Control Engineering Practice 66 (2017) 146–155

Contents lists available at ScienceDirect

Control Engineering Practice

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

Inverse dynamics based robust control method for position commanded servo actuators in robot manipulators

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A R T I C L E I N F O

Keywords:
Position commanded servo
Robust control
Robot manipulators
Sliding mode
Backstepping

A B S T R A C T

In this paper, a simple torque to position conversion method is proposed for position commanded servo actuators used in robot manipulators. The torque to position conversion is based on the low level controller of the servomotor. The proposed conversion law is combined with a backstepping sliding mode control method to realize a robust dynamic controller. The proposed torque based method can control a servomotor which can otherwise be operated only through position inputs. This method facilitates dynamic control for position controlled servomotors and it can be extended to position commanded robotic manipulators also. Simulation and experimental studies are conducted to validate the proposed torque to position conversion based robust control method.

1. Introduction

Industrial robots are constructed with an aim to having a high value of stiffness to enable precise position tracking. As a result, the effect of collision becomes very serious.

In industries, the robot arm and human hardly interact since collision with the heavy rigid manipulators might prove very dangerous, even fatal. However, with the evolution and progress of advanced robotics technology, safe merging of human and robot workspace is increasingly attempted, like in medical robots (Beelen, Naus, van de Molengraft, & Steinbuch, 2013; Joubair, Zhao, Bigras, & Bonev, 2015) and assistive technology (Tapus, Mataric, & Scasselati, 2007; Xu, Chu, & Rogers, 2014) which demand simultaneous control of motion and force. The inverse dynamics control (Del Prete, Mansard, Ramos, Stasse, & Nori, 2016) provides integration of motion and force controlled frameworks which is not possible in the case where position and kinematic controls are used. Since a lot of commercially available arms are inherently position controlled, changing their servos for torque controlled motors will not be very feasible. Therefore, attempts have been made to incorporate dynamical control in such manipulators (Del Prete et al., 2016; Khatib, Thaulad, Yoshikawa, & Park, 2008; Sentis, Park, & Khatib, 2010).

Most of the low cost robotic manipulators normally have servo motors as the joint actuators and these servos have internal microcontrollers for position and speed control. This makes the robots position commanded, meaning that only the joint position can be sent as the input to the actuators. The main disadvantages of this arrangement are as follows:

- The controllers inside the servos are designed for the single motor operation only. When the servos are linked and operated as a whole arm, the dynamics of the entire arm affects each servo motor as a disturbance. Since the servo controllers are proportional integral derivative (PID) or its variants, they are not very effective when effects of such load dynamics are high during various arm motions. As such, the steady state error tends to increase with increasing load.
- While interacting with the external environment or working with humans, position control of the arm alone may not be sufficient since the forces and torques also need to be taken care of. Therefore, to achieve compliant motion, relying solely on the internal position controllers will not be adequate.
- Standard position control does not consider the constraints affecting the humanoid manipulators like torque limits, frictional force cones, center of pressure positions (Murray, Li, Sastry, & Sastry, 1994), which is otherwise possible with inverse dynamics control.

Khatib et al. (2008) proposed a torque to position transformer based on the actuator transfer function which was identified using higher order

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http://dx.doi.org/10.1016/j.conengprac.2017.07.001
Received 6 September 2016; Received in revised form 4 July 2017; Accepted 7 July 2017

Table 1
Parameters of the RX-28 servo.

Supply voltage range	12.0–18.5 V
Angular position range	± 2.6 rad
Angular speed limit	6.24 rad/s
Torque limit	3.6 N m
Armature current limit	1.9 A
Gearbox ratio ($\frac{1}{k_g}$)	193
Gearbox Inertia (J_g)	79.6×10^{-6} kg m^2

Table 2
Technical specifications of RE-max 17 214897.

Rated armature voltage	12.0 V
Motor speed constant	100.7 rad/Vs
Motor torque constant	10.7 mN m/A
Terminal resistance	8.3 Ω
Terminal inductance	0.206 mH
Mechanical time constant (T_m)	6.25 ms
Motor inertia (J_m)	86.4×10^{-9} kg m^2

polynomials without relying on the direct measurement of joint torques. This strategy has been successfully implemented on the humanoid robot Asimo arm (Khatib et al., 2008). In Del Prete et al. (2016), a three part torque control law, which required estimation of the joint torques based on the end-effector torque sensor data and the robot model, was formulated. Both the studies showed that the position command to the digital servos could be manipulated to obtain the dynamic controller effects.

