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INFLUENCE OF INTERACTIVE AUDITORY FEEDBACK ON THE HAPTIC PERCEPTION OF VIRTUAL OBJECTS

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ABSTRACT

In this paper, we investigate how interactive sonification affects the haptic perception of virtual objects. We built a multimodal architecture in which visual and haptic rendering are integrated with a sonic physical model of rubbing and tapping of object surfaces.

Analysis of the test results on audio-haptic perception of virtual textures showed that the test subjects were able to improve their recognition of roughness with the aid of audio cues.

1. INTRODUCTION

Since human perception is based on multimodal processing, the rendering of multimodal haptic and auditory feedback in virtual environments (VE) has the potential to significantly improve the performance, realism and the feeling of presence. Additionally, the ability to combine diverging cues from different modalities to provide a unified percept can potentially compensate for limitations of interface technologies.

Rendering realistic auditory feedback in a virtual environment based on haptic interactions is a rather complex task, because of the tight synchronization needed, and the high degree of interactivity and responsiveness required for the sound models. To overcome these difficulties, we propose to use physically based models. Characteristic for the physical modelling techniques are that they are based on the physical properties of sound generation mechanisms. The advantages of this approach are that it produces high quality sounds, allowing at the same time natural control of the parameters of the models. Another important advantage of this approach is that it is often possible to map velocity and force data directly from the haptic application to the physical model, and thus ensure interactivity and responsiveness.

Multiple projects by Lederman and others have investigated how audition influences the haptic perception of object texture roughness, employing a “Perceptual discrepancy paradigm”, where the percept in one modality is artificially distorted to determine the relative contribution of the modalities on the judgments. As an example, in [2] it is shown that audio can influence the haptic perception of texture, when using a probe for exploration. The results of the investigation suggest that audio cues were weighted with 38% and touch cues by 62%. A previous experiment, however, using finger exploration, showed no effect of audio cues on the haptic perception of texture, which indicates that the availability of cues and experience has an important influence. The audible cues of bare finger sensing are hardly perceivable, and thus often masked by other sounds, while the probe sounds can be quite loud.

In virtual environments, multiple studies have been performed to investigate the effect of sonification on the perceived stiffness of virtual objects.

In [3] subjects were asked to rank the stiffness of equal virtual surfaces based on tapping which was accompanied with various impact sounds. The test showed that subjects ranked the stiffness of the equal surfaces different according to cues of the tap sounds relating to tapping soft or hard surfaces. However, the effect diminished when the subjects were trained in a haptic only condition, or if the haptic stiffness varied.

A similar investigation was performed by Avanzini and Crosato [1], using physical models. In their experiment, subjects rated the stiffness of equal surfaces accompanied by auditory feedback. Consistently with the findings of [3], subjects ranked the surfaces rendered with equal haptic cues according to changes in an elasticity component of the physical model used for synthesizing the impact sounds.

2. AUDIO AND HAPTIC RENDERING

The multimodal rendering architecture used in our experiments consists of two main parts: the haptic and graphical rendering application, and the sound synthesis application.

Figure 1 illustrates the setup and data flow of the auditory and haptic architecture developed in this project.

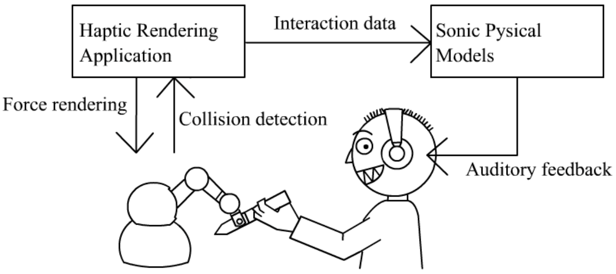

Figure 1. *The Haptic-Auditory Architecture.*

The haptic rendering program is programmed in C++ using the OPENHAPTICS™ Toolkit from Sensable[1] and OpenGL. The sound synthesis is implemented as an “external” plugin programmed for the Max/MSP[2] real time synthesis environment.

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[1] www.sensable.org

[2] www.cycling74.org

The synchronization between the haptic and auditory feedback is very important to ensure that the auditory and haptic feedback is perceived to be caused by the same event. In order to accomplish this tight synchronization we use the Open Sound Protocol (OSC)[3], which is a communication protocol that allows computers, synthesizers and multimedia devices to share performance data in real time over a network. To control the sonification, the position of the cursor, and the force and velocity of impact are sent to the Max/MSP application.

2.1. Audio synthesis of material, size and texture cues

The virtual objects in the application are composed of solid rectangular boxes. The objects can be considered as passive resonators that are excited by the interaction with the stylus of the haptic interface. To synthesize the virtual objects we used modal synthesis.

