Proceedings of the Haptic Interfaces for Virtual Environment and Teleoperator Systems Symposium, ASME International Mechanical Engineering Congress & Exposition 2000, Orlando, Florida, USA .

VIRTUAL SURFACES AND HAPTIC SHAPE PERCEPTION

Gabriel Robles-De-La-Torre **Vincent Hayward**

Department of Electrical Engineering and Center for Intelligent Machines
McGill University
3480 University Street, Montréal, Qc, H3A 2A7, Canada
roblesg@cim.mcgill.ca hayward@cim.mcgill.ca

ABSTRACT

Lateral force fields (LFFs) have been used before to generate haptic textures [3]. We propose that LFFs can be used to study haptic shape perception. We present preliminary results of an experiment in which human subjects interact with realistic LFFs. The LFFs encode shape information in the magnitude of unidimensional force vectors. Subjects explore the LFFs and classify them into haptic categories. We found that subjects can consistently perform this classification. This and subjects' qualitative judgments of the stimuli suggest that haptic interaction with LFFs resembles the experience of touching a real 3D object.

INTRODUCTION

Margaret Minsky's work on lateral force fields (LFFs) indicates that when human subjects interact with such fields they experience them as haptic textures [3]. In general, an LFF associates forces to positions in a way that is not ordinarily found in haptic interaction with objects. For example, consider the association of the position (x, y, z) of a manipulandum with a force field defined in a x-y plane. Surely, a mechanical device can be constructed to produce such an association. But this requires using sliders, springs, etc. For the purpose of this paper, we will consider LFFs which consist of forces whose magnitudes are proportional to the slope of a function that depends on the (x, y) position of a haptic manipulandum. Minsky used LFFs to generate haptic textures, but we propose that the idea is more general and can be used to generate haptic shapes, too. An LFF can be specified from a function $z = S(x, y)$ that describes the local shape of a 3D object. For example, the slope (the partial derivative of S with respect to x, y or both) can be used to modulate the magnitude of force vectors with components in the x and y axes, but not in the z axis. Can haptic interaction with this LFF elicit the perception of touching a 3D object? It seems likely that some of Minsky's stimuli (for example, her virtual gratings) could be haptically perceived by human subjects not only as textured surfaces, but also as 3D shapes with small-sized features. The same may be true about some stimuli that Minsky labeled as "bumps", but she did not not use them to study haptic shape perception. Research in human-machine interfaces suggests that LFFs can be used for haptic rendering of control buttons [5]. Also, the modulation of the direction of a force has been reported to affect the perception of curvature [2].

We believe that studying how human subjects perceive LFFs is a potentially significant problem for a variety of reasons. For example, when we explore the shape of a physical object with our index finger, the movement and position of the finger (as well as that of the hand, forearm and arm) are related to the 3D geometry of the object, described, for example, by three Cartesian coordinates, (x, y, z). This proprioceptive/kinesthetic information gives important cues to perceive the shape of the object. In contrast, an LFF whose force vectors have components only in the x axis has no explicit 3D geometry information. This information is only implicit in the magnitude of the LFF's vectors. Perceiving a 3D haptic shape when interacting with this LFF would suggest that proprioceptive/kinesthetic information about the 3D geometry of a shape is not always necessary to perceive a haptic shape. We would have shape perception without explicit shape geometry. Such a perception could be called an "illusory haptic shape".

As a first step to understand how relevant LFFs are for research on haptic shape perception, we tested human subjects' ability to classify LFFs into shape categories. We also collected preliminary information on subjects' qualitative experiences when interacting with such LFFs.

METHODS

Apparatus

Subjects sat at a table where a force-feedback interface (CAT/Pro, Haptic Technologies, Montréal, Canada)[1] was placed. Due to its direct drive design, the device has negligible friction in the x and y axes. The manipulandum is spring loaded in the vertical direction, so as to return naturally to a neutral position, and produces computer-controlled forces in the horizontal plane only. The haptic interface was connected to a Pentium II computer running at 400 MHz. The position of the manipulandum was sampled and forces were updated at 1 KHz. LFFs were generated using custom-built software. The interface generated LFFs on a horizontal plane. The interface's manipulandum was a rigid arm with a small plate. Subjects used this plate to operate the interface (Figure 1, see "Classification Experiment" below for details). A computer screen displayed a message to prompt the subjects to press down on the manipulandum if its vertical position was above a threshold position. Subjects' hand and haptic interface were covered with a box to exclude visual information. The haptic interface did not produce audible noises during normal operation, except when subjects reached the horizontal limits of the interface's workspace or pressed hard enough for the haptic manipulandum to touch the table on which the interface was placed. Subjects were instructed to avoid these conditions. Subjects were also carefully monitored by the experimenter to correct any such occurrence.

