Haptic Display of Contact Location

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Abstract

This work presents a new haptic device that integrates grounded point-force display with the presentation of contact location. The system centers around a fingertip mechanism attached to the endpoint of a Phantom® robotic arm. The robot applies reaction forces to the user's finger through a tactile element, which can move along the length of the finger pad. Force and contact location are thus displayed concurrently. During operation, the system continually adjusts the position of the contact element based on finger motion and expected or actual contact locations. The finger is modeled as an arc segment, and the environment is represented by a series of lines and arcs. The haptic rendering algorithm is driven by a virtual finger proxy, employing collision detection and collision anticipation. A series of human subject tests compared contact location feedback to standard force feedback. Subjects completed a contour following task in less time and with fewer failures when contact location information was available. The system's success indicates a simple yet promising new avenue for the design of haptic displays.

1 Introduction

Though touch is commonly regarded as a single sensory pathway, the ability to feel the world around us is truly a collection of layered sensations. When you manipulate an object in your hand, you can feel reaction forces, local pressure distributions, contact location, texture, temperature, and vibrations, as well as a kinesthetic awareness of your finger configuration. These sensations all work together to build a rich haptic image of the item you are holding.

Haptics research seeks to recreate this complex sense of touch for users in virtual reality and telerobotics. Ideally, interacting with a virtual or remote environment would be just as simple and vivid as using a hand tool or your own fingers. Technology available today cannot yet meet this ambitious goal, so systems must be streamlined to contain only the information that is most important for the task at hand. Selecting the most salient feedback modes and rendering them with high fidelity can produce haptic displays that start to resemble the ideal.

Force display has become the most prevalent haptic feedback modality, employed in such diverse applications as flight simulation, computer-aided design, and telerobotic surgery. One moves a joystick, stylus, or thimble, and the mechanism applies corresponding forces to one's hand. The human input is modeled as a point, mapped to the user's location in a virtual world or the position of the end-effector of the remote robot. The force feedback vector is continuously computed from the model or measured at the slave and displayed at the system's endpoint.

Using a point-force display is equivalent to prodding the world with a stick. Pressing a single point of contact against a sharp edge will necessarily deflect the contact down one of the two sides, making localization of the feature difficult. Yet when you touch real objects like the edge of a table, you can quickly find the corner by feeling where it acts along your finger. The absence of this contact location feedback in standard haptic interfaces limits the user's dexterity during manipulation and complex exploration tasks.

Tactile displays, on the other hand, provide detailed fingertip feedback of local shape and pressure distribution. Accurate recreation of contact on a patch of skin requires a dense array of actuators, though, and each small element must provide high levels of power via force, velocity, and displacement. Most tactile displays are thus bench-top devices, with a small array of pins in a stationary frame, actuated via wires or tubes [1, 2, 6, 7]. The bulk and complexity of such devices all but precludes their use at the endpoint of a force-feedback system.

Alternatively, a display could render just the centroid of contact on each finger, rather than the entire contact profile. This strategy provides a simpler means of conveying impor-

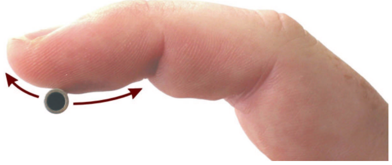


Figure 1. Contact location display concept: a tactile element moves along the fingertip to indicate the position of contact.

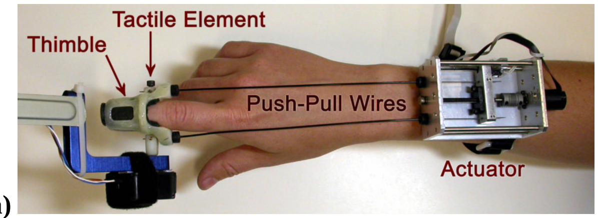
tant tactile information during haptic interactions. As illustrated in Fig. 1, a single contact element can traverse the surface of the finger in the proximal/distal direction as the location of contact with the virtual or remote object changes. This concept requires just one actuator to drive the roller to the desired location along the user's fingerpad. The simplicity of this approach facilitates its integration with traditional force feedback, applied at the site of contact.

