Object Exploration in One and Two Fingered Robots

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Introduction

In this paper, we present a design and analysis of a system that explores an object for purposes of recognition.

We operate under the following assumptions:

1. We assume that we either know a priori, or can sense through vision, an object's position and at least partial extent in space.

2. We accept the object representation developed by Stansfield [1986], which encodes different views or reachable aspects of the object on the surfaces of a polyhedron. However, we further assume that the object representation contains not only properties as form, which have been traditionally used in Computer Vision research, but other less frequently considered properties such as hardness and texture.

3. We view object exploration as suggested by psychological studies of Lederman and Klatzky [1986] and Klatzky and Lederman (in press). These studies imply that attributes of objects such as hardness, surface texture, temperature and shape are each acquired by particular stereotypical hand movement patterns, called "exploratory procedures" (EPs).

Based on the above assumptions, the specific task is to design the exploratory procedures that will deliver the primitive cutaneous and kinesthetic data that determine the "haptic" attributes of objects, where "haptic" refers to the entire perceptual system involved in purposive touch.

The major difference between our studies and those of Klatzky and Lederman is that in the Robotic domain, the end effector, i.e., the hand, varies from that of the human. This implies different exploratory procedures at the very low-level end. The main contribution of our paper is in showing the relationship between the different end effectors and the corresponding exploratory procedures.
What are the Exploratory Procedures?

To introduce and explain the concept of an Exploratory Procedure (EP), we shall first review what we have learned from psychological studies concerning the use of the hand for object recognition. This is called "haptic information processing".

We have accepted the definition of the haptic system from Loomis and Lederman [1986] as a perceptual system which is composed of the following subsystems: a tactile system that processes cutaneous information (pressure, vibration, and thermal inputs), and a kinesthetic system that registers position and movement from muscles, tendons, and joints.

Let us now examine what information this system delivers for higher-level processes such as object recognition. The model developed by Lederman and Klatzky is very appealing to roboticists, since it is structured into computationally feasible components. According to their model, the haptic system computes the following properties of objects: a) structural properties: size, shape, and weight (as affected by volume), b) substance properties: material and its physical manifestations, such as hardness, elasticity, surface texture, temperature, and weight (as affected by density), and c) functional properties, restricted to those that are directly observable and testable by the haptic system.

The most important lesson we have learned from these studies is that each of these properties is associated with a specific exploratory hand movement, hence the name Exploratory Procedure. Below is the table that relates these properties and the corresponding exploratory procedure (based on Klatzky & Lederman, in press; Lederman & Klatzky, 1986).

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<thead>
<tr>
<th>PROPERTIES</th>
<th>HAND MOVEMENTS</th>
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<tbody>
<tr>
<td><strong>Surface Properties</strong></td>
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<tr>
<td>Texture</td>
<td>Lateral Motion</td>
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<td>Hardness</td>
<td>Pressure</td>
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<td>Temperature</td>
<td>Static Contact</td>
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<td>Weight</td>
<td>Unsupported Holding</td>
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<tr>
<td><strong>Structural Properties</strong></td>
<td>(Unsupported Holding)</td>
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<td>(Weight)</td>
<td>Enclosure, Contour Following</td>
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<tr>
<td>Global Shape</td>
<td>Contour Following</td>
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<td>Exact Shape</td>
<td>Enclosure</td>
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<td>Volume</td>
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<tr>
<td><strong>Functional Properties</strong></td>
<td>Part Motion Test</td>
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<td>Part Motion</td>
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<td>Specific Function</td>
<td>Function Test</td>
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Finally, it is emphasized that these procedures can be executed in a variety of ways, while each still maintains its invariant (or its typical) properties. When one wants to implement these procedures in a robotic system, then of course the geometry of the end effector, its degrees of freedom, and the distribution of sensory pads will together determine the actual implementation of the exploratory procedures, although a given procedure will always deliver the same properties.

The design criteria for the EPs under these circumstances will form the topic of the next section.

Exploratory Procedures and the End Effectors

The Scenario

We assume that the robotic haptic system has the following minimal capabilities:

1. A manipulator with at least positioning control capabilities, preferably with at least six degrees of freedom. Hence, one can execute primitive commands: move to given position x,y,z, and angular attributes Phi, Xi, Theta.

2. An end effector with at least one pad containing an array of pressure-sensitive sites. Hence, one can detect contact and measure the reactive normal forces distributed on the pad.

3. We assume that the interaction, i.e., the contact between the surface of the explored object and the pressure sensitive site, must be perpendicular in order to assure uniqueness of interpretation of the gray-scaled data.

4. In addition to the pressure-sensitive sites, the end effector must have an independent force sensor in three directions, in order to satisfy assumption (3), i.e. perpendicular contact between the pad and the object surface.

The EPs for obtaining surface properties

As the surface properties are local, only the manner in which the end effector accesses the object surface in the direction of its surface normal varies across procedures. As stated earlier, we assume that we know from vision the position and the angular inclination of the surface in question. Furthermore, we of course assume that we have a complete geometric model of the end effector, including the distribution of the sensor pad. Hence, only a simple coordinate transformation is necessary to make contact. Following initial contact, the nature of the exploratory procedures introduced above becomes self-explanatory (for texture, lateral motion; for hardness, pressure (i.e. normal); and for temperature, static contact. Our particular experimental set up does not include a thermal sensor; hence we do not know at this moment what adjustments will be necessary for obtaining the temperature measure. An interesting adjustment must be made in the case of a rigid two-fingered gripper which has opposing tactile pads on its inner surfaces and only a limited span. In this case, the hardness measure must be executed as a pinch and/or clamp and the texture measure as a subsequent movement in the pinch mode.
The EPs for obtaining structural properties

Here we are interested in shape, volume and weight properties. It is a trivial statement to say that in the one-finger scenario we cannot extract weight information, since a minimum of two fingers are required. For shape and volume properties, the difference between the one-finger and more-than-one finger scenarios lies in the amount of sequential scanning, as opposed to the amount of data we get from a single grasp and/or touch. In principle, we can get all the information necessary for the shape and volume properties using a single finger and sensor pad. But one must have a manipulator with sufficient degrees of freedom as well as a mechanism for integrating the information over time.

