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Change of Height: An Approach to the Haptic Display of Shape and Texture Without Surface Normal

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Abstract. Several haptic shape display methods rely on the surface normal to compute a force response. Instead, it is possible to use the change of height of an interaction point to compute a force response when a subject explores the surface of an object. The notion of surface normal is no longer needed, and the difficulties associated with it are eliminated. An experiment is designed to illustrate some differences between this approach and previous ones. Open questions are mentioned.

1 Introduction

For the haptic display of rigid objects, it is natural to replicate the experience of point-wise surface exploration by producing a force normal to the simulated surface whose intensity depends on penetration, assuming frictionless local deformation of the said surface. With haptic devices moving and returning forces in three dimensions (e.g. Phantom™, [8]) this model applies directly and gives rise to specific implementations [17,15]. If n is a vector normal to the surface, p is the penetration, and $r(.)$ is the response:

$$f_{\mathrm{norm}} = -r(p)\, n. \tag{1}$$

With haptic devices in two dimensions (e.g. [2,1,11], Immersions's Impulse Engine™, Gravis' Xterminator™) the display of the shape of a surface can be effected by projecting this force onto the workspace of the device [12]. If that patch is represented by $z = S(x, y)$, then only the lateral component of the interaction force is returned to the user. This reduces to the calculation of a force proportional to the gradient of the simulated surface at the contact:

$$f_{\mathrm{lat}} = -r(p)\, \nabla z. \tag{2}$$

It is known that this approach is effective for producing the sensation of texture (high density of details) [9], smoothing geometric discontinuities [10,18], building GUI haptic landscapes [5,13], as well as displaying large shapes, even when penetration is assumed to be constant [14,4].

In terms of the information gained by a user about the shape of a surface, these equations indicate that, during exploration, this information entirely originates from the change of the factor n in Eq. (1), or in the factor ∇z in Eq. (2). In the absence of sliding movement, information is provided about just one point at the surface which contains no indication of shape.

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2 Change of Height Method

While these approaches attempt to artificially replicate some key aspects of the point-like interaction that occur when exploring an object with a small tool, they also come with practical disadvantages.

In the first case (3D forces), the system must create by feedback a surface stiff enough to yield a force of sufficient magnitude even with a small penetration. It is known that this requirement puts demands on the device and on its control to ensure the absence of limit cycles, of saturation, and of other deleterious effects. In the second case (2D forces), either force sensing must be used to measure the actual penetration in the direction normal of the device workspace, or, if constant penetration is assumed, the device will "slide down the slopes" on its own. A third problem results from the simulation of the interaction of a point with a surface. Regardless of the device being used, the normal may not be defined whenever the virtual surface is not smooth, for example when it is polyhedral and has edges and vertices.

The proposed shape display method does not have these disadvantages.

2.1 Approach

With point-wise interaction, it was observed that shape information is gained by a user only when there is movement. Without loss of generality, consider a surface described with respect to two horizontal coordinates x and y (this can be done in any orientation, given appropriate coordinate transformations, or even with other kinds of coordinates, spherical coordinates for example). Referring to Fig. 1 showing a point C sliding on a surface under user control, P is the projection of C so that they are at distance z from each other. The force direction is given by μ the direction of movement to oppose it. The magnitude of the force returned to the user, instead of representing a response to penetration, is now proportional to the change in height as the user explores the virtual surface, the "height gradient" with respect to the user movement.

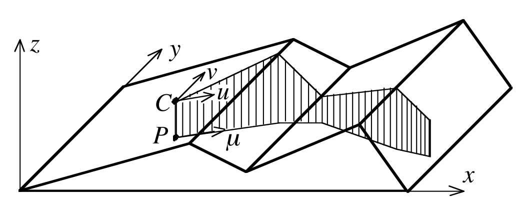

Fig. 1. Surface being explored.

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2.2 Force Calculation

An infinitesimal distance dl travelled by P is measured by the haptic device in order to compute the height gradient dz/dl (in practice, it is a small increment Δl between two discrete updates). The vector $\mu = [dx/dl, dy/dl]^\top$ is also found from the measurement of the position of P (subject to the same proviso). A properly scaled product of this two quantities provides shape information in the form of a change of force when moving in a particular direction:

$$f_{\text{height}} = -k \, \frac{dz}{dl} \, \mu, \quad dl \neq 0. \tag{3}$$

Please see Appendix A for a method to robustly estimate μ that eliminates the problem of dividing by, comparing, or subtracting small noisy quantities. Incidentally, the factor k can be related to a penetration as above, but can also a constant.

