ISA Transactions 50 (2011) 131–140

Contents lists available at ScienceDirect

ISA Transactions

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

Operational space trajectory tracking control of robot manipulators endowed with a primary controller of synthetic joint velocity☆

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ARTICLE INFO

Article history:
Received 25 May 2010
Received in revised form
2 August 2010
Accepted 4 August 2010
Available online 30 August 2010

Keywords:
Operational space
Euler's angles
Tracking control
Robot manipulator
Exponential stability
Real-time experiments

ABSTRACT

In this paper, a new control algorithm for operational space trajectory tracking control of robot arms is introduced. The new algorithm does not require velocity measurement and is based on (1) a primary controller which incorporates an algorithm to obtain synthesized velocity from joint position measurements and (2) a secondary controller which computes the desired joint acceleration and velocity required to achieve operational space motion control. The theory of singularly perturbed systems is crucial for the analysis of the closed-loop system trajectories. In addition, the practical viability of the proposed algorithm is explored through real-time experiments in a two degrees-of-freedom horizontal planar direct-drive arm.

1. Introduction

A robotic task is usually specified through the pose, i.e., the position and orientation of the robot end-effector with respect to the base frame. The operational space is defined by the Cartesian position and the orientation via Euler's angles [1]. The term task space [2] refers the case when the position and orientation of the robot end-effector are described by the Cartesian position and the unit quaternion, respectively.

Many robot pose trajectory tracking controllers require robot full-state measurements, i.e., position and velocity in the joint and operational space. The position and orientation of the robot end-effector is computed through the direct kinematics model from joint position measurements obtained. Unlike optical encoders, velocity sensors (tachometers) are not provided with optical shielding. If a robot equipped with tachometers is working in an environment with high electromagnetic interference, then velocity measurements may be contaminated by noise. A cheap way to artificially obtain velocity measurements is by the numerical derivative of the signals of position and orientation. Although numerical differentiation is a common practice to solve the problem of unmeasurable velocity, sometimes the closed-loop stability cannot be guaranteed. This situation has motivated Lyapunov-based control designs to assure pose motion control by using synthesized velocity feedback from position measurements.

With respect to pose control of the rigid body dynamics, which is closely related to the manipulator dynamics, a passivity-based control law which uses only position measurements was introduced in [3]. The scheme proposed in that study was extended later in [4]. In [5], an adaptive controller which uses only position measurements was introduced by using the modified Rodrigues parameters.

Concerning the manipulator dynamics, as far as we know the first study on pose trajectory tracking control of robot manipulators by using synthetic velocity feedback was due to Caccavale et al. [6], where an experimental evaluation was included also. They showed how the asymptotical stabilization of the closed-loop system is achieved by using the unit quaternion to represent the end-effector orientation. In Xian et al. [7], a pose trajectory tracking controller based on only position measurements was introduced. In that scheme, the end-effector orientation is described by the unit quaternion.

Human beings perform complex assembly tasks, which require the feedback of information of the position of hands, fingers, and manipulated objects. The correct manipulation of the objects depends on the feedback of visual and tactile information. Velocity feedback is required either to predict or to plan motions in situations of coordination. Let us notice that humans do not have a direct velocity sensor, but the velocity of the objects is sensed indirectly through the visual position information (see [8] and

☆ Work partially supported by CONACyT, and SIP-Instituto Politénico Nacional, Mexico.

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0019-0578/$ – see front matter © 2010 ISA. Published by Elsevier Ltd. All rights reserved.
doi:10.1016/j.isatra.2010.08.002

the references therein). Then, from the point of view of control theory, it seems to be natural to incorporate that mechanism (bio-cybernetics) in robot manipulators that perform complex tasks encoded by time-varying trajectories specified in the operational space.

We found that industrial robots are provided with a primary (inner) joint velocity loop and a secondary (outer) task-based loop [9–11]. The most common secondary loop is designed with the aim of satisfying either the motion or the force control objective. The papers [11–19], show designs of robot controllers based on a primary joint velocity and secondary task-based loops.

