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HAPTIC CUSTOMIZATION OF PRODUCT PHYSICAL PROPERTIES IN A VIRTUAL ENVIRONMENT

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Abstract

Product physical properties such as stiffness and surface friction are difficult or even impossible to be perceived in today's computer-aided design (CAD) systems. In this research, a haptic interface is developed to customize product physical properties such as product textures and stiffness. Using the proposed system, a designer can perceive, for examples, the surface roughness of a handle, the stiffness of a toothbrush, and exam the trigger force of a push button, or even feel the vibration while an electronic razor is powered on as if he/she is operating a real product. If any of the above physical properties is not desirable by the designer (or customer), the designer can easily make changes until customized properties are perceived. Since these physical properties of a product, traditionally evaluated based on physical prototypes, can now be perceived and modified without any cost in a virtual environment by designers, the product development cycle can be shortened and the cost in making physical prototypes can be eliminated or reduced.

Keywords: virtual design, customization, ergonomics, haptics

1. Introduction

Current computer aided design (CAD) systems mainly support product geometric properties such as dimension and appearance. Physical properties such as stiffness and surface friction are difficult or even impossible to be perceived. With the recent advance of haptic technologies and rapidly increasing computing powers, it is now possible to model some physical properties in real time. In this research, a haptic interface is developed to customize product physical properties such as product textures and stiffness. Hand tool and hand-held product design will be used as case studies. In the proposed system, a designer can perceive, for examples, the surface roughness of a handle, the stiffness of a toothbrush, and exam the trigger force of a push button, or even feel the vibration while an electronic razor is powered on as if he/she is operating a real product. If any of the above physical properties is not desirable by the designer (or customer), the designer can easily make changes in terms of geometries, materials, or combinations until customized properties are perceived. Since these physical properties of a product, traditionally evaluated based on physical prototypes, can now be perceived and modified without any cost in a virtual environment by designers or customers, the product development cycle can be shortened and the cost in making physical prototypes can be eliminated or reduced. The easy accessibility of the proposed system makes product design customization on a large scale possible even in the early stage of design.

Haptics is related to the sense of touch which is best described by contact force and state of object surface. What is the real value of haptics? Most would agree that humans use their fingers and limbs and skin to discriminate object, manipulate objects, create music and share some of their subtlest communications with each other. This is why haptics is bi-directional to encompass intention, manipulation and gesture. Using haptics, we can probe an object for its state or quality such as detecting the finest scratch on a glass surface, and discerning subtly different grades of sandpaper. In everyday life, we use a lot of hand operated tools. Ergonomics plays a very important role in designing these tools. To some extent, the joyfulness of operating these tools depends on the design of grips, gripping surfaces and trigger mechanisms. Hand operated tools have two most common grips: power grip, and precision grip. The power grip is used when large forces are to be exerted, such as hammers or drills. The precision grip is primarily used for work that requires precise manipulation and control, rather than the use of large forces, such as surgical knives designed for minute manipulation. For comfort of gripping, a maximum gripping force of 90N was recommended [8]. If the applications require repeated force exertion, the recommendation is to use 40-50% of the maximum hand grip strength.

According to Kilborn et al.[1], productivity is strongly related to the relative tool grip force. For grip surfaces, the general recommendation is to use a grip surface that is slightly compressible, non-conductive, and smooth [9]. Compressible materials dampen vibration and allow for better distribution of pressure such as those in tennis racquet, golf club, and baseball bat etc. Figure 1 shows the design of an underwater camera, a cell phone and an electrical toothbrush. All of these use soft touch materials for some parts of the product so that the gripping is more comfortable and firm. Another grip surface characteristic is the friction of grip surface. It has been shown that the frictional characteristic of the tool surface varies with pressure exerted by the hand, with the smoothness and porosity of the surface[9]. In designing a hand tool, if triggers have to be activated repeatedly or for a prolonged period of time, musculoskeletal problems arise as such repeated activities require precision as well as force exertion (for holding and guiding the tool). According to Lee and Cheng [2], the force demanded for triggering should be less than 2 kg for single finger triggering, and less than 4kg for double finger triggering.

