Robotics and Autonomous Systems 58 (2010) 676–683

Contents lists available at ScienceDirect

Robotics and Autonomous Systems

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

A modified adaptive controller design for teleoperation systems

K. Hosseini-Suny [a], H. Momeni [a], F. Janabi-Sharifi [b,*]

[a] Departmental of Electrical Engineering, Tarbiat Modares, Tehran, Iran

[b] Robotics, Mechatronics, and Manufacturing Automation Laboratory (RMAL), Department of Mechanical and Industrial Engineering, Ryerson University, Toronto, Ontario, Canada, M5B 2K3

ARTICLE INFO

Article history:
Received 25 August 2007
Received in revised form
9 November 2009
Accepted 17 November 2009
Available online 22 November 2009

Keywords:
Time delay
Model reference adaptive controller
Feedforward compensator
Command generator tracker
Passive system
Teleoperation system

ABSTRACT

In this paper, a new adaptive controller is proposed to ensure the stability and good performance of a teleoperation system while a wide range of time delays is considered. For this means, a feedforward compensator is designed to ensure system passivity and then a new model reference adaptive controller (MRAC) is developed to provide good performance. The developed system demonstrates good stability and force tracking capabilities. A command generator tracker (CGT) is designed for a sample teleoperation system and the results are compared with the proposed system.

1. Introduction

Teleoperation systems have found many applications in the past decade [1]; however, these systems pose a challenge due to the time delay introduced by the transmission line. The presence of a time delay in most teleoperation systems makes them unstable and/or demonstrate undesired performance. Tests conducted have revealed that the cycle time (the time lapse between sending and receiving a signal) for systems on low Earth orbit (LEO) is at least 0.4 s, whereas for systems on the surface of the moon it is about 3 s. By considering the time taken for computer processing in the satellite and also on the Earth, the measured values would reach about 6 s. Therefore, in the present paper, the maximum time delay of 7 s for the transmission channel is considered and a new approach for controlling such systems is proposed. Due to the importance of stability and performance issues in teleoperation systems, many researchers have focused their efforts on solving these issues.

Anderson and Spong [2] presented a passive model for the transmission channel which improved the system stability against large magnitudes of time delay. However, their control algorithm was not able to respond properly to the master robot and the slave robot against variations of environmental parameters. Leeraphan and Marieewarn [3], by employing variable gain, made the transmission channel passive at any moment of time and consequently improved the system stability, but the system response did not have a proper tracking. Ryu and Hannaford [4] presented a controller and an observer for making a teleoperation system passive. The task of the observer was to report required signals for evaluating the system passivity, whereas the controller made the entire system passive. The simulation responses indicated that viewing signals in real time was problematic for the software used and required more research. In 1991, Niemeyer and Slotine [5] used wave variables to make the transmission channel passive, and in 1997 [6] they used a filter in the path of wave variables to decrease the tracking error of the position between the master robot and the slave robot, and in doing so, they also transmitted their integrals alongside wave variables. One year later [7], they noted that the signal distortion due to fluctuations in the time delay created a tracking error and lost system passivity. Therefore they decided to integrate the wave and the energy and then send it alongside the wave variables, while they also proposed the use of a restoration filter in the receiver to make the system passivity independent of the channel delay.

In 2004, Ueda and Yoshikawa [8] discussed the use of a filter to improve the system response against the time lag over the transmission channel. In 2004, Love and Book [9] calculated the impedance of a remote site, using the method of least returned

* Corresponding author. Tel.: +1 416 979 5000x7097; fax: +1 416 979 5265.
E-mail addresses: Kamal_hosseini@yahoo.com (K. Hosseini-Suny), Momeni_h@modares.ac.ir (H. Momeni), fsharifi@ryerson.ca (F. Janabi-Sharifi).

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doi:10.1016/j.robot.2009.11.006

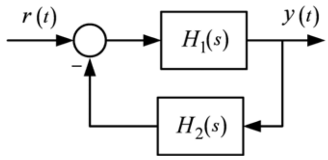

Fig. 1. A closed-loop system.

squares in real time and, by employing a new method for power reflection, reduced the amount of energy required by the operator to carry out the intended operations. Recently, Hosseini et al. extended their group's previous work on augmenting a Smith predictor and wave variables for time delay prediction [10–12]. In their work [10], they proposed an adaptive controller for improving the system performance and response against large delays over the transmission channel. The recent focus of the authors has been on time delay estimation and output prediction [11,12]. A work closely related to the method proposed in this paper is the command generator tracking (CGT) approach, which was proposed in [13] and is based on model reference adaptive control (MRAC) [14] and appropriate compensator design [14–17]. The CGT method is, however, limited to proportional–integral (PI) control design within an MRAC framework. A generalized approach based on MRAC and coupled with a feedforward compensator is required to allow integration of linear control strategies other than PI.

This paper contributes by proposing a controller design that is based on MRAC and a feedforward compensator (FFC) parallel to the plant such that the stability is ensured for a wide range of time delays and, in meanwhile, good tracking performance is preserved. Methodologically, the proposed approach extends the previous CGT work [13,15,16] by allowing the accommodation of any linear control method within the proposed MRAC–FFC framework. The organization of this paper is as follows. Section 2 discusses the design of the feedforward compensator (FFC) augmented with the plant in order to make the process passive. Section 3 provides a new method of designing a model reference adaptive control for the augmented plant to improve system tracking. Section 4 gives a review of a CGT controller design. Section 5 provides the simulation results and compares the results with the previous relevant work, e.g., CGT. Section 6 contains the conclusions.

