ISA Transactions ∎ (∎∎∎∎) ∎∎∎–∎∎∎

Contents lists available at ScienceDirect

ISA Transactions

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

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Research article

Robust H_∞ cost guaranteed integral sliding mode control for the synchronization problem of nonlinear tele-operation system with variable time-delay

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ARTICLE INFO

Article history:
Received 21 July 2017
Received in revised form
25 September 2017
Accepted 19 October 2017

Keywords:
Tele-operation
Nonlinear dynamics
Time varying-delay
Sliding mode control
Delay-dependent stability
LMI
Integral sliding mode control
H∞

ABSTRACT

This paper is devoted to the synchronization problem of tele-operation systems with time-varying delay, disturbances, and uncertainty. Delay-dependent sufficient conditions for the existence of integral sliding surfaces are given in the form of Linear Matrix Inequalities (LMIs). This guarantees the global stability of the tele-operation system with known upper bounds of the time-varying delays. Unlike previous work, in this paper, the controller gains are designed but not chosen, which increases the degree of freedom of the design. Moreover, Wirtinger based integral inequality and reciprocally convex combination techniques used in the constructed Lypunove-Krasoviskii Functional (LKF) are deemed to give less conservative stability condition for the system. Furthermore, to relax the analysis from any assumptions regarding the dynamics of the environment and human operator forces, H_∞ design method is used to involve the dynamics of these forces and ensure the stability of the system against these admissible forces in the H_∞ sense. This design scheme combines the strong robustness of the sliding mode control with the H_∞ design method for tele-operation systems which is coupled using state feedback controllers and inherit variable time-delays in their communication channels. Simulation examples are given to show the effectiveness of the proposed method.

1. Introduction

Tele-operation systems extend human functionality to be applied over long distances to perform tasks or to manipulate objects in inaccessible areas. Providing stable feedback is an essential requirement in bilaterally controlled tele-operation systems, where time-delay inherited in the communication channel between the master and slave systems is the major challenge that threatens system stability. Moreover, in practical networked tele-operation systems external disturbance and uncertainty in the dynamic model parameters are unavoidable issues that should be considered in order to ensure stable tele-operation system with optimal performance for the designed synchronization controller [1–6].

To overcome these challenges many control techniques have been used in the literature started with Anderson and Spong [7,8] whom used scattering theory to stabilize the communication channel that is affected by sustainable time-delay. Followed by Niemeyer and Slotine who suggested wave variables theorem which is based on a modified structure of the scattering theory. However, these techniques were criticized for steady state errors and position drift [9–12]. Many other control schemes were applied for the synchronization problem of tele-operation systems such as sliding mode control (SMC) [13–16], model predictive control [17], adaptive control schemes [18–20], as well as state feedback controllers that are based on LKF stability analysis (see e.g. [21,22,5,2,23–33]). Some results are addressing the design of state feedback controller for linear tele-operation system with delay using H_∞ design method with prescribed disturbance attenuation parameter (γ) see e.g. [34–39]. For detailed description of these methods, interested reader can refer to [40–43] for comprehensive reviews. LK methodology is applied successfully in developing delay-dependent stable controller, but with assuming passive environment and passive human operator, i.e the human force acting on the master device (F_h) and the environment force acting on the slave device (F_e) should comply with the assumption given below, see e.g., [44–48]:

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http://dx.doi.org/10.1016/j.isatra.2017.10.009
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$$\int_0^t F_h(s)\dot{q}_m(s)ds - \int_0^t F_e(s)\dot{q}_s(s)ds \geq 0$$

For the best of the authors' knowledge, there are only very few results that consider the effect of the exogenous inputs from the human operator, and from the environment forces, without any prior assumption regarding their dynamics.

Strong robustness offered by SMC to handle uncertainties, perturbation and bounded external disturbance make it popular technique in the control of robotic systems. An appropriately designed SMC can provide robust and insensitive behaviour with the existence of system uncertainties. SMC design is based on constructing sliding mode surface that represents an ideal behaviour to be followed by a system, then design a proper controller to drive the system to the sliding surface designed before [49]. The robustness of the SMC is ensured during the sliding phase but not during the reaching phase i.e., during the reaching phase the system is still sensitive to the external disturbances and system uncertainties. Different structures of SMC has been applied successfully in many applications of tele-operation systems see for instance, [50,51] where conventional sliding mode controllers are designed, while nonlinear sliding mode controllers are used in [52–55], in addition to Finite-Time Sliding Mode Control (FTSMC) which is used to provide finite-time synchronization in [56–58]. Most of the existing literature considers only constant time-delay and there are only a few studies that consider the effect of varying time-delay on the designed SMC within the form of delay-dependent stability framework. Furthermore, to guarantee the robustness of the controlled system during the entire operation Integral Sliding Mode Controller (ISMC) is proposed in this paper. ISMC can actually eliminate the reaching phase, and force the system to start on the sliding surface, and hence global robustness is guaranteed [49].

Inspired by the above discussion, the contribution of this paper can be summarized in the following points:

- To bring together the merits of LyapunovKrasovskii design methodology and the robustness property of SMC into the control design of tele-operation systems, in this paper a robust ISMC for position synchronization of tele-operation systems with time varying-delay, parameters uncertainty and disturbances is proposed. Sufficient conditions for the delay-dependent stability of the designed ISMC is proposed and formalized as Linear Matrix Inequality (LMI), then solved using LMI toolbox of Matlab to obtain controller gains based on the values of the upper and lower bounds of the time varying-delay.
- The assumption of passive human operator force and passive environment force $\int_0^t F_h(s)\dot{q}_m(s)ds - \int_0^t F_e(s)\dot{q}_s(s)ds \geq 0$ is relaxed, and H_∞ design method is utilized to develop delay-dependent stability criteria that are robust against the external admissible forces from the environment and human operator within a prescribed performance index.
- The design, analyses and synthesis in this paper are conducted by considering two cases; first the velocity measurements is assumed to be available in addition to the position measurements. While in the second case, the analysis and design are conducted depending on the position measurements only.