To investigate the merit of a hybrid tactile–haptic display, we developed a system that provides contact location and force feedback concurrently to the user. The device's effectiveness was previously evaluated in a series of human subject tests, as documented in [8, 9]. That study found that users of the system could discern object curvature with a level of success similar to that of real manipulation. It also found that users could discriminate between different types of virtual object motion, including rolling and anchored behaviors. Encouraged by the success of these initial investigations, we have since enhanced the system hardware, interaction model, and controller to support general exploration of planar virtual environments.

The new contact location display system allows users to explore a planar virtual environment, feeling interaction forces and contact location simultaneously. The user wears a thimble on his or her index finger and moves it around in a vertical plane, watching the interaction graphically on a nearby monitor. The system hardware consists of a planar linkage, as described in Section 2, which measures finger angle and position and regulates contact location and reaction forces. These commands are computed by a real-time model of the interaction between the fingertip and the environment, as detailed in Section 3. The system's controller renders forces and adjusts the position of the tactile element along the user's finger throughout the interaction, as discussed in Section 4. These three system components work together to give the user the illusion of touching a two-dimensional contour, feeling the various features travel along the skin of his or her fingertip.

We performed a human subject experiment in order to evaluate the usefulness of contact location display. As described in Section 5, users completed a contour following task under two test conditions: force feedback with contact location display and force feedback alone. The results from this study, which indicate that contact location significantly improves the user's ability to follow a contour smoothly, are presented in Section 6. Finally, conclusions and suggestions of future work appear in Section 7.

(a)



(b)

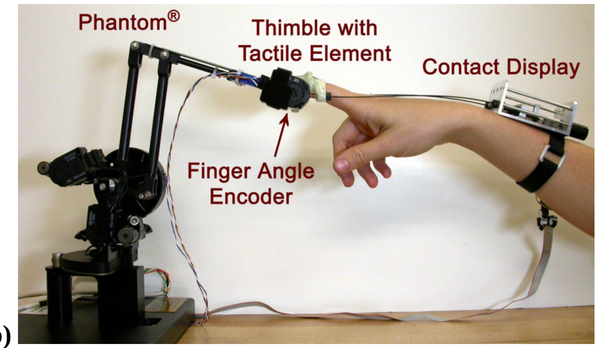


Figure 2. (a) Custom contact location display hardware. (b) System apparatus.

2 Hardware

The contact location display system combines custom hardware with a standard haptic feedback device to create a planar mechanism capable of rendering contact location and force feedback simultaneously. Modulation of contact location is achieved through a one-degree-of-freedom linear mechanism attached to the user's forearm and finger, as shown in Fig. 2(a). The tactile element is a small cylinder suspended beneath the user's fingertip. The cylinder can rotate freely or be held at a fixed orientation to portray sliding contact. This contact element translates along the length of a thimble, about 2.0 cm, driven via two sheathed push-pull wires. A small DC motor actuates the wires via a leadscrew, continuously moving the roller to the appropriate location along the fingertip, as measured by the motor's encoder. Remotely locating this motor on the user's forearm reduces device inertia at the finger and minimizes transmission of actuator vibrations to the user's fingertip receptors. A series of interchangeable open-fingerpad thimbles was created using rapid-prototyping techniques to ensure a snug fit for users with a range of finger sizes.

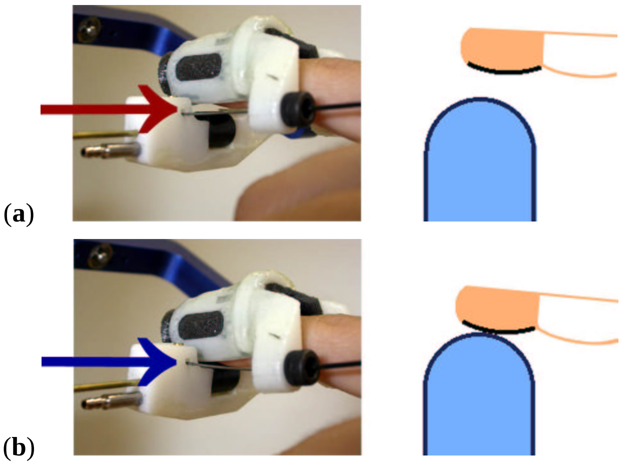


Figure 3. (a) Free-space motion creates no contact with the tactile element. (b) Touching a virtual object yields contact