To describe the effect of Eq. (3), consider the case when the local coordinate v is parallel to y, and when the surface has a constant positive slope in the x direction and no slope in the y direction. The force experienced by the subject is zero when there is no movement, it opposes movement when the subject "climbs" the slope in the direction of u (respectively assists movement when the subject "slides down" in the direction of -u) and is also zero if the movement is in the v direction. The force produced by Eq. (3) is related to both movement and shape, and not to surface orientation at one point, as in Eqs. (1) and (2). It also eliminates their respective disadvantages.

2.3 Possible Interpretations and Observations

The discussion in this section follows from the observation that point-wise exploration of a rigid object can be abstracted to tracing a curve on its surface. A curve describes locally the shape, but does not define a normal.

Change in Height. The first interpretation follows from the reasoning that led to it, that the force experienced by a subject exploring a surface patch to gain information about its shape can vary, among other factors, with movement and slope. In other words, it can depend on the path traced. This seems to be a common mode of interaction when manually exploring an unknown object. This is relevant since it is known that the acquisition of the properties of objects, be it their shape, their structure, their material, is the result of sequential exploration in many directions [6].

Change in Interaction. The exploration of surfaces with a pointed tool in the total absence of friction is admittedly atypical. It also possible to view Eq. (3) as a friction force modulated by a slope causing changes in the the tool/surface interaction, "running into the surface", so-to-speak. The frictionless surface assumption is no longer needed.

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Non Smooth Surfaces. Eq. (3) is defined for any path on continuous surfaces, even if they are not smooth, as illustrated by Fig. 1. No special care is needed to handle undefined normals. Smoothing the haptic surface is equivalent to smoothing dz/dl.

Force Fields. Virtual interactions using Eqs. (1) and (2) describe a field that is uniquely defined for a given shape and a given surface response: to each point in 3D or 2D corresponds a unique force. This is not the case with Eq. (3) for which the force experienced at a point depends on each exploration path.

Specification of Textures. In relation to the study in [16] regarding the possible effects, or lack thereof, of particular models and devices as factors that influence the experience of texture, we also observe that Eq. (3) provides additional possibilities.

Consider the case of a grating represented as a corrugated surface, as in Fig. 2. When that surface is haptically rendered using Eq. (1) or (2), the returned forces tend to force the user to track the grooves. The natural response of a user is then to diminish penetration to maintain free exploration. In contrast, Eq. (3) returns a force which is always aligned with the movement of the user and hence does not disturb its direction whatsoever, but only its speed. It thus combines a damping-based approach with a stiffness-based one.

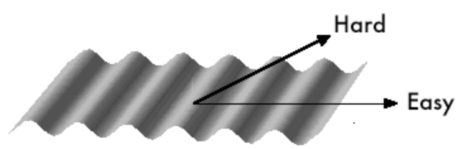

Fig. 2. With surface normal based schemes, it is hard to experience texture while exploring in any direction other than orthogonally to the grooves.

3 Experiment

A preliminary experiment was designed to highlight some of the differences between the present approach and the previous ones. It was also designed to show that the scheme introduced herein was as effective as previous ones in providing shape and texture information without having their limitations. In this experiment, subjects were asked to judge of the relative slope of two nearby surfaces, comparing their performance using the two shape display approaches.

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3.1 Method

Subjects and Apparatus. Six unpaid subjects from McGill University participated in the experiment. The subject pool consisted four males and two females, aged from 25 to 32. All happened to be right handed. All had some experience with a computer mouse, but none with a haptic device. The haptic device was a PenCat/Pro™ (Immersion Canada Inc.) which had a pen-like handle moving in a 14 × 10 cm work-area (Fig. 3.1). It returned forces up to 5 N in a plane. Because of its direct drive design, it operated silently and opposed virtually no friction.

Fig. 3. PenCat/Pro haptic device.

