse of jitter-margin of system, the author proposed new

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tuning rules that not only give optimal performance but also remain robustness of system at the same level with AMIGO rules. Indeed, PID controller designed based on optimization technique provides high control quality while maintaining the robustness of system.

Another approach used to design robust PID controller for NCSs is LMI technique. The PID parameters for multi-input multi-output (MIMO) systems were given by solving the robustness problem of system under the effect of delays, packet dropout, measured noise and load disturbance [10]. The method is complicated but it gives excellent result when the system is MIMO and influenced by many damage sources.

Actually, the above designed PID controllers work well in NCSs with respect to a specific range of random delay. If the values of delay are not in this range, all optimal parameters of the PID controller must be found again for new adaption. In this case, besides complexity, although the optimal parameters can be found [8,14], they cannot guarantee the robustness of system as expected. That means the operating domain of proposed PID controller [8,14,10,11], which depends on process and network properties, has not been considered in the above references.

Motivated by the mentioned problems, we need to propose simple PI and PID controllers respectively for first-order and second-order plus dead-time processes (FOPDT and SOPDT) based on the gain and the phase margin specifications of system under the effect of delays. The PID tuning technique based on gain and phase margin specifications has been studied by many researchers in control systems [21–25], etc. In this paper, we use the same method to formulate the robustness of networked control system in the form of a set of equations. By solving this set of equations, we propose a novel normalized PI controller that meets the following requirements: (1) simplicity without re-solving the optimization problem for a new process, (2) high adaption to cope with large range of random delays, and (3) the upper bound of network-induced delay can be estimated to indicate the operating domain of PID controller so that the designers can decide whether to use it or not.

The paper is organized as follows. We present the system overview and design method in Section 2. In Section 3, the problem of designing PI controller for FOPDT process in NCSs is formulated and solved so that we obtain the normalized PI controller and also introduces the development of the normalized PI controller for SOPDT process. The advantages of proposed controllers are shown via simulations in Section 4. Finally, Section 5 concludes the paper.

2. System description

A typical model of networked control systems consisting of transfer functions is depicted in Fig. 1. $G_c(s)$ and $G_p(s)$ are the transfer functions of controller and process respectively. The controller and the process are connected over a particular network such as CAN, Profibus, Ethernet, Internet, etc. Two types of inevitable communication delays from controller to actuator and from sensor to controller are τ_{ca} and τ_{sc} respectively. They are assumed to be random and measurable [17]. In Fig. 1, practical processes with multiple lags, no-minimum phase zero, etc., can be reduced to FOPDT or SOPDT process by using simple analytic rules for model reduction [18]. Numerous PID tuning rules for FOPDT and SOPDT processes have been proposed in control systems, but they have not been studied well in NCSs.

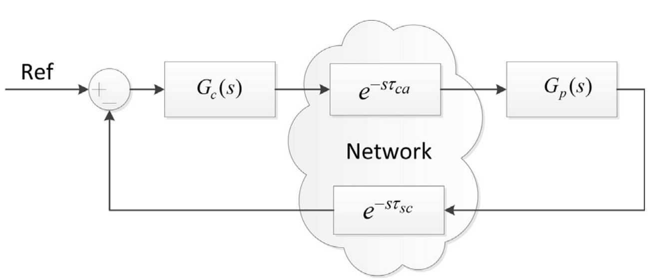

Fig. 1. Typical model of NCSs.

It is known that NCSs always involve delays that seriously affect the stability robustness and the performance of system. Therefore, leaving the system at a desired pre-specified point is a very important issue. To deal with this, a PI controller is proposed for FOPDT processes to meet specified gain and phase margins of system under the effect of delays. The PI parameters are tuned online based on the measurement of total random delays. To make the control signal smooth and thus increase the lifetime of the controller, the total measured delays are necessarily filtered by a low-pass filter before using to generate the control parameters [12].

For easy deployment, it requires the tuning rules to be presented in closed-forms or in tables of normalized values. Thus, the combination of closed-forms and tables of normalized values is used for our proposed PI tuning rules in this paper. Furthermore, it is challenging to design a controller that satisfies system requirements (i.e., stability and robustness) for a given process and a range of delays. To do so, we have to express an inequality constraint between the system requirements and the considered process and range of delays by analyzing the operating domain of the PI controller. It is important to state that the PID controller for SOPDT process is proposed based on the PI controller. All of these mentioned discussions are described in detail in the sequel.

3. Proposed normalized PI/PID controller

In this section, under the effect of network-induced delays, we first describe the problem formulations to form a set of equations of gain and phase margins for FOPDT process. We then propose the normalized PI controller and the allowable upper bound of the network-induced delays in an inequality constraint by solving this set of equations. Finally, we present the normalized PID controller for SOPDT process.

3.1. Problem formulations

From Fig. 1, the transfer functions of the PI controller $G_c(s)$ and the FOPDT process $G_p(s)$ are given by

$$G_c(s) = k_c\left(1 + \frac{1}{T_i s}\right) \tag{1}$$

$$G_p(s) = \frac{k_p}{1 + Ts} e^{-sL} \tag{2}$$

Let us denote $G(s)$ as the closed loop transfer function of system, A_m and ϕ_m as the specified gain and phase margins respectively, and τ_n as the total network time delay (i.e., summary of τ_{ca} and τ_{sc}). The $G(s)$ can be described in the form of

$$G(s) = \frac{G_c(s)G_p(s)e^{-s\tau_{ca}}}{1 + G_c(s)G_p(s)e^{-s\tau_n}} \tag{3}$$

Deriving from (3), the gain and phase margins of system are written as follows:

$$\arg[G_c(j\omega_p)G_p(j\omega_p)e^{-j\omega_p\tau_n}] = -\pi \tag{4}$$

$$A_m = \frac{1}{|G_c(j\omega_p)G_p(j\omega_p)e^{-j\omega_p\tau_n}|} \tag{5}$$