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An identification procedure for rate-dependency of friction in robotic joints with limited motion ranges☆

Masayoshi Iwatani*, Ryo Kikuuwe

Department of Mechanical Engineering, Kyushu University, 744 Motooka, Nishi-ku, Fukuoka 819-0395, Japan

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ABSTRACT

This paper proposes a procedure for identifying rate-dependent friction of robotic manipulators of which the motion is limited due to the configuration or the environment. The procedure is characterized by the following three features: (i) the rate dependency is represented by line sections connecting sampled velocity-force pairs, (ii) the robot is position-controlled to track desired trajectories that are some cycles of sinusoidal motion with different frequencies, and (iii) each velocity-force pair is sampled from one cycle of the motion with subtracting the effects of the gravity and the inertia. The procedure was validated with a six-axis industrial robotic manipulator YASKAWA MOTOMAN-HP3J, of which the joints are equipped with harmonic-drive transmissions of the reduction ratios of 81.5–224. The experimental results show that the identification is achieved with a sufficient accuracy with the 20 degrees of motion of each joint. In addition, the results were utilized for friction compensation, successfully reducing the effect of the friction by 60–80%.

1. Introduction

For the control of robotic manipulators, friction in the joints is one of major disturbances that degrade the accuracy and the precision of control. One straightforward idea to deal with this problem is to calibrate the friction properties of the robot in advance and to compensate the friction force by producing the actuator forces that cancel the friction forces. It is however, usually difficult to find appropriate models of the friction phenomena and, even if an appropriate model is available, it is also difficult to clarify how the values of the parameters should be chosen.

Many friction models have been proposed so far, and they vary in the treatment of the discontinuity around the zero velocity and the microscopic elastic displacement in the static friction. A common point shared by various friction models is that they employ a user-defined function of velocity that represents the rate-dependent friction law. That is, for any kinds of friction models, the magnitude of the friction force as a function of the velocity must be identified experimentally.

Experimental identification of the rate dependency of the friction force is not always an easy task. Problems such as the limited motion range and the effects of the gravity and the inertia make the identification complicated. The motion of an assembled robotic manipulator is generally limited by the configuration or the environment. Appropriate procedures are needed to measure the friction force at high velocities in a limited motion range, and the identification results need to be insensitive to the effects of inertia and gravity.

This paper presents a systematic procedure to identify the velocity-friction force relation of devices with limited motion range. The procedure was validated with an industrial six-joint manipulator YASKAWA MOTOMAN-HP3J. It is shown that the identification with a sufficient accuracy was achieved with 20 degrees of motion of the joints. This paper also shows the application of identified results to friction compensation.

The remainder of this paper is organized as follows: Section 2 overviews previous studies on identification of rate-dependent friction. Section 3 proposes the new procedure. Section 4 and 5 show experimental results obtained with a six-axis manipulator. Section 6 provides concluding remarks.

2. Related work

Many friction models have been proposed for the purpose of control. They have realized friction property such as rate-dependency in the kinetic friction [2], elastic displacement in the static friction [3], hysteresis in the velocity-friction relation, stick slip motion [4], non-drifting [5,6], and smoothness of the output

☆ The paper extends the authors' previous conference paper [1] by including new experimental results.

* Corresponding author. Tel.: +81928023179.
E-mail addresses: iwatani@ctrl.mech.kyushu-u.ac.jp (M. Iwatani), kikuuwe@mech.kyushu-u.ac.jp (R. Kikuuwe).

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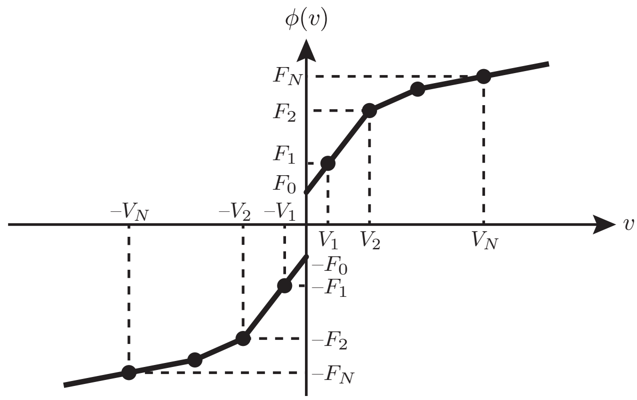

Fig. 1. Fitted curve $\phi(v)$ defined by (8).

