Perception of Curvature and Object Motion Via Contact Location Feedback

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Abstract. We describe a new tactile display for use in dexterous telemanipulation and virtual reality. Our system renders the changing location of a remote or virtual contact by moving a tactile element along the user's fingertip. Mounted at the endpoint of a haptic mechanism, our thimble-sized device concurrently displays contact location and interaction forces. We believe such a design will enable more versatile object manipulation for haptic interactions. To evaluate this display concept, we conducted two perceptual experiments. First, human subjects judged object curvature though direct manipulation of physical models and virtual manipulation with the device. Results show similar levels of discrimination in real and virtual interactions, indicating the device can effectively portray contact information. Second, we investigated virtual interactions with rolling and anchored objects and demonstrated that users can distinguish the interaction type using our device. These experiments provide insight into the sensitivity of human perception and suggest that even a simple display of the contact centroid location may significantly enhance telerobotic and virtual grasping tasks.

1 Introduction

In the middle of the night the telephone rings. You grope for your glasses and fumble for the light switch. Among all the types of sensory information available to you at that moment, none is more important than knowing where objects are touching your fingertips. Early in the study of dexterous manipulation, Fearing [1] demonstrated that contact information is equally indispensable for manipulating objects in a robotic hand. Without this knowledge, grasp errors accumulate rapidly and the object falls. Subsequently, many researchers developed tactile array sensors, capable of measuring contact location, pressure distribution and local object geometry.

In contrast, tactile displays that render contact information for virtual reality or teleoperation have proven far more challenging. Accurate recreation of the local shape and pressure distribution at each fingertip requires a dense array of actuators. The peak force, velocity, and displacement needed for each element all but preclude packaging the system at the fingertips of a standard haptic display system. The tactile displays that have appeared in the literature are instead bench-top devices, with a small array of pins in a stationary frame, actuated via wires or tubes [2–5].

As an alternative, displaying only the location of the centroid of contact on each finger requires far less extensive actuation. Even when objects are handled rapidly, the contacts progress along the fingertips at only a few centimeters per second. Contact location can be displayed by moving a single element over the surface of the

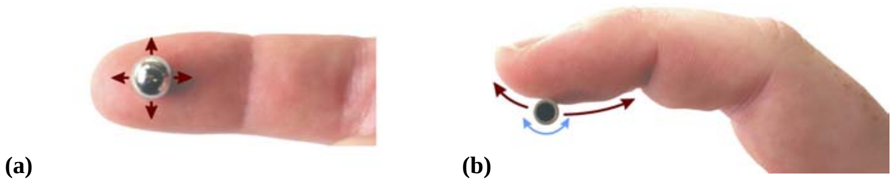


Fig. 1. Contact location display concept. The centroid of contact is represented by a single tactile element. **(a)** Two-dimensional and **(b)** one-dimensional variations are illustrated.

finger in the proximal/distal and lateral directions, which can be accomplished with just two actuators (Fig. 1(a)). The experiments reported in this paper consider only the proximal/distal location of the contact centroid, displayed using a roller that translates along the user's finger pad (Fig. 1(b)).

Current haptic display systems treat contact even more simply, as a point force applied to the user's fingertip via a thimble. Incorporating contact centroid motion into such haptic interactions requires only minor additions to the system but improves the interaction significantly. Such a display has the potential to create a richer, more realistic experience of fingertip manipulation than traditional haptic devices provide. Details of the approach can be found in [6].

The idea of representing arbitrary contacts with a single moving element raises several interesting questions. Of primary concern is how people perceive differences in object curvature. Contact shape and pressure distribution provide local object information. If this full set of tactile information is not available, Montana [7] suggests that the migration of the contact patch over the finger surface during manipulation can also be used to evaluate object curvature via rolling kinematics. Contact location is also useful in other manipulation scenarios, such as pushing a knob or slider. In these cases, the migration of the contact patch can indicate sliding or rolling of the object relative to the finger.

