Tangible Sketching of Interactive Haptic Materials

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ABSTRACT
The activity of sketching can be highly beneficial when applied to the design of haptic material interaction. To illustrate this approach we created a design tool with a tangible hardware interface to facilitate the act of haptic material sketching and used this tool to design an anatomy exploration application. We found this approach particularly efficient in designing non-visual properties of haptic materials. The design tool enabled instant tactile perception of changes in material properties combined with the ability to make on-the-fly adjustments, thus creating a sense of pliability.

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Sketching, Design, Haptics, Interaction Design, Tangible Interfaces

ACM Classification Keywords
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Figure 1. Designer using a PHANToM Omni device and MIDI controller interface to sketch the material properties of a dental anatomy exploration application

INTRODUCTION
Haptic applications enable users to feel virtual objects using a haptic device such as the Sensable Phantom Omni (Figure 1). Shape, position and hardness of virtual objects is conveyed through a combination of haptic and visual rendering. Haptic rendering algorithms such as that presented by Agus et al. [1] enable virtual materials like bone and teeth to be felt and manipulated with a virtual drill. The virtual drill itself has material properties which affect the tactile feedback experienced by users as they drill. The non-visible nature of haptic material properties creates a challenge in designing haptic interactions, as designers cannot see the effects of these properties, they can only feel them.

The design of haptic materials is commonly an iterative process, where designers make adjustments and proceed to interact with materials to feel the effects of those adjustments. To assist in this process, some applications feature a graphical user interface with sliders and other components which allow users to adjust haptic rendering parameters (Figure 2). The utility of these interfaces is limited by the time and effort required to implement them and the fact that in order to operate them, users must interrupt their manipulation of haptic materials and shift their focus to GUI components, thus interrupting their workflow.

There exists a need for flexible and efficient design platforms that facilitate the exploration of solutions with satisfying haptic qualities [2]. The activity of sketching has been used in some haptic applications as a way to explore a design space. Miao et al. [7] used paper prototyping to evaluate tactile interfaces for the visually impaired. De Felice et al. [3] created an authoring tool where a virtual world could be designed interactively. While these studies propose creation and usage of sketches as a way to explore the design space and test ideas, they do not explore the design of the haptic interaction per se. We believe that sketching can be an effective and efficient approach to interactive haptic material design.

Sketching as a design activity plays two valuable roles. The more obvious role is in generating quick, cheap, throw-away prototypes suitable for exploring ideas in early stages of de-

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velopment. The second important role of sketching is the act of sketching itself. When sketching the (graphical) designer does not merely draw a mental picture on paper (or other material), they receive immediate visual feedback and the sketch itself evolves. The sketch "talks back" to the designer [4]. We intend to bring the same level of interactivity to haptic material sketching. Schön's concept of the designer having a conversation with his/her sketch has been applied to digital materials [4] and has transcended into the design of tailored haptic feedback devices, an approach known as "sketching in hardware" [8].

Our approach brings the concept of sketching to the design of haptic applications by allowing the designer to create and explore various sketches of haptic material properties, based on run-time parameter adjustments using a tangible interaction device. We introduce a suitable sketching tool and illustrate its usage with a design study of a dental anatomy exploration application. The primary focus of this paper is not limited to sketching as a means of generating early prototypes or even sketching with physical materials, but the possibility of sketching the haptic material itself.

DENTAL ANATOMY EXPLORATION APPLICATION

Surgical simulation is a common application area for haptics research. Surgical simulators aim to teach theoretical aspects of a surgical procedure and improve trainees' technical skills through practice. Designing and implementing a stable, satisfactory realistic simulation remains a challenge both in terms of hardware, as well as algorithms and application design. Challenges include the elimination of device vibrations and calculation of haptic feedback forces with less than 1 ms delay. Different anatomical materials need to be designed with distinct physical properties which affect the tactile feedback experienced by users. These challenges make surgical simulation a suitably challenging design case for our study of haptic material sketching.

To demonstrate the use of sketching in designing haptic material interaction, we present our experience in developing a tool to facilitate the act of sketching, and using this tool to design an interactive dental anatomy exploration application with haptic feedback. The aim of this application is to help students make the transition from theoretical learning to hands-on practice by enabling them to interact with an anatomically accurate jaw model using their tactile sense.

The objective of the sketching approach in this case is twofold. First, to generate interaction ideas and identify sets of parameters which yield an interesting and educational user experience. Second, and at least equally important, to enable the designer to sketch the haptic material itself, i.e. the material properties of the jaw bone, teeth and drill. Materials do not necessarily have to be realistic for this application; in fact it could be useful to present exaggerated material differences similar to the way medical illustrations exaggerate anatomical colors.

