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Context-Based Adaptation of In-Hand Slip Detection for Service Robots

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Abstract: Mobile manipulators are intended to be deployed in domestic and industrial environments where they will carry out tasks that require physical interaction with the surrounding world, for example, picking or handing over fragile objects. In-hand slippage, i.e. a grasped object moving within the robot's grasp, is inherent to many of these tasks and thus, a robot's ability to detect a slippage is vital for executing a manipulation task successfully. In this paper, we develop a slip detection approach which is based on the robot's tactile sensors, a force/torque sensor and a combination thereof. The evaluation of our approach, carried out on the Care-O-bot 3 platform, highly suggests that the actions and motions performed by the robot during grasping should be taken into account during slip detection for improved performance. Based on this insight, we propose an in-hand slip detection architecture that is able to adapt to the current robot's actions at run time.

Keywords: Manipulation tasks, slip detection, sensor fusion, tactile sensing, force sensing, run-time adaptation

1. INTRODUCTION

Mobile manipulators such as ARMAR (see Asfour et al. (2006)) or the Care-O-bot 3 (see Reiser et al. (2009)) are intended to be deployed in domestic and industrial environments to support humans in their work. Even though, these environments are highly dynamic, the robots are required to successfully and robustly perform a wide range of tasks. The first step to deal with such environments is their perception. Therefore, modern robots, as the ones introduced before, are equipped with a multitude of sensors, not only exteroceptive, but also proprioceptive ones to create a coherent representation of their environment and detect external disturbances. The major problems here are *1*) the limitations inherent to the sensors; *2*) the different characteristics and modalities of the data measured by the sensors; and *3*) the fusion of the measurements considering the previous two problems.

Especially, highly delicate manipulation and grasping tasks that require physical interaction, such as handling of food and fragile goods or handing over objects to humans, demand the precise reaction to disturbances at run time. One such disturbance, which we investigate in this paper, is in-hand slippage, i.e. a grasped object moves within the robot's grasp. To detect in-hand slippage, our robots are equipped with tactile sensors in their hands, but also force/torque sensors in their arms. However, the involved sensors are affected by the actions which the robot performs, for instance, a force/torque sensor is sensitive to motion whereas a tactile sensor might not be affected at all. Also the reactions to accommodate for detected slippage are context-dependent. For instance, when the robot carries an object and feels slippage, it should grasp tighter to avoid loosing the object. Contrary, when a robot hands over an object to a human, a more suitable reaction is to release the grasped object so that the human can take the object.

The contributions of this paper are three-fold:

- We develop three types of slip detectors based on the tactile and force measurements of the robot as well as a fusion of these.
- Then, we experimentally show how the performance of each slip detector varies with the task currently executed by the robot. In this context, the performance of the slip detectors is evaluated on a Care-O-bot 3 platform, where we measure the robustness by comparing the number of successful and unsuccessful slip detection results.
- Finally, we propose an adaptive slip detection approach which enables the run-time selection of slip detectors suitable for the current task.

Following this introduction, Section 2 describes the slip detectors used in this work. The context-adaptive approach and the associated architecture is proposed in Section 3. Section 4 presents the related work and discusses the approach. Finally, our conclusions are summarized in Section 5.

2. SLIP DETECTION

In this section we describe three slip detectors using tactile sensing, force sensing and a combination of them.

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2.1 Approach

Based on the study of human tactile sensing, Howe (1993) proposed to equip robot manipulators with sensors able to perceive different signals (e.g. vibration, contacts). For instance, a tactile sensor estimates a pressure distribution while a force/torque sensor is able to measure external forces and torques. Furthermore, Melchiorri (2000) showed that slip detection can be performed with a combination of force/torque and tactile sensors using a Coulomb friction model. However, it requires knowledge of the friction coefficients which might not be available when handling unknown objects.

We propose an approach to detect slippage of a grasped object that does not require a priori information about the object being manipulated. In this context, a slip is defined as the object being translated within the grasp (e.g. if the object is pulled down this will result in a downwards slip, see Fig. 1 and Fig. 2). Torque and tactile sensors are used to compute signals that indicate a possible slippage.

Based on the torque sensor in each joint, the KUKA Lightweight Robot 4 (LWR4), see Bischoff et al. (2010), can estimate the wrench (force and torque) applied to the arm's end-effector. The wrench is measured at a rate of 50 Hz. For grasping and manipulating objects, the robot is equipped with the three-fingered Schunk dexterous hand SDH-2. Each finger has two tactile sensors built by Weiss Robotics (2015) to measure pressure caused by contacts. The tactile sensors operate at an average rate of 30 Hz.

