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Display of Haptic Shape at Different Scales

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Abstract. This paper describes three haptic devices which can create the experience of haptic shape, each at a different scale. They operate by causing fingertip deformations that match the scale of the features of the objects being virtually touched. For large objects, shape display is obtained by the movement of the deformed contact area on the skin, for medium objects, display is given by the deformation of the fingertip rolling laterally, and for small objects, by stretching and compressing the skin locally. These display modes can in principle be combined to make complex displays operating at different scales.

1 Introduction

It is sometimes assumed that the artificial creation of the experience of interacting with objects requires the detailed replication of all the features of real interactions. While this approach is without a doubt most successful in some cases, specifically if one attempts to create the haptic experience engendered by using a tool to explore or modify objects, there are examples which demonstrate that it is not the only possible approach. In fact, a growing number of researchers have become interested by the idea of building devices designed to replicate only a subset of the phenomena that occur when a fingertip directly encounters an object or slides on it [18, 11, 13, 17, 16, 1, 15].

When one holds the handle of a tool, the replication of the haptic interaction with objects reduces to the replication of the effects of the interaction of a tool with an object. If a real handle is virtually attached to a virtual tool interacting with virtual objects, and if this handle is subject to the same perturbations that would be caused by a real tool interacting with real objects, then realism is achieved [9].

In this paper, three haptic devices are described, each providing a working example of the creation of the experience of haptic shape based on the artificial reproduction of only a small subset of the features of real interactions. These three haptic devices rely on different methods which are applicable at different scales. They all share the characteristic that they engage the skin without forcing the user to hold a handle, and cause deformations of the fingertip corresponding to touching objects having shape features at different scales.

It is thus possible to think that the design of haptic displays and transducers can be generally approached in these terms. It is hoped that work with these devices will eventually help the development of a theory of scale applicable to the haptic perception of shape. In addition, the inherent simplicity of these devices is appealing for the creation of new displays by combining them in various ways.

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2 Large Scale: Morpheotron [2]

2.1 Principle: Normal Finger Deformation and Contact Trajectory

When one explores the shape of a large object, the finger(s) must track its surface. These tracking movements can have many different patterns. We observed, however, that during typical movements, the exploring finger orientation remained largely invariant, presumably to maximize the aquisition of shape information. The result of this strategy is that the location of the mutual contact changes both on the object and on the finger(s), as illustrated in Figure 1a. Eliminating all other aspects of the interaction, including local shape, sliding, proprioception and so-on, yields what is pictured in Figure 1b. A flat plate in rolling contact with the finger tip according to exploratory movements provides the desired moving patterns of normal finger deformation.

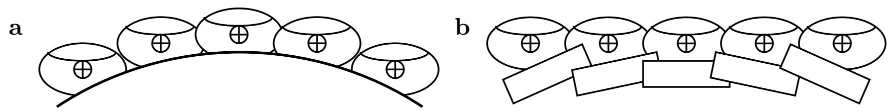

Fig. 1. a) Normal finger tip deformation during exploration, and **b**) how a rolling plate causes the contact region to move.

Experiments indicated that subjects were able to detect the curvature of spheres up to 0.5 m in diameter [2], which is close to the performance of subjects exploring real objects. While work remains to be done to solidify this result, it may be concluded that contact location trajectory on the fingertip provides sufficient perceptual contribution to create the experience of large objects (low curvature). We do not know what is the upper limit of curvatures that can be relayed, but it is clear that a bound is indicated by the size of a finger.

2.2 Description

An appropriate mechanism for causing the desired patterns of finger deformation is a spherical five-bar linkage designed such that its center of location is located inside the touching finger, as show in Figure 2a,c. The flat plate rolls on a finger with two degrees-of-freedom. This way, three dimensional surfaces can be displayed, see Figure 2b,d. The Morpheotron can be used actively or passively [2].