1.1. Notations

The set of all real numbers, positive numbers, and positive numbers and zero are denoted by $\mathbb{R}$, $\mathbb{R}^+$, and $\mathbb{R}_0^+$ respectively; the n-dimensional Euclidean space over $\mathbb{R}$ is denoted by $\mathbb{R}^n$; the space of $n \times m$ matrices, and the space of symmetric matrices are symbolized by $\mathbb{R}^{n\times m}$ and $\mathbb{S}^n$ respectively; * denotes symmetric parameters in a symmetric matrices; $\mathbf{0}$ is a zero matrix with appropriate dimension; $\otimes$ is the Kronecker product operator; I_n is the $n \times n$ identity matrix; $diag(.)$ is refering to diagonal matrix; $|.|$ is the absolute value; λ is the matrix eigenvalue; $sig(c)^a = |c|^a sign(c)$; and $sign(.)$ is the standard signum function.

2. System description and preliminaries

The following nonlinear dynamic model is considered in this paper:

$$\begin{aligned} M_m(q_m)\ddot{q}_m + C_m(q_m, \dot{q}_m)\dot{q}_m + G_m(q_m) &= \tau_m + \tau_{dm} + \tau_h, \\ M_s(q_s)\ddot{q}_s + C_s(q_s, \dot{q}_s)\dot{q}_s + G_s(q_s) &= \tau_s + \tau_{ds} - \tau_e, \end{aligned} \tag{1}$$

where the indices m and s refer to the master and slave respectively; and $q_i, \dot{q}_i, \ddot{q}_i \in \mathbb{R}^n$, $i = \{m, s\}$, are the position, velocity, and acceleration of the master and slave dynamic systems respectively. $M_i(q_i) \in \mathbb{R}^{n\times n}$ is the inertia matrix, $C_i(q_i, \dot{q}_i) \in \mathbb{R}^{n\times n}$ is the matrix representing Coriolis and centrifugal effects, $G_i(q_i) \in \mathbb{R}^n$ is the vector of gravitational effects, $\tau_{di} \in \mathbb{R}^n$ is the vector of external disturbance acting on the system at the joint space, in this paper it is given by $\tau_{di} = [2\sin(t) + 0.5\sin(200\pi t)2\cos(2t) + 0.5\sin(200\pi t)]$ [56]. Moreover, $\tau_h \in \mathbb{R}^n$ represents the torques exerted by the operator on the master device, and $\tau_e \in \mathbb{R}^n$ is the torques acting from the environment to the slave. Given that, $\tau_h = J_m^T F_h$, $\tau_e = J_s^T F_e$, where J_i is the jacobian matrix of the corresponding robotic arm, F_h, F_e forces applied by the human operator and the environment affecting at the end effectors of the master and slave respectively. The Lagrangian dynamic model has the following properties that are utilized in this paper [45,46,48]:

A. $0 < M_i^- \leq \|M_i(q_i)\|_2 \leq M_i^+ < \infty$, where $\|M_i(q_i)\| = \sqrt{max(\lambda(M_i^T M_i))}$.
B. $\dot{M}_i(q_i) = C_i(q_i, \dot{q}_i) + C_i^T(q_i, \dot{q}_i)$.
C. $|C_i(\dot{q}_i, q_i)\dot{q}_i| \leq k_{ci}|q_i|^2$, for some $k_{ci} \in \mathbb{R}^+$.
D. $\frac{1}{M_i^+} \leq \|M_i^{-1}(q_i)\|_2 \leq \frac{1}{M_i^-} < \infty$

In reality, it is almost impossible to obtain an exact dynamic model of a mechanical system such as robotic arm manipulators due to the presence of Coulomb friction, back lash and unknown disturbance so that the following uncertainty parameters are considered

$$M_i = M_{io} + \Delta_{Mi},$$

$$C_i = C_{io} + \Delta_{Ci},$$

$$G_i = G_{io} + \Delta_{Gi}.$$

Thus, dynamical equations of the master-slave robotic arms can be rewritten as follows:

$$\begin{aligned} M_{mo}(q_m)\ddot{q}_m + C_{mo}(q_m, \dot{q}_m)\dot{q}_m + G_{mo}(q_m) &= \tau_m + \tau_h + P_m, \\ M_{so}(q_s)\ddot{q}_s + C_{so}(q_s, \dot{q}_s)\dot{q}_s + G_{so}(q_s) &= \tau_s - \tau_e + P_s, \end{aligned} \tag{2}$$

where Δ_{Mi}, Δ_{Ci}, Δ_{Gi}, are the uncertainty in the inertia, Coriolis and centrifugal and gravity matrices respectively, $M_{io}(q_i)$, $C_{io}(q_i)$, $G_{io}(q_i)$ are the nominal values of the system parameters, $P_i = -\Delta_{Mi}\ddot{q}_i - \Delta_{Ci}\dot{q}_i - \Delta_{Gi} + \tau_{di}$.

Lemma 1 *([59]). For any matrix $V > 0$, and a function $x: [a, b] \to \mathbb{R}^n$, the following inequality holds:*