Lyapunov's theory has been widely used to derive control laws for motion control of robot manipulators. Roughly speaking, such a methodology consists in showing that the energy of the differential equation solution remains equal or lower than a constant. As alternative, the theory of singularly perturbed systems has been recognized as a powerful tool in the analysis and design of robot controllers. Essentially, this technique is based on analyzing the convergence of the solution of differential equation in two time-scales. A few examples of application are given as follows. In [20], singular perturbations are used to derive a tracking controller for electrically driven robot manipulators. The popular PD control of robot manipulator is modified in [21]. Specifically, a high-gain observer was proposed for the estimation of the velocity and, by means of singular perturbation analysis, the closed-loop system was studied. More recently, in the work [22], the control problem of a robot manipulator with flexures both in the links and joints was investigated by using the singular perturbation technique, while in paper [23], a two time-scale (singular perturbation-based) control design for trajectory tracking of two cooperating planar rigid robots moving a flexible beam was introduced.

The main objective of this paper is to present a new solution for the pose trajectory tracking control problem. The new controller is based on a primary joint loop of joint velocity control and a secondary loop of operational space position control. The introduced scheme incorporates synthesized velocity feedback from position measurements and is designed to facilitate the closed-loop system stability analysis by using the theory of singularly perturbed systems [24]. In particular, the proposed primary joint velocity controller follows the concept of filtering the joint positions via a stable first order system to obtain a synthetic version of the joint velocity. This idea has been used in [25] to solve the velocity control of direct-current motors.

Real-time experiments in a horizontal two degrees-of-freedom direct-drive arm prototype have been carried out. The performance of the joint space inverse dynamics controller [26,27], is compared with respect to one of the new operational space control algorithms. The requested task in both implementations is to trace a circular contour in the Cartesian space of the robot.

This paper is organized as follows: In Section 2 the robot kinematics and dynamics is discussed. In Section 3 the new motion controller is described. A detailed experimental study on a two degrees-of-freedom direct-drive robot is described in Section 4. Finally, some concluding remarks are drawn in Section 5.

Notation: Throughout this paper the following notation will be adopted. $\|\boldsymbol{x}\| = \sqrt{\boldsymbol{x}^T\boldsymbol{x}}$, $\boldsymbol{x} \in \mathbb{R}^n$, stands for the Euclidean norm. $\lambda_{min}\{A(\boldsymbol{x})\}$ and $\lambda_{Max}\{A(\boldsymbol{x})\}$ denote the minimum and maximum eigenvalues of a symmetric positive definite matrix $A(\boldsymbol{x}) \in \mathbb{R}^{n\times n}$ for all $\boldsymbol{x} \in \mathbb{R}^n$, respectively. $\|B(\boldsymbol{x})\| = \sqrt{\lambda_{Max}\{B(\boldsymbol{x})^TB(\boldsymbol{x})\}}$ stands for the induced norm of a matrix $B(\boldsymbol{x}) \in \mathbb{R}^{m\times n}$ for all $\boldsymbol{x} \in \mathbb{R}^n$. The symbol B_r denotes the set given by the ball $\{\boldsymbol{x} \in \mathbb{R}^n : \|\boldsymbol{x}\| \le r\}$.

2. Robot modeling and control goal

2.1. Robot dynamics

The dynamics in joint space of a serial-chain n-link robot manipulator considering the presence of friction at the robot joints can be written as [26,27],

$$M(\boldsymbol{q})\ddot{\boldsymbol{q}} + C(\boldsymbol{q},\dot{\boldsymbol{q}})\dot{\boldsymbol{q}} + \boldsymbol{g}(\boldsymbol{q}) + F_v\dot{\boldsymbol{q}} + \boldsymbol{f}_{Cl}(\dot{\boldsymbol{q}}) = \boldsymbol{\tau}, \tag{1}$$

