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Slipping detection and avoidance based on Kalman filter

Alberto Cavallo, Giuseppe De Maria, Ciro Natale *, Salvatore Pirozzi

Dipartimento di Ingegneria Industriale e dell'Informazione, Seconda Università degli Studi di Napoli, 81031 Aversa, Italy

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ABSTRACT

The purpose of this paper is to present the latest slipping detection and avoidance algorithms developed by the authors for application in robotic manipulation tasks. Slipping can happen not only in quasi-static conditions such as in grasping tasks but also during dynamic manipulation, therefore the availability of slip control techniques effective in both conditions, such as those proposed here, are essential in real robotic applications. A new algorithm is also proposed to estimate on-line the actual friction coefficient at the contact with the manipulated object by means of a preliminary exploration phase, thus enabling safe manipulation of objects with unknown surface properties. A detailed dynamic simulator is presented and experimentally validated on a mechatronic test bench used for proving the effectiveness of the proposed approach.

1. Introduction

Many studies proved that manipulation ability is enabled by tactile and force sensing, especially the ability to sense the contact condition between the object and the fingers [1]. A neurophysiological study on human manipulation [2] demonstrated that humans are able to keep objects under load perturbations in the direction tangential to the contact surface by adjusting fingertip force vectors so that the force in the direction normal to the contact surface (the so-called grip force) is high enough in relation to the tangential component to prevent slippage, but, at the same time, avoiding deformation of the object. Contact forces and torques vectors at the fingertips, contact point/area locations, orientation of the contact surface, shape and force distribution of the contact area, friction coefficient are the physical quantities and parameters that play a key role in this kind of tasks. Among them, knowledge of the friction coefficient is particularly relevant for a safe grasping and manipulation [3,4]. Various solutions for estimation of this parameter exist in the literature but most of them rely on ad hoc sensors [5,6]. All these algorithms are mainly based on the Coulomb friction law, which is the most celebrated model exploited for robotic manipulation. However, such model does not take into account some phenomena taking place during the contact between two surfaces. Therefore, many more sophisticated friction models, such as [7–9], have been proposed and used in motion control systems for friction compensation [10] and in robotics [11] for object detection and recognition, or for dynamic modelling of grasping [12]. Among such friction models, the LuGre model has been selected for reproducing as accurately as possible in a dynamic simulator the experimentally observed phenomena, and it will be exploited to tune the control algorithm parameters.

Slip detection plays a central role not only in ensuring a stable grasp by adjusting the grip force, but also in manipulation and tactile exploration, as during the slippage, contact forces or more generic tactile sensory data can provide information about the object properties such as roughness, compliance and shape. A recent survey on slipping detection methods is [13], where a taxonomy of slip sensors is proposed comprising four categories based on the detected physical quantity associated to slip: displacement, force, heat, micro-vibration. The slip control proposed in the present paper belongs to the force sensor category. Nevertheless, the authors of the survey believe that research efforts are still needed not only in terms of hardware development but also in terms of efficient computational methods. Many recent papers, e.g. [14–18], dealing with slip control demonstrate that research effort is still needed in terms of both hardware progress and algorithmic advancements.

If slip detection is certainly a feature of primary importance, slipping avoidance is definitely the final objective during grasping and manipulation of an object. Therefore, availability of good detection algorithms is useless without an effective slip avoidance technique. Methods for slip control can basically be divided into two categories, techniques that exploit contact force measurements and techniques that exploit the geometric characteristics of the contact area. A recent work belonging to the first category is [19], where a sliding mode control strategy is adopted to control the grip force on the basis of a binary slip detection signal obtained

* Corresponding author. Tel.: +39 0815010343.
E-mail address: ciro.natale@unina2.it (C. Natale).

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through an array of linear filters of the measured shear force. Similarly to other approaches of the same category, whose references can be found in the cited paper, the grip force is always increased on the basis of the slip event detection. Even though these approaches are suitable for grasping tasks and for slip avoidance in case of unknown or changing friction coefficient, they could not be effective during manipulation tasks where dynamic interaction forces dominate. In such cases, the grip force should be adjusted depending on the dynamic loading conditions and thus the slip control action should be able to increase and also decrease the grip force.

An example of work belonging to the second category and still focusing on grasping tasks is [20], where a vision-based slip margin feedback is proposed for slip control. Similarly to other approaches that exploit contact surface information, complex sensing equipments are needed to obtain a distributed measurement, simple force sensors are not enough.

This paper extends previous work of the authors on slipping control that initiated in [17], where the force/tactile sensor developed in [21] was exploited to estimate the friction coefficient using an off-line technique; then such parameter was used to setup an elementary slip control algorithm assuming to work in quasi-static conditions. The same sensor was then used in [15] within a slip control loop that exploited the residual of an Extended Kalman Filter (EKF). However, the EKF was not purposefully designed for the slip control law, but it was mainly devoted to estimate position and orientation of the object in contact with the hemispherical soft finger tip. In the recent paper [16], the same EKF was exploited to setup a slipping detection technique and to calculate the orientation of the object in contact with the soft tactile sensor in the 3D case, so as to allow a correct estimation of the normal and tangential components of the contact force and thus of the friction coefficient.