Force slip detection We assume a slip occurs whenever a force is exerted in the right direction (e.g. downwards with respect of the grasp frame). A $f_{direction}$ signal is computed as follows:

$$f_{grasp} = R_{grasp}^{sensor} \cdot f_{sensor} \tag{1}$$

$$f_{direction} = f_{grasp} \cdot (f_x, f_y, f_z)^T \tag{2}$$

Where f_{sensor} is the force measured w.r.t. the sensor frame, and R_{grasp}^{sensor} represents the orientation of the grasp w.r.t. the sensor frame. The orientation depends on the hand and grasp type. (f_x, f_y and f_z) selects the direction in which an object can slip up or down within the hand. For example, as shown Fig. 2 this vector is then set to (1, 0, 0). Note that the torque components, for this particular setup, are ignored since their measurements were in the range of noise level (see Fig. 1a). However, the force components were sufficient to detect a slip.

Tactile slip detection To compute the $slip_{tactile}$ signal we apply the algorithm proposed by Alcazar et al. (2012) to each tactile sensor, which estimates the tangential force on the sensor caused by a sliding pressure (e.g. a grasped object slipping). Specifically, a two-dimensional convolution is computed between a tactile sensor's pressure matrix $\mathbf{P}[k]$ of size $(m \times n)$, and its previous pressure matrix, $\mathbf{P}[k-1]$; the output is the convolved matrix, $\mathbf{C}[k]$, of size $(r \times s)$, with $r = (2m-1)$ and $s = (2n-1)$.

We then compute the tactile flow in each axis using the following equations, adapted from Alcazar et al. (2012), as:

$$flow_x = \frac{\mathbf{a}\mathbf{p}^T}{\sum_{i=1}^{s} p_i}, \quad flow_y = \frac{\mathbf{q}^T\mathbf{b}}{\sum_{i=1}^{r} q_i} \tag{3}$$

Where $\mathbf{a}$ and $\mathbf{b}$ defined as: $\mathbf{a} = [-(n-1), \ldots, -(n-s)]$ and $\mathbf{b} = [-(m-1), \ldots, -(m-r)]^T$, and represent the cell positions in the X and Y direction of the pressure matrix, respectively. Furthermore, $\mathbf{p}$ and $\mathbf{q}$ are vectors representing the mean value of columns and rows of the convolution matrix $\mathbf{C}[k]$, respectively. Defined formally as,

$$\mathbf{p} = \left\{ \frac{1}{r} \sum_{i=1}^{r} c_{ij} \right\} \qquad for \quad j = 1, \ldots, s \tag{4}$$

$$\mathbf{q} = \left\{ \frac{1}{s} \sum_{j=1}^{s} c_{ij} \right\} \qquad for \quad i = 1, \ldots, r \tag{5}$$

Finally, the tactile flow is found using the results of equation 3,

$$flow_{tactile} = \|flow[k] - flow[k-1]\|^2 \tag{6}$$

with $flow = [flow_x, flow_y]$. This computation can be applied to tactile sensors of different shapes, provided their output is a two dimensional array. Having N tactile sensors, we define $slip_{tactile}$ as:

$$slip_{tactile} = \sum_{n=1}^{N} \mathbb{E}\left[\mathbf{P}[n]\right] \cdot flow_{tactile}[n] \tag{7}$$

Where $\mathbb{E}[\mathbf{P}[n]]$ is the pressure average and $flow_{tactile}[n]$ is the tactile flow of the n-th tactile sensor. This linear combination allows tactile sensors with higher pressure values to contribute more information regarding how an object is slipping from the grasp, since sensors with lower intensity values, arising from spurious contacts, might not provide an accurate measure of slippage. Note that the $flow_{tactile}$, as defined in equation 6, is an absolute value and thus the direction of the slippage is not considered to produce the $slip_{tactile}$ (see Fig. 1b).

Combined slip detection The $slip_{combined}$ is computed by combining both tactile and force slip signals as

$$slip = \begin{cases} \texttt{slip up} & \text{if} \quad (slip_{tactile} \geq threshold_{tactile}) \wedge \\ & \qquad (slip_{force} \geq threshold_{force}) \\ \texttt{slip} & \text{if} \quad (slip_{tactile} \geq threshold_{tactile}) \wedge \\ \texttt{downwards} & \qquad (slip_{force} \leq -threshold_{force}) \\ \texttt{n/a} & \text{otherwise} \end{cases}$$

Where the $threshold_{tactile}$ and $threshold_{force}$, represent numerical values[1] for detecting a slip based on the $slip_{tactile}$ and $slip_{force}$, respectively. Both of these thresholds are chosen experimentally.

2.2 Experiments & Evaluation

The three slip detectors were evaluated using two different grasp shapes, namely a grasp that uses all three fingers and one that only uses two fingers. The $threshold_{force}$ and $threshold_{tactile}$ were set to 1.5 and $5e^{-3}$, respectively. Three different objects were used in the experiments. A coffee paper cup, an empty Pringles can and a Sprite bottle. Seven actions were performed on each object ten

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[1] These values can be chosen to increase the sensitivity of the slip detectors, e.g. lower values result in higher false positives.