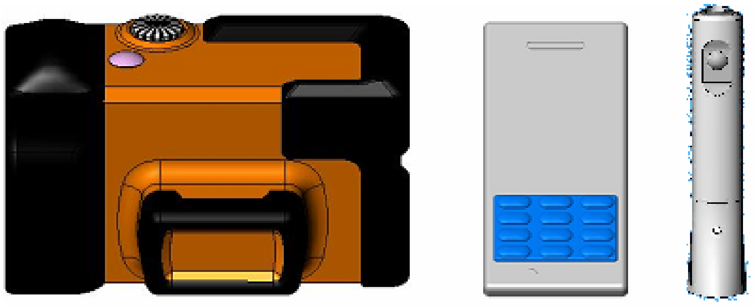


Figure 1 Designs with soft touch materials

In the early design stages, it is impossible to perceive, evaluate and even customize the above mentioned characteristics of hand tools using existing computer aided design systems. In order to do so, virtual reality techniques are being explored. Figure 2 shows that an application can be modeled in the virtual environment by physical laws and the embodiment geometries. Users can interact with the virtual environment using different interfaces for different part properties. For example, the sense of touch can be perceived through a haptic interface. A summary of human sensory features, their related modeling and potential applications to computer based customization is given in Table 1. Not all of human sensory information can be simulated faithfully via today's virtual techniques. In this paper, surface friction and roughness, and part stiffness are modeled using a haptic interface. Their applications to customization in early product design are presented.

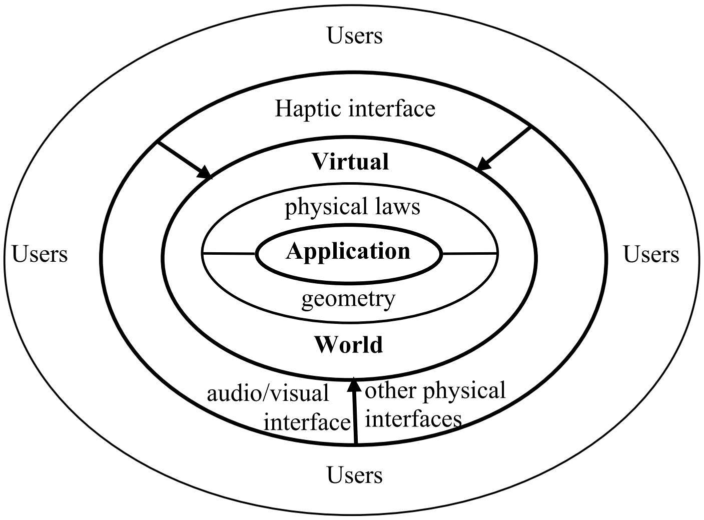


Figure 2 the virtual world interaction model

Table 1. Customizable properties and related virtual reality techniques

Human's sensors	**Virtual Techniques**	**Customizable properties**
Eyes	Computer graphics	Visual comfort, targeting effectiveness…
Ears	Digital audio	Noise level, tune, …
Hands/Skin	Computer haptics	Stiffness, textures, force, CDTs…
Nose	Virtual smell	Fragrance
Tongue	Virtual taste?	flavor

2. Friction Modeling and virtual Surface roughness customization

Many hand tools are made of several materials for the sake of safety and comfort to users. We feel different friction while touching surfaces of different materials even when the geometries and dimensions are the same. Friction is influenced by a number of factors including material nature and surface roughness, etc. Once the product geometry is determined in a computer aided design system, it is desirable to also define the surface properties such as roughness, or textures that interact best with human hands. A mathematical friction model is developed to describe the roughness nature of different materials. Rough surfaces are simulated by a haptic friction simulation method of anisotropic surface. Linear interpolation is employed to calculate the friction force of three types of basic 2D surface patterns. By space projection, the method can be extended to haptic friction simulation of 3D anisotropic surface. Based on this model, stable friction force feedback is simulated using a haptic device PHANToM® . Surface roughness are modeled as a matrix of grids, with different grid sizes representing different surface roughness. Since friction is really dependant on materials, a data base storing different material friction properties needs to be built. These properties are important in haptically rendering product surface friction.

