Robotics and Autonomous Systems 62 (2014) 319–329

Contents lists available at ScienceDirect

Robotics and Autonomous Systems

journal homepage: www.elsevier.com/locate/robot

Repetitive control of servo systems with time delays☆

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HIGHLIGHTS

- A novel repetitive control is proposed for the system with delays in control channels.
- Precise tracking and/or rejection of periodic signals are achieved.
- Only two parameters are required to be selected for control design.
- Sufficient stability conditions and the robustness analysis are studied.
- Simulation and experiments are provided to show the practicality of the design.

ARTICLE INFO

Article history:
Available online 10 October 2013

Keywords:
Turntable servo systems
Repetitive control
Time-delay
Periodic signals
Disturbance rejection

ABSTRACT

In many industrial robotic servo applications there is a need to track periodic reference signals and/or reject periodic disturbances. Moreover, time-delays are usually unavoidable in control systems due to the sensoring and communication delays. This paper presents an alternative repetitive control design for systems with constant time-delays in both forward and feedback control channels, which are dedicated to track/reject periodic signals. An additional delay is introduced together with the plant delays to construct an internal model for periodic signals, and a simple compensator based on the plant model inverse is utilized to stabilize the closed-loop system. Sufficient stability conditions of the closed-loop system and the robustness analysis against modeling uncertainties are studied. The proposed idea is further extended for general time-delay systems with only a delay term in the forward control channel. The "plug-in" structure used in conventional repetitive control designs is avoided, so that it leads to a simpler control configuration, i.e. only a proportional parameter and the cutoff frequency of a low-pass filter are required to be selected. Simulations based on a hard disk drive system and practical experiments on a rotary robotic servo system are provided to evaluate the effectiveness of the proposed method.

1. Introduction

For many industrial robotic servo applications, there is a need of control strategies to track periodic reference signals and/or reject periodic disturbances. Some examples in this context are power supply module with converters [1], robotic manipulators [2], optical disk drives [3–6] and rotary servo motors [7]. In this case, repetitive control [8–10] has been proved to be a powerful solution to achieve output tracking and disturbance rejection for periodic signals. In the repetitive control methodology, a time-delay element is used to construct an internal model for periodic signals such that the tracking or rejection capacity can be guaranteed according to the Internal Model Principle (IMP) [11]. In conventional repetitive control schemes (e.g. [1,3–6] and references therein), the repetitive control loop is superimposed upon a pre-designed feedback controller, which leads to the so-called "plug-in" or "add-in" structure with a complex control implementation.

On the other hand, in some industrial control systems, the controllers, sensors, and actuators may be located at different places and connected through communication channels for information or mass exchanges. This control configuration is particularly useful for the robotic applications of remote handling systems [12] and telerobotics [13], where the human's capacity to perform certain tasks is limited due to the severe environments and the long distance (e.g. handling hazardous material, underwater or space exploration [14]). Due to the sensoring and control signal transmission delays, such control systems usually involve unavoidable delays in both forward and feedback channels. Among those

☆ This work was supported by the National Natural Science Foundation of China under grant No. 61203066, 61273150 and by the Spanish Project DPI2010-15110. Parts of this work was presented in the 2012 FIRA & TAROS.

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http://dx.doi.org/10.1016/j.robot.2013.09.010

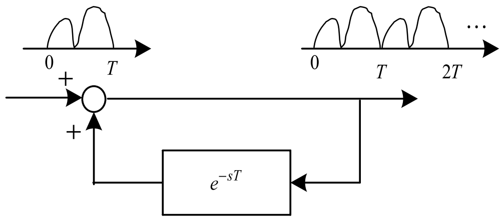

Fig. 1. Ideal internal model.

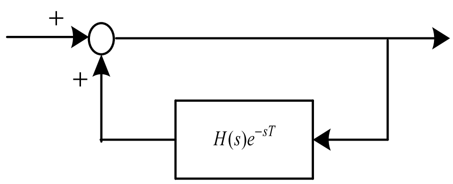

Fig. 2. Internal model with a low-pass filter.

available control approaches, e.g. adaptive control [12] and passivity-based control [13,15], the basic idea is to compensate for the effect of time-delays in the closed-loop dynamics. Moreover, the disturbance rejection is rarely studied.

To the best of our knowledge, only few work has been advanced for time-delay systems from the point of view of repetitive control, e.g. [16–18], which can tackle delays and disturbances. Inspired by this fact, we recently proposed several repetitive control frameworks for time-delay systems [19,20]. The main idea behind the proposed approach is to take advantages of the plant delay in the internal model design. However, a disturbance observer (DO) has to be adopted to eliminate external input/output disturbances in [19,20].