To simulate the sustained interaction when the user rubs the virtual objects we both modelled the excitation caused by friction and the interactions with the surface asperities of the texture. The frictional interaction is simulated using a dynamic elasto-plastic model that simulates the interaction between rubbed dry surfaces [4]. The model describes the dependence of friction on the relative velocity between two contacting bodies through a differential equation, and is called plastic because it considers the plastic deformation at the contact point. The different levels of texture roughness are created using PhISEM (Physically Informed Stochastic Event Modelling [5], a technique which models a system where the sound is created by random collisions of many objects. The technique is based on pseudo-random overlapping and adding of small grains of sound, controlled by particle models. To create the different levels of surface roughness, the number of particles and the amplitude of the model were adjusted to obtain three levels, corresponding to a smooth, a medium and a rough surface.

2.2. Haptic rendering of object size and texture

To simulate the contact with the virtual objects the haptic device must render the appropriate forces to resist the end-effector/stylus from penetrating the objects surface. The forces to be applied are calculated based on the concept of a proxy which in this case is a point that attempts to follow the tip of the stylus of the haptic interface in the virtual environment. When the stylus penetrates the surface of the virtual object the proxy is prevented from violating the objects surface, and based on the distance between tip and proxy the resisting force to be applied can be calculated using a spring-damper control law. The concept is illustrated in Figure 2 for three different points in time (t_1,t_2,t_3).

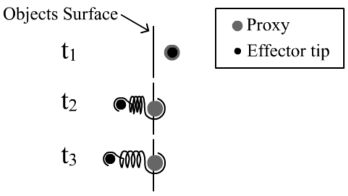

Figure 2. *Resistive force calculation based on proxy.*

The calculation of resistive forces and friction forces are handled by the functionality of the OPENHAPTICS™ Toolkit based on OpenGl primitives. However, the Toolkit doesn't support rendering of different textures needed to simulate the different surface roughness levels needed for the test. Current research proposes different methods to simulate surface roughness based on image based methods and procedural methods The method used in this project is based on a procedural model proposed by Siira and Pai [7]. A pseudo random function with a normal distribution is used to perturb the resistive force in the normal direction of the object surface, when the end-effector moves on the object surface. By changing the variance of the random function it is possible to simulate different levels of roughness. Figure 3 shows an example of the different levels of roughness applied to a constant force.

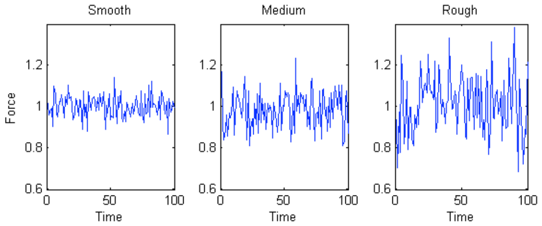

Figure 3. *Resistive force calculation based on proxy.*

3. METHOD

Participants

Twelve test subjects (8 male and 4 female) between the ages of 20 and 30 years old participated in this test. They all reported having normal hearing and being right-handed.

Experimental design

A within-subjects design was used for the experiment.

The purpose of the test was to investigate how haptic and audio/haptic feedback would influence the perceived surface texture in degrees of roughness on a scale from 1 to 7.

Three degrees of surface texture roughness were tested: smooth, medium and rough. Each condition was tested with the correct audio feedback and with the conflicting audio feedback from the two other conditions. This enabled us to observe if conflicting cues affect the perceived texture roughness. The conditions were also tested without auditory feedback to distinguish if audio feedback made a difference in the perception of surface texture.

The different scenarios were tested twice and tested in random order. The test subject also had visual feedback of the virtual object tested. Subjects were instructed to focus on the black screen, as not to unconsciously use visual cues like the distance from his/hers hand to the haptic device. Test subjects were also instructed to rank their confidence in their answer on a scale from 1 to 7, 1 being very unconfident and 7 being very confident.

Procedure

The test subjects were seated in front of the Phantom® Omni™ haptic device, which was placed in front of a 19" screen for visual feedback (see Figure 4). First they were given a brief introduction to the experiment, without being informed about the presence of conflicting audio/haptic cues. After the initial training phase, in which subjects were allowed to practice with the Phantom® Omni™ haptic device in order to get a sense of the device's degrees of freedom and motion, the test started.

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[3] www.opensoundcontrol.org

Figure 4. *The experimental setup with a test subject placed in front of the Phantom® Omni™ haptic device.*

When the test subjects felt comfortable using the Phantom® Omni™ haptic device, they were asked to wear headphones, to provide the auditory feedback and a questionnaire to be filled in after each condition was tested. In all the trials there was no time limit as to how long subjects wanted to test each condition. When the test subject was finished trying the different conditions he/she would nod and we would close the condition just tested, so the test subject could fill in the section of the questionnaire for that specific condition before proceeding to the next condition. This procedure was repeated throughout the experiment. After the test subjects had tried all conditions and answered the sections of the questionnaire belonging to the individual conditions, they were asked whether they thought that auditory feedback was useful or not, on a scale from 1 to 7, 1 being very useless and 7 being very useful.