2.1 One Dimensional Friction Model

Many friction models have been setup to improve the realism of the simulated surface or collision response. In continuous contact simulation in [3] and the simulation of impulse and friction of two dynamic 3D rigid body in [5], straightforward friction model is set up for dynamics friction between two isotropic surfaces as follow,

$$f_t = -\mu|\hat{v}|f_n \tag{1}$$

where f_t is the friction force, f_n is the normal force, μ is the friction coefficient, and $\hat{v}$ is the normalized relative translational velocity.

Baraff proposed a friction model as shown in Fig. 3 [4], where μ_{equi} represents the equivalent friction coefficient for both static and dynamic friction, μ_{dyn} represents the dynamic friction coefficient, and ε is the upper limit of velocity below which the friction between two contact objects is regarded as static friction. This model is particularly meaningful in the haptic simulation of surface by PHANToM® because it eliminates the force vibration when the relative velocity of the two moving objects equals to zero.

For haptic simulation of anisotropic surface, we use the friction model as shown in Fig. 4 by combining part of Richard's model [6] with Baraff's model, where ε has the same meaning with that in [4]. The most important features of the resultant model are: Firstly, it is a continuous function of velocity, which makes the haptic feedback more stable; secondly, it is defined on the basis of 1D rather than the 2D surface, i.e., friction along different directions may take different parameters when applied to the model. And it is asymmetric for positive and negative velocities. A problem of this model is that the operator cannot feel the "stick-slip" phenomenon when exploring the virtual surface with the haptic device. The model can be expressed as,

$$f_t = \mu \cdot \vec{v} \tag{2}$$

where f_t is the friction force and $\vec{v}$ is the relative translational velocity. μ is called the equivalent friction coefficient, which is a piecewise constant.

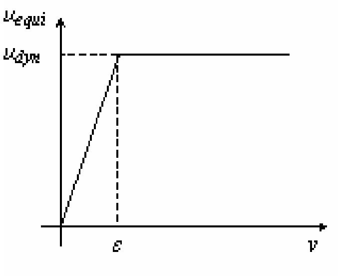


Figure 3 David Baraff's friction model

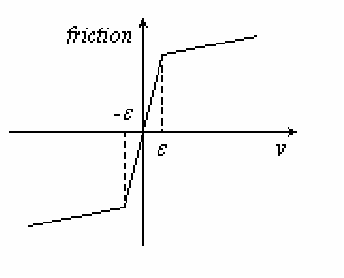
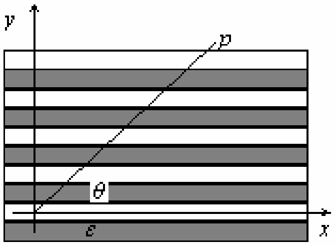


Figure 4 Friction model in this research



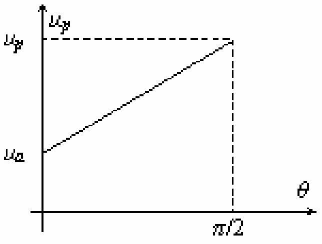


Figure 5 Linear pattern anisotropic surface and its equivalent friction coefficient

2.2 Haptic Exploration of 2D Anisotropic Surfaces

Three basic anisotropic surface patterns, including linear pattern, circular pattern, and user-defined curved pattern are studied here. In all patterns, parallel black and white stripes are used to visually represent the direction along which the friction is the smallest and across which the friction is the largest among all directions.

