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Sliding mode control of position commanded robot manipulators

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ABSTRACT

This paper investigates the method of implementing dynamic controller on a manipulator which do not have direct drive joints. A previously proposed torque to position conversion method for servo actuated robot manipulators is used with an adaptive backstepping based sliding mode controller for dynamic trajectory tracking control. The proposed controller uses a nonsingular finite time sliding surface to achieve finite time stability as well as higher tracking performance. To avoid a structurally complex control law as well as obtain partial model independency of the controller, the soft nonlinearities of the manipulator are estimated using the time delay control philosophy where delayed signals are used to estimate the model nonlinearities. The entire system is validated using simulation and experimental studies.

1. Introduction

The field of robotics has seen revolutionary growth in terms of structure, control and usability in the last few decades. Robotics is an extensively researched topic because of its suitability in applications such as in biohazardous areas like nuclear plants, toxic places and also in high precision tasks like laser cutting, microsurgery etc. Further, robots are successfully used in inaccessible terrains like underground tunnels, underwater and also functioning as assistive technology for disabled people in the forms of replacement limbs. Most of the available low cost robot manipulators mainly contain servo motors as joint actuators which include an internal controller (mainly proportional–integral–derivative (PID) or its variation). Thus only position commands can be sent to the joints actuators and this kind of manipulators can be termed as position commanded manipulators. In such cases only kinematic control is possible. However, often kinematically controlling the robot motion is not enough, for example in order to achieve compliant behavior the dynamics of the manipulator have to be included. In these situations, operating a position commanded manipulator will require some kind of dynamic torque to dynamic position conversion method that will allow the designer to incorporate compliance in the robot motion. Khatib, Thaulad, Yoshikawa, and Park (2008) provided a feedforward method based on the identification of the actuator transfer function that could transform the computed torque to an equivalent position command which could actuate the joint. This strategy has been successfully implemented on the humanoid robot Asimo arm (Khatib et al., 2008). In this paper a more simplified version of the torque to position transformation as suggested in Adhikary and Mahanta (2017) for operating a Coordinated Links (COOL) robot arm having Dynamixel servos as actuators is used to test its practical applicability. Experiments are performed to examine the effects and improvements achieved using the dynamic controller over using only kinematic control using direct position command.

The primary focus of this paper is to demonstrate the applicability of torque to position conversion method (Adhikary & Mahanta, 2017) to a manipulator with position commanded actuators to use dynamic torque control in such position commanded manipulators. A successful application of the procedure will indicate the feasibility of inducing compliant behavior to manipulator motion via impedance control methods, even though the actuators can only be position commanded. Moreover, since robust controllers (Abdallah, Dawson, Dorato, & Jamshidi, 1991; Sage, De Mathelin, & Ostertag, 1999) can withstand a wide range of parametric and nonparametric uncertainties, these are taken as the preferred choice as there are a lot of possibilities of noise entering into the system via feedback paths and the numerical differentiations performed to obtain the state information.

Robust control methods are designed to withstand unaccounted factors affecting the system while yielding good tracking performance. These methods mainly resort to a high controller gain to alleviate the system uncertainty. Sliding mode control (SMC) (Utkin, 1977) is one robust control method which has been widely used owing to its simplicity in design, order reduction properties and consistent performance. However, SMC has seen limited application in the field of robotics because of the high frequency chattering phenomenon in the control input, which makes it highly inappropriate for practical application. Research continues to reduce chattering in the SMC for making it suitable for application in robotics (Baek, Jin, & Han, 2016; Ferrara & Incremona, 2015; Mondal & Mahanta, 2014; Sun, Pei, Pan, Zhou, & Zhang, 2011). Second and higher order SMCs (Capisani &

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Ferrara, 2012; Ding, Wang, & Zheng, 2015; Ferrara & Incremona, 2015) have been designed to eliminate chattering which, however, lead to a complex controller structure. Although the SMC is immune to matched uncertainties, its major drawback is its lack of robustness against mismatched uncertainties. Designing a SMC for the robotic manipulator requires exact knowledge about the system model which is difficult with increasing complexity due to large degrees of freedom (DoF) of advanced manipulators.

