Task–Driven extraction of object contour by human haptics: Part 1

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SUMMARY
The extraction of contour information from objects is essential for purposes of grasping and manipulation. We proposed that human haptic exploration of contours, in the absence of vision, would reveal specialized patterns. Task goals and intrinsic system capacities were assumed to constrain the breadth of processing and the precision with which contour is encoded, thus determining parameters of exploration and ultimately producing movement synergies or “contour exploration procedures.” A methodology for testing these assumptions is described, and the most frequently observed procedures are documented in Part 1. Part 2 will further analyze the procedures, test predictions, and develop implications of the research. The paper (2 parts) is novel in its study of human manipulative behavior from a robotic standpoint; it is thus of interest to robotics research workers interested in the long-term goals of robot manipulation and those interested in an anthropomorphic approach to robotics studies.

KEYWORDS: Objects contours; Human haptics; Grasping; Manipulation; Task goals.

INTRODUCTION
Contour extraction is of considerable importance to the field of robotics, because of its relevance to grasping and manipulation, as well as object description and identification. In order to stably grasp and manipulate an object, it is often necessary to isolate parts; these parts may represent projections to be grasped or regions within which forces can be applied for manipulation, as in disassembly tasks. But to isolate parts in turn requires knowledge of object contours. This makes the question of how robotic systems should extract, process, and represent contour information a highly important one.

When a manipulatory task involves heavy objects or complex activities such as pick-and-place operations, additional considerations pertaining to the coordination of activity between two robotic effector systems arise.\(^1\)\(^-\)\(^3\) Without substantial coordination and communication, not only will the system perform sub-optimally, but there may be collisions.

Many of the problems concerning the design and function of flexible sensate robotic systems—for example, sensor performance, sensor fusion, object processing, active vs passive perception, task planning and motor control—are also of concern to behavioral scientists, who study living systems. In both domains, these topics are enormously complex, extending beyond (as well as including) important hardware considerations. We submit that there are levels of analysis at which one domain may benefit from learning about the other’s conceptualizations, theories, methodologies, and empirical results. In our paper, we describe research on what we believe to be one area of common interest—the extraction of contour information in the absence of vision. Although our interest is in contour extraction by the human haptic system, which is based on sensors in skin, muscles, tendons, and joints, our theoretical perspective and level of analysis are intended to promote comparison with robotic systems. It is hoped that this work will be of interdisciplinary interest, serving to emphasize the potential value of bidirectional interaction between disciplines that study biological and machine sensate systems.

MACHINE CONTOUR PROCESSING WITH NONVISUAL SENSORS
Whereas vision has previously been the premier choice for machine processing of contour, the development of increasingly sophisticated force, tactile and thermal sensors offers potentially valuable alternate approaches. The potential contribution of systems equipped with such sensors goes beyond merely augmenting visual information about object contour. Tactile and force sensors can be combined with a repertoire of purposive exploratory and manipulatory actions, ultimately providing access to a broad domain of sensed object properties. Such sensory systems would seem to be critical in exploration of unknown environments, such as in space or the deep sea. They could also have application in industry. In much of current robotics research, rigid assumptions must be made about the geometry of objects and their materials. By providing flexibility of exploration and utility in varied environments, haptic sensing systems may ultimately allow for automation in workspaces that are less rigidly defined than current industrial settings.

The utility of nonvisual sensors has been demonstrated in previous work on object recognition by machines. For example, several systems have been designed to recognize objects by contour exploration. Goldberg and
Bajcsy used a single contact probe that traced a planar object; the sequence of contact positions was recorded and matched against a set of stored object codes. Gaston and Lozano-Pérez also assumed sensor information about contact locations, along with the surface normal at each location. From a set of such contacts, a model of possible surfaces was constructed and used for object recognition. Bajcsy and Hager have described several scenarios made possible with more advanced sensors and multiple-sensor configurations. For example, if pressure variations can be sensed, relative values across multiple sensors can be used to determine if the surface is planar or curved. Also, position sensors that can detect angles between joints can be used to infer information about the contacted object. A three-dimensional system along these lines was described by Bajcsy, McCarthy, and Trinkle, who suggested that the structure of an object might be inferred through "feeling by grasping."