2.2.1 Linear Pattern

Surface friction pattern as shown in Fig. 5 is named as linear pattern, and the equivalent friction coefficient along and perpendicular to the stripes are defined as μ_a and μ_n, respectively. In order to simplify the haptic feedback model, linear interpolation is used for a certain direction $\overline{p}$. The angle between $\overline{p}$ and the x axis is θ, as shown at the left of Fig. 5. The equivalent friction coefficient μ_p in the direction $\overline{p}$ is illustrated at the right of Fig. 5, and can be calculated as

$$\mu_p = \mu_a + 2\theta(\mu_n - \mu_a)/\pi \tag{3}$$

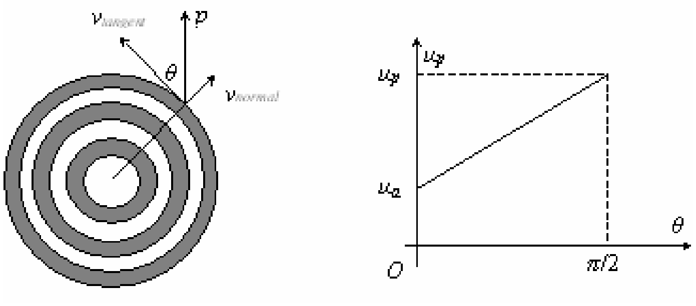


Figure 6 Anisotropic surface with circular pattern

2.2.2 Circular Pattern

Anisotropic surface with circular pattern is illustrated in Fig. 6. Similarly, the equivalent friction coefficient tangent and normal to the circle are defined as μ_a and μ_n, respectively. As shown in Fig. 6, linear interpolation is used to calculate the equivalent friction efficient μ_p in a given direction $\overline{p}$. When the contact point is moving along direction $\overline{p}$, μ_p can also be calculated from Eq. 3. The difference between circular pattern and linear pattern is that the interpolation reference frame for linear pattern is fixed while for circular pattern it is changing with the location of the contact point. Therefore, the interpolation reference frame has to be determined when using the PHANToM$^{®}$ to experience the surface friction, which adds extra workload to the haptic servo loop. Fortunately, in this kind of pattern, the calculation is straightforward when the center of the circular pattern and the contact point is determined.

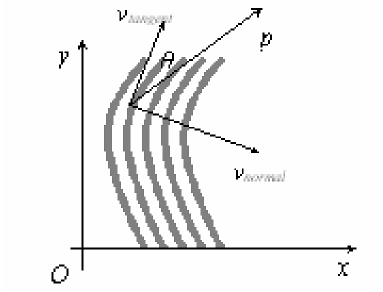


Figure 7 User-defined curve pattern

2.2.3 User-defined curve pattern

The third kind of surface pattern has a series of user-defined curves that are parallel to one another, as shown in Fig. 7. We define the equivalent friction coefficient tangent to the curve μ_a and normal to the curve μ_n. Linear interpolation between the two directions is also made use of for simplification. Similar to what we discussed above, the interpolation reference frame has to be determined in each haptic servo loop. To locate the motional reference frame, a fixed reference frame *xoy* is defined as shown in Fig. 7. Then a lookup table is setup along one direction in the *xoy* reference frame. For the pattern in Fig. 7, we setup a lookup table along *y* direction and take it as the index value, and each index points to a value representing the normal vector of the curve with the corresponding coordinate *y*. To accelerate the process, the size of the lookup table should not be too large.

2.3 Surface roughness perception

Roughness is haptically simulated by the above haptic friction simulation method of anisotropic surfaces. The friction is actually influenced by both surface roughness and material properties. For the same material, surface roughness is a main factor affecting friction. In this paper, surface roughness is modeled as grids where different sizes of grids are related to different surface roughness as in Figure 8. The dimensions of grid sizes are customized to universal roughness parameter value R_a and roughness grade number as shown in Table 2. When perceiving and customizing a part surface roughness of a given material, a surface category can be iteratively selected and perceived by a user until a comfortable surface roughness is perceived as in Fig. 9 where the stripes represent different surface roughness and therefore different friction. It is also desirable to relate material and surface roughness combinations directly to friction coefficient. This can be done through a lot of experiments.