Process overview

Our approach was comprised of the following steps:

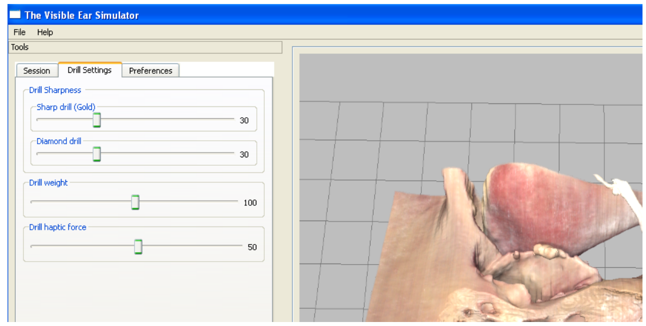

Figure 2. Part of screenshot showing a conventional user interface used to tune the look and feel of a temporal bone surgery simulator [9]

1. *Parameter choice:* We used domain knowledge gained from the literature and from interactions with domain experts to choose a set of parameters that manipulate haptic and visual aspects of the application.

2. *System implementation:* We designed and implemented a sketching tool such that the parameters selected in step 1 were easily adjustable. This was done by attaching the parameters to an interactive interface, making them modifiable at run-time.

3. *Sketch generation:* We used the sketching tool to interactively adjust parameter values and produce a set of sketches with desirable properties, such as high haptic stability or highly accurate representation of haptic material boundaries. In addition, we used this process to evaluate the parameter space and make adjustments such as adding / removing parameters and modifying parameter ranges. The set of sketches produced by this step was the haptic application equivalent of the set of design mockups that graphic designers commonly present to their clients.

Choosing design parameters

Choosing an appropriate set of parameters to vary during sketching requires insight in the form of technical knowledge of application algorithms as well as knowledge of the application domain. In our case, both authors have prior experience in the design and implementation of haptic dental training simulators and have worked extensively with domain experts. This experience was of great assistance in constructing an appropriate set of parameters.

Given the exploratory nature of the task, it is unreasonable to expect that the best set of parameters will be chosen from the very beginning, therefore we used an iterative approach. Parameter sets were chosen, implemented in our sketching tool, and evaluated during a sketching session. Any parameters found to be ineffective or with an inappropriate value range were modified in the next iteration until we reached an ideal set. To facilitate this iterative process, we designed our sketching tool such that parameters could be modified with relative ease.

The final set of sketch parameters is shown in Table 1. The chosen parameters alter both the look and feel of the simulation. Some parameters were chosen from the beginning,

Parameter	Description
Burr size	The diameter of the cutting burr. Range: 0.2 mm - 20.0 mm
Jaw size	The size of the jaw model as a ratio of the original size. Range: 0.5 - 6.8
Haptic stiffness	The overall stiffness presented by the haptic device when touching an object. Range: 0.5 - 3.7
Bone and tooth cutting rate	A number representing the rate at which each material is removed during every time cycle. The smaller the rate, the less material is removed each cycle and vice versa. Range: 0 - 1
Bone and tooth average cutting force	A value (in newtons) representing the force that the user is expected to apply when cutting each material. The higher the value, the more force the user will have to apply to remove material. Range: 0 N - 3 N
Bone and tooth transparency	The transparency percentage of each material. Range: 0% - 100%
Bone and tooth color	The HSV color value of each material. The Hue, Saturation and Value of a material color are each represented by one MIDI control, thus requiring three controls per material color. Range: 0 - 1

Table 1. Description of chosen haptic application parameters

while others were added as the need arose. The range for each parameter was adjusted iteratively during the sketching process.

Parameters such as burr size and jaw size were chosen based on knowledge of the chosen haptic device's position resolution and stability characteristics. Past experience has shown that there is a trade-off between realistic jaw size and haptic rendering fidelity. The size of a tooth is relatively small compared to the workspace of the most common haptic feedback device, the PHANToM Omni. The smaller the tooth size, the smaller the motions that will be made during drilling. As motion size approaches the device's position resolution, we begin to lose haptic rendering accuracy. With a larger jaw model, we use more of the device's workspace, which results in increased haptic fidelity.

Other haptic parameters were chosen to enable detailed fine-tuning of the way in which haptic feedback is rendered by the device. Haptic stiffness was chosen because we know that there is a limit to the stiffness our haptic device can render while maintaining overall stability. Therefore it is necessary to experimentally find the ideal stiffness, both during touching and drilling.

The bone and tooth cutting rate parameters were chosen to enable fine-tuning of the difference in how fast each material can be drilled. We found that a simple time-based cutting rate was not sufficient to fully represent the differences in material hardness, so we added the parameters representing the bone and tooth average cutting force. These parameters represent the force that is expected when cutting each material and can be calculated based on real life force measurements if realism is desired. The amount of material removed during drilling is increased or decreased based on how much force the user applies compared to the value of the parameter. The combination of the material cutting rate and average force parameters enabled detailed fine tuning of material hardness rendering during drilling. One of the differences between novice dentists and expert oral surgeons is their ability to differentiate material boundaries, particularly with differences in material hardness [5]. Thus it was important for our application to facilitate the exploration of material boundaries both visually and haptically. However, in contrast to surgical simulations, in our anatomical exploration application we do not seek to ground the hardness properties in physical attributes but in perception, just as medical illustrations do not necessarily use colors derived from nature.