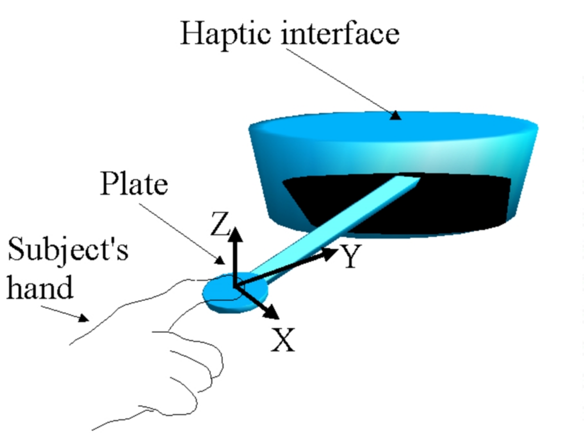

Figure 1. The experimental setup. Subjects pressed down on a manipulandum (plate) to interact with the haptic interface. The manipulandum is shown here positioned at the origin of our coordinate system, located at the center of the workspace.

[1] http://www.haptech.com/prod/cat.htm

Stimuli

The virtual haptic shapes were created using LFFs based on the function:

$$F_{k,w}(x) = -\frac{dG}{dx} = 2\frac{k}{w^2}\, x\, e^{-(x^2/w^2)} \tag{1}$$

Where G is the Gaussian function

$$G_{k,w}(x) = k\, e^{-(x^2/w^2)} \tag{2}$$

Eq. (1) defined the magnitude and direction of forces in the x-axis of the workspace (Figure 1). The parameters w and x (the position of the manipulandum in the x-axis) are given in meters, and k in Nm. Sample $F_{k,w}(x)$ are shown in Figure 2 for $w = 0.02$ m, $k = \pm 7.5 \cdot 10^{-3}$ Nm. Forces in the y direction of the workspace were equal to zero. The center of the workspace was located at $x = 0$.

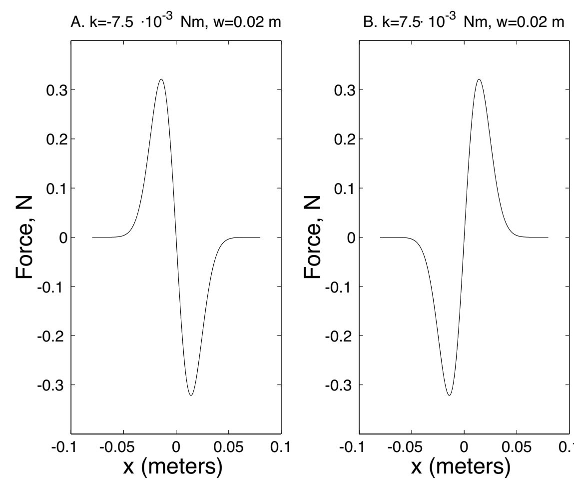

Figure 2. Sample lateral force fields used as stimuli in our experiment. The top of each panel shows the value of the parameters in Eq. (1) that generated each force field; k is given in Nm, w in meters. The LFF in panel A represented a surface with an indentation on it. The LFF in panel B represented a surface with a bump on it. See text for details.

