Haptic Exploration of Objects with Rolling and Sliding

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Abstract

We present an approach for haptic exploration of unknown objects with dextrous robotic hands. The emphasis is on developing a robust manipulation process that allows fingers to traverse the surface of an object. The process consists of a sequence of phases in which some fingers are responsible for grasping and manipulating the object while others roll and slide over the object surface. The rolling/sliding fingers can utilize sensors to determine surface properties such as texture, friction or small features such as grooves and ridges. Simulations and experiments with a two-fingered hand were conducted to investigate the robustness of the approach for exploring various object shapes.

1. Introduction

Haptic exploration is the primary mechanism by which humans learn about the surface properties of objects. We use vision to discern the overall shape and appearance of objects in our world, but we rely on touch to tell if they are rough, wet, slippery, or warm. Although humans and animals use touch sensing in this way, the use of touch for robots has been quite limited, especially in comparison to developments in computer vision. The absence of touch sensing has not been a serious problem in applications where the object properties are predictable, but as robots start to be used in unstructured environments, for example, to explore remote planetary surfaces, they too need to identify and adapt to the surface properties of the objects they find.

A distinguishing characteristic of haptic object exploration is that it is coupled with manipulation. Haptic sensing provides us with information such as object weight and friction needed for stable manipulation, and manipulation lets us explore the entire surface with our fingertips. In addition, control of the sensors' contact force, position, and orientation are required, so precise manipulation control is a prerequisite for tactile exploration. Studies with human subjects have also underscored the coupling between manipulation and sensing; the combination of efferent and afferent activity helps us to integrate the information we obtain [1].

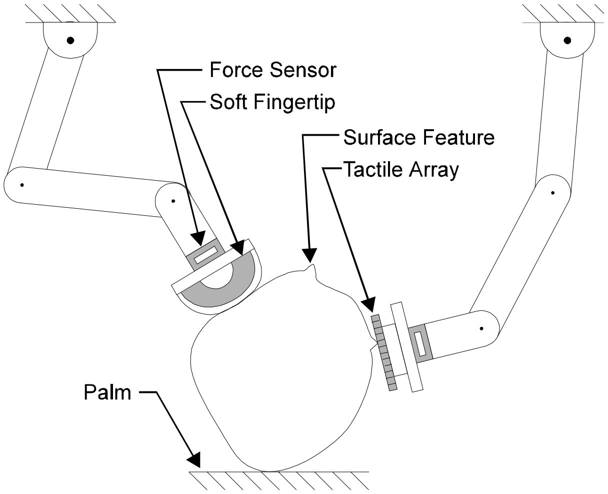


Figure 1: Robotic Fingers and object with haptic features

The purpose of this paper is to present an approach to haptic exploration of unknown objects by dextrous robotic hands. This approach builds on recent developments in several areas including event-driven control of robotic hands, motion planning with rolling and sliding, tactile sensing, and sensor integration.

The basic approach is as follows: exploration proceeds as a sequence of phases in which a subset of the fingertips is used to stabilize and reorient the object while the remaining fingertips roll or slide over the surface in search of suitable contact locations for manipulating the object in the next phase. The fingertips employ a combination of static and dynamic sensors to determine surface properties and locate features such as grooves or ridges.

The reader can confirm that humans take essentially the same approach when manipulating and exploring a small object: "...part of the hand typically stabilizes and part explores. For example, the fingers may hold the object while it is surveyed by the thumb" [1].

In the following sections we first review the related literature, including the main technologies on which this paper builds. We then present our exploration algorithm, specializing the conceptual approach described above for the simplest case, manipulation with two fingers and a palm, shown in Figure 1. In this case, a modest set of states and transitions results. However, this minimal configuration is sufficient for exploring problems associated with ensuring robust and smooth exploration of arbitrary objects. We discuss these issues in the context of simulations and experiments for round and cubic objects manipulated with a two-fingered hand. We conclude with plans for extending the approach to elicit more detailed information about object surface properties.

2. Related Work

The relevant literature includes investigations of tactile sensing and dextrous manipulation for robots and telemanipulators. Surveys of tactile sensing can be found in [2-4].

