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A comparison between optimization algorithms applied to synchronization of bilateral teleoperation systems against time delay and modeling uncertainties

Hamid Shokri-Ghaleh, Alireza Alfi*

Faculty of Electrical and Robotic Engineering, Shahrood University of Technology, Shahrood 36199-95161, Iran

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ABSTRACT

The goal of this paper is to achieve optimal performance for synchronization of bilateral teleoperation systems against time delay and modeling uncertainties, in both free and contact motions. Time delay in bilateral teleoperation systems imposes a delicate tradeoff between the conflicting requirements of stability and transparency. To this reason, in this paper, population-based optimization algorithms are employed to tuning the proposed controller parameters. The performance of tuned controllers is compared with the gains obtained by Cuckoo Optimization Algorithm (COA), Biogeography-Based Optimization (BBO), Imperialist Competitive Algorithm (ICA), Artificial Bee Colony (ABC), Particle Swarm Optimization (PSO), Genetic Algorithm (GA), Ant Colony Optimization with continuous domain (ACOR), Self-adaptive Differential Evolution with Neighborhood Search (SaNSDE), Adaptive Differential Evolution with Optional External Archive (JADE), Differential Evolution with Ensemble of Parameters and mutation strategies (EPSDE) and Cuckoo Search (CS). Through numerical simulations, the validity of the proposed method is illustrated. It is also shown that the COA algorithm is able to solve synchronization problem with high performance in stable transparent bilateral teleoperation systems.

Introduction

Over the past two decades, stability analysis and control design problems of the time delay systems have drawn an increasing attention. Teleoperation systems are one of the most well-known areas of such systems, which are widely applied to carry out complex tasks in hazardous environments such as handling materials; or inaccessible environments such as telesurgery exploring and exploiting the seas and space. A teleoperation system is composed of five interconnected components as shown in Fig. 1.

The teleoperation system is said to be bilateral if the information signal flows in both directions between master and slave robots. The master robot is directly driven by the human operator in the local environment, whereas the slave robot is located in the remote environment, ready to follow commands that human operator orders by moving the master. If the slave accurately reproduces the master's commands and the master correctly feels the slave forces, the human operator experiences the same interaction as the slave would. This is called transparency in teleoperation systems.

Time delay occurs during signal transfer between the master and slave robots in teleoperation systems, which can destabilize the systems. To compensate the time delay, different schemes are available [1–11]. An extensive survey of bilateral teleoperation schemes can be found in Ref. [8]. Based on the terminology provided in Ref. [9], three categories can be considered for teleoperation systems including (i) scattering-based schemes [1,2], (ii) damping injection schemes [12,13], (iii) adaptive schemes [14–16]. Other control schemes can be also found in Refs. [17–20]. Therefore, main challenge in the teleoperation systems is the selection of the control architectures as well as controller parameters. Generally the main shortcoming of the controller design is that it leads to non-optimality of the resulting controller.

To achieve optimal performance, the most elegant and precise numerical techniques are gradient descents. These techniques have some fundamental issues including their dependence on unrealistic assumptions such as unimodal performance and differentiability of the performance function [21]. In addition, they are easily getting trapped into local optimum depending on the initial guess of solution. Once the model structure exhibits nonlinear performance, this approach often fails in finding a global optimum and becomes ineffective [22–25]. To overcome this shortage, modern optimization algorithms with stochastic search

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* Corresponding author. Tel.: +98 23 32300250.
E-mail address: a_alfi@shahroodut.ac.ir (A. Alfi).

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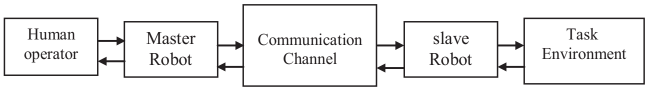

Fig. 1. General structure of the bilateral teleoperation systems.

techniques have been proposed in literatures such as Genetic Algorithm (GA) and Particle Swarm Optimization (PSO) and they have been successfully applied in different optimization problems [26–30]. Although GA and PSO are alternative approaches for the problem, they always encounter premature convergence and their convergence rates are not thus satisfactory when dealing with some complex or multimodal functions. To handle this problem, many researchers incorporated different search and heuristic techniques [31–49], like Imperialist Competitive Algorithm (ICA) [32,35,37], Biogeography-based optimization (BBO) [33,40], Artificial Bee Colony (ABC) [36,39,41], Cuckoo Optimization Algorithm (COA) [38,42], Ant Colony Optimization with continuous domain (ACOR) [44], Self-adaptive Differential Evolution with Neighborhood Search (SaNSDE) [45], Adaptive Differential Evolution with Optional External Archive (JADE) [46], Differential Evolution with Ensemble of Parameters and mutation strategies (EPSDE) [47] and Cuckoo Search (CS) [48].

Until now, few works have been reported for teleoperation controller design using the optimization algorithms. In Ref. [49], H_∞ controller design based on hierarchical GA proposed. In Ref. [50], evolutionary programming has been used for designing the self-tuning controller of teleoperation system. The main drawback of the former approaches is that the time delay in communication channel has not been considered. Considering the effect of time delay on the stability, a controller has been designed using GA in Ref. [51].