To further explore these issues, we developed a device that displays contact location together with force feedback, as described in Section 2. Two separate experiments were conducted to evaluate the device and the user's relevant perceptions. The first examined subjects' ability to distinguish between objects of different curvature for both real and virtual interactions, as discussed in Section 3. The second experiment, detailed in Section 4, studied the perception of virtual object motion, including rolling and anchored behaviors. Finally, Section 5 presents conclusions and new research questions raised by this work.

2 Device Description

The contact location display apparatus is shown in Fig. 2(a). The tactile element is a small roller housed in a thimble that slips over the user's finger. A servo-motor drives the roller along the user's finger via two sheathed push-pull wires. This actuator is located on the user's forearm to reduce device inertia at the hand and minimize the transmission of motor vibrations to the user's fingertip receptors. The roller is

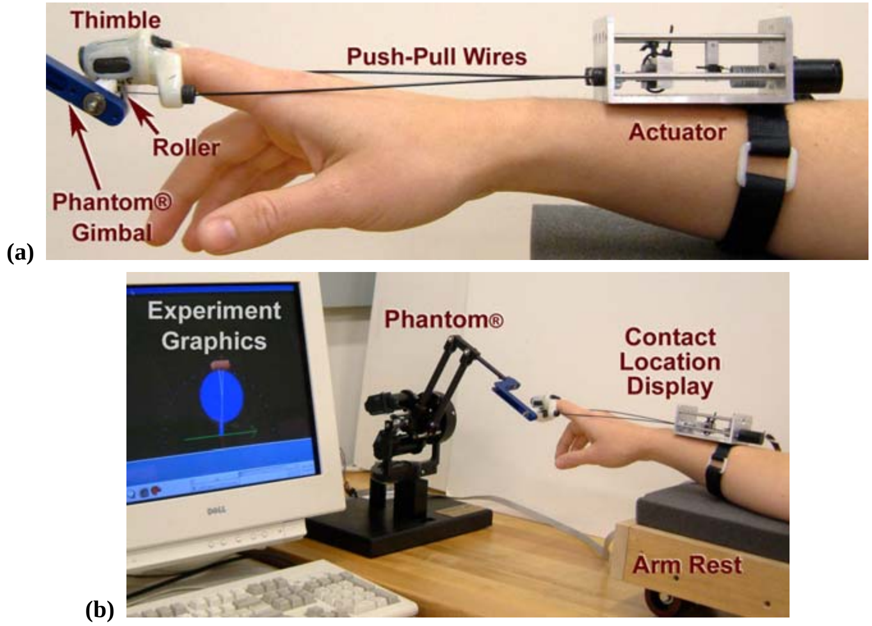
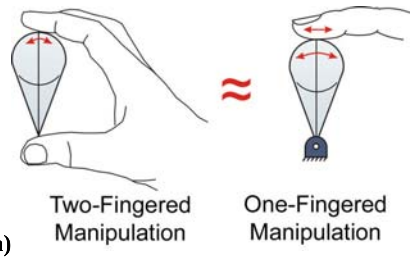


Fig. 2. Contact location display system. **(a)** Fingertip contact is rendered by a roller housed in a thimble, which is attached to a commercial force-feedback device. A small servo-motor precisely positions the roller via push-pull wires. The roller is suspended below the finger, only touching the user when the Phantom® applies interaction forces. **(b)** Experimental setup and graphics showing contact between the user's finger and a virtual object.

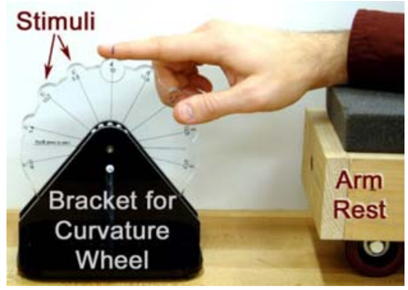
suspended underneath the fingertip by the drive wires so that it does not touch the user until they contact a virtual object.

The display's roller is attached to a SensAble Technologies Phantom®, a robotic arm used for haptic feedback, as depicted in Fig. 2(b). This haptic device measures the position of the roller and provides reaction forces, which push the suspended element into contact with the user's finger. Making and breaking contact in this manner yields a realistic sensation of touch as the roller stimulates mechanoreceptors in the user's fingertip [8,9].

