Grip force regulation via low-dimensional incipient slip estimation

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***Abstract*—Robotic manipulation requires regulating grasp forces to maintain stable yet delicate contact with objects of unknown properties. A critical cue for this regulation is how far the contact is to slipping, called the safety margin. This margin determines the minimum force needed to prevent object fall without causing damage. However, detecting slip precursors is challenging because it requires interpreting complex spatio-temporal tactile signals that vary with contact conditions. In this work in progress, we propose to estimate incipient slip through a low-dimensional representation of the deformation of a soft membrane. By projecting the measured deformation field into a compact latent space, the safety margin can be described by only two dominant modes. This representation provides a continuous estimate of the proximity to slip via the safety margin. Its compact structure enables fast and robust estimation suitable for real-time grasp control.**

***Index Terms*—Incipient slip, tactile sensor, grasp regulation**

I. INTRODUCTION

Reliable manipulation requires robots to regulate grasp forces while interacting with objects whose properties are unknown. A key tactile cue used for this regulation is the perception of slip: detecting its onset allows controllers to adjust grip forces before an object slides away, while avoiding the excessive forces that would damage fragile objects [1]. A useful quantity to characterize the proximity to slip is the Safety Margin Γ, which measures the remaining tangential force capacity before full sliding begins [2].

High-resolution tactile sensors provide rich measurements at the contact interface and thus, have been efficient in estimating the proximity to slip [3]. However, many of these approaches estimate the incipient slip directly from the raw images, which is both computationally expensive and practically infeasible to transfer across tactile sensors.

An alternative is to estimate the safety margin from the three-dimensional membrane deformation field using a shallow neural network [4]. However, full 3D displacement fields are high-dimensional and tend to entangle slip-related deformation with object properties such as shape and softness [5].

Interestingly, humans do not appear to process raw tactile signals in their entirety either, and evidence suggests that the somatosensory system encodes contact information through a small set of spatial bases [6]. This raised the question of whether a compact, low-dimensional representation of deformation could isolate information relevant to slip, independently of other properties.

In this paper, we projected the dense three-dimensional displacement field obtained with the ShadowTac sensor onto a compact latent space describing two dominant deformation modes. We estimated the safety margin directly from the low-dimensional representation. This approach generalizes across object shapes, contact directions and loading conditions and provides a contact-invariant description of slip progression. The efficiency of the method allows a 20 Hz refresh rate, suitable for real-time grasp force regulation.

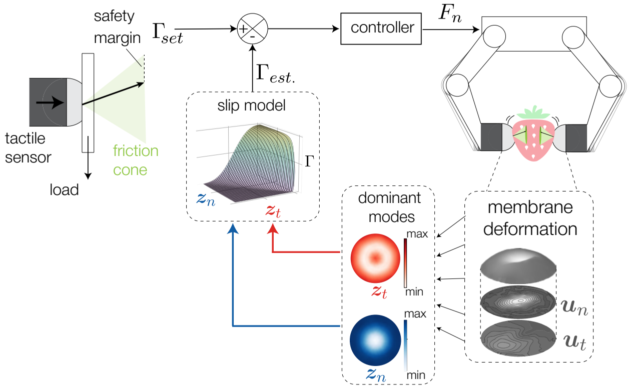

Fig. 1. Slip estimation and grasp control pipeline. The safety margin Γ is defined with respect to the friction cone and quantifies proximity to slip. Tactile membrane deformation (u_n, u_t) is projected onto dominant modes (z_n, z_t) to estimate Γ_{est} via an analytical model. A controller regulates the normal force F_n to maintain a desired safety margin Γ_{set}.

II. MATERIAL AND METHODS

A. Sensor and dataset

Experiments were performed using the ShadowTac vision-based tactile sensor, which reconstructs the three-dimensional displacement field of a soft membrane during contact interactions, providing normal and tangential deformation measurements at approximately 200 sensing locations.

We used the sliding dataset from [4], in which controlled tangential motions were applied to the sensor while recording tactile images and contact forces. The dataset includes sliding interactions under varying indentation depths (1–4 mm), object geometries (spheres and cylinder), and friction conditions (dry and wet).

From the measured forces, the Safety Margin Γ was computed for each sample as follows:

$$\Gamma = \frac{F_t^* - F_t}{F_t^*}, \tag{1}$$

where F_t^* is the critical tangential force at which full slip occurs and F_t is the current tangential force. Each tactile frame is therefore associated with a displacement field and its corresponding Γ value describing slip progression.

Finally, the dataset was augmented by rotating the displacement fields in six angular directions to simulate sliding along multiple directions.

B. Data organization and analysis

The 3D displacement field of each tactile frame was organized into two datasets: X_n is the normal displacement measurement, and X_t is the tangential displacement magnitude computed as the norm of the lateral displacements of the membrane markers.

To identify the dominant deformation modes associated with slip progression, we applied Singular Value Decomposition (SVD) to both datasets. This yields basis vectors that describe the principal deformation modes of the membrane. The displacement data were then projected onto these bases, providing a low-dimensional representation of the deformation field that captures the mechanical patterns correlated with the evolution of the safety margin.