As depicted in Fig. 2(b), the tactile element is attached to the endpoint of a desktop Phantom®, a commercial device commonly used for point-force feedback [5]. The shoulder and elbow joints of this robotic arm allow motion in a vertical plane; a restoring torque applied to the base joint keeps finger movement in the center plane of the device's workspace. An encoder mounted at the endpoint, coincident with the top of the tactile element, measures the orientation of the mechanism's drive wires relative to the last link of the Phantom®. The encoders on the arm joints are used to compute endpoint position, and the motors act to apply forces to the user's finger through the contact cylinder.

The tactile element is suspended underneath the fingertip by its two drive wires. When the user's virtual finger is in free space, the contact element does not touch the finger since no forces are applied. As illustrated in Fig. 3(a), there is a gap between the finger and the cylinder in this situation. When the user comes into contact with a virtual object, the system moves the contact to the correct location and applies a contact force at this point. This force pushes the suspended cylinder into the user's finger, as shown in Fig. 3(b), giving the user the impression of touching a virtual object. Such an arrangement creates a realistic sensation of making and breaking contact by stimulating appropriate mechanoreceptors in the user's fingertip[10, 11]. The simple addition of a linear positioning element, open-bottom thimble, and finger-angle sensor transforms a standard haptic interface into a combined force and contact location display, a new type of haptic device.

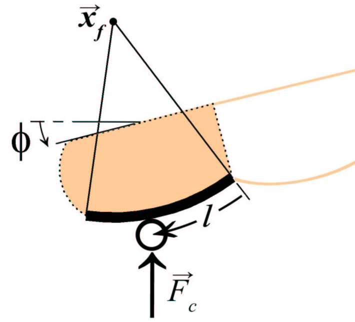


Figure 4. The user's finger is modeled as an arc segment with a radius of 2.6 cm.

3 Interaction model

Combining the haptic display of contact location and force feedback requires a unique virtual interaction model. The system must treat the user's finger as an object, rather than a point, so that it can touch the environment at any location along its length. The position of contact along the finger must be continuously updated based on the user's motions and the geometry of the virtual environment. The tactile element must be positioned correctly both while in contact with an object and when in free space, in order to adequately anticipate future contacts. The algorithm that drives this continual selection of contact location is based on simple models of the user's finger and the environment.

The interaction model for contact location display monitors the position and orientation of the user's finger and also keeps track of a matching virtual finger. Following standard haptic display methods, this virtual finger acts as the user's proxy in the virtual environment [12]. It tracks the real finger's motions in free space but remains on the surface of the environment during contact, minimizing separation. The contact location of the virtual finger drives the contact location display when the user's finger is penetrating the environment.

The system models the user's finger as an arc segment, corresponding to the surface of the distal fingerpad, as illustrated in Fig. 4. The chosen arc segment has a radius of 2.6 cm, matched to the curvature observed in human subjects. It has an arc length of 2.0 cm, equal to the length of travel of the contact display. The finger's configuration is described by the position $\vec{x}_f$ of its center of curvature and angle ϕ from horizontal. Although the body of the finger is depicted in illustrations and on-screen graphics, the system does not consider the top, front, or back of the finger for collision detection. The finger is modeled simply as an arc segment, which can touch the environment along its curve or at either of its endpoints.

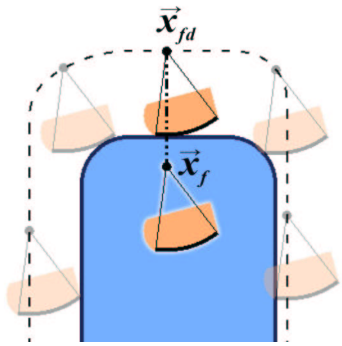


Figure 5. For a given finger orientation, tracing the arc segment along the environment boundary produces the configuration space contour, depicted with a dashed line. The desired position for the finger, $\vec{x}_{fd}$, is the projection of the finger position, $\vec{x}_f$, onto this boundary.