In Jin, Chang, Jin, and Gweon (2013), Jin et al. proposed a time delay controller (TDC) (Hsia & Gao, 1990; Youcef-Toumi & Ito, 1990) producing a terminal sliding surface like error dynamics for manipulator control. The terminal sliding surface was introduced for enhancing the system performance, which was degraded due to the time delay estimation error. The terminal attractors initially proposed by Zak (1988) have been used as sliding surface to design a terminal sliding mode (TSM) control (Wu, Yu, & Man, 1998). But the main disadvantages of the TSM were the singularity problem and the degradation of convergence performance when the error states were far from the equilibrium. To avoid the singularity problem, the nonsingular terminal sliding mode was proposed in Feng, Yu, and Man (2002) and for consistent convergence performance, the fast terminal sliding mode (FTSM) control was suggested in Yu and Zhihong (2002). Combination of these two have resulted in nonsingular fast terminal sliding mode control, which has been effectively used for various nonlinear systems (Hou, Wang, & Liu, 2014; Jin, Lee, Chang, & Choi, 2009; Li, Dou, & Su, 2013).

This paper uses the concept of time delay control (TDC) (Youcef-Toumi & Ito, 1990) to estimate the soft nonlinearities of the manipulator dynamics. In the discrete domain, this methodology uses the information acquired in the previous time instant to estimate the model nonlinearities of the next time instant, assuming the signal is smooth in the continuous domain. Such estimation of the model nonlinearities is termed as time delay estimation (TDE), whose application can be found in Jin et al. (2013), Jin, Lee, and Ahn (2015), Jin, Kang, and Chang (2008), Cho, Chang, Park, and Jin (2009).

The organization of the paper is as follows. In Section 2 the problem under consideration is discussed. Controller design methodology is explained in Section 3. Simulation results are presented in Section 4. Experimental studies and their results are described in Section 5. Conclusion is drawn in Section 6.

2. Problem formulation

The dynamics of an n-DoF robotic manipulator in its joint space can be described as (Murray, Li, Sastry, & Sastry, 1994)

$$\boldsymbol{M}(q)\ddot{q} + \boldsymbol{C}(q,\dot{q})\dot{q} + \boldsymbol{G}(q) = \tau + \tau_f \tag{1}$$

where the $n \times 1$ vectors $\boldsymbol{q}$, $\dot{\boldsymbol{q}}$, $\ddot{\boldsymbol{q}}$ $\in \mathbb{R}$ are respectively the joint angle position, angular velocity and angular acceleration of the manipulator, $\boldsymbol{M}(q) \in \mathbb{R}^{n\times n}$ is the inertia matrix, $\boldsymbol{C}(q,\dot{q}) \in \mathbb{R}^{n\times n}$ is the centripetal and Coriolis force matrix and $\boldsymbol{G}(q) \in \mathbb{R}^n$ is the gravitational force vector. The input torques acting on each of the joints are represented by the vector $\tau \in \mathbb{R}^n$. The vector $\tau_f \in \mathbb{R}^n$ represents the frictional torque acting on the joints and is the unknown disturbance torque. Under nominal condition, (1) can be written as

$$\boldsymbol{M}(q)\ddot{q} + \boldsymbol{C}(q,\dot{q})\dot{q} + \boldsymbol{G}(q) = \tau. \tag{2}$$