Features are a useful way to organize the information obtained when exploring an object. A number of investigators including [5, 6] consider features that are intrinsically relevant for haptic sensing. Nicolson and Fearing [7] consider the accuracy limits that can be obtained with array sensors. Son et al. [8] compare methods for obtaining contact point location with tactile arrays and intrinsic force/torque sensors. Zhang et. al [9] compare methods for obtaining object curvature during manipulation.

Studies of human haptic perception reveal that edge or contour following is one of a set of common “exploratory procedures” that people use for determining object geometry [1]. A number of investigators, including [10-15] have developed robotic edge tracking algorithms for use with tactile sensors. Dario et al. [16] describe algorithms for palpation. Others, including [17, 18] have developed exploratory strategies for determining object geometry with haptic sensing. However, most of this work focuses on using a minimal set of contacts to determine overall geometry rather than on discerning fine surface features or properties such as texture or coefficient of friction.

A large body of work exists regarding dextrous manipulation. The relevant topics include nonholonomic motion planning, grasp stability analysis and optimization, finger gaiting, and coordinated control of external and internal grasp forces. A few notable examples are [19-21], and a survey by Shimoga [22]. Most implementations are based upon the kinematic models of [24] or [25]. However, Maekawa et al. [8] show that rolling can be executed using only instantaneous kinematics if a tactile sensor provides continuous updates of the contact location. This is an advantage when manipulating and exploring unknown objects. But for motion planning the object curvature is needed to predict how far the fingertips can travel before they will encounter joint-space or grasp stability limitations, which would necessitate regrasping. Thus there is a tradeoff between the amount of knowledge required about the object and the efficiency with which exploratory motions can be performed. We will return to this issue when discussing the algorithm and results in the next sections.

In other work related to the present investigation, Son et al. [26] present results of using a tactile array sensor and intrinsic sensing to improve the accuracy of peg-in-hole assembly using a two-fingered hand with rolling contact. Fearing [27] and Sarkar et. al [20] also demonstrate manipulation with tactile sensing

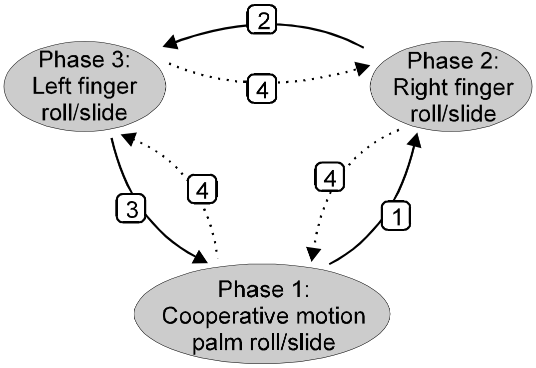
3. Exploratory Procedure Algorithm

3.1 Algorithm and States

As mentioned in the introduction, our object exploration proceeds as a repeated series of phases in which some fingers manipulate the object while others traverse the object surface. The goal of the manipulation algorithm is to ensure complete and smooth traversal of a wide range of object shapes.

In this paper we consider manipulation with two 3DOF fingers and a fixed palm, as shown in Figure 1. With this minimal testbed, the state transition diagram can be represented as a three phase cycle (Figure 2).

To simplify the discussion we will assume that we start the cycle in the cooperative motion phase and rotate the object clockwise. In practice, the cycle can begin with any phase that admits a stable grasp, and manipulation can proceed in either direction.



Transition	Current Grasp	Transition Into
1	right & left fingers	left finger & palm
2	left finger & palm	right finger & palm
3	right finger & palm	right & left fingers
4	bypass next phase if cannot do forward transition	

Figure 2: Exploratory procedure states and transitions

In the first phase, the object is grasped by the two fingers and rotated clockwise while optionally maintaining contact with the palm (useful if the palm is equipped with sensors). The objectives are to reorient the object and to bring the left finger into a suitable location for holding the object.[1]

In the second phase, the left finger holds the object while the right finger rolls and/or slides over the surface to a location that will allow it to hold the object in the next phase. The third phase is similar to the second; the object is held between the palm and the right finger while the left finger rolls and/or slides to a location suitable for stable two-fingered manipulation.