The aim of this study is to devise a simple torque to position conversion law similar to the method of Khatib et al. (2008). A simplified torque to position conversion method is explored and the ideal motor parameters are used in this method. The simplification strategy, as well as the use of only nominal motor parameters, can lead to issues like structured uncertainties due to inaccuracies in system parameters and payload variation. Unstructured uncertainties caused by external disturbances, nonlinear friction and saturation nonlinearities will also affect the motor dynamics. A suitable robust control method having immunity to matched uncertainties is the sliding mode control (SMC) (Corradini, Fossi, Giantomassi, Ippoliti, Longhi, & Orlando, 2012; Moreau, Pham, Tavakoli, Le, & Redarce, 2012; Utkin, 1977), which also offers fast dynamic response. The robustness of the sliding mode controller makes it a perfect tool to be used with the proposed simplified torque to position transformation based method as the inaccuracies in the transformation will be compensated by the sliding mode working as the high level dynamic controller. The sliding mode design produces a two part control law, the first part being the equivalent control containing the inverse dynamics of the controlled system and the second part being the discontinuous control where the controller switches between two structures depending upon a sliding surface. The main disadvantages of the SMC are the chattering phenomenon due to the discontinuous part of the controller and the inability to deal with mismatched uncertainties. The backstepping algorithm (Krstic, Kanellakopoulos, & Kokotovic, 1995), which has a recursive design process, has been used in combination with the SMC giving rise to backstepping sliding mode control (BSMC) (Adhikary & Mahanta, 2013; Lin, Shen, & Hsu, 2002), which can tackle both matched and mismatched uncertainties affecting the system. Motivated by this earlier work, in this paper, a BSMC is used in combination with the time delay estimation (TDE) (Hsia & Gao, 1990; Jin, Chang, Jin, & Gweon, 2013; Youcef-Toumi & Ito, 1990), which facilitates estimation of the uncertainties in the system.

The organization of the paper is as follows: the servo motor and its technical specifications are described in Section 2. The dynamic controller and the torque to position converter are described in Section 3. Simulation and the experimental results are presented in Section 4 and Section 5 respectively. Conclusion is drawn in Section 7.

2. System description

The servo motor used in this study is the Dynamixel RX-28 and a detailed analysis of the motor can be found in Wojtusch (2011). The technical details of RX-28 as well as its motor RE-max 17 214897 are listed in Tables 1 and 2 respectively.

The basic principle of a servo motion system is to use feedback gain to obtain the desired output at the motor shaft. The proportional(P)-integral-(I)-derivative(D) controller is the most common controller used in the servo system owing to its simplicity in design. In Wojtusch (2011) it was shown that in RX-28 the proportional control played the dominant part and therefore in this study also it is assumed that the operating internal controller of the servo is P type. The output of this lower level controller is generally obtained as the motor torque required to produce the desired movement. The electrical time constant of the dc motor in RX-28 is $T_e = \frac{L}{R} = 0.025$ ms (L and R are the armature inductance and resistance respectively) whereas the mechanical time constant is $T_m = \frac{J_m}{B} = 6.25$ ms (J_m and B are motor inertia and damping respectively). As such, the non-significant electrical dynamics can be neglected and the motor's mechanical dynamics can be expressed as

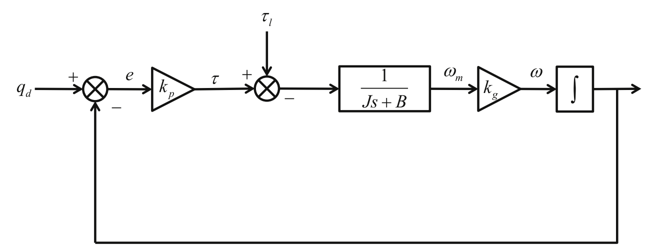

Fig. 1. Simplified servo motor block diagram.

$$\frac{J}{k_g}\ddot{q} + \frac{B}{k_g}\dot{q} = \tau - \tau_l \tag{1}$$

where q, $\dot{q}$, $\ddot{q}$ are respectively the angular position, speed and acceleration of the gear shaft, k_g is the motor gear ratio. Moreover, $J = J_m + k_g^2 J_g$, where J_g is the gearbox inertia. The simplified block diagram of the motor dynamics is shown in Fig. 1, where ω_m is the motor shaft speed and ω is the speed output of the gear-box. The tracking error is denoted as $e = q_d - q$. The servo motors in the arm already have bounded position and velocities and it can be assumed that the joint accelerations are also bounded. In Fig. 1, k_p is the proportional (P) gain of the controller, τ is the motor torque and τ_l is the disturbance torque. Further, q_d, q are the desired and the actual motor positions respectively.

Thus the output of the lower level P controller can be written as

$$\tau = k_p(q_d - q) = k_p \Delta q$$
$$\Rightarrow \Delta q = k_p^{-1}\tau \tag{2}$$

3. Controller design

An inverse dynamics controller using a torque to position conversion law and the backstepping sliding mode method is proposed as shown in Fig. 2. The aim of the controller is to track a reference trajectory q_d. It is assumed that the second derivative of q_d exists. Both the inverse dynamics control and the torque to position conversion are briefly described in the following subsections.

3.1. Backstepping sliding mode control (BSMC)

In order to derive a robust dynamical control law, the sliding mode control methodology is combined with the backstepping method to obtain a backstepping sliding mode controller (BSMC), which will be able to tackle any bounded uncertainty such as modeling error, sensor noise and time delay.