To display haptic interactions with this device, virtual objects were programmed in C and C++ on a computer running RTAI Linux. The kinematics of each simulated environment determine a characteristic relationship between finger motion and contact location. A PID feedback controller uses the display's servo-motor to adjust the position of the roller based on detected finger motion. The bandwidth of the roller exceeds 5 Hz for a 10 mm amplitude signal. Roller positions along the finger are rendered with a maximum error of 0.05 mm for fast hand motions (5 cm/sec) and an error of about 0.01 mm for the slow motions typically used by subjects.



(a)



(b)

Fig. 3. Use of contact location during object exploration. **(a)** One-fingered planar perception of curvature provides a simplified form of object manipulation. **(b)** Subjects explored 15° sectors of a "curvature wheel" via direct and virtual manipulation.

3 Curvature Discrimination for Real and Virtual Objects

A series of experiments was performed to quantify a user's ability to discriminate between objects of varying curvature. To simplify testing, only planar objects were studied and the interaction was limited to horizontal motion of a single finger. This arrangement allowed a comparison of results between direct physical manipulation and virtual interaction with the contact display device. The experiments were designed following standard psychophysical procedures involving constant stimuli, with forced-choice comparisons between pairs of cases [10]. A detailed description of the experimental protocol is given in the Appendix.

3.1 Experimental Setup and Procedure

These discrimination tests focus on the user's perception of curvature while rolling planar objects with a single finger. As illustrated in Fig. 3(a), such simple one-fingered interaction is representative of more general object manipulation. All objects, whether real or virtual, pivot about a fixed axis distinct from the center of curvature. This pivoting behavior allows the user to explore the curved surface using only fingertip motion. For the direct manipulation experiments, fourteen such test curves were arranged onto a single "curvature wheel" as shown in Fig. 3(b). The wheel could pivot 15° for each curve, corresponding to approximately ± 1 cm of fingertip movement.

During the tests, subjects were blindfolded and used an armrest to maintain a horizontal hand position. Both real and virtual versions of the curvature wheel were presented in the same fashion. For the physical wheel, the limits of travel for each sector were indicated with spring-loaded ball detents; analogous forces were implemented in software for the virtual wheel.

The curvature discriminations were conducted as a randomized series of comparisons in which users compared two stimuli and reported which of the two samples had a larger radius of curvature. For each comparison, one of the two samples was a standard value while the other was selected from among six smaller and larger

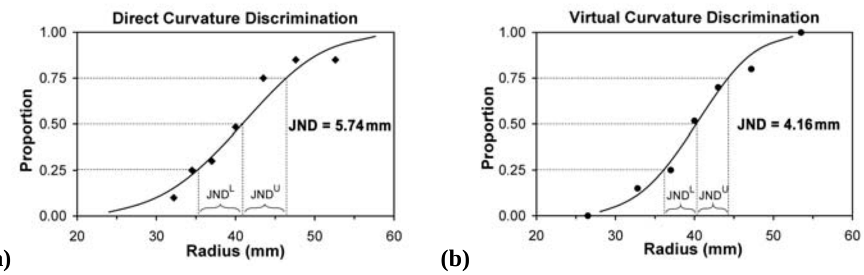


Fig. 4. Pooled results of all subjects for radius of curvature discriminations on the 40 mm standard during **(a)** direct physical interaction and **(b)** virtual interaction using the contact location display. The graphs display the proportion of times a particular stimulus was reported as having a greater radius of curvature. JNDs are indicated with dotted lines.

Table 1. Results of direct and virtual radius of curvature perception experiments for each radius standard.

