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Thermal effects in identifying the dynamic parameters of an industrial robot

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***Abstract*—This work describes the influence of temperature on the identification of the dynamic model of an industrial manipulator. The tests show that the joint friction changes during the robot operation. The variation is due to the heat generated by friction. A model is used to estimate the temperature and related friction variation. Experimental data collected on an industrial robot are discussed. Repetitive tests performed on different days showed that the inertial and friction parameters can be robustly estimated.**

***Index Terms*—Robot Dynamics; Friction; Temperature**

I. INTRODUCTION

The study of the dynamical performance of robotics machines is one of the most relevant problems in the design of effective robot control strategies. Parameter identification allows obtaining reliable dynamic models of industrial manipulators [1]. It is worth pointing out that a reliable dynamic model can improve position control. Many other applications may require the knowledge of a good model, e.g. predictive maintenance, trajectory planning for energy efficiency, safety systems for robotic cells, or management of robot interaction with humans or the environment. The robot's dynamical parameters include inertial parameters (masses, centers of mass, and moments of inertia) and friction description. The inertial parameters can be obtained by developing a model and by performing experiments on the robot. The model is linear on these parameters and their regression matrix depends on the position, velocity, and acceleration of the joints. The linearity in the parameters does not hold in long time intervals, because the friction might change due to thermal effects. The introduction of these non-linearities might cause several problems related to motion control, such as trajectory tracking errors, limit cycles, and dynamic instabilities (stick-slip). For these reasons, many friction models have been proposed in the technical literature [2] to provide a suitable description of the physical phenomenon and to obtain effective mathematical formulations.

II. MATERIALS AND METHODS

The dynamics model of a robotic manipulator can be expressed by exploiting the Lagrangian formulation, where the dynamics of a robot manipulator can be expressed by considering motor torques τ as the sum of the inertial effects τ_i, the friction contribution τ_f and the external forces acting on the robot end-effector τ_e:

$$\tau = M(q)\ddot{q} + V(q,\dot{q})\dot{q} + G(q) + \tau_f + J^T(q)F_e \tag{1}$$

where q, $\dot{q}$ and $\ddot{q}$ are the joint position, velocity and acceleration vectors respectively, $M(q)$ the inertial matrix, $V(q,\dot{q})$ the matrix containing the centrifugal and Coriolis terms, $G(q)$ the gravitational term, $J^T(q)$ is the Jacobian matrix and F_e denotes the vector of the forces and the moments exercised by the end-effector on the environment. Fro a given temperature, the friction can be modeled with good approximation by a polynomial function as in [3]:

$$\tau_f = f_1 sign(\dot{\theta}) + f_2\dot{\theta} + f_3\dot{\theta}^2 sign(\dot{\theta}) + f_4\dot{\theta}^3 \tag{2}$$

where $\dot{\theta}$ is the velocity of the joints, and f_1, f_2, f_3 and f_4 are the coefficients of the friction model. To find the numerical value of the parameters it is possible to use the Least Square criterion. In practice, the robot can be moved on suitable joint trajectories, the motor torques are collected at predefined sampling instants, and afterwards they are used in the identification process. To better identify friction and inertial parameters, the trajectories are divided into three stages: the first is optimized for inertial parameter estimation, the second is specially designed for friction estimation, and the third allows the robot heating through an high speed movement. The friction parameters are highly dependent on temperature. The temperature of the gearbox is not available in most of the industrial robots in the market. Thus, it is necessary to estimate both the temperature and the thermal model from the experimental data. The estimation is possible by exploiting the variation of the joint torque, as proposed in [3] for a first-order thermal model and extended in [4] for second-order models. The exchanged heat with the environment is assumed linearly dependent on the temperature of the thermal capacities. The heat generated by friction is the product $W_f = \tau_f\dot{\theta}$. Thus, the temperature evolves as described by the following transfer function:

$$\frac{T(s)}{W_f(s)} = \frac{c_1}{s+\tau_1^{-1}} + \frac{c_2}{s+\tau_2^{-1}} \quad (3)$$

where s is the Laplace variable, T is the gearbox temperature, and τ_1, τ_2, c_1, and c_2 are model parameters. According to [5], when one robot is actuated on a repetitive working cycle, sufficiently shorter than the time constants t_1 and t_2, the joint temperatures changes as the step response of (3) where the heat is given by the root-mean-square value $W_{f,rms}$ computed in the working cycle:

