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Adaptive torque estimation of robot joint with harmonic drive transmission

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ABSTRACT

Robot joint torque estimation using input and output position measurements is a promising technique, but the result may be affected by the load variation of the joint. In this paper, a torque estimation method with adaptive robustness and optimality adjustment according to load variation is proposed for robot joint with harmonic drive transmission. Based on a harmonic drive model and a redundant adaptive robust Kalman filter (RARKF), the proposed approach can adapt torque estimation filtering optimality and robustness to the load variation by self-tuning the filtering gain and self-switching the filtering mode between optimal and robust. The redundant factor of RARKF is designed as a function of the motor current for tolerating the modeling error and load-dependent filtering mode switching. The proposed joint torque estimation method has been experimentally studied in comparison with a commercial torque sensor and two representative filtering methods. The results have demonstrated the effectiveness of the proposed torque estimation technique.

1. Introduction

Harmonic drives, invented in the 1950s [1], are widely used in robotic systems, due to their desirable features of near-zero backlash, compactness, light weight, high torque capacity, high gear ratio and coaxial assembly. These distinctive characteristics of harmonic drives vindicate their widespread applications, especially in electrically-driven robot manipulators.

Joint torque feedback (JTF) has been widely recognized to improve the performance of robot control in the robotics community [2,3]. JTF is typically used in motion control of robot manipulators to suppress the effect of load torques [4] and can be used in the dynamic control of robots without the need of computing the robot inverse dynamics [3]. Joint torque sensing or estimation is also essential for controlling robot force and compliance, as well as for collision detection.

Conventionally, joint torque sensors or a multi-axis force/torque (F/T) sensor is utilized in robot force control. When estimating joint torques using F/T sensor at the robot wrist, extensive calculations are needed, and the results are affected by computation delays and model errors [5]. There are several techniques of direct joint torque sensing, e.g., joint torque sensors based on elastic elements that are placed in the output transmission line of each joint of the robot [6,7].

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In [8], a linear encoder is used to measure the torsional deformation of the additional elastic body of a joint torque sensor. As measurement accuracy is in inverse proportion to sensor stiffness, low sensor stiffness is desirable in order to achieve high measurement resolution, which leads to complicated joint dynamics. Another joint torque sensing technique is based on the method proposed by Hashimoto et al. [9]. Joint torque sensing is achieved by mounting strain gages directly on the harmonic drive, which is usually referred to as built-in torque sensing for harmonic drives [9–11]. The torsional compliance of harmonic drives lends itself to torque sensing, but it is difficult to achieve durable accurate torque measurement with this technique due to signal ripples and amplifier drifts [12].

Torque estimation using harmonic drive compliance model provides an effective way of torque estimation for robots with harmonic drives, which is shown in [13], a previous work of our laboratory. The joint torque estimation technique uses link-side position measurement along with a proposed harmonic derive model to realize stiff and sensitive torque estimation, obtaining joint torque with minimal mechanical modifications. However, in [13], a low-pass filter is used to filter the output of the harmonic drive model. While the low pass filter provides a simple and convenient way to resist high frequency noises, the torque estimation response speed is limited by the filter bandwidth.

Kalman optimal filtering technique is commonly used in torque estimation algorithms. However, the filter gain is optimal and cannot be self-adjusted in the standard Kalman filter algorithm, and the external environment is only reflected by the pre-set measurement noise variance, which makes it difficult to adapt to changes in the actual external disturbance and respond timely. Disturbances are taken into account in real time according to the actual measurement in the robust filtering algorithms [14,15], where the online estimation of the noise variance [14] and resetting recursive prediction error variance [15] are incorporated to adjust the filter gain online, which improves the adaptability of the filters to disturbances and ensures the robustness of the algorithm.

Traditionally, optimality is mainly considered in controlling robot force and compliance. In [16], a neural network learning using approximate dynamic programming is developed to achieve optimal control. In [10], to cancel the torque measurement ripples due to the gear teeth meshing, standard Kalman filter estimation is used. By on-line implementation of the Kalman filter, it has been demonstrated with experiments that this method is a fast and accurate way to filter torque ripples and torque due to misalignment. However, standard Kalman filter only guarantees optimality for the torque estimation, while the robustness is also indispensable.

As robustness conflicts with optimality, robust performance improvement is often associated with loss of optimality. In the meantime, strong robustness is not essential all the time, and it may cause excessive loss of optimality. In [15], an adaptive robust extended Kalman filter (AREKF) is proposed to switch the working mode of the filter between robust and optimal, adaptively adjusting the filtering gain with the functions of automatic determination and switching. However, nonlinear modeling errors in the state and measurement models may cause failure in the switching function of judgment mechanisms of AREKF. To solve this problem, redundant parameters are introduced into the AREKF, and a redundant adaptive robust extended Kalman filter (RAREKF) [17] is proposed to make the switching function work stably to provide capability of tolerating the modeling error and load-dependent filtering mode switching in torque estimation.

Torque estimation represents an efficient, economical and convenient to obtain joint torque with minimal mechanical modifications. In [18], joint torque estimation is based on EMG signals, in which matrix modifier is applied to make the controller adaptable to every upper-limb posture of any users. In this paper, a torque estimation method is developed for robot joint with harmonic drive based on a harmonic drive model and a redundant adaptive robust Kalman filter, in that Kalman filter based filtering method is commonly used and has been proved to be conveniently realized in practice.

The proposed method provides desirable tolerant capability to the modeling error and enables dynamic balance of optimality and robustness according to the load variation. The proposed method consists of a modeling part and a filtering part. The modeling part models the harmonic drive compliance on the basis of link-side absolute encoder readings, motor-side encoder readings and the motor current. In the torque estimation, the motor current and the output of the modeling part provide the inputs to the filtering part that consists of a redundant adaptive robust Kalman filter. The proposed method has been studied experimentally in comparison with a commercial torque sensor and two representative filtering methods, and the experimental results have demonstrated the superior effectiveness of the proposed robot joint torque estimation method.

A brief version [19] of this approach was published in ICRA 2014. In this paper, the modeling part and experiments setup are briefly presented. The filtering part is redesigned and simplified to improve the performance, using the motor current as an input parameter. Meanwhile, the experimental analyses are extended in detail and comprehensively presented. The comparisons with several typical commonly used filtering methods are given from the aspects of optimal and robust modes, especially the influence of time delay on the torque estimation. The rest of the paper is organized as follows: the overall structure of the torque estimation method is presented in Section 2. The system model and torque estimation algorithm are presented in Section 3 and Section 4, respectively. Experimental results are given in Section 5, including comparison results. Concluding remarks are in Section 6.

2. Overall structure of torque estimation

The overall structure of the proposed torque estimation method is as shown in Fig. 1. The redundant adaptive robust Kalman filter (RARKF) approach is introduced in the filtering part. Generally, the joint loading is directly reflected by the motor