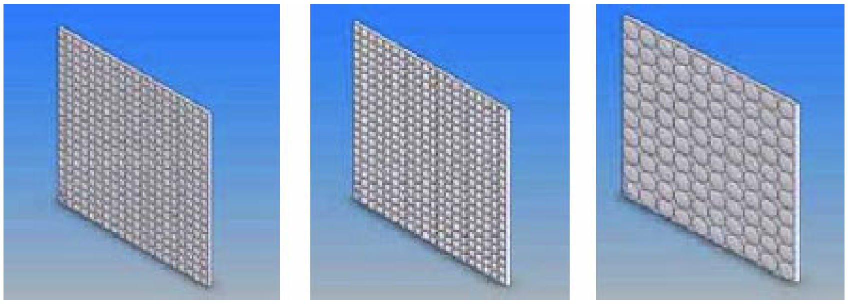


Figure 8 surface roughness modeled as different grid sizes

Table 2. Surface roughness customization

Surface Categories	Roughness Values Ra Um (ISO 1992)	Roughness Grade Numbers (ISO 1992)	Computer Grid Ball Size (mm)
1	~~ 0.05	N1, N2	0.1
2	0.05~~0.2	N3, N4	0.3
3	0.2~~0.8	N5,N6	0.6
4	0.8~~3.2	N7,N8	0.9
5	3.2~~12.5	N9,N10	1.2
6	12.5~~50	N11,N12	1.5
7	50~~	Unclassified	3.0

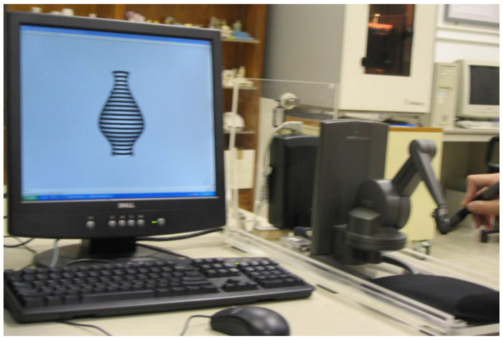
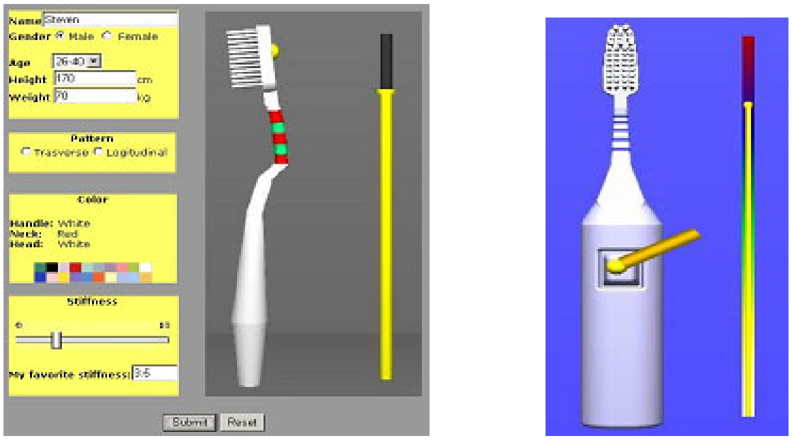