LFFs described by Eq. (1) contained information about the shape described by Eq. (2) (see the "Discussion and Future Work" section for technical details). LFFs created with $k > 0$ Nm represented a surface with a haptic bump on it. Let us explain intuitively why this was so by referring to Fig. 2B, which shows an LFF with $k = 7.5 \cdot 10^{-3}$ Nm. Assume that a subject positioned the haptic manipulandum at $x = -0.1$m, and that he/she then moved it toward $x = 0$m. As the manipulandum gets closer to $x = 0$m, the haptic interface generates a force to the left of the workspace ($-x$ direction) that resists the movement of the manipulandum. This force reaches a maximum and then decreases to zero at $x = 0$m. This is analogous to what happens when we use a finger to touch a physical bump. When we move our finger from the base of the bump toward its top, the slope of the bump resists the lateral movement of our finger until we reach the apex of the bump. Here, the shape of the bump does not resist the movement of our finger anymore. When the position of the manipulandum starts at $x = 0.1$m and the subject moves it toward $x = 0$m, a similar situation occurs, but the LFF opposes the movement of the manipulandum toward $x = 0$m.

A similar reasoning applies to LFFs with $k < 0$Nm which corresponded to a haptic surface with an indentation on it. We chose Gaussian functions to describe our LFFs because they are defined by just two parameters. This makes it simple to systematically vary their features. Also, their haptic rendering is simple because these functions vary smoothly.

Subjects

Four McGill University undergraduate students, ages 18–22, were paid for their participation in the experiment. All were right-handed and naïve as to the purpose of the experiment. Subjects did not report any hand injury or disease. Subjects' handedness was evaluated using a questionnaire from [1]. Subjects did not have backgrounds in physics or engineering.

Classification experiment

Subjects were instructed to haptically explore a "virtual surface" generated by the haptic interface. In each trial, subjects had to decide if the virtual surface had an indentation (a "hole") or a bump on it. To help explain what the experimenter meant by "hole" and "bump", subjects were presented during instructions with a small, plastic object with a physical indentation and bump on it. The shape of this object was not Gaussian.

Subjects were instructed to explore the virtual surface by lightly pressing down the haptic interface's manipulandum ($-z$ direction, Figure 1) with the index finger of their right hand and by moving their hand sideways (x direction, Figure 1). Subjects' forearm rested on the table where the haptic interface was placed. There was no time limit imposed to explore the virtual surface, but subjects were encouraged to give quick, intuitive judgments. Subjects input their responses by pressing one of two buttons (labeled "bump" and "hole") on a computer keyboard. Subjects used their left hand to input responses and were encouraged to give their best guess if they were not sure about the features of the virtual surface. No feedback was given to subjects about their decisions. A message on a computer screen signaled subjects to press the return key on the keyboard to go on to the next trial.

A session started with 8 practice trials, after which subjects proceeded to complete 240 experimental trials. Subjects were allowed to rest at any time, and had also periodic rest breaks after 15 minutes of testing. The duration of the experiment was typically one hour and twenty minutes. The LFFs used as stimuli followed Eq. (1) with $w = 0.02$ m and $-7.5 \cdot 10^{-3} \leq k \leq 7.5 \cdot 10^{-3}$ Nm. The magnitude of the maximum force was 0.32 N. The range of k was divided to create four sets of stimuli (Table 1). A total of 60 stimuli were drawn from each set and presented to subjects in random order.

Table 1. SETS OF STIMULI USED IN THE EXPERIMENT

set	range of k used ($10^{-3}Nm$)
1	$-7.5 \leq k < -3.7$
2	$-3.7 \leq k < 0.0$
3	$0.0 \leq k < 3.7$
4	$3.7 \leq k \leq 7.5$

RESULTS

We calculated p("bump"), the probability of subjects classifying an LFF as having a bump on it, for the stimuli in each of the four intervals described above. These probabilities were obtained by dividing the number of stimuli classified as "bump" by the total number of stimuli in each interval. We show these probabilities in Figure 3 for all the subjects. These probabilities indicate that subjects can classify the different LFFs in a very consistent way. Low p("bump") correlates with $k < 0$ Nm. This means that subjects classify stimuli in this range as virtual surfaces with indentations. As explained in Methods, these stimuli represented the shape of a surface with an indentation on it. These stimuli include the one shown in Figure 2A. In contrast, higher p("bump") correlates with $k > 0$ Nm. These stimuli represented the shape of a surface with a bump on it. The probabilities of classifying an LFF as having an indentation, p("indentation"), are not shown because they can be easily calculated as $p(\text{"indentation"}) = 1 - p(\text{"bump"})$.