More sophisticated models have expanded the structural descriptions of objects available from robotic sensors. Using a sensor that provided force and array data, Stansfield developed an active perceptual system that extracted structure, among other object properties, in the form of primitives (point contact, surface normal, area contact, and edge contact, the first two of these being equivalent to parameters considered earlier) and features (edges, contours, and cavities/holes). Browse has described a more limited feature-based system using similar sensory information.

GOALS OF THE PRESENT RESEARCH

A motivating question for the present research was addressed to us by our robotics colleague, Ruzena Bajcsy, who asked, "What is the role of the second hand during human object exploration by touch?" This question raises the joint issues of how humans haptically explore objects in order to extract contour information, and how they coordinate the hands in doing so. Addressing the first issue appears to be considerably more complex than has been represented in robotic systems to date. In such systems, the range of exploratory processes has generally been limited, for example, to a sequence of point contacts. In contrast, when humans attempt to haptically extract object structure, their hand movements appear to be quite varied. The second issue, effector coordination, arises because both hands are often employed during human contour exploration. We have commonly observed that one hand is often used for essentially manipulatory purposes – to stabilize the object or to reorient it. But are additional functions served by the second hand?

A principal goal of the present study was to investigate the nature and function of human movements for extracting contour information from objects, in the absence of vision. We deliberately minimized the need for manipulatory support of exploration by stabilizing the object. Haptic contour exploration then further provided a paradigm with which to study whether, and if so how, humans coordinate two hands during a complex, unpracticed activity.

Our approach to the foregoing issues builds on our ongoing program investigating the haptic apprehension and recognition of objects. We have previously documented the existence of haptic "exploratory procedures" – stereotyped movement patterns that are purposively directed toward the extraction of particular object properties (see also). For example, extraction of texture information is associated with "lateral motion," relative movement between skin and textured surface. Although dimensions unrelated to contour (e.g., surface texture) appear to be used to some extent, extraction of structural (i.e., shape, size) information appears to be critical to object identification, particularly at the "basic level," where common names are assigned.

Our analysis of exploratory procedures has proven to be useful in addressing a number of issues related to human haptics. For example, we have demonstrated that whether distinct properties of objects are integrated during perception depends in part on the motonic compatibility of the associated exploratory procedures. Certain exploratory procedures have been shown to be sufficient to extract multiple properties, and the most broadly sufficient – essentially, a grasp – generally initiates object identification through touch. Several exploratory procedures were adapted by Stansfield for her object-identification system.

In the present paper, we extend this same approach to the encoding of contour information about planar objects. That is, we assume that specific patterns of human contour exploration are adopted, in response to the constraints of a task environment, and that these patterns, or "contour exploration procedures" (CEPs), have relatively specialized functions. This research, then, attempts to identify underlying task constraints that affect human contour exploration, and to determine how exploration is affected in terms of CEP selection.

Variations in human exploratory movements go beyond whether one or two hands are used. Two commonly observed components of these movements are (i) following edges continuously for some period of time and (ii) static molding of object surfaces or edges, which we called "Contour Following" and "Enclosure," respectively, in our earlier work. Our initial hypothesis was that humans have developed a number of such procedures for extracting haptic attributes of objects. A match-to-sample task was used to investigate the links between object attributes and exploratory procedures: Individuals were first given a sample object, then three alternative objects. Their task was to choose the alternative that best matched the sample on a targeted dimension. The hand movements performed during exploration of the sample were recorded and analyzed, to determine which patterns of exploration were elicited by a given target dimension. The structural dimensions under consideration included volume, exact shape (high spatial frequency details), and global shape (defined for the subject as the regular-shaped container into which the object would best fit). Both shape dimensions were found to elicit substantial Contour Following, whereas
volume (and to some extent, global shape) was found to elicit Enclosure.

The present research was intended to provide a more detailed description of the human hand movements used for extracting contour information about objects, and to infer how exploration is guided by important features of the task context. Our assumption that exploratory behavior will vary with task goals is similar to the view that an optimal manipulatory configuration depends on task demands.\textsuperscript{16,17} Li and Sastry\textsuperscript{18} have suggested that the selection of a grasp should be based on the task appropriateness of the wrenches that it would generate. For example, the configuration used in writing with a pencil requires dexterity at the point, a constraint that does not apply when picking up the pencil.

