Using arm-side position measurements and hysteresis model in robot identification

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In this paper, a methodology for identifying a high-fidelity dynamic model of a collaborative robot is presented, with a particular focus on the identification of nonlinear joint dynamics using hysteresis modeling and both motor- and arm-side position measurements. Unlike large industrial robots, collaborative robots are characterized by lower structural stiffness and the use of gearboxes, typically harmonic drives (HD), that exhibit pronounced nonlinear behaviors, such as hysteresis and complex friction phenomena. Consequently, standard rigid-body modeling approaches are insufficient for capturing the full dynamic behavior of such systems. Our overarching goal is to derive a complete robot model that not only includes the rigid-body dynamics but also integrates joint and structural flexibilities, enabling accurate and efficient simulation and control in real-time applications. To achieve this, a two-step identification strategy is proposed. The first step, addressed in this paper, focuses on identifying a detailed joint model, while the second step will use this model to estimate lumped stiffness parameters describing the structural flexibility of the robot's links.

The joint model is designed to predict the arm-side gear torque, which serves as an intermediate signal for the subsequent identification of the structural flexibility. Since dedicated joint torque sensors are typically expensive components, it is desirable to estimate the gearbox output torque using a model. To identify such a joint model, position sensors both on the motor- (input-) and arm- (output-) side of the gearboxes are used, which allow direct measurement of the movement influenced by joint nonlinearities. Different joint models incorporating nonlinear stiffness and hysteresis are implemented, where the hysteresis model is selected among established hysteresis models such as LuGre [1], Bouc-Wen [2], [3] (see [4] for a survey), Prandtl-Ishlinskii [5], and Preisach [6]. The LuGre model is a dynamic friction model which directly interprets physics observations by incorporating micro-slip and pre-sliding displacement. The Bouc-Wen model is known for its ability to flexibly represent a wide variety of hysteresis shapes with a relatively small number of parameters, which makes it well-suited for real-time applications. The Prandtl-Ishlinskii model, in contrast, is an analytical model characterized by its simplicity and computational efficiency, and it is especially appealing for its invertibility property – useful in feedforward control. Lastly, the Preisach model provides a highly accurate description of rate-independent hysteresis with memory effects, at the expense of increased computational complexity and the need for a detailed calibration procedure. These models offer a trade-off between accuracy, interpretability, and computational effort, allowing for informed selection based on the target application's requirements.

In addition to the flexibilities in the joints, collaborative robot manipulators have structural flexibility that are modeled in this paper as lumped stiffness located in each link's origin. This paper's approach for identification of these lumped link flexibilities draws inspiration from previous work in which frequency response functions (FRFs) were estimated from motor torque to motor acceleration using only motor-side measurements [7]. Here, the FRFs from gear torque (predicted via the joint model) to gear acceleration (measured with arm-side sensors) are estimated. Once the FRFs are estimated, nonlinear optimization is applied assuming a known parametric model structure and analytical FRF.

To calibrate and validate the joint model, a series of test-bench experiments targeting joint-level dynamics is performed. The experiments are designed to stimulate the system with varying amplitudes and velocities. Known excitation profiles are evaluated, see e.g. [8], and a more optimal design in terms of practical constraints of industrial environments will be proposed, targeting the need for rapid and efficient calibration procedures during production. A study with preliminary measurement data is presented and implementations of the LuGre, Bouc-Wen, Prandtl-Ishlinskii, and Preisach model are compared. The measurement setup includes an arm-side torque sensor allowing direct calibration and validation of the hysteresis models. First results demonstrate that the proposed joint modeling approach with Preisach hysteresis captures essential nonlinear characteristics of the joint behavior with high accuracy, reducing the error of the estimated arm-side torque by 67.6 % compared to a model without hysteresis.

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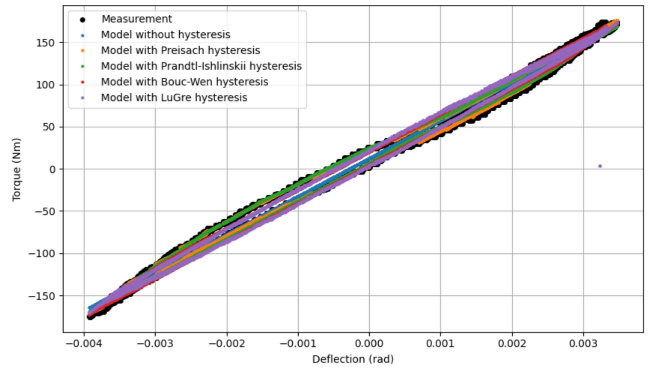

Fig. 1. Hysteresis fit of different models for measurement data (black) of a robot joint.

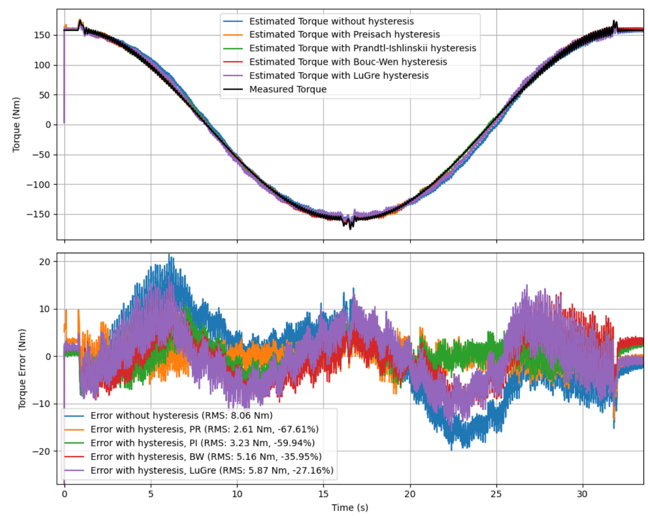

Fig. 2. Hysteresis error using different models. (RMS: Root Mean Square error and relative improvement compared to a model without hysteresis.)