	Direct Discrimination		Virtual Discrimination	
Nominal Radius (mm)	Radius JND (mm)	Weber Fraction	Radius JND (mm)	Weber Fraction
10	0.84	0.084	1.35	0.135
20	1.49	0.074	2.25*	0.112*
30	4.00	0.133	3.77	0.126
40	5.74	0.143	4.16	0.104

*Data reported from pilot study with 5 subjects

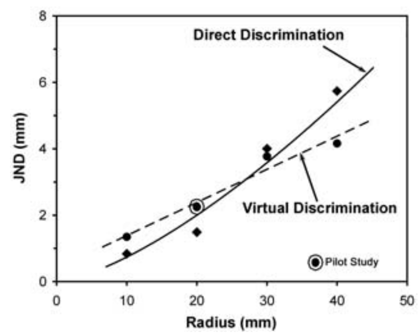


Fig. 5. JNDs of direct and virtual discrimination for each radius standard.

neighboring sizes. The sizes were chosen to determine the just noticeable difference (JND) [10] relative to the standard size. Subjects made curvature discriminations with respect to four radius standards of 10, 20, 30, and 40 mm, and comparison radii varied from 8.3 to 52.6 mm.

3.2 Results and Discussion

Typical results for direct and virtual curvature comparison tests are shown in Fig. 4. These graphs represent the pooled responses of all subjects for the 40 mm standard. They plot the proportion of times subjects reported each stimulus as the larger of the two presented. As expected, the data have a sigmoidal distribution; stimuli that are considerably different from the standard are consistently identified while smaller differences are harder to discern. By convention, the JND for each standard is established as the average of the lower and upper difference thresholds (JND^L and JND^U, see Fig. 4), being the difference between 0.25 and 0.50, and 0.50 and 0.75 proportions respectively [10].

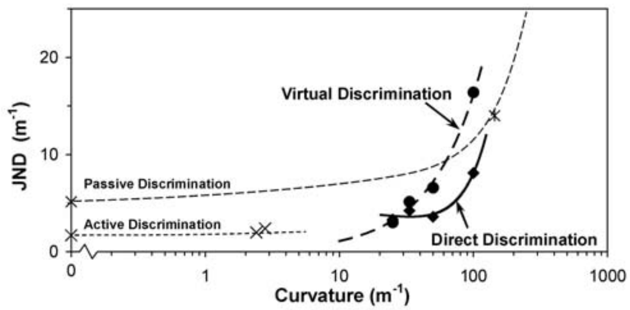


Fig. 6. Our results are framed by data reported in the literature for active fingertip curvature discrimination (Gordon and Morison [11]) and passive discrimination (Goodwin et al. [12]).

Similar results for other standards are summarized in Table 1, where the data are shown as both the JND and the Weber fraction. The Weber fraction is the ratio of the JND to the nominal stimulus value. The JNDs are also plotted against the nominal values in Fig. 5. The direct discrimination data are slightly nonlinear and are fit by a power curve (as suggested by Steven's Power Law [10]). In contrast, the virtual discrimination data are nearly linear with object size, in agreement with the underlying motion kinematics of the simulation. The average Weber fraction for virtual discriminations across the range of stimuli tested is 0.11.

For objects with a radius smaller than 25 mm, direct exploration yields better performance (smaller JND) than virtual discrimination. Local pressure distribution becomes the dominant mode of perception with small objects, which is not rendered by the virtual display. For radii above 30 mm, however, subjects performed better during virtual exploration. Here we believe the relatively small roller in the contact display provides better localization and hence better contact movement cues than the increased contact patch experienced in direct manipulation. Subjects also commented that the large radius virtual discriminations were easier to perform.

By design, the contact location display relies on tactile perception of motion on the fingertip. Limited to 15° sectors, objects with radii of curvature of 10, 20, 30, and 40 mm lead to nominal contact movements of 2.67, 5.33, 8.00, and 10.67 mm and JNDs of 0.36, 0.60, 1.01, and 1.11 mm respectively. As with radius, the Weber fraction for tactile length discrimination averages to 0.11.

Figure 6 compares our work to data presented in the literature. Gordon and Morison [11] had subjects actively explore plano-convex lenses with their fingertips, providing the expected lower bound for our experiment. In contrast, Goodwin et al. [12] pressed hemispherical stimuli onto the fingertips of their test subjects. This passive curvature discrimination represents the expected upper bound for our results. With the exception of extreme virtual cases, our data are indeed bounded.

While trends in the JND data hint at different perception strategies, especially at extreme object sizes, the JND magnitudes are similar for real and virtual tests. This experiment not only quantifies the user's perceptual capability, but also validates the system's ability to portray information necessary for virtual object discrimination.

