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Brief paper

On stability and regulation performance for flexible-joint robots with input/output communication delays[☆]

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ABSTRACT

Networked control of robotic systems is widely recognized as a potentially transformative technological enabler for several applications. However, the issues of time delays in communication and recovery from data losses have emerged as the pivotal issues that have stymied practical deployment. The study for control of robotic system with input/output communication delays has attracted many researchers' attention, but the existing results have been primarily developed for rigid-joint robots. Since joint flexibility is largely unavoidable in practical manipulators, in this paper the set-point control problem for flexible-joint robots with input/output communication delays is studied. It is demonstrated that the scattering variables address the stability problem for unknown constant delays, however, in contrast to the rigid-robot case, they cannot guarantee set-point regulation. In addition, we compute the explicit dependence of the regulation errors on the communication delays, control gains, and the desired set-point configuration. Without exact knowledge of time delays, a scattering variable based controller with position feedback is subsequently studied in this paper to guarantee stability with improved regulation performance. The control architecture is further extended to the case with time-varying delays. Simulation results are presented to validate the efficacy of the proposed control algorithms.

1. Introduction

Control of network robotic manipulators has attracted the attention of several researchers (Chopra, 2009, 2010; Kottenstette, Hall, Koutsoukos, Sztipanovits, & Antsaklis, 2013; Liu & Chopra, 2012, 2014; Matiakis, Hirche, & Buss, 2005, 2009). Although such system frameworks lead to the advantage of modularity and potentiality, most of the previous studies assume rigid joints in the robotic manipulators. Joint flexibility in robotic manipulators is significant and unavoidable in modeling and for high-performance control. The source of joint flexibility emanates from the use of harmonic drives, long shafts, belts, and cables for torque transmission in practical robotic systems. It is well known that control for flexible-joint robots is challenging (Spong, 1987; Tomei, 1991) as compared to rigid-joint robots. When joint flexibility is neglected in the control design, oscillatory behavior may appear during free motion, and instability can occur when interacting with an environment (Spong, 1989). Therefore, the presence of joint flexibility in robotic manipulators should be taken into account in practical applications.

The problem of controlling robotic manipulators with joint flexibility has attracted considerable attention (Ailon, Lozano-Leal, & Gil, 1997; De Luca, Siciliano, & Zollo, 2005; Liu & Chopra, 2013; Lozano & Brogliato, 1992; Nicosia & Tomei, 1995; Ortega, Kelly, & Loría, 1995; Qu, 1995; Spong, 1987; Tomei, 1991). By considering the dynamical model proposed in Spong (1987), a simple PD controller was presented to globally stabilize a flexible-joint robot for set-point regulation (Tomei, 1991). A passivity-based regulator was developed for flexible-joint robots without requiring velocity measurement (Ortega et al., 1995). An output feedback controller, utilizing only link positions, was proposed for robots with joint flexibility to guarantee asymptotic tracking (Nicosia & Tomei, 1995). Without the knowledge of stiffness matrix, an adaptive control scheme was addressed to ensure the link position

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tracking with the use of link and motor shaft position and velocity (Lozano & Brogliato, 1992). Recently, a PD controller with online gravity compensation was proposed for flexible-joint robots to improve the regulation performance (De Luca et al., 2005). In the aforementioned studies, however, signal communication between the robot and the controller is assumed to be instantaneous, thereby limiting the scope of potential applications for robots in the networked case.

Guaranteeing stability of a nonlinear control system under time delays is a challenging problem (Richard, 2003). In the case of nonlinear robotic manipulators, passivity-based control has been demonstrated as an efficient technique to mitigate the deleterious effect of time delays in the closed-loop system. Based on the property that a feedback interconnection of passive systems is also passive, scattering or wave variables (Anderson & Spong, 1989; Niemeyer & Slotine, 1991) were proposed for bilateral teleoperation (Hokayem & Spong, 2006) to guarantee passivity of the communication block. This idea has been adopted recently in the study on control of robotic manipulators under constant input/output delays (Chopra, 2009; Kottenstette et al., 2013; Liu & Chopra, 2012; Matiakis et al., 2009). However, the problem studied in the previous papers was for rigid-joint robots under the assumption that there is no gravitational torque. Since the flexibility of robotic joints can induce position errors at the end-effector due to static deformation under gravity, the presence of gravitational torque for flexible-joint manipulators is non-negligible.

In this paper, we study the problem of set-point control for flexible-joint robots under input/output delays with the consideration of gravity compensation term in the controller. The controller is adapted from Tomei (1991) with a constant gravity compensation term evaluated at the desired reference position. The proposed controller takes only the signals of motor shaft as input, so that the control system can be implemented by using the sensors mounted on widely available robots. Exploiting the passivity property of the flexible-joint robot and the set-point controller, the regulation control problem under delays is first studied by using the scattering transformation. It is demonstrated that stability of the proposed closed-loop system is recovered independent of the unknown constant time delays; however, this control algorithm cannot guarantee position regulation. Hence, a delayed position feedback in conjunction with the scattering representation is utilized so as to achieve the regulation objective. The studied control algorithm guarantees stability and regulation performance of the flexible-joint robot under both constant and time-varying input/output delays.