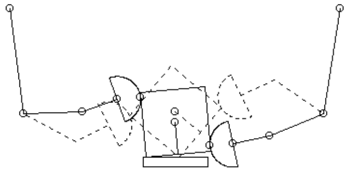
The usual ending condition of each phase is when a finger reaches a workspace limitation. However, a phase will also terminate if the grasp is starting to become unstable. Depending on the size and shape of the object, a phase may reach a workspace limitation *before* reaching a stable grasp for the next phase. In this case, it becomes necessary to modify the sequence and bypass the nominal next phase in an effort to reorient the part and obtain better contact locations. This is shown as transitions (4) in Figure 2.

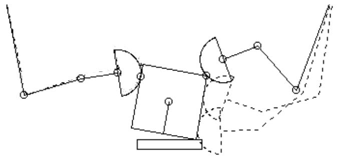
3.2 Rolling and Sliding: Motion Planning and Control

During phase 1, the control variables are the object position and orientation, the distance that each contact moves over the object surface, and the internal grasp force. The object is rotated as far as possible, subject to finger workspace and grasp stability limits. Trajectory planning is done assuming pure rolling. This is an idealization since the fingertips are soft and have a distributed contact patch. However, as shown in [29], the deviations in rolling distances are negligible if contact forces are light.

During phases 2 and 3, the control variables for the moving finger include the trajectory of the contact, the orientation of the fingertip and the normal force. The specification of the fingertip orientation determines the amount of relative sliding that takes place. At one extreme, the orientation can be made consistent with pure rolling, and at the other the fingertip orientation can be kept constant.

In practice, the duration of each phase is mainly a function of the workspace of the fingers. Therefore, the fingertip orientations (or equivalently, the amount of rolling at each fingertip) are planned using a simple heuristic that attempts to keep the fingers within their workspaces for as long as possible. The cartesian workspace of each finger is divided into four regions, each of which has a “preferred” fingertip orientation – one that maximizes the local configuration space. As each phase is planned, the approximate final position of the finger is mapped to one of the four work space regions and the corresponding preferred orientation is found. The orientation is then interpolated between the initial value and this final value.


Phase 1: Object rotated by two active fingers


Phase 2: Right finger rolls/slides on object

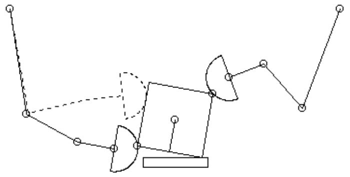

Phase 3: Left finger rolls/slides on object

Figure 3: Simulation of exploratory procedure

The planning is done dynamically at the start of each phase, using a current estimate of the object curvature and surface orientation. When the exploration task is just beginning this estimate may be poor (for example, there may be an unexpected corner), in which case the phase will end quickly as the finger reaches the edge of its workspace. If the fingertip has not moved far enough to grasp the object stably in the next phase, the algorithm reverts to the previous phase (transitions (4) in Figure 2). If a stable grasp within the finger workspace still cannot be found, the algorithm terminates.

During the experiments with a two-fingered manipulator, the control of the object orientation and internal force is performed using dynamic object impedance control [30]. In phases 2 and 3 the moving fingertip is controlled independently using dynamic impedance control in the tip workspace. The control framework has been discussed in [31]. Transitions from one phase to the next occur in response to events. In the present case the main events are fingers reaching the limits of their workspaces and a computed loss of grasp stability.

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[1] Grasp stability is computed using the method of Yoshikawa and Nagai [28].

Some care is needed to assure smooth transitions that will not excite the tactile and force sensors. For example, in the transition from phase 3 to phase 1 the control changes from fingertip impedance to object impedance. Smooth ramping is provided by an explicit “startup” segment that is part of the phase definition. The commanded internal and external forces on the object are initially computed to be consistent with the commanded tip forces at the end of the previous phase and gradually ramped to their desired values for object manipulation.

4. Simulations and Experiments

4.1 Simulation

The exploratory procedure was first simulated numerically to determine how well the algorithm would traverse a range of object shapes, including round and square objects, and to test the sensitivity of the approach to workspace limits. The simulation modeled the grasp kinematics and included forces and friction coefficients in testing the grasp stability but did not include inertial terms.