III. RESULTS AND DISCUSSION

A. Low-dimensional structure of slip

Both X_n and X_t datasets exhibited a highly compact structure, the dominant modes are shown in Fig. 1. For X_n, the first three components explained 96% of the variance, with the first component alone accounting for 93%. Similarly, for X_t, the first three components explained 98% of the variance, with the first component explaining 81%.

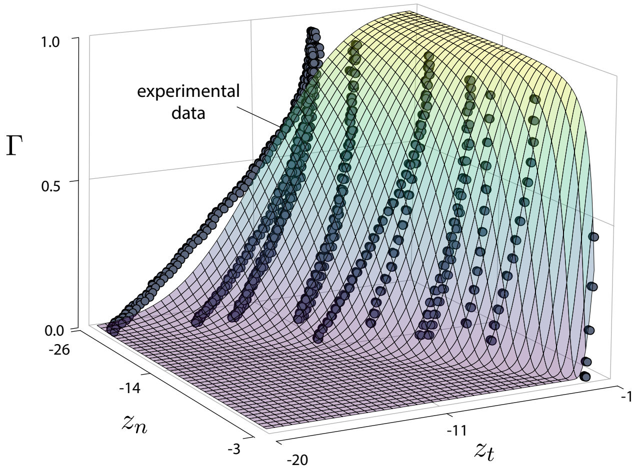

Fig. 2. Safety margin Γ as a function of the two dominant deformation projections z_t and z_n. The surface is a fit of the experimental data ($R^2 = 0.77$).

Given the dominance of the first components, we projected the displacement measurements onto these bases (Fig. 2). Let u_t and u_n denote the first principal components of X_t and X_n, respectively. The corresponding projections were computed as $z_t = u_t^\top X_t$ and $z_n = u_n^\top X_n$. In this coordinate system, the safety margin Γ exhibited a regular structure, suggesting that slip progression could be described by a simple functional relationship.

Based on this observation, we fitted an analytical model relating z_t and z_n to Γ:

$$\Gamma(z_t, z_n) = 0.005134^{\left(\frac{z_t}{z_n + 1.1316}\right)^3}. \tag{2}$$

The functional form was chosen empirically to maximize the goodness of fit while maintaining a simple and interpretable structure. To ensure physical plausibility, the model output was constrained to the interval [0,1] with a clipping operation. The model achieved a MAE of 0.11 and $R^2 = 0.77$.

This result indicates that slip progression could be approximated using only two scalars related to the deformation field. This suggests that slip dynamics lie on a low-dimensional manifold of the membrane deformation field, where two dominant deformation modes captures the essential behavior.

B. Gripper Implementation

To evaluate the proposed representation in a manipulation scenario, the ShadowTac sensor was mounted on a robotic gripper and integrated into a real-time grasp controller (Fig.3). The control architecture consisted of two nested PID loops. An inner loop running on a Teensy microcontroller regulated motor commands at 100 kHz, while an outer loop estimated $\Gamma(z_t, z_n)$ using equation (2), and adjusted the grasp force to maintain a desired Γ_{set}. This outer loop operated at approximately 20 Hz on a regular laptop CPU (Intel i7-1265U @ 1.80 GHz).

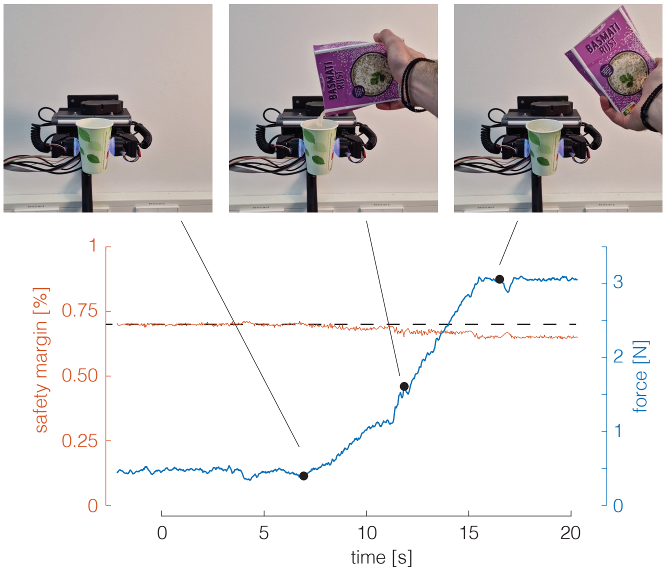

Fig. 3. **Grasp regulation.** Estimated safety margin Γ (red) and grip force (blue) while a paper cup is progressively filled with rice. The controller maintains $\Gamma_{set} = 0.7$ by adapting the normal force as the load increases.

The controller was evaluated by maintaining $\Gamma_{set} = 0.7$ while grasping a paper cup with previously unseen geometry. The cup was gradually filled with rice, increasing the load over time. The controller adapted the grasp force to maintain the desired safety margin and prevent slip throughout the task. Additional experiments suggest that the controller responds rapidly to sudden disturbances applied in arbitrary directions (see Video), maintaining stability under transient perturbations.

These results demonstrate that the proposed low-dimensional representation enables fast incipient slip estimation suitable for real-time and robust grasp regulation. Future work will investigate the robustness of the method across a wider range of contact conditions, and its ability to generalize to unseen geometries and frictional regimes.

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