As the user moves his or her finger around in the plane, the interaction model must determine the contact force $\vec{F}_c$ and contact location l to display, as defined in Fig. 4. The system calculates contact force based on the position difference between the real and virtual fingers. The user feels a force pulling his or her finger towards the location of the virtual proxy on the environment's surface. Similarly, the system calculates contact location as the site of contact along the virtual finger's arc segment. In the event of multiple contact points, the system renders the centroid of contact along the arc segment.

The planar environment with which the finger interacts is modeled as a continuous series of arc segments and line segments, as shown for example in Fig. 5. An implicit representation was chosen to facilitate quick changes to the environment's geometry, as well as to simplify the calculations required during an interaction. A variety of layouts can be composed from these simple elements, creating a rich haptic environment for the user to explore.

3.1 Collision detection

During operation, the system detects collisions between the arc segment of the virtual finger and the composite contour of the environment. Performing such calculations with a finger that is free to move and rotate requires a careful examination of the geometry involved. Standard two-dimensional methods based on distance alone cannot be used because collisions depend on the orientation of the arc segment. One way to address this problem is to treat it as a three-dimensional configuration space (c-space) with x_f, y_f, and ϕ as coordinates. In such an approach, each configuration is mapped onto the virtual environment, delineating whether it results in a collision [4]. When the user moves his or her finger into an obstacle, the virtual finger moves to the closest free-space configuration, and the system displays forces and torque to pull the user towards the virtual finger's configuration.

However, the contact location display mechanism cannot provide torque feedback on finger angle, so a modified approach is required. Finger angle must be treated as a driven coordinate; the angle of the virtual finger always tracks ϕ, the angle of the user's finger. For a given value of ϕ, the environmental constraint becomes a two-dimensional region where the center of the finger's arc segment cannot travel. This c-space contour can be computed by tracing the arc segment along the surface of the environment, as shown in Fig. 5. Such a treatment transforms the collision detection problem into a two-dimensional interaction between a point and a region, which can be handled with standard approaches. The system merely tracks the location of the finger and compares it with the presently computed boundary, noting that this boundary changes continuously with finger orientation.

Once the system has determined that the user is in contact with the environment, it computes the appropriate virtual finger location on the c-space-derived boundary, as shown in Fig. 5. This location becomes the desired position, $\vec{x}_{fd}$, for the user's finger in the contact force controller. The system also calculates the desired location of contact, l_d, along the fingertip for the contact location controller, based on the virtual finger's contact with the environment.

3.2 Collision anticipation

When the user's finger is in free space, the device must predict and track the most likely point of contact so that the tactile element will be correctly positioned when the user touches the environment. This collision anticipation can be performed as an extension of the collision detection strategy discussed above. When the user is not in contact with the environment, the system identifies the c-space segment to which the finger is closest, as illustrated in Fig. 6. It then projects the finger position $\vec{x}_f$ perpendicularly onto that c-space segment and calculates the contact location l_d that would result from such a collision. This tactic effectively divides the free space into zones based on the normal vectors of the boundary, as shown by the three regions in Fig. 6. Each zone corresponds to a certain type of environmental contact, involving either the arc or one of its two endpoints.

With convex environments, such a strategy creates a continuous mapping between finger center position and contact location. Avoiding discontinuities is critical for smooth system operation because the contact location actuator has fi-

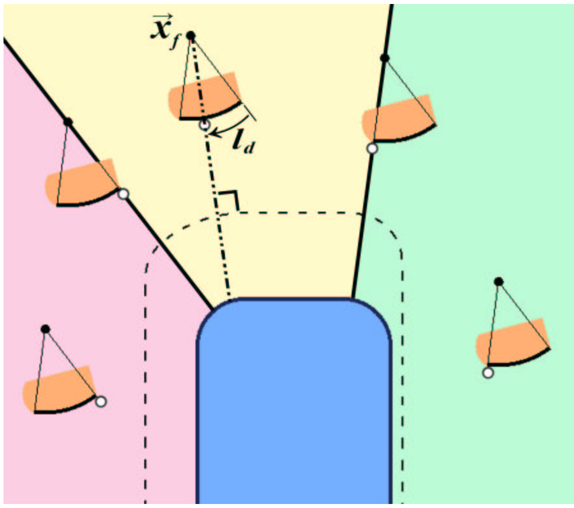


Figure 6. Free space is divided into zones for collision anticipation: the tactile element is driven to the finger arc's back endpoint, a point along its span, or its front endpoint.

nite bandwidth. Implementing more complex environments which include concavities will require a more sophisticated collision anticipation algorithm. The system will need to estimate the imminence of all the reachable contacts, average them together, and smooth the signal to prevent any discontinuities in contact location. The present c-space algorithm provides a framework for such improvements.