**PREVIOUS INVESTIGATIONS OF HAPTIC CONTOUR ENCODING**

Experimental psychologists have previously investigated haptic encoding of planar contour in tasks such as shape matching and object identification. Generally, performance in such tasks is poor, especially when touch is compared to vision.\textsuperscript{19-21} However, we have also demonstrated the remarkable ability of humans to haptically identify real, three-dimensional common objects.\textsuperscript{22} There have also been earlier efforts to classify the movements of human hands during haptic exploration. Davidson and colleagues\textsuperscript{23-25} analyzed hand movements during tasks like haptic shape matching and found they could be reliably classified into such categories as global search, palm search, tracing, gripping, and pinching. However, the different purposes of these activities and the task demands that elicit them were not systematically considered.

A more systematic integration of haptic contour exploration and processing goals, as well as a comparison between hand and eye movements during perception, was offered by Zinchenko and Lomov\textsuperscript{26} in a review of research from the Soviet Union. They divide haptic contour exploration into two phases, each with subcomponents. In Phase 1, the object is found by a search stage and oriented relative to the explorer by a directing stage. Search is characterized as a continuous, essentially symmetric, and synchronized movement of the hands toward and away from the explorer. This process is assumed to extract only "minimal and fragmentary" information about the object's contours. In Phase 2, object contours are more specifically encoded in three stages: image construction, measurement, and correction. The first of these stages is characterized by discontinuities in contact with the object; the movements are not isomorphic to the object's contour. Such deviations are assumed to be part of the constructive process. Dynamic movement components of the process "unwind" the contour, while pauses at informative points of contour change provide spatial referents or "reckoning off" points. The image constructed in this fashion is then checked and corrected by repetitious contour tracing, involving movement of the hands in the same direction (which we will call "yoked" movement) with several passes over the same contour segment. Both phases of haptic exploration share patterns of fixation with visual perception.

The present research provides a more quantitative and detailed analysis of the components of exploration, particularly those involved in image construction per se (Zinchenko and Lomov's Phase 2, as contrasted with Phase 1 - finding and orienting the object). We also use a variety of tasks involving contour extraction, to allow stronger inferences about the purposes of particular exploratory patterns.

**FROM TASK GOALS TO CONTOUR EXPLORATION: A CAUSAL CHAIN**

We conceive of the transition from task goals to exploration as involving a chain of effects, as shown in Figure 1. The task goal that is set for an information processor, along with capacities of the processor, establish two types of processing constraints: the scope or breadth of processing, and the precision with which contour is encoded. These constraints in turn determine parameters of exploratory patterns, such as end-effector configuration and persistence of exploration. The desired parameters emerge in the form of movement synergies—the contour exploration procedures (CEPs) we wish to define.

To initiate this causal chain, we have chosen a set of experimental tasks that should elicit fundamental perceptual processes, including detection, localization, and storage of information about contour segments. These processes are likely to be involved in most contexts in which contour information must be obtained haptically, particularly in preparation for grasping by humans or robots. In each task, the subject is given an object to explore without sight, and he or she is tested on knowledge of the object's contours. The tasks vary with respect to the type of test, which is described to the subject in advance of exploration. These test variations are assumed to induce differences in the processing goal. Our assumptions about the tasks are summarized in Table 1. (For three of the tasks, the test requires a

![Fig. 1. Sequence of processing mechanisms by which task goals constrain contour extraction procedures.](image)

**Table 1. Assumed goals, scope and precision of each of four experimental tasks**

<table>
<thead>
<tr>
<th>Task</th>
<th>Goal(s)</th>
<th>Scope</th>
<th>Encoding precision</th>
</tr>
</thead>
<tbody>
<tr>
<td>Part detection</td>
<td>Search</td>
<td>Broad</td>
<td>Low</td>
</tr>
<tr>
<td>Part-relation</td>
<td>Relational</td>
<td>Moderate</td>
<td>High</td>
</tr>
<tr>
<td>identification (incl. detection)</td>
<td>(+ search)</td>
<td>(two-part)</td>
<td></td>
</tr>
<tr>
<td>Part congruence</td>
<td>Segment encoding</td>
<td>Narrow</td>
<td>High</td>
</tr>
<tr>
<td>Whole congruence</td>
<td>Segment encoding</td>
<td>Broad</td>
<td>Low</td>
</tr>
</tbody>
</table>
comparision between the initially explored object and another, subsequently presented one. In this case, our concern is with how the subject processes the first object in preparation for the test. We do not evaluate the subject’s processing during the test itself.