The contributions of this paper can be summarized as follows: (1) in contrast to Chopra (2009, 2010); Kottenstette et al. (2013); Liu and Chopra (2012, 2014), we study the problem for control of flexible-joint robot under input/output delays with the consideration of gravity compensation in the controller; (2) we demonstrate that in contrast to the case of rigid-joint robots (Chopra, 2009, 2010; Kottenstette et al., 2013; Liu & Chopra, 2012), the flexible-joint robots with the use of scattering representation can only ensure stability and cannot guarantee position regulation. Moreover, the explicit dependence of the regulation errors is studied in this paper; (3) a controller with position feedback and scattering representation is studied to ensure both stability and regulation performance. Additionally, the control architecture is further extended for flexible-joint robots under time-varying input/output communication delays.

This paper is organized as follows. The preliminaries and the problem formulation are presented in Section 2. Subsequently, the theoretical results for control of flexible-joint robots with input/output delays are developed in Section 3. The numerical examples for the proposed system are discussed in Section 4. Finally, Section 5 summarizes the results and discusses future research directions.

2. Preliminaries and problem formulation

2.1. Preliminaries

The robotic system considered in this paper is modeled as a Lagrangian system. Following (Spong, Hutchinson, & Vidyasagar, 2006) in the absence of friction and disturbances, the equations of motion for an n-link robot with flexible joints are given as

$$\Sigma_r : \begin{cases} M(q_1)\ddot{q}_1 + C(q_1,\dot{q}_1)\dot{q}_1 + g(q_1) + K(q_1 - q_2) = 0 & \text{(a)} \\ J_m\ddot{q}_2 + K(q_2 - q_1) = -\tau_s + \tau_e = \tau_t & \text{(b)} \end{cases} \quad (1)$$

where $q_1 \in R^n$ is the vector of joint angles, $q_2 \in R^n$ is the vector of motor shaft angles, $\tau_s \in R^n$ is the motor torque acting on the system, $\tau_e \in R^n$ is the external torque acting on the system, $M(q_1) : R^n \to R^{n\times n}$ is the positive definite inertia matrix, $C(q_1,\dot{q}_1)\dot{q}_1 \in R^n$ is the vector of Coriolis/Centrifugal forces where $C(q_1,\dot{q}_1) : R^n \times R^n \to R^{n\times n}$, $J_m \in R^{n\times n}$ is the inertia matrix of the actuators, $K \in R^{n\times n}$ represents the positive diagonal matrix of the joint stiffness, and $g(q_1) = \frac{\partial U_g(q_1)}{\partial q_1}$, where $U_g(q_1)$ is the gradient of the potential energy due to gravity and there exists a global minimum such that $U_{gmin} := \min_{q_1} U_g(q_1)$. Assuming revolute joints, the above flexible-joint robot Σ_r exhibits several fundamental properties due to the Lagrangian dynamic structure (Spong et al., 2006; Tomei, 1991).

Property 1. *Under an appropriate definition of the matrix $C(q_1,\dot{q}_1)$, the matrix $\dot{M}(q_1) - 2C(q_1,\dot{q}_1)$ is skew symmetric.*

Property 2. *The matrix $M(q_1)$ is symmetric positive definite, and there exist positive constants λ_m and λ_M such that $\lambda_m \mathcal{I}_n \le M(q_1) \le \lambda_M \mathcal{I}_n$, where $\mathcal{I}_n \in R^{n\times n}$ is an identify matrix.*

Property 3. *For $q,\ \dot{q},\ \xi \in R^n$, there exists a positive constant k_c such that the matrix of Coriolis/Centrifugal torques is bounded by $\|C(q,\dot{q})\xi\| \le k_c\|\dot{q}\|\|\xi\|$.*

Property 4. *A positive constant β exists such that $\|\frac{\partial g(q_1)}{\partial q_1}\| \le \beta$ for $q_1 \in R^n$. The above inequality implies*

$$\|g(q_1) - g(\bar{q}_1)\| \le \beta\|q_1 - \bar{q}_1\| \quad \forall q_1, \bar{q}_1 \in R^n.$$

The following lemma states the passivity property of the robotic system Σ_r.

Lemma 1 (*Lozano & Brogliato, 1992*). *The dynamical system (1)*(a) *and (1)*(b) *is passive with $(\tau_t, \dot{q}_2)$ as the input–output pair.*

Throughout this paper, the notations $\lambda_{\min}(\cdot)$ and $\lambda_{\max}(\cdot)$ denote the minimum and maximum eigenvalue of the enclosed matrix. The norm of vector $x \in R^n$ is defined as $\|x\| = (\sum_{i=1}^n x_i^2)^{1/2}$, and the norm of matrix $A \in R^{n\times n}$ is defined as $\|A\| = \left(\lambda_{\max}(A^TA)\right)^{1/2}$, which implies that if A is symmetric positive definite, we have $\|A\| = \lambda_{\max}(A)$. In addition, for the sake of simplicity the notation $\xi^{[i]} = d^i\xi/dt^i$ is used as required.

2.2. Problem formulation

In this paper, the closed-loop system is studied when the signals exchanging between the flexible-joint robot Σ_r and the controller are transmitted through communication channels, as shown in Fig. 1. In this framework, we consider that only the signal of motor shaft is transmitted to the controller, and the closed-loop system is studied in the absence of external torque i.e. $\tau_e \equiv 0$. The controller dynamics Σ_c for the set-point regulation are given as

$$\Sigma_c : \begin{cases} \dot{x}_c = u_c \\ y_c = K_p(x_c - q_{2d}) + K_d u_c - g(q_{1d}) \end{cases} \quad (2)$$