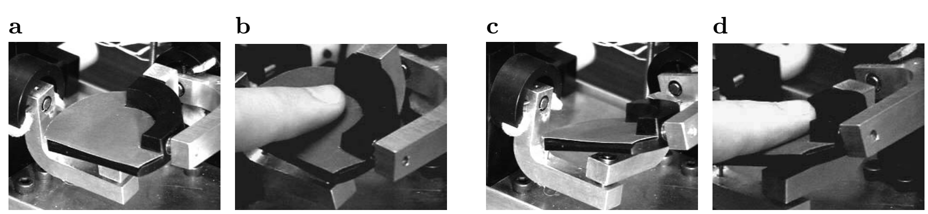

Fig. 2. a, **c**) Servo-controlled spherical linkage. **b**, **d**) Finger undergoes almost no rigid motion w.r.t. to mechanism's ground link.

Keynote paper. Eurohaptics 2004. Munich Germany, pp. 20-27.

2.3 Technical Issues

The preferred implementation currently calls for the servo-controlled spherical five-bar mechanism to be mounted on a light-weight gantry rolling on a table in the x and y directions. This enables people to explore arbitrarily large surfaces. Whether a Morpheotron is used in conjunction with a passive or a motorized carrier, a primary figure of merit is its total mass. The current device uses 3W DC motors with gear-head reduction. This results in a satisfactory device but it could be improved. A second factor of merit is speed. Exploring something of ping-pong ball size can result in fairly high angular velocities (of the order of a revolution per second) which conflicts with the low mass requirement. The third factor of merit is resolution which, presently, is limited by backlash in the gear-head. There exists many techniques to improve these factors in the future.

3 Intermediate Scale: Pantograph [4]

3.1 Principle: Lateral Rolling Finger Deformation

We again consider the exploration of the shape of an object, but this time, of finger-size scale. Among the many correlates of shape exploration, we found that lateral force fields were able to make a powerful perceptual contribution to shape [13, 6]. It is possible to speculate that one source of information that the brain uses to experience shape when lateral force fields are employed is the rolling deformation of the finger tip. This is illustrated in cartoon fashion in Figure 3a. A lateral force field applied through a flat plate as in Figure 3b, causes finger deformations that resembles that of exploring frictionless surfaces.

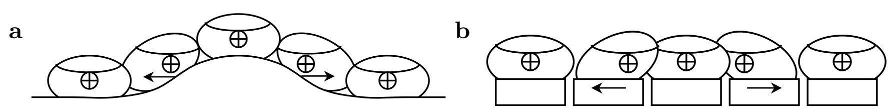

Fig. 3. a)Rolling fingertip deformation. **b**) As a method for relaying shape.

While lateral force fields that depend only on position are effective, the knowledge of the vertical component of the force applied by the user on the plate allows for better realism and for the creation of interesting paradoxical virtual objects [14].

3.2 Description

The preferred device for creating such lateral force fields is the Pantograph haptic device (Figure 4a). This device was recently re-engineered to include a force sensing pedestal and high resolution digital encoders, see Figure 4b.

Keynote paper. Eurohaptics 2004. Munich Germany, pp. 20-27.

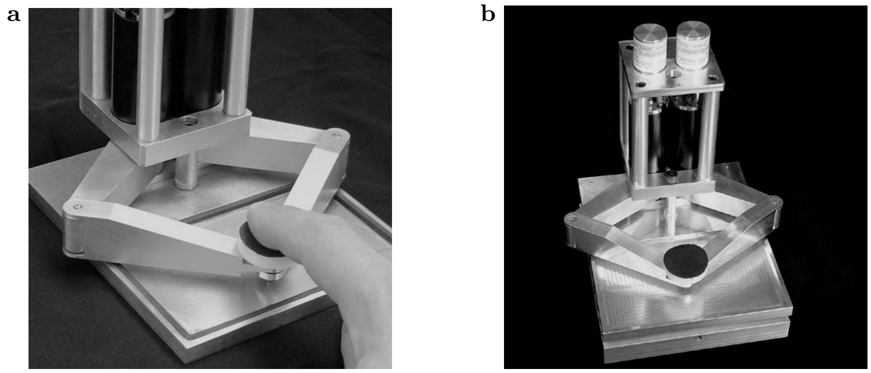

Fig. 4. a) Pantograph with planar workspace. **b**) System with force sensing pedestal and high resolution encoders.