One-finger scenario. The one-finger scenario was used in Peter Allen's Ph.D. dissertation (1985): He integrated vision and touch for purposes of recognizing 3D objects. In terms of exact shape, he emphasized three kinds of features: surfaces, cavities, and holes, all of which in turn required different Verification Procedures, reminding us a little of the higher-level Exploratory Procedures. Again the principle emphasized in the Verification Procedures was that contact with the surface must be normal. A hole was modeled as a plane; the verification procedure then used this fact to compute the normal to this plane through which the finger passed. Only when the hypothesis of a hole had been verified was its contour followed.

Two-fingered gripper: A challenge for EPs that extract shape and volume. Consider the geometry of most current two-fingered grippers: they are usually rigid devices that are limited in finger span, but equipped with tactile pads on opposing inner sides of the fingers. We need to address the following questions.

(i) If the size of the object falls within the span of the claws, how many grasp positions are necessary for computing global shape, and how do we integrate the readings from these multiple sensing pads? (Clearly, for exact shape, the exploration must be exhaustive.)

For global shape, if the size fits within the hand, one can approximate the object with an ellipsoid. Thus, for two opposing fingers, three orthogonal grasp points should suffice. Of course the contact positions will not be random; rather they must describe those axes that are extreme (min or max) in order to integrate the information into a shape representation. This follows from the model of an ellipsoid which is characterized exactly by the three parameters of length, height and width. Information concerning local shape may further be derived from the tactile pad readings, which can be used to discriminate between planar and curved sites, and between symmetric or asymmetric surfaces. Incidentally, size also falls out since for each reading, there is available a direct measurement of the spread between the two fingers by contrasting their positions. This information can be passed directly to Stansfield's frame representation for further higher-level interpretation.

(ii) If the size of the object is greater than the extent of the two fingers and the object has a cavity (for example, in a coffee cup or other larger kitchen containers), what will the exploratory procedure be? What is the EP for a hole and/or handle?
If the object does not fit within the hand, then one does not have the option of obtaining an estimate of global shape and/or volume from a few select hand movements. The two-fingered hand becomes, in effect, a "one-finger probe". Thus, the enclosure procedure is not possible and the system must perform a sequential scan of the object.

Under such circumstances, a cavity will be explored only to the depth reached by the fingers. Beyond that point, one can infer but not measure the depth of the cavity. As for integrating the two-finger readings, they must be recorded simultaneously in the frame for the outer surface as well as in the frame for the cavity/inner surface. Verification of a hole using the two-finger hand can proceed in a manner similar to that implemented by Allen [1985]. That is, the plane that covers the hole is used as the starting point. The fingers approach in a direction that is normal to this plane (just as the fingers would approach any other surface), and attempt to close. If there is a hole, the distance between the fingers will be zero. In other words the hole is a plane with zero thickness. The handle can be explored as is done with any other object.

(iii) How is weight extracted?

As was pointed out earlier, with the two-fingered hand one can lift the object and hence measure the weight.

The EPs for obtaining functional properties

The work on implementing EPs for extracting the functional properties of objects is too preliminary to report on at this stage.

Conclusions

The most important lesson for Robotics from the psychological studies performed by Klatzky and Lederman is that haptic attributes of objects are extracted using hand movements that are both purposeful and specific. This in turn allows us to design computational procedures that deliver these object properties.

Vision makes hypotheses about the identity of objects, and about features such as extent, surfaces, cavities and holes. Touch verifies these. But it does much more than that--it is well known that the eye can be fooled! Haptics provides the primary information concerning substance (e.g. hardness, surface texture, and heat conductivity), as well as weight, the motion of parts of an object and some specific functions. We have argued that, in principle, one finger can extract most of these object properties (except weight, and of course functional properties). The problem is with economy.

With more fingers, more degrees of freedom and more tactile pads, it is possible to obtain the haptic information in an enclosure considerably faster (parallel data acquisition). Unfortunately, the price one pays is in the accompanying complexity of the control of these multifingered, high-degrees-of-freedom devices. It was mentioned earlier that three fingers, each with at least three degrees of freedom, is a necessary minimum [Salisbury, 1982] for an intelligent robotic hand. One should also add that tactile pads are required, not only on the inside of each finger, but completely surrounding at least one finger so that one has the option of using it in a one-finger scenario [Bajcsy, 1984].
What can robotic system studies offer Psychology? While the exploratory procedures deliver specific object properties, the details of these procedures, the individual sequences of grasping and touching depend on the geometry of the hand and on the sensor pad distribution throughout the end effector. This is not so obvious with human studies, since the end effectors are essentially the same for all normally functioning human hands. From our analysis of the rigid one- and two-finger scenarios, we suggest that the true primitive actions from which the exploratory procedures are composed are: move from one point to another; contact the object surface with the tactile pad oriented perpendicularly; and then record the position, angular and force information wherever contact occurs. Furthermore, the work in Robotics underscores the need for a geometric model of the end effector and calibration of the sensors. However, it is important to recognize that these two components change when the effectors and sensors do so. Such principles are likely important in developing computational models of human haptics as well.
References


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