4. RESULTS

Nine different conditions with audio and three without audio were tested twice.

To compensate for the test subject's individual differences in the numerical scales used, the results were normalized by dividing each score by the individual participant mean, then multiplying by the grand mean.

The analysis of the results in the second part showed that in the conditions with a smooth surface texture with and without auditory feedback, the test subjects perceived the smooth surface texture of the virtual object, as being smoother in the condition where they had haptic and audio feedback compared to the condition with only haptic feedback.

The normalized mean of all the test subjects was 2,10 in the condition with haptic/audio cues and 2,38 with haptic cues on a scale from 1 to 7 The normalized means for the two conditions are graphically illustrated with boxplots in Figure 5, where the bold horizontal line represents the median (Q_2), the vertical line the minimum and maximum values and the top of the box the upper quartile (Q_3) and the bottom of the box the lower quartile (Q_1). As can be seen in the boxplots in Figure 5, the median and lower quartile have lower values (one being the smoothest) in the condition with audio.

The t-test was conducted, which showed that the results were statistically significant ($p<0.05$).

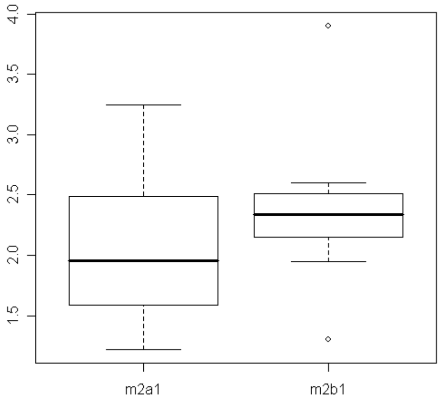

Figure 5. *Boxplots of perceived surface texture roughness. Condition m2a1 is a smooth surface with audio and condition m2b1 is a smooth surface without audio.*

In the conditions with a medium surface with and without auditory feedback the test subjects normalized mean was 3,76 with audio cues and 3,93 without audio cues. The mean, median, upper and lower quartiles are closer to the middle of the scale (3,5) in the boxplot with audio cues compared to the condition without audio cues (see Figure 6).

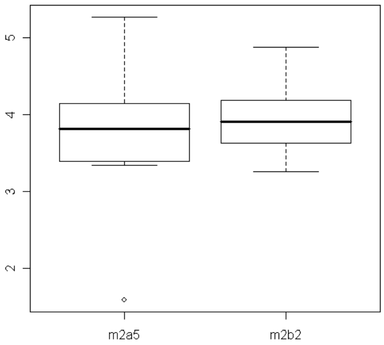

Figure 6. *Boxplots of perceived surface texture roughness. Condition m2a5 is a medium surface with audio and condition m2b2 is a medium surface without audio.*

When comparing the conditions with a rough surface texture with and without audio cues, the results showed that only 4 out of the 12 test subjects perceived the condition with audio cues to have a rougher surface then the ones without audio cues. The normalized mean with audio cues was 5,26 and 5,40 without audio cues. As can be seen in Figure 7, the median and lower quartile is perceived as rougher in the condition without audio cues, but the upper quartile has a higher value in condition with audio cues.

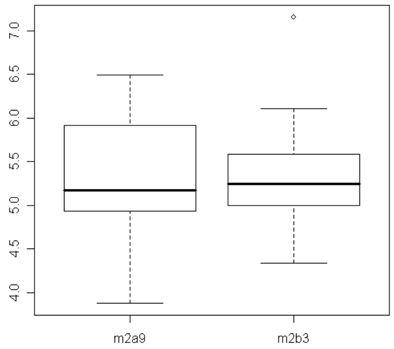

Figure. 7. *Boxplots of perceived surface texture roughness. Condition m2a9 is a rough surface with audio and condition m2b3 is a rough surface without audio.*

Exploratory technique adopted by the test subjects in the second part was primarily the rubbing of the surface texture technique. However, some of the test subjects rubbed very hard, which will increase the Phantom® Omni™ haptic device's Haptic feedback. This makes it harder to detect the surface textures roughness.

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5. CONCLUSIONS

Results show how auditory feedback improves the test subjects' ability to perceive the accurate degrees of roughness. The conditions with audio cues were scaled more accurately than the conditions without audio cues. Furthermore the conditions with the same haptic feedback, but different auditory feedback were influenced by the audio cues and perceived as being smoother or rougher depending on the conflicting haptic/audio cues.

Observations of the test subjects during the experiments and analysis of the positional data showed that most of the test subjects only rubbed the surface of the virtual object to determine the texture roughness. A few rubbed very hard, which makes it more difficult for the perception of the different degrees of roughness.

6. REFERENCES

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