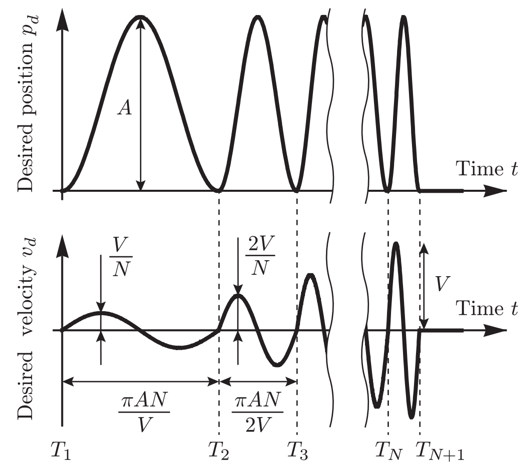

Fig. 2. Desired trajectory $p_d(t)$ and its derivative $v_d(t)$ for the proposed identification procedure.

force [7]. Discrete-time models have also been considered [8,9]. There have been applications of the models to friction compensation [5,10], and harmonic drive transmissions especially have been the target of applications of modeling studies [11–13]. One common feature shared by many models including dynamic friction models is that they employ functions of velocity for representing the rate-dependent friction force in the kinetic friction region. It means that the velocity-friction relation must be calibrated in advance for using any kinds of existing models including dynamic friction models.

Rate-dependent friction of manipulators can be identified by maintaining a constant velocity for a certain period of time [10,14]. In such methods, constant velocity commands are sent to the devices, and the resultant actuator torque to maintain the velocity is observed. One drawback of such methods is that maintaining high velocity is generally difficult within a limited range of motion.

Another kind of approach is to apply sinusoidal or saw-tooth torque signals to devices to be identified [15,16]. Such torque command, resulting reciprocating motion, requires a certain level of carefulness in choosing the torque amplitudes so that the trajectory of motion is bounded to a limited range.

The gravity and the inertia affect the accuracy of the identified results. A straightforward idea to deal with these factors is to incorporate a system model including the gravity and the inertia into the identification procedure [10,15–17]. Major drawbacks of this approach are that the identification of the system model is usually a hard task, and that the identification accuracy of the friction depends on the accuracy of the whole system model.

3. Procedure

3.1. Overview

This section describes a new identification procedure for rate-dependent friction laws. The procedure is to obtain a set of N velocity-force pairs

$$\mathcal{S} \triangleq \{[V_1, F_1], \cdots, [V_N, F_N]\}, \tag{1}$$

which describes the relation between the velocity and the friction force as shown in Fig. 1. The joint to be identified is controlled to follow sinusoidal trajectories with N different frequencies with a high-gain PID position controller. One cycle of motion is performed for each frequency. The pair $[V_n, F_n]$ is chosen so that the effects of inertia and gravity are small. The identification on each joint is performed on a one-by-one basis, with the other joints being locked by local position controllers.

3.2. Details

The input to the procedure is the following three parameters:

- V : The maximum desired velocity
- A : The amplitude of the sinusoidal motion
- N : The number of sampled velocities

The maximum velocity V should be chosen so that it includes the range of velocity in which the friction force should be identified. The amplitude A should be chosen small enough to match the hardware limitation, and should be smaller to save the time needed for the identification procedure. Its lower bound is determined by the capacity of the actuator because, with a fixed V value, the desired acceleration command is inversely proportional to the A value, as will be shown later. The number N of sampled velocities should be chosen considering the trade-off between the precision of the fitted curve and the time needed for the identification.

The desired trajectory for the identification of the set $\mathcal{S}$ is generated as the following function of the time t:

$$p_d(t) \triangleq \frac{A}{2}\left(1 - \cos\left(\frac{2\nu(t)V}{AN}(t - T_{\nu(t)})\right)\right) \tag{2}$$

where

$$T_n \triangleq \sum_{j=1}^{n-1} \frac{\pi AN}{jV} \tag{3a}$$

$$\nu(t) \triangleq n \text{ s.t. } t \in \mathcal{T}_n \triangleq [T_n, T_{n+1}). \tag{3b}$$

This position trajectory $p_d(t)$ is based on the following velocity trajectory:

$$v_d(t) \triangleq \frac{\nu(t)V}{N} \sin\left(\frac{2\nu(t)V}{AN}(t - T_{\nu(t)})\right). \tag{4}$$

These trajectories $p_d(t)$ and $v_d(t)$ are illustrated in Fig. 2. Here, it can be seen that $p_d(t)$ is composed of N times of sinusoidal movements with N different frequencies. The amplitude of the desired position p_d is fixed to A, and the maximum velocity of the nth cycle is nV/N. It should be noted that the amplitude of $\dot{v}_d$ is proportional to V^2/A, and thus the choice of the A value is lower-bounded by the capacity of the actuator.

Once the joint is position-controlled to track the aforementioned desired trajectory, the data as shown in Fig. 3 is expected to be obtained. Here, it is advisable that the gains of the position