Figure 3 shows three phases of the simulation during a clockwise manipulation of a square object. The dotted lines show the finger positions at the start of each phase and the solid lines show the final positions (the final position of one phase becomes the starting position of the next). The coefficient of friction between the object and fingertips and palm was assumed to be 1.0, a typical value for the rubber-coated fingertips used in the subsequent experiments.

In general, the robot transitions from one stable configuration into the next. In some cases, rotating about a sharp corner on an object would drive the right finger outside of its workspace in phase 2 before reaching a stable configuration for phase 3. In several of these cases, the robot was able to recover by skipping phase 3 (transition 4 in Figure 2) and rotating the object with two fingers again.

The simulation revealed that finger workspaces were the most serious limitation and lead to the development of the heuristic, mentioned in the previous section, for specifying the fingertip orientation at the end of each phase. Even so, the algorithm usually cannot handle long, thin objects.

The simulation did not account for the effects of noisy sensors and imperfect control of the fingertip trajectories and forces. These effects were evaluated in experiments described in the next section.

4.2 Experiments

As mentioned, the experimental testbed is a two-fingered planar robot with a passive palm. Strain gauge force sensors and an 8x8 tactile array were used to collect haptic information. Contacts can be located to within approximately 1mm using the array and forces can be measured to an accuracy of approximately 0.02N [8].

The robot was controlled using dynamic object impedance control [30] and the phase/event/transition framework of Hyde et al.[31].

Figure 4 shows results obtained while exploring a 4.6cm plastic ball with a ridge approximately 3mm high and 4mm wide on its surface. The ball is manipulated clockwise so the tactile array slides from left to right over the ridge in the “snapshots” at the top of the figure.

During the first 3.8 seconds (phase 2) the right finger slides over the object while the left finger holds it against the palm. The left finger tangential force is slightly positive (pointing downward on the ball surface) and reveals little noise, which indicates that the right finger is sliding smoothly without exciting vibrations in the ball. At 3.8 seconds the right finger workspace limits are reached and a transition to phase 3 occurs. At this point the left finger tangential force becomes negative, indicating sliding friction. As the fingertip slides over the feature the tangential force increases and becomes subject to stick/slip vibrations.

The model of the object used for motion planning is a sphere with approximately the same diameter as the actual ball, but no features. The normal force is controlled to remain at approximately 0.3N but, as the plot reveals, the sliding force varies as the finger passes over the surface feature.

The first and last tactile images show the pressure distribution produced by contact with the plastic ball. The middle images show the presence of the ridge. The pressure distribution becomes significantly sharper and changes from the characteristic pattern of a spherical contact to a ridge.

5. Discussion and future Work

The simulation and experiments confirm our basic conviction that the state of the art in tactile sensing and dextrous manipulation planning control are reaching the point at which autonomous haptic exploration becomes feasible. The long-term goal is to enable haptic exploration of small objects such as rocks on remote planetary surfaces or wreckage on the murky ocean floor.