Motivated by the aforementioned research, the contribution of this paper is to achieve an optimal controller design for bilateral teleoperation systems for reducing time delay effects as well as modeling uncertainty, in both free and contact motions. The control framework used in this paper is adopted from Ref. [51]. In this paper, to optimize the parameters of synchronization control laws, the optimization algorithms including COA [38], BBO [33], ICA [32], ABC [34], PSO [55], GA [56], ACOR [44], SaNSDE [45], JADE [46], EPSDE [47] and CS [48] are employed. According to our knowledge, this is the first research to apply aforementioned algorithms except GA for synchronization problem for controlling of the teleoperation systems. Results show that the performance of COA is superior to other algorithms.

The paper is organized as follows. In Preliminaries section, a general description of the teleoperator system is presented, and assumptions are introduced. In Control design section, the control objective and the controller design is formulated. Simulation results are discussed in Simulations section. Finally, conclusions are given in the last section.

Preliminaries

This section presents the dynamical model of the nonlinear teleoperator together with the assumptions needed for the stability analysis of the controller covered in this paper.

Dynamic model of the teleoperator

In this paper, the master and slave robot dynamics with n-degree-of-freedom are assumed to be modeled as

$$M_m(q_m)\ddot{q}_m + C_m(q_m, \dot{q}_m)\dot{q}_m + g_m(q_m) = F_h + \tau_m \tag{1}$$

$$M_s(q_s)\ddot{q}_s + C_s(q_s, \dot{q}_s)\dot{q}_s + g_s(q_s) = \tau_s - F_e \tag{2}$$

where $q_i, \dot{q}_i, \ddot{q}_i \in R^n$ denote the joint position, velocity and acceleration, respectively; $M_i(q_i) \in R^{n\times n}$ is the positive definite inertia matrices; $C_i(q_i, \dot{q}_i) \in R^{n\times n}$ is the matrix of centripetal and coriolis torques; $g_i(q_i) \in R^n$ the gravitational torque; $F_h, F_e \in R^n$ indicate the forces at the joints due to the forces exerted by the human and the environment interaction, respectively; $\tau_i \in R^n$ is the applied torque; $i = m, s$ stands for the master and the slave, respectively.

In these equations, there are some fundamental properties [52].

Property 1. The inertia matrix $M(q)$ is symmetric positive definite and there exist lower and upper bounds, i.e.,

$$0 < \lambda_m\{M_i(q_i)\}I \le M_i(q_i) \le \lambda_M\{M_i(q_i)\}I \tag{3}$$

where I is the identity matrix with the corresponding condition, λ_m and λ_M represent the minimum and the maximum Eigen values of $M_i(q_i)$, respectively.

Property 2. The matrix $\dot{M}_i(q_i) - 2C(q_i, \dot{q}_i)$ is skew symmetric, i.e.,

$$\eta^T(\dot{M}_i(q_i) - 2C(q_i, \dot{q}_i))\eta = 0, \qquad \forall \eta \in R^n \tag{4}$$

Property 3. The dynamics are linearly parameterizable. Therefore,

$$M_i(q_i)\ddot{q}_i + C_i(q_i, \dot{q}_i)\dot{q}_i + g_i(q_i) = Y_i(q_i, \dot{q}_i, \ddot{q}_i)\theta_i \tag{5}$$

where $Y_i(q_i, \dot{q}_i, \ddot{q}_i) \in R^{n\times p}$ is a matrix of known functions and $\theta_i \in R^p$ is a constant vector of the manipulator physical parameters, which is unknown.

General assumptions

The control schemes presented in this paper rely on the following assumptions:

Assumption 1. Both human operator and task environment are passive.

Assumption 2. The time delay in the communication channel $T > 0$ exists between the master and the slave symmetrically.

Control goals

For the synchronization control strategy, firstly the goals need to be clarified. The main goals can be itemized as follows.

Goal 1: The closed-loop of the overall system must be stable, in both free and contact motions, independent of the constant time delay.

Goal 2: The position tracking between the master and the slave robots must be guaranteed. It means that the slave output q_s has to follow the master output q_m with an acceptable accuracy.

Goal 3: Force tracking must be guaranteed in contact motion. It means that the environment reflecting force F_e has to follow the operator force F_h.

Define position synchronization errors between the master and the slave as follows:

$$e_m(t) = q_s(t - T) - q_m(t) \tag{6}$$

$$e_s(t) = q_m(t - T) - q_s(t) \tag{7}$$

Therefore, the bilateral teleoperation is said to state synchronize if

$$\lim_{t\to\infty} e_m(t) = \lim_{t\to\infty} e_s(t) = 0 \tag{8}$$

As a result, from Eq. (8), the master/slave robots states synchronize if the coordination errors and their derivatives approach the origin asymptotically [16]. In contact motion, the force tracking errors can be also defined as

$$e_{fm}(t) = F_e(t - T) - F_h(t) \tag{9}$$