AUDIO-HAPTIC PHYSICALLY BASED SIMULATION AND PERCEPTION OF CONTACT TEXTURES

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ABSTRACT

We propose a multimodal architecture in which audio and haptic textures are simulated in real-time using physical models. Experiments evaluating audio-haptic interaction in textures perception show that auditory cues significantly influence the haptic perception of virtual textures.

[Keywords: physical models, audio-haptic interaction]

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.

While many everyday tasks can be performed using touch alone, it is more common for multiple sensory modalities (i.e., vision, hearing, etc.) to be used. However, relatively little research has investigated the specific contribution of each modality to task performances. The present study explores the impact of multisensory feedback on the perception of surface roughness. The specific question addressed is whether appropriate auditory feedback, when presented together with haptic feedback, can alter the perception of virtual surface texture.

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 can produce 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.

Several projects by Klatzky, Lederman and colleagues have investigated texture perception, and how visual and auditory cues affect it [1, 2, 3]. Their approach employs 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 [4], it is shown that auditory feedback can influence the haptic perception of texture, when using a probe for exploration. Participants used both tactual and auditory information to make their judgments when exploring the surfaces with a rigid probe. In this case, touch cues contributed 62% and auditory cues 38% to the bimodal judgments, a considerably different result from the 100% touch dominance found in the study described in [1]. This difference is largely due to the use of the rigid probe as opposed to the bare fingers for auditory exploration of surface texture. Since the sounds generated by bare fingers on a rigid surface are considerably less loud than those created by a rigid probe on a rigid surface, those softer sounds may be ignored completely [4].

Other investigations by DiFranco and colleagues examined how auditory cues affect the haptic perception of stiffness [5]. In their experiments, the authors used recorded impact sounds of surfaces with different stiffness level. In these experiments the subjects utilized a Phantom haptic device by Sensable.[1] As subjects tapped on different virtual surfaces, they were presented with different impact sounds. Subjects were asked to rank the surfaces according to their perceived stiffness. Results show that when the physical stiffness of the surfaces were the same, subjects ranked surfaces according to the sound. Recently, the same experiments have been repeated using physical models of impact sounds [6].

Investigations on multimodal perception of virtual roughness using synthesized sinewaves were recently performed in [7]. Results show that auditory feedback affects the haptic perception of virtual textures.

In this paper, we are interested in achieving a better understanding of the relationship between auditory and haptic textures simulated by using physical models. To achieve this goal, we built a multimodal architecture described in the following section.

2. RENDERING OF AUDIO-HAPTIC TEXTURES

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. The haptic rendering is programmed in C++ using the Openhaptics Toolkit from Sensable[2] and OpenGL. The sound synthesis is implemented as an external plugin programmed for the Max/MSP[3] real time synthesis environment.

The synchronization between the haptic and auditory feedback is very important to ensure that the auditory and haptic feedback

[1] www.sensable.org
[2] www.sensable.org
[3] www.cycling74.com

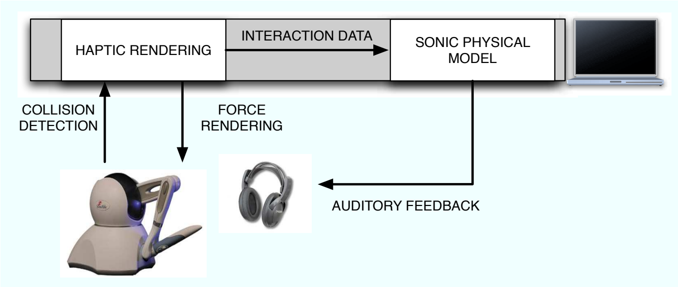

Figure 1: *A multimodal audio-haptic architecture.*

is perceived to be caused by the same event. In order to accomplish this tight synchronization we use the Open Sound Protocol (OSC)[4], 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. Simulation of auditory textures

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. Our interaction model is decomposed as following:

$$f = f_f + f_t$$

where f_f represents the deterministic friction force while f_t represents the dynamic texture simulation.

The frictional interaction is simulated using a dynamic elastoplastic model that simulates the interaction between rubbed dry surfaces [8]. This model, originally used in robotics, was recently adapted for sound synthesis purposes [9].

The model describes the dependence of friction on the relative velocity between two contacting bodies through a differential equation rather than static mapping, as commonly done by traditional friction models. The model assumes that friction results from a large number of microscopic elastic bonds called bristles, in which case the velocity force relationship is expressed as:

$$f(z, \dot{z}) = \sigma_0 z + \sigma_1 \dot{z} + \sigma_2 v$$

where z represents the average bristle deflection, σ_0 is the bristle stiffness, σ_1 the bristle damping and $\sigma_2 v$ accounts for viscous friction.