In this paper, the preliminary control design of [21] will be further developed for a class of continuous-time systems with delays in the forward and feedback control channels. Different to [19,20], the delays existing in both forward and feedback channels are considered, and the proposed control in this paper can guarantee the tracking and disturbance rejection simultaneously without using DO so that this control configuration is simpler. Compared to [21], we further introduce a compensation scheme for the induced phase shift of the low-pass filter such that the control performance can be further improved. Moreover, we exploit the relationship between the proposed case with two delays and the case with a single forward delay as [19,20], and generalize the current idea to the control of single delay systems. This control configuration is also clearly different to conventional control methodologies for time-delay systems, which are dedicated to compensate for the delay effect in the closed-loop transfer function (see [22] and references therein).

The proposed control employs inherent system delays and an additionally introduced delay to construct an internal model for periodic signals to be tracked or rejected, which will be included in a stable closed-loop. To address the closed-loop stability, a compensator based on the plant model inverse plus a proportional constant is introduced in an outer negative feedback loop. Sufficient conditions for the closed-loop stability are derived and robust stability against modeling errors (e.g. parameter uncertainties and time-delay errors) is investigated. Compared to the traditional repetitive controllers with a "plug-in" (or "add-on") structure [1,3–6], the proposed scheme provides a simpler control design and implementation requiring only the cutoff frequency of a low-pass filter and a proportional gain to be chosen.

The efficacy of the suggested control approach is demonstrated for versatile turntable systems (e.g., hard disk drive (HDD) system and rotary servo motor system). From the viewpoint of robotic application, turntable systems are of significant importance. They have been widely used in aerospace systems and industrial production (e.g. turntable-based robots supporting plasma spraying [23]). These robotic servo systems are inevitably affected by repetitive production disturbances and unavoidable sensoring and transmission delays, i.e. the suggested control approach is highly suitable to deal with these issues. Thus, simulation on a HDD system [24,25] and experimental results on a rotary servo system [20] are all provided.

The remainder of this paper is organized as follows: the problem formulation and some preliminaries on the repetitive control are given in Section 2; Section 3 presents the repetitive control scheme, the stability criterion and the robustness analysis; The special case with only a forward delay is studied in Section 4; Simulations and practical experiments are provided in Section 5, and conclusions are given in Section 6.

2. Problem statement and preliminaries

2.1. Repetitive control basis

Repetitive control has been developed based on the IMP [11]. The IMP claims that if a certain signal must be tracked or rejected with null steady-state error, the generator of this signal must be included in the control loop, in the controller, or in the plant itself.

For a T-periodic signal $r(t)$, the following Fourier series can be derived

$$r(t) = \sum_{n=-\infty}^{\infty} a_n e^{j\frac{2\cdot n\cdot\pi\cdot t}{T}} \tag{1}$$

where $a_n \in \mathbb{C}$ are the Fourier series coefficients. Then the following generator (internal model) can be utilized in the control loop

$$R(s) = \frac{1}{s}\prod_{n=1}^{\infty}\frac{\left(\frac{2n\pi}{T}\right)^2}{s^2+\left(\frac{2n\pi}{T}\right)^2} \tag{2}$$

which can be stated in a closed form [26] as

$$R(s) = \frac{Te^{-Ts/2}}{1-e^{-Ts}}. \tag{3}$$

Since $Te^{-Ts/2}$ is a delay term with a gain T, it is sufficient to include the internal model $R(s) = \frac{1}{1-e^{-Ts}}$ in the control loop [7], which can be implemented as a positive feedback loop with e^{-Ts} in the feedback path (Fig. 1). This internal model learns a signal of length T and repeats it as a periodic signal if the input to the system is set to zero. From the frequency point of view, this internal model contributes with infinity gain at frequencies $n/T, \forall n \in \mathbb{Z}$. This property can guarantee zero-error tracking at these frequencies if this internal model is introduced in the open-loop transfer function of a stable closed-loop system [11]. In order to improve the robustness, the internal model shown in Fig. 1 is usually modified by introducing a low-pass filter $H(s)$ inside its feedback loop (see Fig. 2), which must be designed making a trade-off between the robustness and the tracking performance [7,9].

2.2. Problem formulation

This paper is dedicated to extend the principle of repetitive control to systems with time delays in both forward and feedback channels. The practical application covers many industrial control systems, e.g. telerobotics [13]. The overall diagram of such control systems can be found in Fig. 3. In this kind of control systems, the controller, the sensors, and the actuators may be located at different places so that substantial delays τ_i, $i = 1, 2$ are introduced due to the sensoring and control signal exchanges.