2. Designing a feedforward compensator (FFC) to make the process passive

The first integral part of our controller is designing a feedforward compensator (FFC) parallel to the plant to make the plant with uncertainty and time delays passive. Our proposed design is based on the results obtained in [13–16] as follows.

Given a closed-loop system (Fig. 1), the purpose of system stabilization would be to make H_1 strictly output passive, if the controller H_2 is passive [14]. Therefore, in order to make the system passive, we will use a parallel feedforward compensator $H(s)$, namely an FFC, on the basis of the following theorems. For this purpose, one can consider the augmented plant transfer function as $G_a(s) = G_p(s) + H(s)$, where $G_p(s)$ is the actual plant transfer function. The following theorems give the design conditions for $H(s)$.

Theorem 1. *If $G_a(s) = H(s) + G(s)\mathrm{e}^{-ds}$ is strictly positive real, then $G_a(s)$ will be strictly output passive.*

Proof. See Appendix A. □

In the above theorem, d is the time delay and the actual plant includes delay in the form of

$$G_p(s) = G(s)\mathrm{e}^{-ds}, \tag{1}$$

with $G(s)$ as a rational transfer function:

$$G(s) = \frac{b_m s^m + b_{m-1}s^{m-1} + \cdots + b_0}{a_n s^n + a_{n-1}s^{n-1} + \cdots + a_0}. \tag{2}$$

Without loss of generality, one can assume that the parameters of a plant can be changed in a defined range.

$$\begin{aligned} &\underline{b}_{m-j} \le b_{m-j} \le \bar{b}_{m-j}, \quad j = 0, 1, \ldots, m \\ &\underline{a}_{n-j} \le a_{n-j} \le \bar{a}_{n-j}, \quad j = 0, 1, \ldots, n. \end{aligned} \tag{3}$$

The above theorem implies that, in order to make the augmented plant $G_a(s)$ strictly output passive, the condition of strictly positive real must be satisfied using the following theorem.

Theorem 2. *If a feedforward compensator $H(s)$ is designed according to the following conditions, then the augmented process of $G_a(s) = G_p(s) + H(s)$ with plant perturbations will be almost strictly positive real (ASPR).*

(1) *$H(s)$ is stable with relative degree one.*
(2) *The augmented nominal plant $G_0(s) + H(s)$ is ASPR.*
(3) *$\tilde{\Delta}(s) \in RH_\infty$ and $\|\tilde{\Delta}(s)\|_\infty < 1$, where $\tilde{\Delta}(s) = \frac{G_0(s)W(s)}{G_0(s)+H(s)}$ is the uncertainty of the augmented plant.*

Proof. Provided in [13]. □

In the above theorem, $G_0(s)$ is the nominal transfer function of $G(s)$ using the nominal values of the parameters, $\tilde{\Delta}(s)$ is the additive perturbation of the augmented plant, and $W(s)$ denotes the upper bound of combined plant uncertainty, $\Delta(s)$, that will be introduced in Eq. (8). By introducing additive and multiplicative uncertainties, $\Delta_a(s)$ and $\Delta_m(s)$, respectively, as follows,

$$\Delta_a(s) = G(s) - G_0(s), \tag{4}$$

$$\Delta_m(s) = \mathrm{e}^{-ds} - 1, \tag{5}$$

we can write the actual process under control by the following equation:

$$G_p(s) = (G_0(s) + \Delta_a(s))(I + \Delta_m(s)). \tag{6}$$

If the combined uncertainty, $\Delta(s)$, is defined by

$$\Delta(s) \equiv \Delta_m(s) + G_0^{-1}(s)\Delta_a(s)(I + \Delta_m(s)), \tag{7}$$

we can write the actual plant using Eq. (6) as

$$G_p(s) = G_0(s)(I + \Delta(s)). \tag{8}$$

The uncertainty $\Delta(s)$ is a function of the plant parameters, which vary in a given range. Given a plant and the estimated upper bound of delay time and range of plant parameter drift, Eqs. (4)–(7) allow one to approximate $W(s)$. Next, an appropriate $H(s)$ can be designed to satisfy conditions 1–3 of Theorem 2. Conditions 1 and 3 can be readily checked. Condition 2 of Theorem 2 can be tested by checking if (i) $\Theta(s) \equiv G_0(s) + H(s)$ has no poles on the right-hand side of the $j\omega$ axis, and in the case of poles on the $j\omega$ axis or at infinity, they are simple with positive residues; and (ii) $\mathrm{Re}(\Theta(j\omega)) \ge 0$ [14].

Therefore, noting the above theorems, a feedforward FFC, $H(s)$, can be designed to make the process strictly output passive [14], and a model reference adaptive controller can be designed to provide closed-loop system stability. The point of significance here which must be accounted for is that by making the feedforward compensator parallel with the process, an appropriate design of the adaptive controller block of the model reference can ensure good tracking performance.