In the Part Detection task, the subject is told to locate a highly discriminable segment of contour on a planar object (e.g., a sharp point embedded in a curved contour). We assume that this sets the goal of searching for a local feature, with no deliberate attempt to store information about contour encountered up to the point of detection. In the Part Congruence task, the subject is to compare two successively presented contour segments (parts) and determine if they are identical. This task requires that the initially presented part be encoded into memory. By “encoding,” we meant that an internal representation is constructed. In the Part-Relation Identification task, the subject is directed to (i.e., detects) a target segment of contour on an initial stimulus. This segment must be identified on a subsequent stimulus despite a change in its shape. This task is intended to elicit the goal of encoding intersegment relations in the first stimulus. For example, the critical segment might be encoded as being “immediately clockwise of the roughly symmetric protrusion.” Note that encoding the exact shape of the critical segment in the first stimulus will not suffice, because its shape will be changed in the subsequent comparison stimulus. Finally, the Whole Congruence task requires the subject to compare two successive stimuli and determine if they differ in shape. This task requires encoding the entire contour of the first stimulus into memory, because the subject cannot be sure where the shape difference (if any) might occur.

To summarize, the set of four experimental tasks is intended to elicit three task goals, to varying degree across tasks. The goals are (i) search for a critical feature of contour, (ii) segment encoding – storing a continuous (or roughly so) sequence of contour into memory, and (iii) relational encoding between distinct contour segments.

As shown in Figure 1, task goals in turn constrain two aspects of processing of contour information. One is how much contour is to be processed, that is, the relative breadth or scope of the processing focus. We distinguish among three levels of scope. Processing can be restricted to a local segment or part of an object, as in the part congruence task (narrow scope). Processing can be devoted to two distinct parts, as is likely to occur in the relation identification task (moderate scope). And the scope of processing may go beyond one or two parts, to incorporate a more extensive segment of contour, as is assumed to be necessary in the whole congruence task (broad scope).

The second aspect of contour processing that is assumed to be affected by task goals is the precision with which contour information is encoded into memory. Specifically, assume that constructing a representation of some target contour requires that points on the contour be localized relative to intrinsic or extrinsic referents. In the human, because of system limitations such as cutaneous resolution, memory, and the size of the exploring effector (by which we mean the functional instrument of exploration, be it one or several fingers; see below), localization is determined only within some range of uncertainty or noise (the resolution bandwidth). A representation is precise to the extent that it is low in noise, and it therefore provides a description of the target contour that allows it to be discriminated from similar contours.

Scope and precision may trade off, even though they are logically independent concepts. At least when the human information processor is considered, capacity constraints become a factor, and encoding more contour means that the ultimate representation will be noisier.

Although in the present experiment, the task goals were set so as to most directly affect the scope of processing, precision was also intended to be affected, albeit under greater control by the subject than by the experimenter. In the Part Detection task, the critical segment to be detected was highly discriminable from the others, and there were minimal demands on memory (because there was no comparison required with a subsequent stimulus). For this reason, the subject would have little reason to encode the stimulus contour with much precision. The other three tasks, however, had greater memory demands and required finer discriminations. Under these circumstances, precision is a requisite, but the extent to which it is obtained is likely to vary with scope. In particular, scope/precision tradeoff will make the precision achieved in the Whole Congruence task, where the entire stimulus contour must be encoded (broad scope), relatively low.

The scope and precision of contour processing are assumed to affect parameters of exploration, in ways that will be considered in detail in a later section. Each exploratory parameter is a variable that can be considered to be set to some value when a CEP is actually executed. One variable is the number of effectors simultaneously employed in exploration. For these purposes we define an effector as an integrated unit for exploration, that is, one or a set of adjacent fingers on a single hand that effect forces in a common direction rather than opposing (similar to the concept of a “virtual finger”).27 (Note that use of two hands, by definition, involves multiple effectors.) Another variable is whether multiple effectors are coordinated vs. independent in space or time. Coordination can be said to occur if the exploratory pattern of one effector is predictable from another. Two other variables are whether an exploratory pattern is transient or persists over time on any one segment, and whether one or multiple parts of the object are explored during execution of a single CEP.