4 Controller

Coordinating the hardware with the virtual world during an haptic interaction requires precise control. The interaction model uses finger position, $\vec{x}_f$, and angle, ϕ, to generate desired positions for the finger, $\vec{x}_{fd}$, and the tactile element, l_d. But the device does not directly sense these parameters, and it can output only forces, not positions. The controller links the system's two halves together with three components: finger configuration, contact force, and contact location, as illustrated in Fig. 7. The system hardware is connected to a computer running RTAI Linux, which performs a real-time servo loop at 1 kHz. During each cycle, the controller computes finger position and angle for the interaction model and then closes control loops around the desired positions for the finger and contact element.

4.1 Finger Configuration

The system cannot directly measure finger position and angle, but instead must construct these parameters from

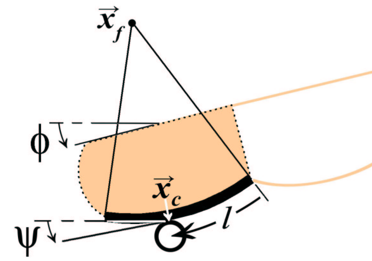


Figure 8. The geometry of the finger model allows the controller to determine ϕ and x_f from the sensed parameters ψ and x_c.

other signals. Forward kinematics are used to transform the device's four raw encoder readings to four coordinates of the mechanism's configuration: $[x_c\ y_c]^T$, ψ, and l. As illustrated in Fig. 8, $\vec{x}_c$ is the Cartesian position of the top of the contact element and also the endpoint of the robotic arm, ψ is the angle of the drive wires relative to the last arm link, and l is the contact location along the finger's arc segment. The controller uses the finger model's geometry to determine the position, $\vec{x}_f$, and angle, ϕ, of the finger from these readings.

4.2 Contact force

Contact forces stem from differences between the user's finger position and that of the virtual finger. Because the angles of the virtual and real fingers are identical, the position error can be computed at either the arc center, $\vec{x}_f$, or the contact location, $\vec{x}_c$. The present interaction model simulates a simple stiffness, K_e, generating forces that are normal to the environment's surface as follows:

$$\vec{F}_c = K_e(\vec{x}_{fd} - \vec{x}_f) = K_e(\vec{x}_{cd} - \vec{x}_c) \qquad (1)$$

This contact force is rendered using the shoulder and elbow motors of the robotic arm, and it acts on the user through the tactile element. At maximum current, the device can output about 1.5 N in any direction, which easily deflects the drive wires and pushes the contact cylinder into the user's finger. Future work on the interaction model could include simulated friction or other haptic cues in addition to stiffness.

4.3 Contact location

The system uses a position control loop on the contact display's linear degree of freedom to track the interaction model's specified contact location. Proportional and integral forces draw the tactile element to its desired location along the fingertip. Local derivative feedback is used to

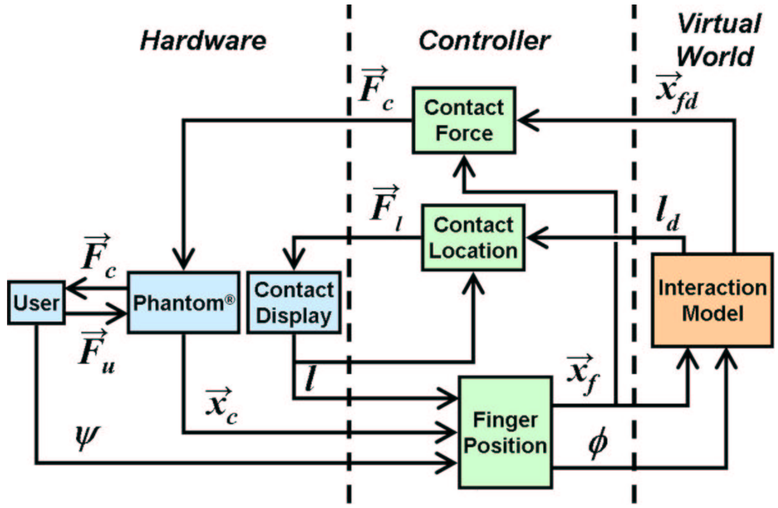


Figure 7. System Diagram. The controller connects the hardware to the virtual world, computing finger position, generating contact force, and tracking contact location.