Stimulus. A "virtual surface" was defined as three contiguous patches, each of the form:

$$z(x, y) = \tan(\alpha)\, x + A \sin(\omega\, x)\, y. \tag{4}$$

Such a patch is represented in Fig. 4a, where a general slope in the x direction is defined by an angle α. The middle patch was horizontal, $\alpha = 0$, and the two other had slopes α_1 and α_2 (between 0 and 1.05 radian) of opposite sign defining a trough pictorially represented in Fig. 4b. The surface had no slope in the y direction. When the user explored the surface, the interaction point was tracing a path constrained to $y = 0$, as indicated in the figure by a line.

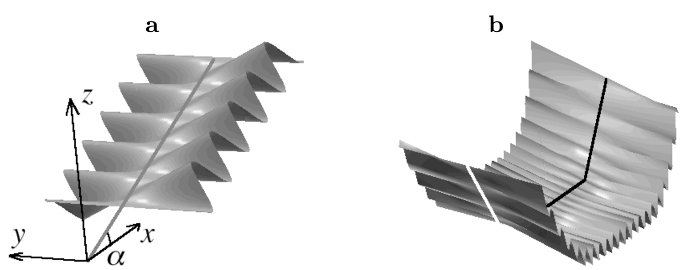

Fig. 4. See text.

The force vector generated by the normal based display approach, on paths $y = 0$, obeys:

$$f_{\text{lat}} = -k \left[\frac{\partial z}{\partial x}, \frac{\partial z}{\partial y}\right]^{\top}_{y=0} = -k\left[\tan(\alpha), A\sin(\omega x)\right]^{\top}, \tag{5}$$

where α depends on which of the three patches is being explored.

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The force vector generated by the height gradient display approach is

$$f_{\text{height}} = -k\,\frac{dz}{dl}\,\mu, \tag{6}$$

which in general cannot be specified further since μ is under the control of the subject. But for the case of a path in the x direction and provided that *the subject moved*, $dl = dx$, it reduces to

$$f_{\text{height}} = -k\left[\frac{\partial z}{\partial x}, 0\right]^{\top} = -k\,[\tan(\alpha), 0]^{\top}. \tag{7}$$

The scalar A was set to 1 and k was set so that the magnitude of the force did not exceed 4.77 N for both approaches. ω was such that the surface oscillated about 100 times over the length of the line.

The visual stimulus was the same in all conditions. A line was seen on a computer screen as in Fig. 5a, with a red ball on the left (marked A in the figure), a green ball on the right (marked B), and a blue cursor moving in between under subject control. The subjects were not visually aware of the location of the cursor on the surface, but only of its location on the line between the colored balls. Fig. 5b shows the correspondence between what was seen on the screen and the location of the interaction point on the virtual surface.

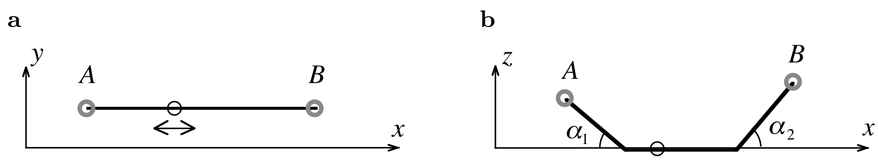

Fig. 5. See text.

Procedure. For each trial, the values of α_1 and α_2 were randomly selected, and so was the display method. The task was to determine haptically which side had the largest slope.

Subjects were asked to sit on a chair approximately 60 cm away from the computer screen, with their dominant hand holding the stylus as if they were writing. The other hand was placed on the computer keyboard. Subjects were instructed to explore back and forth the line segment, to experience the sliding forces, and to simultaneously watch the cursor on the screen. They were asked to make a decision as to which side had the largest slope based on the haptic stimulus and to indicate their decision by pressing a key dyed with the corresponding color. When the decision was acknowledged, the computer would automatically prompt the subject for the next trial. If after a few

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tens of seconds, a subject was still unable to make a decision, she/he would give her/his best guess and proceeded to the next trial. Each subject was informed that both the accuracy and decision making time would be recorded automatically, and was encouraged to proceed as accurately and quickly as possible. Each subject completed 151 trials and was asked before hand to practice for 10 trials in order to learn how to use the stylus to manipulate the cursor on the screen. Feedback was never given as to their performance.

3.2 Results

Fig. 6 shows a summary the subjects' average performance in terms of accuracy and decision-making time plotted as a function of the slope difference between the two sides of the trough.

