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Modeling, observation, and control of hysteresis torsion in elastic robot joints

Michael Ruderman [a,*], Torsten Bertram [b], Makoto Iwasaki [a]

[a] Department of Computer Science and Engineering, Nagoya Institute of Technology, 466-8555 Nagoya, Japan
[b] Institute of Control Theory and Systems Engineering (RST), Technische Universität (TU) Dortmund, 44221 Dortmund, Germany

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ABSTRACT

Hysteresis torsion in elastic robot joints occurs as a coupled nonlinearity due to internal friction, backlash, and nonlinear stiffness, which are coactive inside of mechanical transmission assemblies. The nonlinear joint torsion leads to hysteresis lost motion and can provoke control errors in relation to the joint output at both trajectories tracking and positioning. In this paper, a novel modeling approach for describing the nonlinear input–output behavior of elastic robot joints is proposed together with the observation and control method, which aim to compensate for the relative joint torsion without load sensing. The proposed modeling approach includes the recently developed 2SEP dynamic friction model and Bouc–Wen-like hysteresis model, which is originated from structural mechanics, both arranged according to the assumed torque transmitting structure. The proposed method is evaluated with experiments using the laboratory setup which emulates a single rotary joint under impact of nonlinear elasticities, friction, and gravity.

1. Introduction

Elasticities in robotic joints always have drawn an attention in the research since being one of the key challenges for an accurate joint dynamics modeling and control. The early works on modeling and control of elastic robot joints date back to [29,28]. Considering the joint elasticities by means of linear rotary springs the authors have established a Lagrangian dynamics frame suitable for analysis and control of flexible joint robots. Based thereupon, an adaptive control of flexible joint manipulators has been proposed in [9] which extends the adaptive algorithm derived former in [27] for the rigid robots. Following the proposed consideration of elastic joints a simple PD controller has been applied in [34]. It has been shown, that this control suffices to globally stabilize the elastic joint robots about a reference position. The simulations tests, referred to a manipulator with three revolute elastic joints, have been shown, however, without experimental evaluation on a real robotic system.

Since then, the research on elastic robot joints and flexible robotic structures, in a broad sense, has been advanced inspired from both robotics and control theory points of view. So in [8] an impedance control for elastic joints industrial manipulators has been addressed, where the joint elasticities have been considered as linear stiffness and damping connected in parallel. A PD control with online gravity compensation for robots with elastic joints has been presented in [5], providing both the theoretical and experimental results. In addition, an adaptive position/force control of uncertain constrained flexible joint robots has been addressed in [11]. Here, the joint stiffness and motor inertia also have been assumed as unknown, in addition to the robot inertia parameters.

Collaterally to elastic robot joints the problems of compliance robot control in Cartesian space came into consideration. So in [37] the interaction between robots and environment has been addressed with the main objective to reduce the vibrational and chattering phenomena caused by the robot joints elasticities. The vibration effects, propagated from the joint elasticities into Cartesian space, have been also considered in [32] by involving inverse dynamics models solved in real-time. A significant improvement could be shown by comparison between the feedback PD controller and a two structural degrees of freedom controller which includes the feedback PD and feed-forward inverse model action. A passivity-based impedance control for flexible joint robots has been described in details in [16], while combining a motor-position-based gravity compensation term with the stiffness and damping terms. Two control strategies have been shown, both having a cascaded structure

* Corresponding author.
E-mail addresses: ruderman.michael@nitech.ac.jp, mruderman@yahoo.com (M. Ruderman).

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with an inner torque feedback loop and an outer impedance control loop. Among others, the relation between flexibilities in the joint space and generalization of an impendence controller in Cartesian space have been emphasized in details. Furthermore, a unified passivity-based control framework for position, torque, and impedance control of flexible joint robots has been presented by the same authors in [1].

The above mentioned approaches on modeling and control of robotic joints with elasticities considered explicitly the linear stiffness and damping characteristics. This proved to be sufficient, above all with regard to identifiability and robustness of the applied methods. At the same time, it should be stressed that the mechanical joint transmissions can exhibit substantial nonlinearities [24], which become remarkable in particular during precise positioning and tracking tasks with frequent motion reversals. It is worth noting, that in this regard the modeling of nonlinear joint behavior has been significantly advanced by explicit studies of harmonic-drives transmission [7,10,14,26,30,33]. Recall, that the harmonic-drives are widely used in robotics due to their compact size, high reduction ratios, high torque capacities, and low (nearly zero) backlash. However, a specific mechanical assembly provides them with additional elasticities which are coupled with internal frictional mechanisms.