damp out the dynamic oscillations excited by the push-pull wires and the stiction of the leadscrew. The entire contact location control law is:

$$\vec{F}_l = (K_p + \frac{K_i}{s})(l_d - l) - K_d s l \qquad (2)$$

where s is the Laplace operator. Because the leadscrew is non-backdrivable, the controller can force the tactile element to track its desired trajectory closely regardless of finger movements. The small motion bandwidth of the roller exceeds 5 Hz for a travel of 1.0 cm. 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. This simple PID controller yields good performance and stable operation for the contact location display hardware, enabling it to be used for general exploration of planar haptic environments.

5 Experiment

Humans use a variety of procedures to explore the environment around them. Specifically, contour following provides information about the global shape of the object being touched, relying on highly sensitive fingertip receptors [3]. Conventional haptic display systems provide only a single interaction point or sphere; following contours with such systems is difficult, especially when the surface has abrupt changes in direction or curvature, e.g. a table edge. Adding contact location display can improve the user's ability to perform these tasks by rendering the environment more realistically.

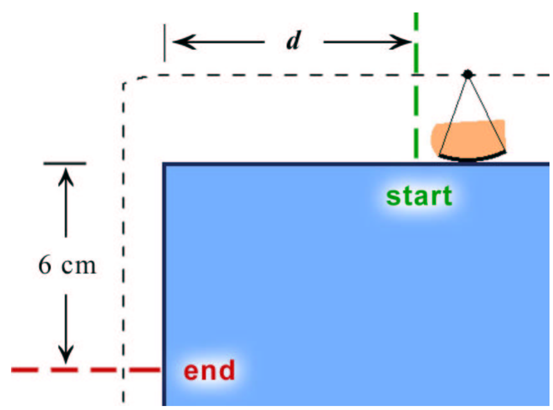


Figure 9. Subjects followed a virtual contour, trying to maintain contact throughout the interaction. Time was measured as the finger's arc segment traveled from the start to the finish line.

We constructed a simple virtual exploration task to investigate the possible benefits of contact location display when finding edges and following sharply changing contours. In this task we presented subjects with a rectangular environment like that shown in Fig 9. While blindfolded, they were asked to trace their finger forward along the top surface and down the far edge of the virtual block without breaking contact with it. Subjects completed the task both with and without contact location display. In both cases the bottom of the finger was modeled as an arc segment, as de-

Without Contact Location Display

	5 cm	7.5 cm	10 cm
Average Completion Time	3.10 s	4.73 s	5.54 s
Standard Deviation	0.78 s	1.01 s	1.38 s
Failure Proportion	50.0%	41.7%	21.6%

With Contact Location Display

	5 cm	7.5 cm	10 cm
Average Completion Time	3.00 s	3.01 s	3.34 s
Standard Deviation	1.42 s	1.02 s	0.71 s
Failure Proportion	11.4%	11.8%	14.3%

Table 1. Pooled subject data for contour following performance with and without contact location display for the three tested values of d. The average completion time and standard deviation are reported for successful trials only.

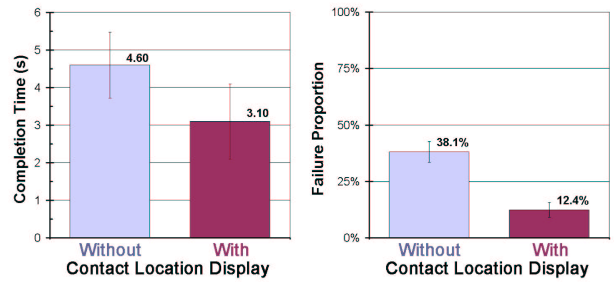


Figure 10. Experimental results pooled across subjects and trials. Average completion time and failure incidence both decrease with contact location feedback. Standard deviations are indicated by error bars.

scribed in Section 3, and force feedback was provided. In the trials where no contact location information was presented, the contact element was held stationary against the finger by an immobilizing strap.