where $\boldsymbol{q}$ is the $n\times 1$ vector of joint displacements, $\dot{\boldsymbol{q}}$ is the $n \times 1$ vector of joint velocities, $\boldsymbol{\tau}$ is the $n\times 1$ vector of applied torque inputs, $M(\boldsymbol{q})$ is the $n \times n$ symmetric positive definite manipulator inertia matrix, $C(\boldsymbol{q},\dot{\boldsymbol{q}})\dot{\boldsymbol{q}}$ is the $n\times 1$ vector of centripetal and Coriolis torques, $\boldsymbol{g}(\boldsymbol{q})$ is the $n\times 1$ vector of gravitational torques, F_v is a $n \times n$ diagonal positive definite matrix which contains the viscous friction coefficients of each joint, and $\boldsymbol{f}_{Cl}(\dot{\boldsymbol{q}})$ is a continuous and uniformly bounded function, which approaches the behavior of the Coulomb friction.

Based on the assumption that matrix $C(\boldsymbol{q},\dot{\boldsymbol{q}})$ is expressed in terms of the Christoffel symbols, the property

$$C(\boldsymbol{x},\boldsymbol{y})\boldsymbol{z} = C(\boldsymbol{x},\boldsymbol{z})\boldsymbol{y}, \quad \forall \boldsymbol{x},\boldsymbol{y},\boldsymbol{z} \in \mathbb{R}^n, \tag{2}$$

is satisfied [27].

2.2. Robot kinematics

Denoting $\boldsymbol{h}(\boldsymbol{q}) : \mathbb{R}^n \to \mathbb{R}^m$ the direct kinematics map, the position and orientation $\boldsymbol{y} \in \mathbb{R}^m$ of the end-effector is given by

$$\boldsymbol{y} = \boldsymbol{h}(\boldsymbol{q}). \tag{3}$$

A common physical interpretation is the case

$$\boldsymbol{y} = \begin{bmatrix} \boldsymbol{p}(\boldsymbol{q}) \\ \boldsymbol{\phi}(\boldsymbol{q}) \end{bmatrix}$$

where $\boldsymbol{p} \in \mathbb{R}^3$ denotes the end-effector position in the three-dimensional Cartesian space and $\boldsymbol{\phi} = [\varphi\ \vartheta\ \psi]^T \in \mathbb{R}^3$ is the set of Euler's angles which describes end-effector orientation. Let us notice that Euler's angles can be extracted from a given rotation matrix R describing the orientation of the end-effector frame by using the closed-loop inversion formula [26].

The time derivative of the direct kinematic model (3) yields the differential kinematic model

$$\dot{\boldsymbol{y}} = \frac{\mathrm{d}}{\mathrm{d}t}\boldsymbol{h}(\boldsymbol{q}) = \frac{\partial \boldsymbol{h}}{\partial \boldsymbol{q}}\dot{\boldsymbol{q}} = J(\boldsymbol{q})\dot{\boldsymbol{q}} \tag{4}$$

where $J(\boldsymbol{q})$ is the so-called analytical Jacobian matrix [26,28]. The robot Jacobian describes a map from velocities in joint space to velocities in operational space. The Jacobian right pseudo-inverse [28], is given by

$$J(\boldsymbol{q})^\dagger = J(\boldsymbol{q})^T\left[J(\boldsymbol{q})J(\boldsymbol{q})^T\right]^{-1},$$

assuming that $J(\boldsymbol{q})J(\boldsymbol{q})^T$ is nonsingular.

Assumption 1. The analytical Jacobian $J(\boldsymbol{q})$ is assumed of full-rank (rank $= m$) and bounded by $k_J > 0$, i.e.

$$\|J(\boldsymbol{q})\| \le k_J \quad \forall \boldsymbol{q} \in \mathbb{R}^n. \tag{5}$$

At the same time, it is also assumed that

$$\|J(\boldsymbol{q})^\dagger\| \le k_J^\dagger \quad \forall \boldsymbol{q} \in \mathbb{R}^n, \tag{6}$$

with $k_J^\dagger > 0$. □