Tactile Resolution and Grasp Stability Prediction

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***Abstract*—Understanding the relationship between tactile sensor quality and functional performance is key to a rigorous design process for tactile sensors. We quantitatively analyzed the effect of sensor resolution on stability prediction. Resolution limits of contact sensors cause ambiguity in contact location and surface normals, which leads to ambiguous predictions of grasp outcomes in some instances. Our analysis enables calculation of the specific contact locations on an object where the tactile sensors are trustworthy, as well as calculations of the success prediction ceiling for data-driven methods.**

I. Introduction

In theory, predicting grasp stability can make use of well-developed grasp analysis methods [1]. This involves determining whether the forces exerted on the object by the fingers and the environment (e.g. gravity) are in equilibrium with the forces required by the task. For simple lifting tasks using precision grasps, this calculation can be performed using contact locations, contact forces, surface normals, coefficients of friction, masses, and object's centers of mass. However, the sensors today are incapable of delivering the needed parameters accurately and quickly. They suffer from insufficient resolution, sensitivity, signal-to-noise ratio, etc. These limitations render analytical methods too inaccurate to be useful in real-time and real life.

To reliably use imperfect sensors for stability prediction, we need a deeper understanding of the relationship between stability calculations and sensor characteristics. Using grasp analysis as a guide, we developed methods to quantitatively evaluate the reliability of the stability prediction as a function of the spatial resolution of contact sensors.

II. Analysis

Assuming the finger contact surface shape and the distribution of sensors are known a priori, then when a particular sensor reports contact, the corresponding surface normal, friction cone, and contact location on the finger can be deduced. However, when the spatial resolution of the sensors is limited, a single sensor responds to a large receptive field, and exact location of the contacts inside the receptive field is indistinguishable. This can result in uncertainties in the orientation of contact normal and location(Fig. 1). Most grasp stability analyses heavily depend on variables such as contact surface normal, contact forces and locations. Therefore uncertainties in these parameters can lead to predicting different grasp outcomes for the same grasp.

The uncertainties in contact normal and location will result in a range of possible predicted grasp outcome for any given configuration. As long as all the predictions are congruent with each other, then the prediction at the given configuration is reliable. Otherwise the prediction is not reliable. Therefore, to check the reliability of the grasp prediction for a particular contact configuration, we must check if the grasp stability predicted using the perceived normal and location may be different from the true stability.

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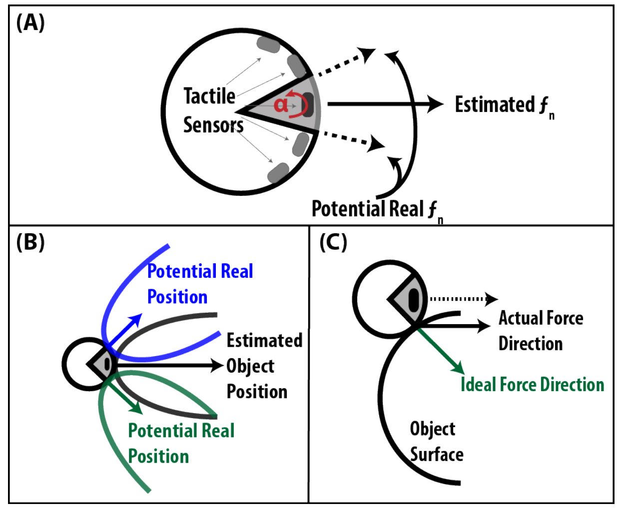

Fig. 1: (A) Each sensor‘s active area extends over resolution angle α, so the actual contact surface normal can differ from the estimated normal vector by as much as $\alpha/2$. (B) object location uncertainty due to the multiple places the finger can make contact with the object and still stay within the same sensor's receptive field.(C) Force direction difference due to difference between perceived and actual contact normal.

We demonstrated the concept on a spherical object, or a circle for two-fingered planar grasps. We assumed spherical fingertips, embedded with sensors whose receptive regions are parameterized by α, making point-with-friction contacts, and we used ϵ defined by Ferrari and Canny [2] as definition of stability. To examine all possible grasp configurations on a circle, we fixed one finger at one point on the circle and scanned the second finger along the perimeter (Figure 2A). The angle between the two fingers is parameterized by $\theta = [0, 2\pi)$.

When contact is made, the object can be touching the finger anywhere on the receptive surface of the corresponding sensor, and the resulting perceived surface normal can be rotated from the true surface normal up to $\pm\alpha/2$. This range of surface normals results in a range of ϵ output. The potential ϵ at each point of a sphere's surface are plotted in Figure 2B for two sensor resolutions: $\alpha = \pi/6$ and $\alpha = \pi/12$. In both plots, the black lines represent the true ϵ values at each point on the perimeter, and the blue and green lines are ϵ's calculated using the two worst case scenarios combinations of perceived