Subjects were presented with blocks of three different lengths: $d = 5.0$, 7.5, and 10.0 cm. Each of these sizes was presented approximately 15 times under each of the two test conditions, and the order in which the lengths were presented was randomized to reduce habituation. After a short training period, subjects completed all trials for one test condition. They were then given a short break before beginning the second session. The order of the two test conditions was balanced among test subjects to reduce the effects of learning and fatigue. Each subject took approximately 30 minutes to complete the experiment, performing a total of about 90 trials.

Preliminary test results presented herein represent data from two subjects. The system automatically recorded completion time and trial success for each run. The timer started when the user's finger crossed a horizontal threshold at a distance of d from the edge and ended when the finger crossed a vertical threshold 6 cm from the top of the block, as shown in Fig. 9. A success was recorded only when subjects remained in contact with the block during the entire trial.

6 Results

Results from the human subject experiment are presented in Table 1 and Fig. 10. Table 1 gives the mean completion time and standard deviation for the contour following tests with and without the display of contact location. The data presented was pooled from all subjects, with completion times reported for successful trials only. The percentage of times subjects failed to complete the task by breaking contact with the environment is also listed for each trial type.

Interestingly, the completion time for tests without contact location display roughly scales with block length, d. This trend indicates that subjects proceeded cautiously in order to avoid failure in the absence of contact location information. In contrast, users required an approximately fixed time when contact location information was available. On average, users completed tasks 32.6% faster when provided with contact location information, as indicated in Fig. 10.

We also observed a significant decrease in the proportion of failed trials when users received contact location information. As indicated in Fig. 10, subjects were 25.7% less likely to break contact with the environment when provided with contact location feedback. Statistical analysis shows the differences in both completion time and failure proportion to be significant at a 99% confidence level.

To complete the task successfully, a user must be able to sense that the edge of the block is imminent. Once the user has identified the corner, he or she must pivot the finger around the edge of the block to maintain constant pressure and avoid leaving the surface. Detecting the edge is impossible when the finger is treated as a point and is difficult even when the finger is modeled as an arc segment. Without contact information, one must find the edge of the object based on a subtle height drop as the arc segment of the finger approaches the edge. Quite often, subjects overshot the left edge of the object under this test condition. In contrast, having contact information provides a clear cue that one has reached the edge of the block.

7 Conclusions

This work presents a novel device for displaying contact centroid location along with force feedback during haptic interactions. The data show that contact location information significantly improves contour following capabilities, resulting in a reduction of completion time and fewer failures. Subjects also commented that the task was easier to complete and felt more natural with the addition of contact location display. This result complements previous work on curvature discrimination and object motion judged via contact display [9]. These findings indicate that this simple device is a valuable addition to traditional force feedback for virtual and remote exploration and manipulation.

The contact location display system extends the paradigm of standard force-based haptic rendering by providing local tactile information. With this approach, the finger is no longer modeled as a point, but rather as an arc, similar to the commonly used spherical proxy. The arc segment was chosen to correspond to the travel of the tactile element along the user's finger. In contrast to previous force-only haptic interactions, the addition of contact location necessitates anticipation of collision to pre-position the tactile element. A method for predicting nearest contact based on configuration space is presented.

The current implementation of the haptic environment was adequate for the contour following used in our experiment. However, while using the system for other types of exploration, we noticed that some contact signals can be misleading because friction is not rendered. Users expect the virtual world to match their experience in real interactions, in which friction is ubiquitous. Without friction, it is nearly impossible to differentiate between rolling and sliding behaviors, which contradicts user expectations.

This investigation suggests many future developments. The addition of friction to the environment model will improve the realism of local fingertip exploration. A rotational brake on the tactile cylinder could be used to render the contrast between rolling and sliding contacts, as computed by the friction model. Conversion to two degrees of freedom would enable display of lateral as well as proximal/distal contact motion. Finally, we believe that the development of a multi-fingered contact location display system would be particularly useful for dexterous manipulation, allowing users to feel object geometry and changes in contact configuration.

Acknowledgments

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