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Control of Nonlinear Elastic Joint Robots using Feed-forward Torque Decoupling

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Abstract: This paper proposes and evaluates the feed-forward decoupling of joint torque in elastic joint robots. The joint elasticities, captured by the third-order polynomial function, are considered together with the inverse manipulator dynamics so as to provide the required driving torque for the reference trajectories. Therewith decoupled joint actuators can be robustly controlled in a feedback manner for which a convenient proportional-derivative (PD) regulation is sufficient. Using the inverse manipulator dynamics and joint model the reference value in the joint output (load) and not input (motor) space is provided to the feedback control of decoupled actuators. This allows compensating for the joint torsion and improve the load positioning accuracy without output sensors. The proposed control strategy is evaluated experimentally on a single elastic joint under gravity. We show an improved accuracy of the load positioning without adapting the underlying control loop and remarkable changes in the transient response.

Keywords: robotics, elastic joints, nonlinearities, feedforward control, torque control, torsion

1. INTRODUCTION

Evermore structures with elasticities, including actuated joints, are utilized in the modern robotic systems due to inevitable trends towards the lightweight and hence more energy and material efficient and inherently safe solutions (see e.g. Albu-Schaffer et al. [2008] and references therein). Another trend is going towards the so-called variable stiffness actuators (VSA) which allow for the energy storage and after that efficient release on the one hand, and more compliant and therefore safe interaction of robotic systems with their environment on the other hand, see e.g. Vanderborght et al. [2013]. The challenges related to the modeling and control of elastic joint robots are, among others, due to a weakly-known and often time-varying damping, disturbing joint vibrations and torsion under load, and often hidden internal nonlinearities such as friction and hysteresis (see e.g. Ruderman et al. [2009]).

Earlier works on the robots with joint elasticities go back to Spong [1987] and De Luca [1988]. Since then an established model structure, which assumes the joint elasticities as a linear spring with eventually linear damping connected in parallel, has been widely used for modeling and correspondingly control of robotic systems. To mention some of them here, the related works have been reported in Ghorbel et al. [1989], Tomei [1991], De Luca [2000], Albu-Schäffer and Hirzinger [2001], Ferretti et al. [2004], De Luca et al. [2005], Ott et al. [2008]. When the operational range of joint torque is expanded and the accuracy requirements posed on the load positioning, at the same time, are increasing the joint nonlinearities come into the foreground and should be taken into account and correspondingly compensated.

In the following we present the control of elastic joint robots which decouples the reactive joint torques in feed-forwarding. The approach is similar to the feed-forward control law which has been shown theoretically for the flexible robots with linear elasticities in the former work De Luca [2000]. In the recent work we extend the approach by considering the nonlinear joint elasticities and manipulator dynamics with friction, which are the matter of fact. We provide experimental evaluation of the control with feed-forward and feedback coactions, in particularly, in view of the relative joint torsion which deteriorates the output (load) accuracy. The rest of the paper is organized as follows. In Section 2 we describe the dynamics of elastic joint robots in a general matrix equations form, and that including the frictional and stiffness nonlinearities. Section 3 explains the joint torque feed-forwarding and thereupon based decoupling of the single joint actuators. The tracking control of joint output reference is described in Section 4. An experimental case study accomplished on a single elastic joint under gravity is provided in details in Section 5. The final conclusions are given in Section 6.

2. DYNAMICS OF ELASTIC JOINT ROBOTS

Elastic joint robots differ from their rigid-body counterparts by accounting for additional degrees of freedom between the motor and link positions $\mathbf{x}$ and $\mathbf{X}$ respectively. Note that the vectors $\mathbf{x} \in \mathbb{R}^n$ and $\mathbf{X} \in \mathbb{R}^n$ are given in the general joint coordinates, where n is the number

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of degrees of freedom denoted in the joint space. In the most common case of rotary robotic joints, however, both vectors describe the relative angular displacement, and the vector $\mathbf{z} = \mathbf{x} - \mathbf{X}$ represents the relative joint torsion. The latter characterizes the principal occurrence of joint elasticities and increases the system order by twofold, while separating the joint input (motor) and output (link) motion variables. It is worth nothing that, properly spoken, the joint torsion should be captured by $\mathbf{N}^{-1}\mathbf{x} - \mathbf{X}$, where $\mathbf{N} \in \mathbb{R}^{n\times n}$ is the diagonal matrix of nominal gear transmission ratios. However in the following, equally as one can find in the most works related to elastic joint robots, we will denote the motor positions by $\mathbf{x}$ while keeping in mind that this is already including the gear reduction numbers. Approaching the pioneer works of Spong [1987, 1989] on the elastic joint robots the overall manipulator dynamics can be written as

$$\mathbf{M}(\mathbf{X})\ddot{\mathbf{X}} + \mathbf{C}(\mathbf{X}, \dot{\mathbf{X}})\dot{\mathbf{X}} + \mathbf{G}(\mathbf{X}) - \mathbf{T}(\mathbf{z}, \dot{\mathbf{z}}) = \mathbf{0}, \tag{1}$$

$$\mathbf{J}\ddot{\mathbf{x}} + \mathbf{F}(\dot{\mathbf{x}}) + \mathbf{T}(\mathbf{z}, \dot{\mathbf{z}}) = \mathbf{u}. \tag{2}$$