After the experiment was over, subjects were questioned about their qualitative judgments of the virtual surfaces. Subjects reported that they experienced the LFFs as surfaces and not literally as forces that pushed their fingers sideways. Subjects considered that the virtual surfaces felt like "slippery", "soft" surfaces. They also reported that, as they explored the virtual surface, it seemed as if their fingers followed the contour of the surface. For example, when exploring a surface with an indentation on it, subjects considered that their finger descended/ascended into/from the indentation. Such impressions seemed to be stronger for LFFs perceived as indentations than for those LFFs that were perceived as bumps. Also, these perceptions were reported for

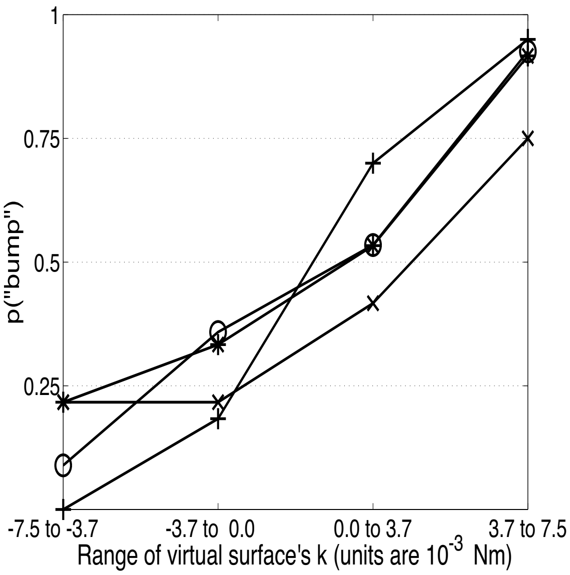

Figure 3. The probability of classifying a virtual surface as a bump for stimuli with different values of k. When $k < 0$ Nm, stimuli are classified as bumps with a low probability. As k increases to become greater than zero Nm, stimuli are classified as bumps with higher probability. Data from all four subjects are shown. Data points from a given subject are plotted using the same marker and connected with lines for illustrative purposes. Each probability was computed from 60 experimental trials.

virtual surfaces that were easily sensed by the subjects. Presumably, these involved the LFFs with high levels of force (i.e., stimuli where the magnitude of k was close to $\pm 7.5 \cdot 10^{-3}$ Nm).

DISCUSSION AND FUTURE WORK

Our preliminary results indicate that subjects can consistently classify LFFs into different shape categories by haptically interacting with them. This and subjects' qualitative reports about how they experience the LFFs suggest that haptic exploration of these stimuli resembles touching physical surfaces to some extent. We believe that these preliminary results are encouraging, but we need to understand which sensory/cognitive factors play a role in subjects' decision to classify an LFF into a category. For example, in this experiment we did not collect data on the movement of the manipulandum in the z direction, which existed because subjects pressed down on the manipulandum. It is possible that this vertical movement was involved in subjects' reports about their fingers following the contour of the virtual surface when exploring it. But movement in the z direction did not provide information about object geometry. This suggests that subjects may interpret their finger/hand motion as caused by the virtual surface and not by their control actions to press down and move the manipulandum. Or perhaps subjects' finger/hand motion in the z direction corresponded to their expectations about the physical shape of the virtual surface. Measuring and correlating vertical finger/hand motion to the features of the LFFs is important to decide between these cases. Because we are interested in exploring these possibilities, we decided not to have a rigid haptic manipulandum to restrict motion in the z axis. As a result, forces corresponding to a moderately stiff spring were felt by subjects when they pressed down the manipulandum. These forces were always present, and it is possible that they contributed to subjects' judgments. We can see why by considering the case shown in Figure 4. Here, a subject is sliding a finger on a frictionless surface S. At any point P of S, the subject applies a force F that is normal to the slope of S. This slope is equal to the derivative of S with respect to x, dS/dx. By Newton's third law, the surface S returns a force $-F$ to the subject's finger. It can be easily shown that $-F_x$, the horizontal component of this force, is $-F_x = -F\sin(\alpha)$. The slope of the curve at P is equal to $\tan(\alpha)$. For a small α, $\tan(\alpha)$ closely approximates $\sin(\alpha)$. It follows that