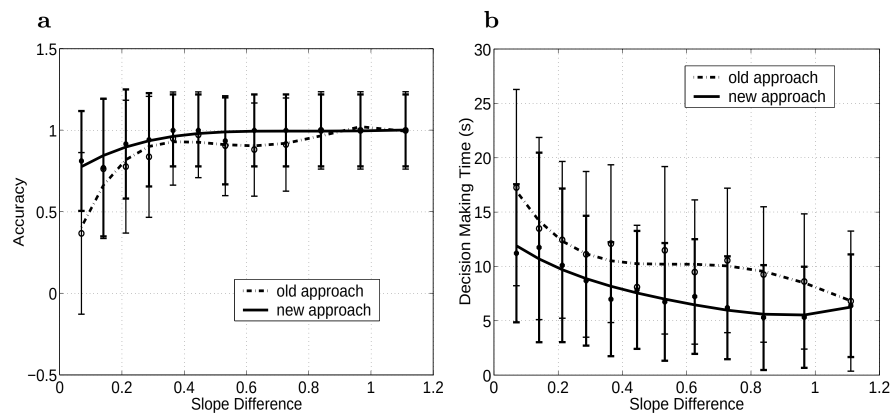

Fig. 6. Accuracy vs the difference of slope (radian) (**a**). Task completion time vs the difference of slope (radian) (**b**).

For both display methods, subject performance improved with the slope difference, both in accuracy and task completion time. Their performance was however always greater and more consistent with the height change display approach than it was with the lateral force display method. The mean accuracy for the height change approach was 92.4% with a standard deviation of 26.5% compared to 84.6% with a standard deviation of 36.1% for the lateral force approach. The two approaches are significantly different in mean accuracy of slope difference judgment, t_{accuracy}=5.4571, $p < 0.005$. The mean decision making time for the height change method was 8.6 seconds with standard deviation of 6.52 seconds compared to 11.52 seconds and 8.04 seconds respectively for the lateral force approach. The two approaches are significantly different in their effect on decision making time, t_{decision}=-3.3681, $p < 0.005$.

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It can be concluded that a textural component in a direction orthogonal to movement direction may have a dramatic effect on subjects' ability to judge slope haptically, given that slope is probably an important component of the haptic experience of shape. Moreover, in both cases the underlying "virtual surface" was the same, but the display method was different.

4 Discussion and Conclusion

The change-of-height display method addressed practical problems in the artificial display of shape. The results show, however, that the law of the variation force at the point of a virtual interaction with a surface in a virtual setting can be subject to arbitrary choices. These choices can be made by the designer to convey specific aspects of the available information to a subject using a haptic interface. Experimental evidence suggests that these choices can have dramatic effects on human performance according to the task being performed, that of judging the slope of a surface in this example.

Of course, these results open more questions than they answer, as briefly discussed in Section 2.3. These questions apply equally to 1D, 2D, 3D, and other devices.

Undoubtedly, there are surfaces and tasks that would yield the same subject performance regardless of the method employed. Alternatively, there probably exist surfaces and tasks that would yield even more dramatic differences. It is likely that the display of round shapes would yield differences in tasks such as discriminating their geometry or their size. What about the display of combination of small and large scale features, of material properties, and so-on? These questions clearly have strong connections with the notion of exploratory movement pioneered by Lederman and Klatsky [7].

The discussion and results also indicate that the surface normal, which plays such an important role in vision research and in computer graphics because of its influence on the reflection of light, may also plays a role in the haptic perception of objects, but a possibly very different one, since an effective display of key aspects of shape may be achieved without it.

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In Experimental Robotics VIII, Springer Tracts in Advanced Robotics, Springer Verlag, New York. 2003. pp. 570-579.