The different levels of texture roughness are created using the algorithm proposed in [10]. The same algorithm is used to simulate both auditory and haptic textures.

2.2. Simulation of haptic textures

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).

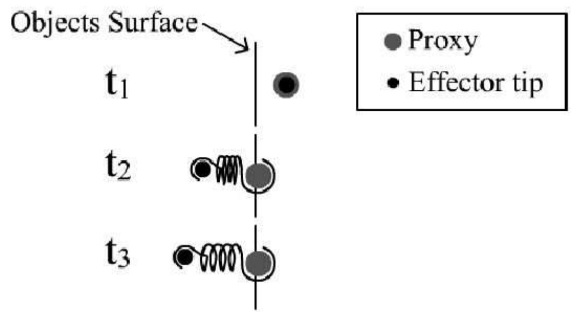

Figure 2: *Resistive force calculation based on proxy.*

The calculation of resistive forces and friction forces are handled by the functionality of the Openhaptics Toolkit based on OpenGL primitives. However, the Toolkit does not support rendering of different textures needed to simulate the different surface roughness levels needed for the investigation. Current research proposes different methods to simulate surface roughness based on image based methods and procedural methods. The method used in this paper is based on a procedural model proposed in [10]. A pseudorandom 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.

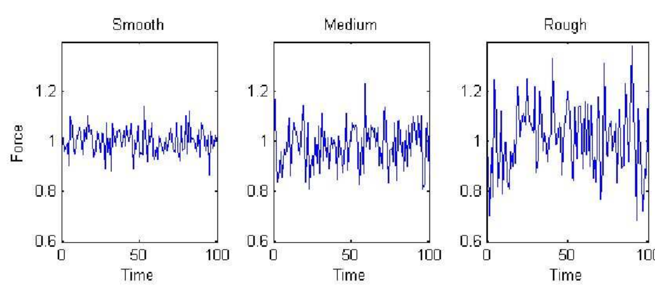

Figure 3: *Different levels of roughness simulation. Left: a smooth surface; center: a medium surface; right: a rough surface.*

3. EXPERIMENT DESIGN

3.1. 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.

[4] www.opensoundcontrol.org

3.2. Method

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 her 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.

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

3.3. Procedure

The test subjects were seated in front of the Phantom Omni haptic device, which was placed in front of a 19 inches 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 devices degrees of freedom and motion, the test started.

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.

The questionnaire asked to judge the surface texture in a scale from 1 to 7, where 1 was very smooth and 7 very rough. Subjects were not informed on how the virtual haptic and auditory surfaces were varied.

The test was divided in two parts. In the first part subjects were asked to judge surfaces' roughness with and without auditory feedback. In the second part they were asked to judge surfaces' roughness, with conflicting auditory and haptic cues. Subjects were not aware of the presence of conflicting cues.

In all the trials there was no time limit as to how long subjects wanted to test each condition. When the test subjects were finished trying the different conditions they would nod and the condition just tested was closed, 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 not useful and 7 being very useful.

4. RESULTS

4.1. Influence of auditory feedback

Three different conditions, with and without auditory feedback, were tested twice. To compensate for the test subjects' 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 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 (Q2), the vertical line the minimum and maximum values and the top of the box the upper quartile (Q3) and the bottom of the box the lower quartile (Q1). 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 ($p < 0.05$). 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).

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 are perceived as rougher in the condition without audio cues, but the upper quartile has a higher value in condition with audio cues.

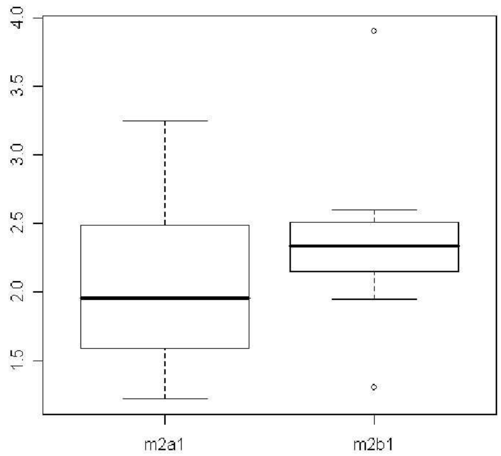

Figure 5: *m2a1 represents a smooth surface with audio and condition m2b1 is a smooth surface without audio. Notice how auditory feedback influences the perception of surface's roughness.*