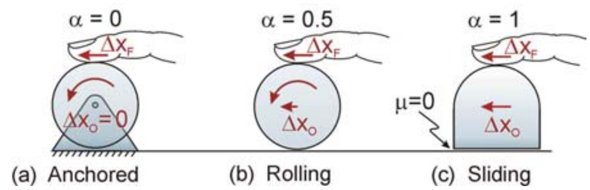


Fig. 7. Differences in apparent object motion can be described in terms of the ratio $\alpha = \Delta x_O / \Delta x_F$, as defined in Eqn. 1. Values of α for familiar object motions are depicted above.

4 Perception of Virtual Object Motion

A second set of experiments was performed to investigate the user's perception of object motion via the contact location display. Relative movement of a grasped object provides important cues about the object's behavior and state. A simple test illustrates the applicability of our device to manipulation and sets the stage for future use in robotic and haptic grasp control.

4.1 Experimental Setup and Procedure

Typical object motions include anchored, rolling, and sliding behaviors, as shown in Fig. 7. Changes in contact location along the finger pad indicate relative movement between the finger and the object. At one extreme, sliding an object along a surface maintains a constant contact location on the fingertip. In contrast, touching an anchored object fixes the contact in space regardless of finger motion. More generally, the object motion ratio, α, relates finger and object movements according to

$$\Delta x_O = \alpha \cdot \Delta x_F \quad (1)$$

where Δx_F is the absolute motion of the user's finger while in contact with the virtual object and Δx_O is the resulting object motion.

Similar to the previous virtual discrimination tests, subjects performed a series of comparisons in which various object motion behaviors were presented. Ratios of $\alpha = -0.5$ to 0.5 were tested against an anchored object ($\alpha = 0$: Fig. 7(a)). In a second series, ratios of $\alpha = 0.1$ to 0.9 were compared to a rolling object ($\alpha = 0.5$: Fig. 7(b)). In each comparison, subjects were asked which of the pair felt more anchored or rolling, respectively. The case of pure sliding ($\alpha = 1$: Fig. 7(c)), with no motion relative to the fingertip, was not tested because it is too easy to distinguish from the other cases.

4.2 Results and Discussion

Figures 8(a) and 8(b) show the proportion of times that subjects identified a virtual object with a given value of α as anchored or freely rolling, respectively. We hypothesize that people evaluated object motion based on a comparison between absolute

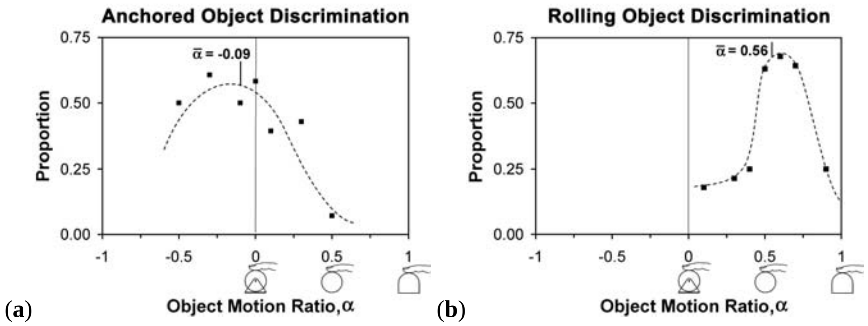


Fig. 8. The graphs display the proportion of times a given object motion ratio was reported as being (**a**) anchored or (**b**) rolling.

finger movement, observed via proprioception, and relative contact centroid movement, observed cutaneously. The results of our curvature discrimination experiment indicate that the cutaneous contribution to this comparison is quite accurate. Proprioceptive length estimates are not nearly as precise, which could explain the spread of the data.

The means of the anchored and rolling distributions are -0.09 and 0.56 respectively, falling close to their nominal values of 0.0 and 0.5. This mismatch is an interesting perceptual result of these unsighted object manipulations, though its exact origin is unknown. Particularly noteworthy is users' preference for negative object motion ratios in the anchored object tests. Unlike real objects, negative motion ratios move the object in opposition to the fingertip input, exaggerating normal sensations. We believe unfamiliarity with such objects also caused the substantially larger standard deviation observed in anchored object discrimination.