Our strategy in the present work was motivated by the causal chain analysis in Figure 1. As has been mentioned, we manipulated the subject’s task goal, with the intention of affecting processing scope and, indirectly, precision. We then examined videotaped records of contour exploration, in order to classify and measure the duration of various exploratory patterns. From the exploratory parameters of the observed CEPs...
for a given task (the first stimulus only, in tasks with two successive stimuli), we inferred the scope and precision of exploration, and hence the goal(s) to which the CEP was relevant. We could then compare the inferred aspects of processing to those anticipated for the given task. To the extent that task manipulations and exploratory outcomes agree in this respect, our assumptions about the functions of contour exploration are supported. Our methodologies and statistical approaches are used commonly in experimental psychology, and we will present them as would be conventional for readers in that field.

**EXPERIMENTAL ANALYSIS OF CONTOUR EXTRACTION**

In order to define patterns of exploration as clearly as possible, the present domain of objects was constrained to planar forms varying in two dimensions (while a third was held constant). (Implications for fully threedimensional objects will be considered in the General Discussion section.) Structural information under these circumstances can be found at the edge of the object's larger surface, which here formed a set of projecting segments or "parts." The stimuli were designed to be moderately complex, so that they could not easily be verbally labeled, and so substantial exploration would be required for contour encoding. They were also sized so that the hand could follow the entire contour without wedging at part junctures, but so that the object could readily be spanned within two hands. Each task was performed with planar stimuli varying in complexity, size of local features, and curvature.

To reduce the need for what we have called "task maintenance," or purely manipulatory aspects of exploration, we fixed the object in place, which stabilized it and allowed both hands to be free for exploration if desired. The object was also oriented so that its informative contour was readily accessible to the exploring hand(s), without reorienting. It can therefore be assumed, in the task contexts to be described, that most contact with the object is for exploratory purposes.

1. **Tasks**

Each subject took part in all 4 tasks. The tasks used planar objects, each roughly shaped like a circle with curved or pointed projections from its circumference (see Figure 2). These projections will be termed "parts." Each object was backed with a velcro patch, which allowed it to be mounted on a velcro-topped pedestal, tilted backward so that the face of the object approximated a 45 deg angle from the frontoparallel plane. The velcro allowed the object to remain stable while being explored. The four tasks were (Table I):

Part Detection - The participant is presented with an object having one anomalous and highly distinctive part, either a pointed segment among curves or a curved segment among points. The subject is told to locate either the pointed or curved segment, as appropriate. (No speed constraint was imposed.)

Part Congruence - The subject's hands are guided to the base of one part of an object, with the peak of that part oriented upward. He or she explores it as much as desired, and is then given a test part in the same orientation and asked whether or not it is identical to the first.

Part-Relation Identification (plus Part Detection) - The participant is first presented with the same type of object as in the detection task, with one anomalous part. The anomalous part must be detected as well as explored as needed. Next the subject is given a randomly oriented test object, identical to the first except that the anomalous part has been replaced with one that has the same general shape (curved, pointed) as all the others (and is otherwise matched as closely as possible to the original). The task is to find the part that replaced the previously anomalous one.

Whole Congruence - The subject is presented with an object having all curved parts or all pointed parts. He or she explores it as desired, and is then presented with a randomly oriented second object that is either identical to the first or changed slightly. The subject decides whether the second object is identical to or different from the first.

As noted above, in tasks involving a comparison of two objects (part congruence, relation identification, whole congruence), only the period during which the first object was explored was submitted to analysis.

2. **Stimuli**

Each object consisted of a set of projections from a roughly circular base. Examples are shown in Figure 2. The objects had two general shapes - curved or pointed - and two levels of complexity - four or six projecting parts. They were designed so that the finger could smoothly traverse the contours without wedging, in a size that was slightly larger than the hand - the radius of a circumscribed circle was at most 10.8 cm and that of an inscribed circle was at least 4.4 cm. One part on each object was an oblique-angle projection that was required.
in order to close the contour. In addition, parts of three sizes were represented on each object (with the other parts being arbitrarily sized). The size of a part refers to the length of the shorter (and generally steeper) side of the pointed version of a projection (1.9 cm, 4.4 cm, or 8.9 cm for the small, medium, and large projections, respectively). Further details of stimulus construction can be obtained from the authors.