$$T{=}T_0{+}\left(c_1\tau_1\left(1-e^{-\frac{t}{t_1}}\right){+}c_2\tau_2\left(1-e^{-\frac{t}{t_2}}\right)\right)W_{f,rms} \quad (4)$$

where t is the time and T_0 is the initial temperature. Given an estimated temperature, the friction changes as:

$$\tau_f{=}\tau_0\left(1{+}\alpha\left(T{-}T_0\right)\right) \quad (5)$$

where α is a constant dependent on the thermal model and τ_0 is friction torque at the initial temperature T_0. By combining the polynomial equation (2) with (5), it is possible to obtain a friction estimation formula that is valid both for constant velocity situations as well as for transients, as described in Algorithm 1. Line 3 of the algorithm is the finite difference equation obtained by discretizing (3).

It is worth noticing that, in the special case of repetitive short cycles the friction torque changes as:

$$\tau_f{=}\left(1+\alpha W_{f,rms}\left(c_1\tau_1\left(1-e^{-\frac{t}{t_1}}\right){+}c_2\tau_2\left(1-e^{-\frac{t}{t_2}}\right)\right)\right)\tau_0 \quad (6)$$

Then it is possible to identify the parameters α, c_1, c_2, τ_1, and τ_2 of the thermal model following the procedure described in [4], where a genetic algorithm tunes the model parameter to fit multiple warming cycles with different values of $W_{f,rms}$.

Algorithm 1: Evolution of the estimated temperature

Input: velocity $\dot{\theta}(k)$; estimated temperature $T(k-1)$ and $T(k-2)$ at the steps $k-1$ and $k-2$; discretization period δt

Output: estimated temperature $T(k)$ at step k

1 $\tau_f(k){=}\left(1{+}\alpha\left(T(k-1){-}T_0\right)\right)\left(a_0 sign\left(\dot{\theta}(k)\right)+\right.$
2 $\left.a_1\dot{\theta}(k){+}a_2\dot{\theta}^2(k)sign\left(\dot{\theta}(k)\right){+}a_3\dot{\theta}^3(k)\right);$
3 $W_f(k) = \tau_f(k)\dot{\theta}(k)$;
4 $T(k)$ =thermal model$(W_f(k), T(k-1), T(k-2), \delta t)$;

III. Results

The robots used during the experiments are the EFORT models ER3A-C60. The data acquisition was repeated four times on different days. To have comparable environmental

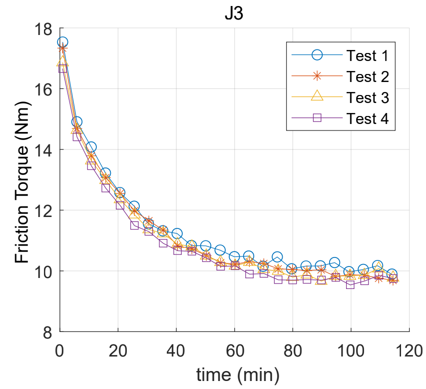

Fig. 1. Mean value of friction torque versus time of 4 different test performed on the robot. Experimental data, Joint 3, and velocity at 60%.

conditions, all tests were executed in the morning after at least 8 h of robot rest and with an environmental temperature of about 20 °C. In order to fit the complete robot model, the data collected during experiments were analyzed to estimate inertial and friction parameters. Inertial parameters should be independent of the temperature and their numerical estimation would be expected to give constant results. The friction instead depends on temperature which increases with the robot activity, therefore a time-dependent trend with asymptotic behavior is expected for these parameters. The results show that the estimated dynamic parameters also had an asymptotic behavior; however, the range of the variation is generally minimal. The results showed that the estimated values of parameters change with cycles, but the variation is very little and the steady-state value is reached after about 1.5 h from the start of the experiment. The coefficient f_i of (2) change with behavior similar to (6). This trend is due to the model mismatches introduced by the thermal effect and the resulting identification error. In fact, the friction torque of one Joint and its estimation are reported in Figure 1. It is worth pointing out that the friction torque at the cold state can be 70% higher than the final value, highlighting the relevance of the phenomenon.

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