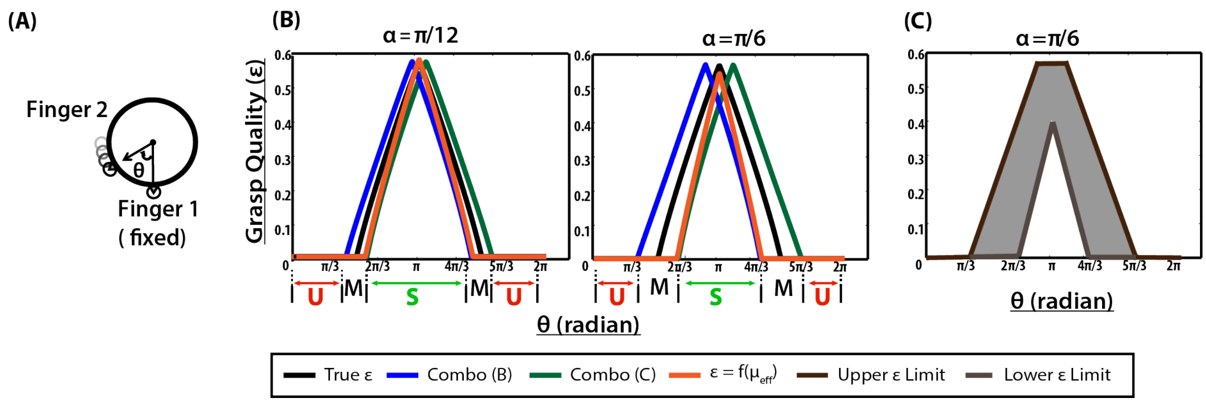

Fig. 2: (A)The full range of ϵ values are achieved by fixing one finger at the bottom of the circle, and scanning the second finger along the perimeter. (B) the variability of ϵ increases with lower sensor spatial resolution. The blue and green lines are ϵ's calculated using the worst case scenarios for each θ. The regions of definite stable(S), definite unstable(U), and ambiguous(M) are labeled along the bottom. (C) The boundary of ϵ as a function of θ.

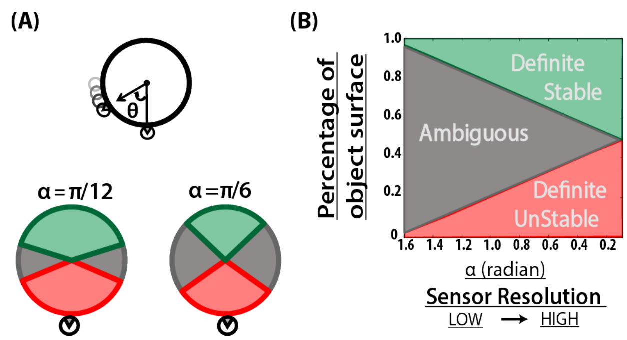

Fig. 3: (A)The placement of the second finger that produces stable, unstable, and ambiguous regions on the circle, (B)As the resolution increases, the size of regraspable region (definitely unstable+ambiguous) decreases.

surface normals for the same grasps.

As shown in Figure 2C, for a given contact configuration where finger 2 is at θ, the corresponding ϵ can have a range. If the signs of all the possible values are all positive, then the grasps corresponding to these θs are definitely stable despite resolution-induced uncertainties(S). When they are all zeros, then the corresponding grasps are unmistakably unstable(U). But if they disagree and have different signs(M), then the predictions corresponding to these θs can go either way, and the outcomes is indistinguishable by tactile sensors. Grasps that land in region A are definite successes, and those that land in either region B or C require regrasping.

For most objects, the size of the ambiguous region increases as the tactile resolution decreases. Hence, higher tactile resolution allows for more certainty when making grasp stability predictions. It is also correlated with more area on the object that is graspable with 100% certainty. The result of the described analysis for a spherical object is shown in Figure 1 (B,C).

The indistinguishable region corresponds to sensor signals that may not be correlated with the grasping outcome. Therefore, the size of this region can also define a performance ceiling for data-based prediction algorithms using machine learning, for grasp trials that are inside the ambiguous region will have seemingly random outcome labels.

Our full paper also includes the same analysis done on a square and a sphere in 3D in order to establish some intuition for the effect of object geometry. We also layout a method for determining the reliability of grasp prediction when the object shape is unknown a priori. The insights derived here can be used to improve both physics-based and data-based stability predictions, as well as hand design, sensor design, control, and planning.

III. Conclusion

We present a method to quantitatively identify the range of contact measurements that can guarantee grasp stability as a function of tactile sensor resolution. Using grasp analysis as a guide, we also layout in detail the ways tactile sensor resolution introduces uncertainties in surface normal and contact location, and how it ultimately influences not only grasp stability calculation, but also design, control, and planning of grasping systems. While we used point-contact-with-friction models for contact, spherical shape for fingertip, and Ferrari and Canny [2] for grasp stability. Any of them can be substituted for more complex or customized models. Although we focused on the spatial resolution of the sensor, other sensor characteristics, such as sensitivity and force resolution, can also contribute to errors in contact location, surface normal, and estimation of various object properties, and analysis similar to our study can be done to understand how those parameters contribute to grasp performance.

References

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[2] Carlo Ferrari and John Canny. Planning optimal grasps. In *Robotics and Automation, 1992. Proceedings., 1992 IEEE International Conference on*, pages 2290–2295. IEEE, 1992.