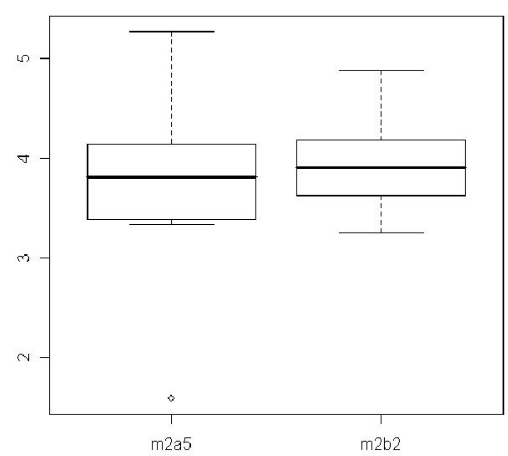

Figure 6: *Boxplots of perceived surface texture roughness. Condition m2a5 is a medium surface with audio and condition m2b2 is a medium surface without audio.*

4.2. Perception of conflicting cues

In the second part of the experiment the test subjects were asked to rank conditions with conflicting haptic and audio cues. This was done to see how the different audio cues would affect the perception of the surface texture with the same haptic feedback. In this second part, 9 conditions (3 auditory x 3 haptics) were tested. The analysis showed that the conditions with smooth audio cues was perceived as having a smoother haptic surface then the other conditions in the three groups with the same haptic feedback, as can be seen in Figure 8. The conditions with rough audio cues also have higher values than the conditions with smooth or medium audio cues, although they have the same haptic feedback.

In the three groups of conditions with the same haptic feedback, the mean, median, upper and lower quartiles have higher values when the audio cues are changed from smooth to medium and medium to rough. The level of confidence is lower in the conditions with conflicting audio and haptic cues compared to the condition with the correct audio cues.

5. CONCLUSIONS

In this paper, we proposed a multimodal architecture in which auditory and haptic cues are simulated using physical models. Audio and haptic cues were simulated designing a physical models of rubbed surfaces, with a stochastic texture model modeled using a pseudo-random function with a normal distribution.

Results concerning the investigation on the interaction between auditory and haptic cues on the perception of virtual textures show how auditory feedback improves the ability of the test subjects 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.

Overall the test subjects did not notice any delay while interacting with the architecture, and became quickly adjusted in using the system.

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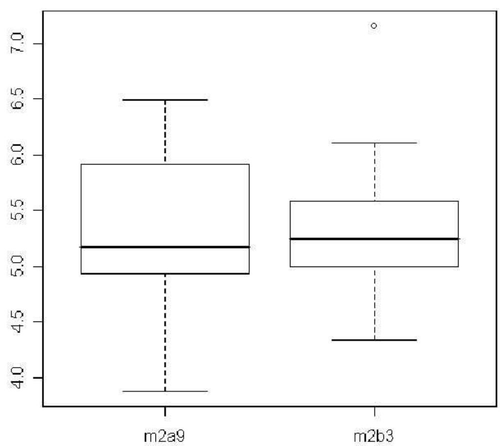

Figure 7: *Boxplots of perceived surface texture roughness. Condition m2a9 is a rough surface with audio and condition m2b3 is a rough surface without audio.*

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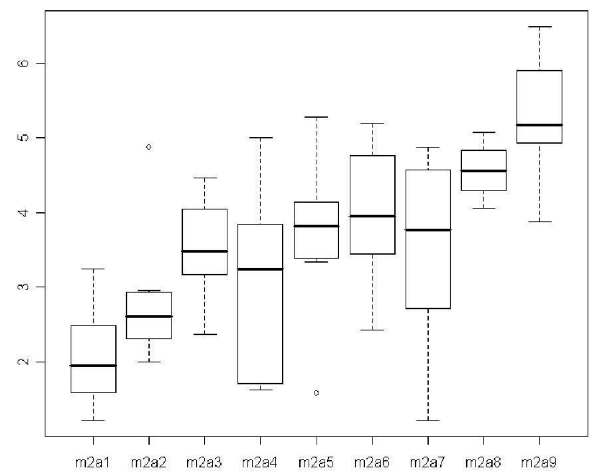

Figure 8: *Boxplots of perceived surface texture roughness with conflicting cues. Conditions m2a1, m2a2 and m2a3 have smooth haptic feedback. Conditions m2a4, m2a5 and m2a6 have medium haptic feedback and m2a7, m2a8 and m2a9 have rough haptic feedback. The first condition in each scenario has smooth audio feedback, the second medium and the third rough.*