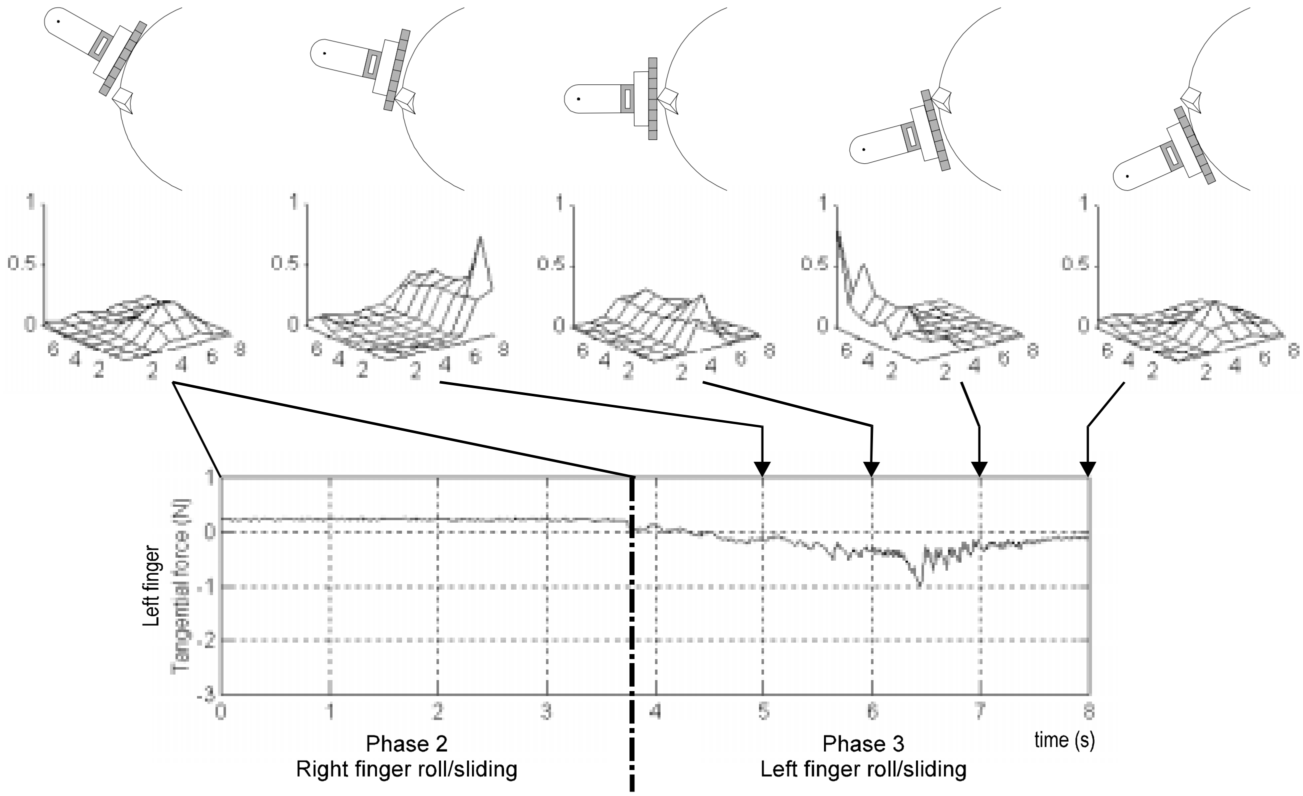

Figure 4: Tactile array sensor and force data taken during two phases of an exploration.

Although the results presented are for the simple case of two independently controlled fingers we believe that the basic approach can be applied to additional fingers. This is a subject of ongoing work. The two-fingered manipulations have already revealed several issues that should be addressed:

- The workspace of the fingers is the main limitation. The fingers employed in our experiments have joint angle ranges of approximately 110 deg. at each joint. A full 180 deg. of motion would significantly increase the range of sizes and shapes that could be handled. However, we also note that with more fingers, the motions required of each can be reduced.
- A second way to increase the useful workspace of the fingers is to change the fingertip geometry, which changes the rolling distance for given joint motions. The combination of one flat fingertip and one 2.5cm radius fingertip was fairly restrictive. We are therefore redesigning the tactile array to fit over a 1.5cm radius and to apply it to both fingertips.
- Although the soft, rounded right fingertip, equipped with a texture of rubber “nibs’ slid easily, the tactile array produced stick slip vibrations, especially when passing over features. This is not surprising because the array was designed for rolling rather than sliding. We have observed sliding difficulties with smooth skins in the past [32] and we are therefore working on a new array skin that will permit easier sliding without distorting the sensor readings. It may also be possible to suppress stick-slip vibrations through better control.
- For detecting small features such as seams and grooves, or patches that are rough or slippery, we will want to repeat our experiments using the stress-rate and skin-acceleration sensors developed previously [32]. These sensors work best with sliding fingertips.
- The purpose of our exploratory procedure is the recording of object properties, which must be stored and identified to be of use. Thus, the next step is to integrate data from the tactile sensors in an object model. This information should be updated during manipulation, so that the exploration can be modified to explore interesting features in more detail. Identification of features will take some reduction of the sensor data, which may be done concurrently with exploration. The structure of the object model should be simple enough that object features may readily be extracted, but detailed enough to incorporate several types of haptic information. The structure will also depend on the projected use of the information, for example, whether for played back through a haptic interface or displayed visually.

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