The first nonlinear vector equation constitutes the well-known rigid body dynamics of robotic manipulator which is driven by the vector of the joint torques $\mathbf{T} \in \mathbb{R}^n$. Here $\mathbf{M}(\cdot) \in \mathbb{R}^{n\times n}$, $\mathbf{C}(\cdot) \in \mathbb{R}^{n\times n}$, and $\mathbf{G}(\cdot) \in \mathbb{R}^n$ are the state-dependent inertia matrix, coriolis and centrifugal matrix, and gravity vector correspondingly. The second nonlinear vector equation describes the dynamics of joint actuators, i.e. motors and gears, and relates the input motor torque $\mathbf{u} \in \mathbb{R}^n$ to the angular motor displacement which enters the gear transmission. Here $\mathbf{J} \in \mathbb{R}^{n\times n}$ is the diagonal matrix of motor inertia and $\mathbf{F}(\cdot) \in \mathbb{R}^n$ is the vector of friction torques which mainly damp the excited motion of joint actuators. Here it is worth noting that equation (1) can equally incorporate the joint output friction subject to specific mechanical structure and bearings of the connected joint links. However, these friction torques are often neglected during the modeling and that due to a quite challenging identification and, in particular, separation from the friction acting upon the joint actuators. Nevertheless, later in Section 3, we well transfer the friction term from the motor side to the link side, i.e. from equation (2) to (1), when designing the joint torque feed-forwarding. This is a justifiable assumption at the unidirectional motion, where the friction is mainly dependent on the sign and amplitude of the relative velocity.

Several previous works captured the joint torque, which maps the behavior of transmitting elastic element, by quite different modeling approaches. These relate to the required level of detail and reliable identification data for determining the static, quasi-static, or dynamic relationship between the joint torsion and torque. One of the most widespread approaches, e.g. to be found in Albu-Schaeffer et al. [2007], assumes a linear stiffness and damping of elastic joints so that $\mathbf{T}$ becomes a linear combination of $\mathbf{z}$, correspondingly $\dot{\mathbf{z}}$. However, from several experimental studies it turns out that the contribution of linear damping to $\mathbf{T}$ is challenging to be identified and, in particular, decoupled from the viscous damping terms of the joint input and output, i.e. damping related to $\dot{\mathbf{x}}$ and $\dot{\mathbf{X}}$. More advanced studies on elastic robotic joints try to capture a nonlinear z to T relationship, while accounting also for hysteresis, which is typical and well-detectable in various joint mechanisms, particularly those based on harmonic drive gear transmissions. In the recent work, we will abstain from the dynamic as well as hysteretic effects and approximate the nonlinear joint stiffness by means of a third-order vector polynomial function only

$$\mathbf{T} = \mathbf{K}_1\mathbf{z} + (\mathbf{Z}\,\mathbf{Z}\,\mathbf{Z})\mathbf{K}_3. \tag{3}$$

Here $\mathbf{K}_1 \in \mathbb{R}^{n\times n}$ is the diagonal, positive definite linear stiffness matrix, $\mathbf{K}_3 \in \mathbb{R}^n$ is the positive definite cubic stiffness vector, and $\mathbf{Z} = diag(z_i) \in \mathbb{R}^{n\times n}$ is the diagonal matrix of joint torsion. Important to note is that the real solution of inverse $z_i = T_i^{-1}$ is element-wise available, so that the torsion vector can be equally computed provided the joint torques are given.

In this work, we consider the velocity-dependent nonlinear friction at steady-state only, since this is to be computed from the reference trajectories without noise (see further in Section 3). For the use of more advanced dynamic friction models we refer to e.g. Armstrong and Chen [2008] and Ruderman and Bertram [2011, 2013]. For capturing the velocity-dependent friction term the well-known Stribeck characteristic curve

$$\mathbf{F}(\dot{\mathbf{x}}) = \mathrm{sign}(\dot{\mathbf{x}})\left(\mathbf{F}_c + \mathbf{S}\exp\left(-\left|\frac{\dot{\mathbf{x}}}{\mathbf{V}_s}\right|^{\mathbf{w}}\right)\right) + \mathbf{d}\,\dot{\mathbf{x}}, \tag{4}$$

with $\mathbf{S} = \mathbf{F}_s - \mathbf{F}_c$, is applied. Note that the vector of friction torques (4) should be computed element-wise since including the nonlinear (exponential) term. Here $\mathbf{F}_c$, $\mathbf{F}_s \in \mathbb{R}^n$ are the vectors of Coulomb and stiction friction coefficients correspondingly. The vector $\mathbf{d} \in \mathbb{R}^n$ describes the linear, i.e. viscous, friction term, and $\mathbf{V}_s$, $\mathbf{w} \in \mathbb{R}^n$ are the vectors of Stribeck velocities and shape factors which mainly control the curvature of the Stribeck map.

3. JOINT TORQUE FEED-FORWARDING

The joint torque feed-forwarding can be equally applied to elastic joint robots as to the rigid-joint manipulators. Recall that the latter are usually implementing a feed-forward control part which solves the inverse dynamics and computes the required driving torques from the given vector of reference trajectories $\mathbf{X}_r \in \mathbb{R}^n$. Note that the reference trajectories should be $\mathbf{X}_r(t) \in \mathcal{C}^k$ with $k \geq 2$, that is at least twice continuously differentiable so as to allow for solving the inverse dynamics which includes the acceleration-dependent terms. The impact of joint elasticities on the single actuator dynamics under control can be illustrated by means of the block diagram shown in Fig. 1. Here one can see that the cut-free 'black-box' of

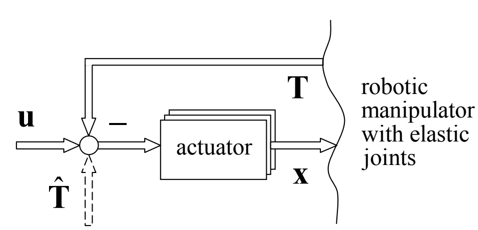

Fig. 1. Joint actuators disturbed by the reactive torques from the robotic manipulator with elastic joints

robotic manipulator with elastic joints receives the vector of motor positions as input and feed back the vector of reactive joint torques. The latter is acting on the joint