Figure 9 Perceive the surface roughness using a Phantom®

3. Stiffness modeling and customization

Stiffness customization requires the use of forces by a user. In this paper, toothbrush and push-button switches are used as case studies. The mechanics models of the case studies were reported in a previous study by the authors [7]. In this research, a design customization user interface is developed. A snap shot of the user customization menu is shown in Figure 10. Using this interface, a designer can apply a force to the toothbrush or pushbutton button design using a haptic interface Phantom. While applying a force, the corresponding deflection can be observed. The stiffness value of the design is also shown as a relative scale as in Figure 10(a). When a preferred stiffness is perceived by a user, the personal data of the user can be recorded. By recording data from a lot of users with different background information, a table such as Table 3 can be got. These data provide a guidance to designing product with the appropriate stiffness for different groups of customers. When the currently selected material and geometry design do not satisfy the designer or customer requirement, a change of the material, the geometry or a combination of both material and geometry can be done until a suitable stiffness value is found. In fact, this system can be used in a number of different ways to validate a product design. For example, a tooth brush with proper material and shape can be designed by a user first, the design is then haptically evaluated by a group of targeted customers. Statistics from this group about the product stiffness can be used to dictate if a change should be made or not.



Name Steven
Gender ● Male ○ Female
Age 26-40
Height 170 cm
Weight 70 kg
Pattern
○ Trasverse ○ Logitudinal
Color
Handle: White
Neck: Red
Head: White
Stiffness
My favorite stiffness: 3.5

(a) Bend a tooth brush

(b) Trigger a push-button

Figure 10 User interface for toothbrush customization

Table 3 Personal data and preferred stiffness

Name	**Gender**	**Age**	**Weight(kg)**	**Height(mm)**	**Stiffness (N/mm)**
Steven	M	26-40	70	170	4.5
Yang	M	41-60	60	168	3.5
…	…	…	…	…	…
Zhang	F	26-40	52	165	3.5

4. Conclusion

In this paper, a haptic interface based on a proposed friction model and surface roughness model has been developed to customize product physical properties such as product surface friction (roughness) and stiffness. Hand-held product designs are used as case studies. Using the interface, a designer can perceive, for examples, the surface roughness of a handle, the stiffness of a toothbrush, and exam the trigger force of a push button as if he/she is operating a real product. If any of the above physical properties is not desirable by the designer (or customer), the designer can easily make changes in terms of geometries, materials, or combinations until customized properties are perceived. The cohort data collected from different users can be used for customized design.

References

- Papers in journals:

[1]. Kilbom, A, Mararairen, M, et. Al., "Tool design, user characteristics and performance: a case study on plate-shears", Applied Ergonomics, 24. 1993, pp. 221-230.

[2]. Lee, YH and Cheng SL, "Triggering force and measurement of maximal finger flexion force", International Journal of Industrial Ergonomics, 15, 1995, pp. 167-177.

[3]. Kry, P. G., and Pai, D. K., 2003, "Continuous Contact Simulation for Smooth Surfaces" ACM Transactions, 22, pp. 106–129.

[4]. Baraff, D., 1991, "Coping with Friction for Non-penetrating Rigid Body Simulation", Computer Graphics, Volume 25, 1991.

- Papers in proceedings:

[5]. Kawachi, K., Suzuki, H., and Kimura, F., "Technical Issues on Simulating Impulse and Friction in Three Dimensional Rigid Body Dynamics," in the Proceedings of IEEE Computer Animation '98 Conference, June, 1998.

[6]. Richard, C., and Cutkosky, M. R., "Friction Identification for Haptic Display," in the Proceedings of the 8th Annual Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems, ASME / IMECE, 1999.

[7]. Chen YH, Yang ZY, "Haptic-based function analysis and shape modeling of Multi-Material Product: A Case Study", DETC2004-57782, Proceedings of ASME International Design Engineering Technical Conferences, Salt Lake City, USA, 28/9 to 2/10, 2004.

- Books:

[8]. Greenberg. L and Chaffin, DB, "Workers and their tools", Midland, MI: Pendell, 1977.

[9]. Konz, S, "Work Design: Industrial Ergonomics", Worthingto, OH, Publishing Horizons Inc. 1990.

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