For each combination of shape and complexity, three distinct sets of objects were made. Each curved set was derived from a pointed set by smoothing the contours of the corresponding objects. Within a set, there were three or four objects, variants of one another to be used for the four tasks. They included a basic object, having all curved or all pointed parts, and three anomalous versions of the same object, each having one part that differed in general shape from the remainder (e.g. a curved projection among points). One of these resulted from changing the shape of the basic object’s large-sized projection, one the medium-sized and one the small-sized. Finally, for half the sets of each shape and complexity level, a changed basic object was made, by moving the peak of one projection of the basic object into or out from the center (from 1.9 to 3.8 cm). (See Figure 2 for examples.)

For use as the second stimulus in the Part Congruence task, a set of pointed and curved shapes was constructed. Each shape corresponded to a single part (projection) of a basic stimulus. Changed versions of half of these stimuli were also made, by elongating or shortening the original from 1.9–3.8 cm.

The stimuli in each set were assigned to tasks as follows: (1) In the Part Detection task, one of the anomalous versions was used. (2) In the Part-Relation Identification task, an anomalous version was used as the first object, and the basic object was used as the second object. (3) In the Part Congruence task, the basic object was used as the first stimulus, with subjects being guided to one of its parts. The second object was a single part, either identical to the initially felt projection or changed. (4) In the Whole Congruence task, the basic version was the first object, and either it was re-presented (a positive trial) or the changed basic object served as the second item (a negative trial).

3. Procedure
Trials were blocked by task for each subject, with the task order counterbalanced across subjects. The particular stimulus order was randomized within a block. There were equal numbers of positive and negative trials for the Whole and Part Congruence tasks. The series of trials for each subject used stimuli from each set no more than once per task, thus minimizing repetition. The size of the critical part in the Part Detection, Part-Relation Identification, and Part Congruence tasks was small, medium, and large equally often. (The critical part is that of anomalous shape in the Part Detection and Part-Relation Identification tasks and is the explored part in the Part Congruence task.) The particular object used for a given trial type (as defined by task, curved/linear shape, complexity, and size of critical part) was held constant over subjects.

On each trial, the subject placed his or her hands on a sheet, which was then guided down to the stimulus object (on the tilted pedestal) and then gently pulled away. (On the Part Congruence task, the subject’s hands were guided by the experimenter directly to the target part, without the sheet.) The subject explored the object freely and indicated vocally when he or she was satisfied. The test object if any was then presented in the same way as before and was explored until a response was made.

There were a total of 40 trials per subject: 12 Part Detection and 12 Part-Relation Identification (representing all combinations of stimulus shape, complexity, and size of critical part), 12 Part Congruence (again representing all combinations, although complexity was a dummy variable here because the subject felt only the critical part), and 4 Whole Congruence (2 shapes × 2 complexity levels; there was no critical part).

RESULTS

1. General aspects of exploration: relative speed and accuracy by task
Initially, we note that by far the greater proportion of time was spent with two hands in contact with the object. Of the total exploratory durations scored (3,478 s), almost 90% involved two-handed exploration. There might be some bias toward use of two hands because both were guided to the object; however, as will be seen below, the data suggest that two-handed exploration was adopted for specific functional purposes.

The four tasks clearly varied with respect to time and accuracy, as expected. The average exploration time for the initial item in a task was 4.4, 8.1, 12.8, and 19.8 s, for Part Detection, Part Congruence, Part-Relation Identification, and Whole Congruence, respectively. Error rates by task were 1.0%, 26.0%, 29.2%, and 43.8%, respectively. This pattern suggests that the broad scope of encoding required for the Whole Congruence task precluded the level of precision needed for accurate performance. A high error rate would also be expected in that task from the previous literature on shape matching by touch (see introduction).

2. Scoring of preliminary response categories
As described in Figure 1, we assumed that task goals and the resulting scope and precision of processing affect certain parameters of exploration, or exploratory variables. They include the number of effectors exploring simultaneously, whether multiple effectors are independent or coordinated, the extent of persistence on an explored segment, and the number of parts contacted by one CEP.