With respect to this previous work, the novel contributions of the present paper mainly consist in a new slipping detection algorithm based on a simple linear Kalman filter (KF), though it assumes that tangential and normal components of the contact force are already available, e.g. through the EKF cited above, that is mandatory for in-hand manipulation. The second contribution is a technique to estimate the friction coefficient by exploiting the slipping detection algorithm. This technique is applied during a preliminary exploration phase of the object to manipulate and it can estimate the actual friction coefficient of the contact surface, which depends on environmental conditions such as humidity, temperature and cleanliness. The third contribution is a slip control law that exploits the KF residual and the estimated friction coefficient to compute a grip force adjustment. The control strategy can work not only in static conditions but also when dynamic interaction forces dominate.

The paper is organized as follows. Section 2 is focused on the dynamic modelling of the contact between an object and a compliant sensor pad mounted on a force sensor able to measure both normal and tangential components of the contact force. Contact friction is modelled according to the LuGre dynamic model, which is briefly reviewed and then implemented in the simulator. Section 3 presents the design of the KF based on the dynamic model of the previous section, and whose residual is exploited to detect the slippage and as input to the slipping control algorithm presented later in Section 5. The filter equations reveal that its residual contains the effects of forces not balanced by the static friction, including inertial forces, hence the idea is to exploit the residual as a tool for slip detection and avoidance. The experimental setup used to carry out the experiments is described in Section 4, where the model dynamic parameters are tuned so as to have a good accordance between the simulation and the experimental results. The experimental validation of the slipping detection method is then presented. The slipping avoidance algorithm is designed in Section 5 on the basis of the dynamic model and the developed simulator. The haptic exploration procedure for friction coefficient estimation is also presented in this section as a method to provide this parameter needed by the slip controller. Both simulation and experimental results, that confirm the effectiveness of the proposed approach, are presented.

2. Modelling

The dynamics of the contact between the sensor and the object is modelled taking into account the inertia of both the sensor pad (assumed deformable) and the object as well as the friction force at the contact surface. The aim of the analysis carried out in this section is to describe the dynamics of the object slippage when both normal and tangential forces are applied to it, therefore it is sufficient to write the equations of motion only along the tangential component of the external force, call it f_t.

With reference to Fig. 1, let m be the mass of the moving part of the force sensor (the sensor pad), k its stiffness, β the damping coefficient of the material and M the mass of the manipulated object. The friction force acting between the two contact surfaces will be modelled by resorting to the LuGre model, which is able to describe the complex phenomena that happen during a friction contact and it is indicated as $g(\boldsymbol{x},f_n)$, where f_n is the normal load and $\boldsymbol{x} = (x_1\ x_2\ x_3\ x_4\ x_5)^T$ is the state vector of the dynamic model, defined as follows: x_1 and x_3 are the displacements of the sensor pad and of the object, respectively, $x_2 = \dot{x}_1$ and $x_4 = \dot{x}_3$ are their velocities, thus $x_2 - x_4$ is the relative speed between object and sensor pad. x_5 is the state of the dynamic friction model whose meaning will be detailed below.

The equations of motion can be easily written in the form

$$m\dot{x}_2 + kx_1 + \beta x_2 + g(\boldsymbol{x},f_n) = 0 \tag{1}$$

$$M\dot{x}_4 - g(\boldsymbol{x},f_n) = f_t \tag{2}$$

$$\dot{x}_5 = n(\boldsymbol{x},f_n) \tag{3}$$

where the expressions of the friction force $g(\boldsymbol{x},f_n)$ and of the nonlinear function $n(\boldsymbol{x},f_n)$ depend on the specific friction model that one intends to adopt. In the case of the LuGre friction model [9], they are defined by the following equations

$$g(\boldsymbol{x},f_n) = \sigma_0 x_5 + (\sigma_1 + \sigma_2)(x_2 - x_4) - \sigma_0\sigma_1 \frac{|x_2 - x_4|}{s(\boldsymbol{x},f_n)} x_5 \tag{4}$$

$$n(\boldsymbol{x},f_n) = x_2 - x_4 - \sigma_0 \frac{|x_2 - x_4|}{s(\boldsymbol{x},f_n)} x_5, \text{ with} \tag{5}$$

$$s(\boldsymbol{x},f_n) = \mu_d f_n + f_n(\mu_s - \mu_d) e^{-\left(\frac{x_2 - x_4}{v_0}\right)^2} \tag{6}$$

where $\mu_d \leqslant \mu_s$ is the kinetic friction coefficient, σ_0 is the asperity stiffness, σ_1 is the micro-viscous friction coefficient, σ_2 is the

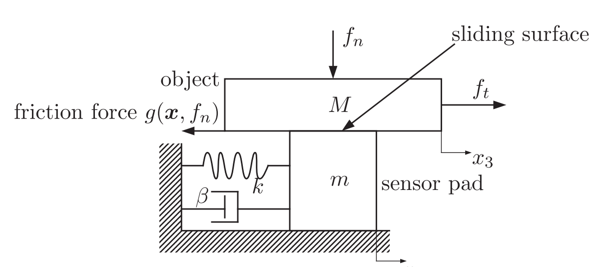

Fig. 1. Sketch of the contact model: tangential dynamics.