Furthermore, from the recent reviewing studies e.g. [2,31] it can be seen, that the modern robotics tends to a variable impedance with compliant actuation. These developments take place for different reasons from which e.g. a safe human–robot interaction, increasing energy efficiency, reducing the effect of impacts can be emphasized as most motivating from application's viewpoint. Besides, the novel technologies and actuation principles like antagonistic driven compliant joints [35], double actuated joints with variable stiffness mechanism [31], and embedded torque sensors and safety joint mechanisms [13] allow at all to realize the active and/or passive compliance of robotic manipulators. To this end it can be emphasized that evermore lightweight design co-determine the development of modern robotics as well, where evermore nonlinearities constitute an inherently growing challenge.

In this paper, we proposes a novel control framework which allows compensating for the nonlinear torsion with hysteresis in elastic robot joints, and that without measuring the load-side output during the operation. It can be noted, that most of nowadays robotic manipulators are equipped by the motor-side sensing devices only, even if some advanced load-side sensing robotic manipulators, like e.g. LWR III [2], are also available. Thus, improving the load-side accuracy without additional sensing can be cost-, space-, and weight-saving as well and is highly desirable for numerous applications.

The recent work bases on the former modeling results presented in [17,22]. The proposed phenomenological model of nonlinear robot joint dynamics allows to compute the direct and inverse torque transmission in real-time. Based thereupon, the concept of 'virtual sensor' of the joint torsion is derived by using only the joint actuator measurements. The observed reactive joint torque serves as an internal state of 'virtual sensor' which, for his part, is involved in the control loop, so as to provide the online correction of reference position with respect to the joint torsion.

The rest of the paper is organized as follows. The recent modeling of elastic robot joints is described in details in Section 2. First, we show the joint transmission structure and describe the joint input dynamics. Afterwards, the used two-state dynamic friction model with elasto-plasticity [18,23] is revisited for convenience of the reader. At the end of the Section we describe the modeled hysteresis spring and based thereupon direct and inverse joint torque transmission. The principal structure of proposed sensorless hysteresis torsion control is explained in Section 3. Section 4 contains an experimental case study which proves the suitability of the proposed method on a real hardware. Finally, conclusions are given in Section 5.

2. Modeling of elastic robot joint

2.1. Transmitting joint structure

An idealized rigid-gear revolute robotic joint provides reducing the angular motion, that is given by

$$\theta = N^{-1} q, \tag{1}$$

and correspondingly enhancing the drive torque

$$T = N\tau. \tag{2}$$

Here, N denotes the nominal gear transmission ratio. The general motor and load displacement and force (torque) coordinates are denoted by $q,\ \theta$, and $\tau,\ T$ correspondingly. However, a disturbing torsional compliance and backlash can occur in the gearing structure during the loaded operation of robotic joints. This is due to the gear teeth meshing and elastic deflections inside the constructive elements of joint assembly. Thus, the angular relative displacement

$$\delta = N^{-1} q - \theta, \tag{3}$$

across the joint transmission (also denoted as *joint torsion*), appears as an undesirable compliance effect, which has often a pronounced nonlinear character. Note, that apart from the nonlinear stiffness characteristics, the internal frictional mechanisms, inside the teeth engagement area, contribute to the overall joint compliance. As impact, the compliant joint behavior is subject to substantial hysteresis phenomena. From the input–output point of view it means that after a closed load-release cycle a revolute joint can exhibit non-zero torsion states, also denoted as hysteresis lost motion (see [22] for details). Further, it is worth noting that the backlash (also known as mechanical play) is mostly coupled with an internal toothing slider, thus giving rise to a bedstop motion across the joint transmission. Here we make aware, that the bedstop motion, which occurs in the relative δ-coordinates, is not of a pure kinematic nature and is a nonlinearly-damped dynamics governed by internal friction. Due to a mutual interaction of the mentioned nonlinear phenomena, the overall resulting hysteresis is hardly decomposable in proper frictional, structural, and backlash contributions. Note, that an accurate decomposition and identification of these nonlinearities appear to be hardly accomplishable, if at all, and can require the joint disassembly and installation of special measuring equipment. Therefore, the joint transmitting behavior can be rather considered as a composite input–output nonlinearity. At the same time, the apparent sources of hysteresis torsion should be kept in mind, in order to conduct an appropriate joint modeling.

The proposed modeling structure [17,22] of an elastic robotic joint is shown in Fig. 1. The driving torque produced by the joint actuator is denoted by u and the overall counteracting joint input friction is denoted by f. The lumped inertial mass, which is aggregate for the joint actuator and input transmission elements as well,

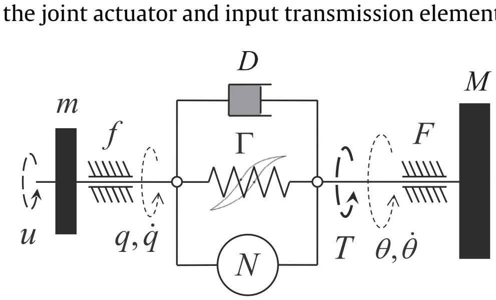

Fig. 1. Structure of elastic robot joint.