Based on our earlier analyses of contour exploration, along with preliminary viewing of the present tapes, we began by defining five basic CEPs. These were primarily related to the variables of number of effectors and persistence over time, but the basic categories were then
<table>
<thead>
<tr>
<th>CEP</th>
<th>Definition</th>
<th>Effector(s):</th>
<th>Coordination:</th>
<th>Part(s) Contacted:</th>
<th>Persistence:</th>
</tr>
</thead>
<tbody>
<tr>
<td>PartEn/1-hand</td>
<td>part enclosure with one hand</td>
<td>typically multiple (opposing fingers)</td>
<td>yes</td>
<td>single part</td>
<td>high</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Part/En/2-hands</td>
<td>Part enclosure with two hands</td>
<td>multiple (two hands)</td>
<td>yes</td>
<td>single part (two hands on one part)</td>
<td>high</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CntrFol/1-part</td>
<td>simple contour following on a single part</td>
<td>single (usually uses finger(s) of one hand)</td>
<td>no</td>
<td>single part (by definition)</td>
<td>low</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CntrFol/multi-part</td>
<td>simple contour following on a sequence of multiple parts</td>
<td>single (usually uses finger(s) of one hand)</td>
<td>no</td>
<td>multiple parts (by definition)</td>
<td>low</td>
</tr>
<tr>
<td>SYMME-CntrFol/1-part</td>
<td>symmetric contour following on a single part</td>
<td>multiple (predominantly two handed)</td>
<td>yes</td>
<td>single part (by definition)</td>
<td>high (often repetitive)</td>
</tr>
<tr>
<td>SYMME-CntrFol/multi-part</td>
<td>symmetric contour following on a sequence of multiple parts</td>
<td>multiple (predominantly two handed)</td>
<td>yes</td>
<td>multiple parts (by definition)</td>
<td>low</td>
</tr>
<tr>
<td>YOKE-CntrFol</td>
<td>yoked contour following</td>
<td>multiple (two-handed by definition)</td>
<td>yes</td>
<td>single part or multiple parts</td>
<td>low</td>
</tr>
<tr>
<td>PartEn + PartEn</td>
<td>simultaneous compound of two part enclosures</td>
<td>multiple (usually one part with each hand)</td>
<td>yes</td>
<td>multiple parts (usually 2)</td>
<td>high</td>
</tr>
<tr>
<td>PartEn + CntrFol/1-part</td>
<td>simultaneous compound of part enclosure and simple contour following, each on a single part of the object</td>
<td>multiple (usually one procedure with each hand)</td>
<td>yes</td>
<td>Multiple parts (each CEP contacts one part, by definition)</td>
<td>high</td>
</tr>
<tr>
<td>PartEn + CntrFol/multi-part</td>
<td>simultaneous compound of part enclosure with simple contour following on a sequence of multiple parts</td>
<td>multiple (usually one procedure with each hand)</td>
<td>yes</td>
<td>Multiple parts (i.e., more than two parts total, by definition)</td>
<td>low (although the part enclosure persists, contour following does not)</td>
</tr>
<tr>
<td>PartEn + SYMME-CntrFol</td>
<td>simultaneous compound of part enclosure with symmetric contour following</td>
<td>multiple (predominantly one procedure with each hand)</td>
<td>yes</td>
<td>Multiple parts (usually each procedure on a single part)</td>
<td>high</td>
</tr>
<tr>
<td>CntrFol + CntrFol</td>
<td>simultaneous compound of two cases of simple contour following that are not sufficiently coordinated to be called yoked or symmetric</td>
<td>multiple (usually, each hand executes contour following)</td>
<td>no</td>
<td>single part or multiple parts</td>
<td>low</td>
</tr>
</tbody>
</table>
refined by considering the number of parts explored and patterns of coordination involving multiple CEPs. The initial procedures were enclosure (molding that maximizes the effector surface in contact with object contour), placeholder, (contact with an uninformative part of the object with no attempt to mold to its contours), simple contour following, (essentially continuous movement along a contour with finger(s) of one hand), yoked contour following, (like simple contour following, but with fingers of two hands moving in the same direction), and symmetrical contour following (like simple contour following, but two hands or two fingers of the same hand move along contours in mirror-image fashion). (A sixth category, whole enclosure, or molding of as much as possible of the hand(s) surface to the object, was scored as a basic CEP but did not occur with sufficient frequency to be retained. This is likely to be due to the size and curvature of the present stimuli, which made it difficult to mold the entire envelope.)