Beyond the successful discrimination, subjects also commented that these virtual object interactions felt realistic. These findings suggest that the device forms a promising new approach to haptic and tactile display.

5 General Discussion and Conclusions

This work presents a novel device for displaying contact centroid location during haptic interactions. Unlike pin arrays, it is easily mounted on a traditional haptic display and integrated with force feedback.

In controlled experiments we found that human subjects could easily use the device to determine the curvature of virtual objects. Moreover, the just noticeable difference (JND) values obtained with the device were comparable to those obtained with physical specimens and direct finger contact. Different trends between virtual and direct contact suggest slightly different perception modes and lead to heightened virtual discrimination for large radii of curvature.

The virtual objects were discriminated with a Weber fraction of approximately 0.11, indicating that users can detect changes in object radius greater than 11%.

Based on the motion of the contact point, these results also imply a tactile length Weber fraction of 0.11. These findings indicate that humans have highly accurate cutaneous length perception.

We also found that users of our device could identify various types of object motion based on the contact location change, specifically discerning rolling and anchored objects. Anecdotally, subjects reported that they found the sensation of traveling contacts a convincing simulation and a welcome improvement over probing the virtual world with a stylus.

The contact location display is a valuable addition to force-feedback for virtual and remote environments. We are encouraged that this approach will enable users to determine object geometry and changes in contact configuration during dexterous manipulation. The system's success also suggests many additional developments, including conversion to two degrees of freedom for display of lateral as well as proximal/distal contact motion. Use of a brake to optionally prevent roller rotation may improve the simulation of rolling and sliding contacts. Finally, we believe that incorporation in a multi-fingered system will be particularly useful for dexterous manipulation, and we have begun developing experiments to test this hypothesis.

Acknowledgments

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Appendix: Protocol for Discrimination Experiments

All experiments employed the method of constant stimuli with a paired-comparison forced-choice protocol to evaluate perceptual thresholds (JNDs) and sensitivity. To investigate perceptual sensitivity over a broad range, the experiment was divided into blocks. In each block, subjects were presented with stimuli clustered around a nominal value, referred to as a standard stimulus. Each standard was accompanied by six comparison stimuli (three larger and three smaller, presented twice each). Subjects were presented with two stimuli in rapid succession (separated by 2-4 seconds) and asked to state which met the specified condition. Established methods were employed to prevent presentation order bias. To isolate the effects of learning and fatigue, half of the subjects completed virtual discrimination experiments first. Subjects were blindfolded and wore hunter's earmuffs to reduce distractions.

Sighted and blindfolded training preceded each block of testing. Virtual interactions were accompanied by computer graphics to reinforce haptic cues during training. Positive feedback on comparison accuracy was provided at the beginning of curvature discrimination experiments, but it was not provided in virtual motion tests to prevent habituation.

All subjects completed the experiment using the index finger of their right hand. For consistency between virtual and direct discrimination experiments, subjects performed these tests with their fingers extended and horizontal. The virtual apparatus did not measure rotations of the subject's finger, and kinematic modeling assumed the finger orientation was always horizontal. The subject's finger was placed at the center of each stimulus. They made a single sustained contact with each stimulus and were not to allowed to slide on the stimulus surface while exploring the physical models.

There were no time restrictions made on subjects during testing. However, to minimize the time required of each subject, tests were completed by two test groups. A majority of subjects completed the test in under one and a half hours. There were 14 people in the first test group, which consisted of 10 males and 4 females ranging in age from 20 to 34. All subjects in this group were right-handed. There were 10 people in the second group, which consisted of 8 males and 2 females ranging in age from 20 to 38. Two of the males in the second group were left-handed. The number of people completing virtual or direct experiments first was equally balanced (i.e., for the second group, 1 left-handed and 3 right-handed males, and 1 female subject completed the virtual experiments first). Subjects completed a short questionnaire at the conclusion of the experiments.