Hierarchical Fingertip Space for Synthesizing Adaptable Fingertip Grasps

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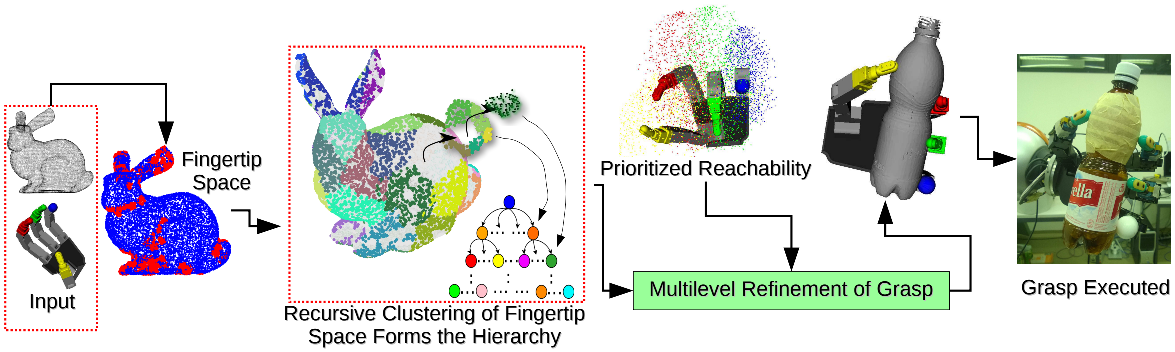

Fig. 1. Given object point cloud and hand model, our system generates a hierarchy of *fingertip units* (blue) by recursive cluster analysis of the *fingertip space*. This hierarchy is searched for feasible combinations of contacts with multilevel refinement. The search is prioritized by hand reachability and grasp adaptability measures. Finally, the synthesized grasp is realized by solving inverse kinematics for the selected contacts through optimization.

***Abstract*— The ability to synthesize and execute fingertip grasps are bases for dexterous in-hand manipulation. Reliable fingertip grasping is difficult to achieve due to noise and uncertainties in object and hand model, as well as hand control etc. Moreover, in many cases it is desirable to employ an adaptive approach that can deal with changed external forces. In this paper, we propose an approach to jointly optimize stability, adaptability, and reachability of grasps using combinatorial optimization for a hierarchical representation of the *fingertip space*. To illustrate our approach, we demonstrate an example synthesized by the proposed framework and executed by an Allegro hand. We also show how it is adapted when a perturbation is applied.**

I. INTRODUCTION

Synthesizing fingertip grasps on novel objects is important for dexterous manipulation. Due to the intrinsic complexity of fingertip grasping, grasp synthesis and grasp execution are usually addressed as separate problems [1]. Analytic grasp synthesis defines grasp quality measures based on the properties of grasps, such as contact positions and contact wrenches, and it seeks for a hand-object configuration that optimizes these. To this end, force closure analysis has been widely adopted. However, modeling assumptions such as known point contacts and wrench cones [2], and that the contacts can exert the same forces omni-directionally, are rather strong for realistic applications. Given uncertainties in perception and execution, synthesized contacts and forces can not be always realized perfectly. Methods such as Independent Contact Regions [3] have been introduced to quantify to what extent a grasp can allow these uncertainties in order to remain stable. However, planning corrective actions in case of perturbations is yet to be investigated.

In this paper, we address the problem of adaptive grasping and propose a framework based on the hierarchical *fingertip space* representation, shown in Fig. 1, to synthesize grasps by jointly optimizing grasp stability, reachability and adaptability. Our framework aims at providing: 1) grasps that can be locally adapted to deal with potential perturbations and 2) grasps that are not close to singular configurations. Based on an offline learning process, an online grasp adaptation procedure is triggered to locally adapt the current grasp by repositioning one of the fingers.

II. HIERARCHICAL FINGERTIP SPACE

Differently from the approaches that represent skeletal or topological features of target objects [4], we construct a hierarchical representation directly on the object's surface geometry for synthesizing fingertip grasps. The representation is built upon a set of potential contact locations (*Fingertip Units*) on the object's surface called *Fingertip Space*. In order to ensure that the robot's fingertips can be stabilized on the object's surface and that nearby contacts can be used for the local grasp adaptation, the *Fingertip Units* are extracted from the object's surface at positions where features of the fingertips and the surface geometry match.

To facilitate grasp synthesis by multilevel refinement [5], we construct a multiresolutional model of the object as a hierarchy of *Fingertip Units* by recursively clustering the object's *Fingertip Space*. To enable handling of noise inherit to our input data, a probabilistic approach – Gaussian Process with Thin Plate kernel [6] – is employed in cluster analysis to partition the object surface recursively. This process is examplified in Fig. 1 (mid-left).