3.3 Technical Issues

It is known since the work of Minsky that lateral force fields can give rise to the perception of textured surfaces, that is, of small scale surface features [8]. Consequently some basic performance figures are important to create a wide range of effects [5].

Figure 5a maps the *dynamic dexterity* figure of merit over the workspace of the Pantograph: the ratio of the singular values of the transformation from actuator torques to end-point acceleration. This shows that the device performs uniformly from the view point of acceleration over its workspace. Because of the consideration of fine textures, or of small shape details such as sharp steps, resolution and bandwidth are also important. Figure 5b maps the smallest distances that the device can resolve. This, with possible sampling rates in excess of 10 kHz afforded by Linux realtime extensions, allows the system to stay away from the Nyquist rate both in space and in time, as well as to provide a good passivity margin for precise reproduction of a wide range of stimuli.

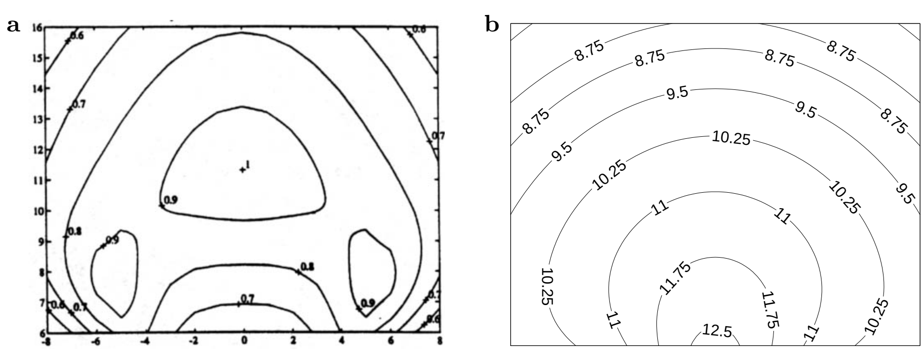

Fig. 5. a) Dexterity of the acceleration map (original device reprinted with permission from [4]). **b**) Resolution over the workspace measured in micrometers of the new design.

Figure 6 reports the response of the device measured, as it should, with an accelerometer mounted where the device interacts with the skin [5]. Figure 6a shows the response of the device loaded with a soft rubber band. The response is well behaved up about 400 Hz where a sharp structural resonance occurs (this typical pattern can be safely attributed to the cantilevered structure of rotor of the Maxon™ core-less motors; a second resonance exists at 600 Hz). Figure 6b shows the device in normal operating condition, that is, when it is loaded by a finger.

While, unsurprisingly, the response varies with the load, it is worth noting that the finger dynamics do not seem to vary very much with the state of deformation, except in the highest frequencies. These results indicate that, in order to provide accurate stimuli as specified by the input, the system response should be frequency-shaped, a topic which is currently under investigation.

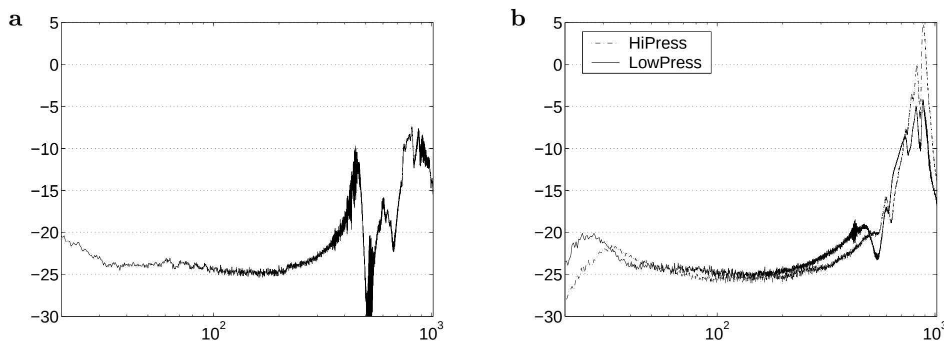

Fig. 6. a) Free acceleration response. **b**) Response with the load of a finger.