References

1. Buttolo, P., Hannaford, B. 1995. Advantages of actuation redundancy for the design of haptic-displays. *ASME Fourth Annual Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems*, vol. DSC-57-2, pp. 623–630.
2. Hayward, V., Choksi, J., Lanvin, G., and Ramstein, C.. 1994. Design and multi-objective optimization of a linkage for a haptic interface. *Advances in Robot Kinematics*, pp. 352–359. J. Lenarcic and B. Ravani (Eds.), Kluver Academic.
3. Hayward, V., Armstrong, B., 2000. A new computational model of friction applied to haptic rendering. In *Experimental Robotics VI*, P. I. Corke and J. Trevelyan (Eds.), Lecture Notes in Control and Information Sciences, Vol. 250, Springer-Verlag, pp. 403-412.
4. Han, H., Yamashita, J., Fujishiro, I. 2002. 3D haptic shape perception using a 2D Device. in *Technical Sketches, SIGGRAPH 2002.*
5. Keyson, D. 1996. *Touch in user interface navigation.* Doctoral dissertation, Eindhoven University of Technology.
6. Lederman, S. J., Klatsky, R. L., 1987. Hand movements: a window into haptic object recognition. *Cognitive Psychology,* Vol. 19, pp. 342–368.
7. Lederman, S.J., Klatzky, R.L. 1996. Action for perception: Manual exploratory movements for haptically processing objects and their features. In Wing, A., Haggard, P., Flanagan, R. (Eds.), *Hand and Brain: Neurophysiology and Psychology of Hand.* pp. 431–446. San Diego: Academic.
8. H. Massie, T., Salisbury, J. K. 1994. The Phantom interface: A device for probing virtual objects. Proc. *ASME Winter Annual Meeting, Symposium on Haptic Interfaces for a virtual environment and teleoperator systems.* DSC-Vol. 55-1, pp. 295–301.
9. Minsky, M. 1995. *Computational haptics: The sandpaper system for synthesizing texture for a force-feedback display.* Ph.D. dissertation, Massachusetts Institute of Technology.
10. 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.
11. Prisco, G.M., Frisoli, A., Salsedo, F., Bergamasco, M. 1999. A novel tendon driven 5-bar linkage with large isotropic workspace, *Proc. ASME Eight Annual Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems*, vol. DSCD/DSC-6B-3.
12. 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.*
13. Ramstein, C. 1995. MUIS: Multimodel user interface with force feedback and physical models. Proc. *IFIP International Conference Interact'95*, Lillehammer, Norway, pp. 157–162.
14. Robles-De-La-Torre G., Hayward, V. 2000. Illusory surfaces and haptic shape perception. *2000 Symposium on Haptic Interfaces for Virtual Environments and Teleoperator Systems,* Proc. ASME Vol. DSC-69-2, pp. 1081-1087.
15. Ruspini, D., Khatib, O. 2000. A framework for multi-contact multi-body dynamic simulation and haptic display. Proc. *2000 IEEE/RSJ International Conference on Intelligent Robots and Systems.*

In Experimental Robotics VIII, Springer Tracts in Advanced Robotics,
Springer Verlag, New York. 2003. pp. 570-579.

16. Weisenberger, J. M., Kreier, M. J., Rinker, M., A. 2000. Judging the orientation of sinusoidal and square-wave virtual gratings presented via 2-DOF and 3-DOF haptic interfaces. *Haptics-e*, Vol. 1, No. 4.
17. Zilles, C. B., Salisbury. J. K., 1995, A constraint-based god object method for haptic display. Proc. *IEEE Int. Conf. Intel. Rob. and Syst.,* Vol. 3, pp. 146–151.
18. Yamashita, J., R. W. Lindeman, Y. Fukui, O. Morikawa, and S. Sato. 2000. On determining the haptic smoothness of force shaded surfaces, in *Conference Abstracts and Applications of SIGGRAPH 2000*, p.240.

A Robust estimate for μ

A robust technique to estimate μ was provided in [3] (Section 4.1). It is such that μ is defined when P is stationary, i.e. when $\Delta l = 0$ or when Δl it is very small.

Compute the location of a point W from a measurement $\bar{P}$ as:

$$W_k = \begin{cases} \bar{P}_k - \frac{\bar{P}_k - W_{k-1}}{|\bar{P}_k - W_{k-1}|}\, z_{\max}, & \text{if } |\bar{P}_k - W_{k-1}| > z_{\max}, \\ W_{k-1}, & \text{otherwise.} \end{cases} \tag{8}$$

where $z_{\max}$ is set according to the resolution of a particular device. Then a robust estimate of μ (no division nor difference of measurements involved when $|\bar{P}_k - W_{k-1}|$ is small) is found from scaling the quantity $Z_k = P_k - W_k$ to one:

$$\hat{\mu}_k = \frac{1}{z_{\max}}(\bar{P}_k - W_k). \tag{9}$$