$$-F_x = -F\sin(\alpha) = -F\tan(\alpha) = -F\,dS/dx \qquad (3)$$

By making $S = G_{k,w}(x)$ (Eq. (2)) and $F = 1$, Eq. (3) becomes Eq. (1), the basis of our LFFs. For the parameters of our LFFs, this approximation is valid (and fast). This means that our LFFs represent important aspects of the physics of the real-life haptic exploration of a surface whose shape is described by Eq. (2). Our LFFs describe the horizontal force components of a normal force that is applied by a subject when haptically exploring a surface described by Eq. (2). In the case depicted in Figure 4, F_z and $-F_z$ are the components of F in the vertical z-axis. In our experiment, a subject applies F_z when pressing down the haptic manipulandum, and the spring-like action of the manipulandum reacts with $-F_z$. By combining these forces, an equivalent force can be obtained. This equivalent force is analogous to $-F$ (Figure 4).

In our experiment and in the physical case we have essentially the same force information. But the virtual surfaces do not have explicit geometrical information in the z-axis. To perceive a haptic shape in either the virtual or the physical case, is it necessary to press down on the object/manipulandum with a certain force while physically moving the finger/manipulandum up or down? Or, is it enough to press down without vertically moving the finger/manipulandum? In other words, what is the relative importance of geometric and force information in shape perception? Recent research highlights the importance of slope information in curvature comparison [4]. But it is very difficult to experimentally separate the perceptual contributions from geometrical and force sources. As shown in Figure 4, force and geometry are related. By isolating force information, our experimental setup may contribute to clarify this problem.

Undoubtedly, there are also cognitive factors that could con-

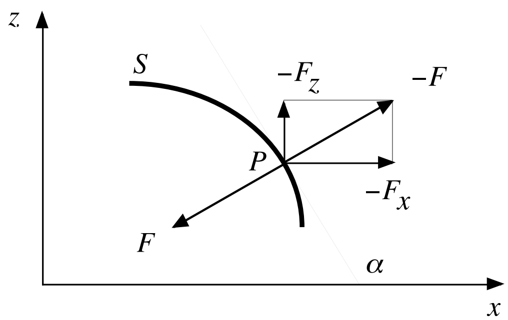

Figure 4. The forces involved in haptic exploration of a physical, frictionless surface S. Our LFFs can be related to $-F_x$, the lateral component of the normal force $-F$ that the surface returns when a subject applies a force F to the surface.

tribute to subjects' perceptions. For example, a subject could have inferred that an LFF represented a bump because he/she felt a force that was overcome after he/she moved his/her finger beyond a certain position in the workspace, which is similar to what happens when we touch a physical bump. If this is the case, we believe that our setup can help to understand these cognitive components of subjects' perceptions. We are currently conducting several experiments to explore these and other possibilities.

ACKNOWLEDGMENTS

We wish to thank Luda Requadt for her editorial comments.

This research is funded by project "Core Issues in Haptic Interfaces for Virtual Environments and Communication" supported by IRIS-III, the Institute for Robotics and Intelligent Systems which is part of Canada's National Centers of Excellence program (NCE). Additional funding is provided by NSERC, the Natural Sciences and Engineering Council of Canada, in the form of an operating grant for the second author.

REFERENCES

1. Coren, S. 1992. *The left-hander syndrome*. New York:Maxwell Macmillan International.

2. Morgenbesser, H. B., Srinivasan, M. A. 1996. Force shading for haptic shape perception. Proc. *Fifth Annual Symp. on Haptic Interfaces for Virtual Envir. and Teleop. Syst., ASME Dyn. Syst. and Cont. Div.*, DSC-Vol. 58. pp. 407–412.

3. Minsky, M. 1995. *Computational Haptics: The Sandpaper System for Synthesizing texture for a force-feedback display*. Ph.D. dissertation, Massachusetts Institute of Technology.

4. Pont, SC, Kappers, AML and Koenderink, JJ. 1999. *Similar mechanisms underlie curvature comparison by static and dynamic touch*. Perception and psychophysics 61(5) pp. 874-894.

5. Ramstein, C. Hayward, V. 1994. The Pantograph: a large workspace haptic device for a multi-modal Human-computer interaction. Proc. *CHI'94, Conference on Human Factors in Computing Systems ACM/SIGCHI*.