Further details of these procedures are given in the Appendix (to appear in part 2 of this paper in a subsequent issue of Robotica).

Trained scorers recorded the events occurring during exploration of the first object on a trial, terminating with the subject's signal to the experimenter that he or she had finished. Intervals of activity less than 10 frames (1/3s) were ignored. Events that seemed to serve no exploratory function were labeled as task maintenance; these constituted only a small portion of the period (on average 384 ms/trial or less than 3-1/2%). Included here were the subject's initial attempts to contact the object or to recontact it after a loss of contact.

The scorer segmented the entire record into intervals, each devoted to one of the six preliminary CEP categories. Two repetitions of the same activity, separated only briefly by a change in hand position or hand used, were considered as part of the same interval. Within each interval, the scorer noted each incidence of any of the six CEPs. For example, if a part enclosure was performed with each hand, that category was scored twice. The scorer also indicated whether one or both hands were used during the interval, and if two hands, whether they executed a single category (e.g., part enclosure) or whether each performed a distinct CEP. Finally, the scorer also indicated whether any single category observed in the interval occurred over multiple object parts, for example, a sequence of contour following that crossed a part boundary or enclosure of a segment larger than one part (but not with sufficient molding to constitute whole enclosure). Note that two distinct CEPs, each executed on a single part, would not constitute observation of any one CEP over multiple parts.

For these purposes, as well as for distinguishing part and whole enclosure, a part was formally defined as two contour segments contiguous about a peak or a trough (a convex or concave contour). Thus exploration was called single-part if the subject stayed within one part (including molding to a subset of the part contour, such as one side of a peak) and multiple-part if he or she explored beyond it within a single exploratory pattern. Note that part enclosure, or molding, is unlikely with concave parts, but contour following on a single concave segment is common.

3. Most frequently observed exploratory patterns
As noted above, the basic categories were starting points for the documentation of a set of frequently observed CEPs. Initial analyses of the data were concerned with eliminating unnecessary categories and augmenting the basic set as necessary to represent variables such as number of effectors and number of parts contacted. We also considered possible two- and three-CEP combinations as well as the basic six, to determine frequent patterns of coordination. Steps in the development of the final CEP categories are given in the Appendix.

Table II lists the final set of 12 CEPs that were considered in the data analysis, along with abbreviations to be used in other tables. The basic CEPs are represented, as are "compound" CEPs, which simultaneously execute two basic patterns. Also indicated is the relation of each CEP to the four movement variables mentioned above: number of effectors, independence vs.

![Part Enclosure + Part Enclosure](image1)

![Part Enclosure + Contour Following](image2)

![Symmetric Contour Following (Single Part)](image3)

![Symmetric Contour Following (Multiple Parts)](image4)

![Part Enclosure + Two Hands](image5)

Fig. 3. Schematicized examples of CEPs; arrows indicate movement direction. Clockwise from upper left: PartEn + PartEn, PartEn + ContrFol (number of parts not indicated in figure), SYMME-ContrFol/multi-part, PartEn/2-hands, and SYMME-ContrFol/1-part.
coordination (multiple effectors only), persistence, and number of parts explored. Some of the CEPs explicitly represent breakdowns on these latter two variables, because both conditions were frequently observed (e.g. part enclosure was observed frequently both with one hand and with two hands, and there is a CEP for each condition). In other cases, one of the two conditions predominated (e.g. symmetric contour following usually used two hands), and only one CEP was therefore included in the final set. In such cases, we indicate which was the predominant condition. Figure 3 illustrates a prototypical version of some of the CEPs.

CONTINUATION OF THE PAPER
Part 2 of this paper, by Lederman, Klatzky, and Balakrishnan, will further develop the theoretical analysis of CEPs, by indicating how each is assumed to be related to the scope and precision of processing and what functions it is likely to serve. These assumptions are tested by statistical analysis of the data on CEP durations. Finally, we discuss implications of this human research for a number of issues that have been of considerable interest in robotics. All the references will be provided at the end of Part 2, and tables will be numbered consecutively throughout.