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III. Grasp Adaptability and Online Adaptation

The goal of the grasp adaptation is to move or slide fingertips on the object's surface in order to generate a more stable grasp to counteract perturbations. By decomposing the hand Jacobian and calculating the *manipulability* [7] of a grasp in the tangential plane of contacts, we measure the *adaptability*, denoted as $A(g) \in \mathbb{R}$, for a grasp g by its ability of moving fingertips tangentially along the object's surface. Intuitively, a grasp with high adaptability should allow local adaptation of the fingertips to counteract detected perturbations, and the grasp should be not close to singular configurations of the hand.

Our online grasp adaptation procedure is illustrated in Fig. 3(a). By offline learning of a probabilistic model of the joint density over grasp parameters and the corresponding tactile readings at fingertips, the system is able to estimate the grasp stability from tactile sensing. When a grasp is classified as unstable, the corresponding corrective movements for fingertips are computed based on the experience [8].

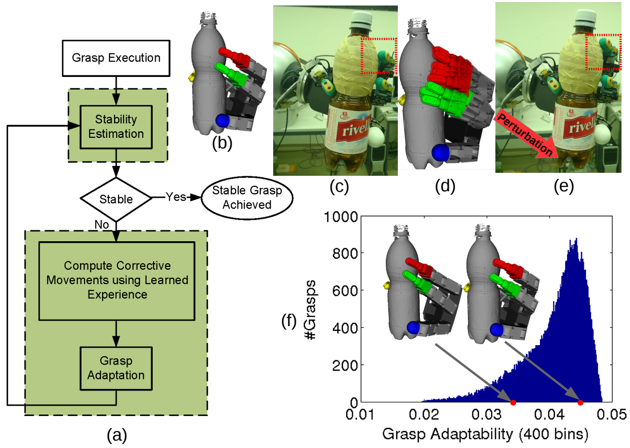

Fig. 3. (a) The pipeline for grasp adaptation using tactile sensing, which includes two main components: *Grasp Stability Estimation* and *Grasp Adaptation*. (b) The grasp synthesized by the proposed framework. (c) The grasp is executed. (d) Fingertips can be freely moved along the object's surface for local adaptation, multiple example fingertip positions are shown for two fingertips to demonstrate potential adaptations. (e) The grasp is adapted w.r.t the given perturbation (pulling) by moving one fingertip upwards, as shown in the red box. (f) Grasp adaptability histogram of 10^5 random grasps. Two example grasps are with different adaptabilities and have the same contacts as the grasp in (b). We can see that the grasp on the left is not very adaptable as it is already at a singular configuration.

IV. Grasp Synthesis

We adopt the grasp quality measure $Q(g)$ reported in [9] to estimate grasp stability. To represent contact reachability, we densely sample hand configurations for online lookup. We encoded the sampled configurations by relative geometry relationships between fingertips. In this way, distances between encoded hand configurations are invariant under affine transformations. The $\mathcal{L}_2$-distance between the query grasp g and the closest sample in the encoding space defines our reachability residual $R(g)$. We apply the multilevel refinement metaheuristic for a hierarchy of combinatorial optimization problems [10]. In this work, the hierarchy consists of the *Fingertip Space* described in Sec. II. Additionally, we extend our objective function $\theta(Q(g), R(g), A(g))$ to also consider the grasp adaptability.

V. Preliminary Results and Discussions

We show an example grasp synthesized by the proposed framework and how it is adapted under a given perturbation. The synthesized grasp is executed by a 16 DoFs Allegro hand[1]. The fingertips[2] are equipped with the tactile sensors – BioTac[3]. As shown in Fig. 3(d), the synthesized grasp allows fingertips (only two demonstrated) to freely move on the object surface since the adaptability is optimized. When a perturbation (pulling at the shown point) is applied to the grasped object, our system (Fig. 3(a)) computes corresponding corrective movements for one of the fingertips so that the adapted grasp (Fig. 3(e)) can counteract the perturbation to keep the grasp stable.

VI. Future Work

Robust fingertip grasping is a difficult problem that involves grasp stability, adaptability, and reachability etc. We will extend the current framework to enable our system to automatically learn the structure of the joint objective function from example grasps, such that new objectives can be flexibly added and the system can properly weight between different objectives. Moreover, by estimating more specific characteristics of perturbations using tactile feedback, the adaptation strategy will be more informed such that more complicated situations can be considered.

Acknowledgement

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[1] http://www.simlab.co.kr/Allegro-Hand.htm

[2] Currently, only three fingertips are equipped with the tactile sensors.

[3] http://www.syntouchllc.com/