The dynamics of the actuators that drive the joints need to be considered with the main manipulator dynamics (Wang, Chai, & Zhai, 2009). Each joint of the manipulator is driven by a dc servo motor which has the following dynamics:

$$\boldsymbol{J}_m\ddot{q}_m + \boldsymbol{B}_m\dot{q}_m = \tau_m - r\tau \tag{3}$$

where $\boldsymbol{q}_m \in \mathbb{R}^n$, $\dot{\boldsymbol{q}}_m \in \mathbb{R}^n$ and $\ddot{\boldsymbol{q}}_m \in \mathbb{R}^n$ respectively represent the angular position, the angular velocity and the angular acceleration of the motor shaft, $\boldsymbol{J}_m = diag\{J_{m1}, J_{m2}, \dots J_{mn}\}$ is the moment of inertia matrix of the motor combined with the gearbox inertia, $\boldsymbol{B}_m = diag\{B_{m1}, B_{m2}, \dots B_{mn}\}$ represents the viscous friction matrix of the motor shaft, $r = \frac{q}{q_m}$ is the gear reduction ratio and $\tau_m \in \mathbb{R}^n$ is the motor torque. Substituting (2) in (3) yields

$$\boldsymbol{M}_h\ddot{q} + \boldsymbol{C}_h\dot{q} + \boldsymbol{G}_h = \tau_m \tag{4}$$

where $\boldsymbol{M}_h = rM(q) + r^{-1}\boldsymbol{J}_m$, $\boldsymbol{C}_h = r\boldsymbol{C}(q,\dot{q}) + r^{-1}\boldsymbol{B}_m$ and $\boldsymbol{G}_h = r\boldsymbol{G}(q)$.

The manipulator dynamics and the combined manipulator-motor dynamics (Adhikary & Mahanta, 2014) have the following properties:

Property 1 (*Inertial Property*). *The inertia matrix $\boldsymbol{M}_h$ is bounded, symmetric and positive definite which means,*

$$\boldsymbol{M}_h^T = \boldsymbol{M}_h, \quad m_{min}\|x\|^2 \le x^T\boldsymbol{M}_h x \le m_{max}\|x\|^2 \tag{5}$$

where $x \in \mathbb{R}^{n\times 1}$ is any nonzero vector.

Property 2 (*Passivity Property*). *The robotic manipulator is a passive system which means the matrix $(\frac{1}{2}\dot{\boldsymbol{M}}_h - C_h)$ is skew symmetric i.e.,*

$$x^T(\frac{1}{2}\dot{\boldsymbol{M}}_h - \boldsymbol{C}_h)x = 0 \tag{6}$$

The assumptions made while designing the controller are the following:

Assumption 1. All the joints of the robotic manipulator are revolute. This assumption makes Property 1 valid. A revolute joint is like a hinge and allows relative rotation between two links (Spong & Vidyasagar, 2008).

Assumption 2. The desired trajectory $q_d \in \mathbb{R}^n$ for each joint is smooth and continuous, meaning that the time derivatives $\dot{q}_d$, $\ddot{q}_d$ exist for all time and are continuous and bounded.

Assumption 3. The unmodeled coupling dynamics as well as the frictional torques effecting the manipulator dynamics are bounded and can be expressed as

$$|\tau_f| \le \upsilon_0 + \upsilon_1\|q\| + \upsilon_2\|\dot{q}\|^2 \tag{7}$$

where, $\upsilon_0, \upsilon_1, \upsilon_2 \in \mathbb{R}$ are nonzero parameters.

The objective is to design a stable controller so that for a given desired trajectory q_d the tracking error $q_e = q - q_d$ converges to zero. The controller will be designed in two main parts as given below

- The first part will involve the design of a control torque based on the system dynamics.
- The second part will be the feedforward law that will convert the generated control torque signal to a position command to be sent to the motor. This way a control signal based on the manipulator dynamics for each of the servos in the motor joints will be generated for driving the robot arm.

The block diagram of the proposed control method is shown in Fig. 1 where q_{cmd} is the position command sent to the robot joints.

3. Controller design

The adaptive backstepping based sliding mode controller uses backstepping to derive the sliding surface and eventually the control law for the robot manipulator system. Following the backstepping methodology, the design process starts with the position error as the first regulatory variable and then based on a defined candidate Lyapunov function (CLF), a synthetic control law is derived considering the system velocity as the control input. The error between this derived synthetic control and the velocity is taken as the next regulatory variable and then based on this a sliding surface is defined and the actual control law is then designed based on this sliding surface. The advantage of