4 Small Scale: STReSS [12]

The previously described two devices depend on the production of gross deformations of the fingertip according the scale of features of the shape of the object to be displayed. Similar ideas apply at the scale of deformations caused by objects which are much smaller than the size of a finger.

4.1 Principle: Distributed Skin Deformation Fields

The principle of the STReSS display is best described by first inspecting Figure 7 and its caption (Please see [7] for methodological details). In essence, the STReSS tactile display relies on the fact that when a finger contacts an object, its deformation is accompanied by local area changes of the skin. We observed that a system designed to cause lateral skin deformation, that is, causing the *effect* of touching a shape rather than attempting to copying the shape itself, could make powerful perceptual contributions to the experience of small shapes [3].

Keynote paper. Eurohaptics 2004. Munich Germany, pp. 20-27.

Fig. 7. a) A finger slides on a ridge of millimetric scale (0.5 mm high). **b**) The skin is imaged and its anatomical features tracked. **c**) Regions of skin compression are represented by darker segments, while regions of stretch have lighter segments [7].

4.2 Description

A key motivation behind the STReSS design is miniaturization, given that tactile displays are notoriously difficult to integrate. We believe that a device designed to create the effect of touching objects can be made far more economically than a device designed to re-creating the objects themselves. The current STReSS is made of a two dimensional array of piezoelectric bending motors which can be made fine enough to create the sensation of continuous objects. Figure 8a shows a mode of construction whereby a series of piezoelectric bimorph plates have been first partially cut to form a linear array of individual benders and then assembled to form a two-dimensional array. The whole system is driven by a set of ultra-simple PWM amplifiers driven by an embedded FPGA chip [12].

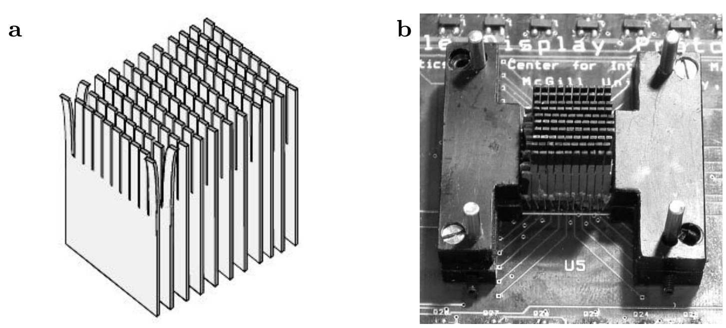

Fig. 8. a) Stacking of bimorphs cut in the shape of a comb forms a two dimensional array. **b**) The presently realized system with a 1 cm^2 active surface. Interestingly, the driving electronics (not shown) is currently far more bulky than the electromechanical transducer itself.

4.3 Technical Issues

Given that the density of one skin contactor per millimeter square appears to be adequate, the construction of a three-dimensional device with submillimeter-size features is clearly a challenge. Another problem is coping with the basic maximum deflection-stiffness tradeoff of benders, which currently limits the range of sensations that are in principle possible to create. This problem is compounded by the lack of knowledge the micro-mechanical behavior of the skin. In contrast with other types of tactile displays, a rate of operation is easily achieved due to the small movements required for the skin contactors. A compact design for the driving electronics of 100 channels is also a challenge.

5 Interesting Combinations

These devices are sufficiently simple to consider combining them in many possible ways. For example, a whole hand palpation device could be made by assembling six Morpheotrons arranged to contact the five fingers and the thenar eminence. A Morpheotron combined with a Pantograph could presumably be capable of displaying a very wide range of curvatures indeed. Needless to say, a STReSS display combined with either a Pantograph-type device or a Morpheotron, or both, would allow for many possibilities and many different applications.

6 Conclusion

We have commented on the possibilities that exist for the design of haptic displays that do not necessarily rely on force feedback to first reproduce the forces applied to the handle of virtual tools, to then indirectly relay shape. While we have discussed the display of shape only, presumably, other haptic object attributes could be displayed using analogous approaches. Some interesting attempts regarding friction properties are made currently and were made in the past, but unfortunately for lack of space cannot be commented here. Surely, some other object attributes could be considered as well.

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