Finally, we introduced parameters to vary the transparency and color of each material. We chose to vary these parameters in order to explore less realistic colors that help highlight material differences. Varying the transparency can also help understand the anatomical relationship of teeth and bone, such as how deep the teeth reach inside the bone.

Hardware and software

To allow for rapid creation of sketches we created the setup shown in Figure 1. Each rendering parameter is linked to a slider or knob of a USB-connected Behringer BCF2000 MIDI-controller such that the user of the system can interactively modify all parameters at run-time, while interacting with the Sensable PHANToM Omni haptic device. The open source project Forssim (http://dev.forsslundsystems.se) was used as a basis for the software. This system was chosen because it had most of the required functionality already implemented and it is built on the H3D API (http://www.h3d.org) which provides access to a wide range of haptic and visual parameters. The haptic rendering algorithm is a modified version of the Agus volume-sampling algorithm [1], which enables a direct rendering of the interaction of a spherical drill and a segmented volume model of bone and teeth, derived from Computed Tomography images. The system runs on a Linux-based PC (Intel Xeon 3.2 GHz CPU, 4GB RAM, nVidia Quadro 4000 graphics).

Creating design sketches

To develop a set of sketches for our anatomical exploration application, we ran the sketching tool and varied the parameters using the MIDI controller, until a pleasing result was achieved. Once a good parameter combination was found, it was saved as one of many pre-sets on the MIDI controller. Saved pre-sets could easily be recalled using the MIDI controller, which has motorized sliders that are automatically set to correct positions based on the pre-set being loaded.

DISCUSSION

The sketching tool and workflow presented above facilitated iterative, interactive sketching of haptic materials for a specific application. This experience with haptic sketching has been very positive. Although both authors have several years of experience in haptic simulation programming, we had not previously had the opportunity to manipulate the parameters of haptic rendering algorithms in such direct manner. The sketching process provided an intuitive understanding of the effects of parameter variations on haptic rendering which we had not experienced with previous approaches. We were able to quickly and efficiently sweep the application parameter space to identify the parameter values that produce a good educational experience.

The MIDI controller proved to be a highly effective user interface for our sketching tool. The use of a tangible interface enabled us to manipulate haptic materials without having to look away and stop drilling. Multiple parameters could be changed at once, using two or more fingers, and feedback was instantly received both visually and proprioceptively. These features of the design tool created a strong sense of pliability [6].

Furthermore, the use of a tangible interface eased the process of creating the sketching tool itself by eliminating the cumbersome effort of having to link simulation parameters to a graphical interface. Additionally, the MIDI controller's ability to save pre-sets of parameters provided an easy way to store several different sketches of the application without additional programming effort.

That said, it should be noted that creating the sketching tool was non-trivial. The choice of parameters, their ordering, as well as their mapping to sliders and knobs required prior knowledge of rendering algorithms and an understanding of the constraints they impose on the application. For this reason, the development of the design tool is best left to experienced simulation programmers. However, once the tool has been developed, it is quite possible to involve non-technical people in the sketching process, provided they are presented with a simplified and clearly labelled set of parameters that intuitively relate to what they are seeing on the screen and feeling through the haptic device. In particular, direct expert involvement could enable designers to capture tacit knowledge such as how a bone should feel when drilled. The sketching tool could allow both experts and end-users to evaluate a range of sketches to identify the most desirable ones and further fine-tune sketch parameters interactively. This is a novel concept in the design of haptic applications.

Generalizing the approach

Given the success of applying the sketching approach to the example presented here, there is merit in suggesting that such an approach could be helpful in other haptic application domains.

The steps of choosing a set of parameters, iteratively creating a sketching tool, and generating a set of design sketches can easily be applied to other domains. For example, following the success of the design study presented in this paper, one of the authors proceeded to apply the same approach to the design of a temporal bone surgical simulator. As in our example, a set of suitable application-specific parameters was chosen and linked to the MIDI controller, which enabled the creation of a set of sketches. Preliminary evaluation of these sketches by otolaryngology experts has yielded a highly positive response. Another possible application is haptic sculpting, where the sketching parameters could control the effects of various sculpting gestures.

CONCLUSION

We have introduced the idea of sketching as a means for designing haptic material interaction. The case study presented above illustrates how this approach can be applied successfully to provide unique insight into the design space of a haptic application and empower designers in creating desirable haptic interactions. Our experience in developing the sketching tool and using it to generate sketches was so positive that we have began applying this approach to other haptic projects, such as temporal bone surgical simulation. We see potential in applying the steps followed in this design study to sketch haptic material interaction in a wide range of applications.

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