



Technische Universität München

Chair of Media Technology

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Bachelor Thesis

Refined Methods for Creating Realistic Haptic Virtual
Textures from Recorded Acceleration Data

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Abstract

Several decades of research have been dedicated to the representation of real interactions in virtual or remote environments. Haptic interfaces give the possibility to touch virtual objects and to produce sensations during texture exploration by sliding a hand-held tool across a textured surface. This process elicits perceptual information about the properties of a texture based on the data recorded from real interactions. This thesis describes mathematical models for synthesizing acceleration signals at different velocities of a user during the surface exploration. These acceleration signals are then used for producing audio data to present microscopic roughness of a texture. The application of Linear Predictive Coding (LPC) is shown for interpolating between signals. Furthermore, computing recorded signals' major frequencies to predict acceleration data is introduced as another possible method for switching between audio recordings when the user's scanning speed changes. For both cases, high correlations are obtained between the predicted and recorded data without creating perceptually noticeable artifacts.

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Chapter 1

Introduction

Varying one's scanning speed and normal force, and normal force alters these vibrations, but it does not change the perceived identity of the tool or the surface. Previous research de-

This thesis aims to evaluate the prediction results obtained from mathematical models, namely LPC and major frequency analysis to be able to perform realistic audio signals

Chapter 2

Microscopic Roughness

girizgah

To provide a more efficient and robust method of building haptic texture models from tool-surface interaction data...

2.1 Methods for Interpolating Audio Signals

Interpolate audio signals for different velocities.

There are methods: lpc and major frequency.

2.1.1 Linear Predictive Coding

The basic idea of Linear Predictive Coding (LPC) is to develop a transfer function that can predict each sample of a signal as a linear combination of the previous samples. It has applications in filter design and speech coding.

We consider an IIR filter $H(z)$ of length n in the form $H(z) = [-h_1z^{-2} - h_2z^{-1} \dots - h_nz^{-n}]$. Our acceleration data vector from PCA is called $\vec{a}(k)$ in the following. The resulting prediction vector from our filter is $\vec{\hat{a}}(k)$. The residual signal $\vec{e}(k)$ is the difference between these two signals. The transfer function $P(z)$ is the result of the following equation:

$$\frac{\vec{e}(k)}{\vec{a}(k)} = 1 - H(z) = P(z) \quad (2.1)$$

It is possible to compute the residual at each step using the vector of filter coefficients $\vec{h} = [h_1 h_2 h_3 \dots h_n]^T$:

$$\vec{e}(k) = a(k) - \hat{a}(k) = a(k) - \vec{h}^T \vec{a}(k-1) \quad (2.2)$$

At this step, we aim to find the minimum value of the residual function $e(k)$. We are able to reduce the problem to Wiener-Hopf equation by a cost function based on mean-square error. The Wiener-Hopf equation can be solved by Levinson-Durbin [Dur60] algorithm, so that we can obtain our optimal filter vector \vec{h}_0 .

To synthesize new signals, we use a white noise signal $\vec{e}_g(l)$ as input, which is filtered with $1/P(z)$, in order to generate our desired response $\vec{a}_g(l)$. For a better overview, we can rewrite the equations (2.1) and (2.2) as follows:

$$\frac{\vec{a}_g(l)}{\vec{e}_g(l)} = \frac{1}{1 - H(z)} = \frac{1}{P(z)} \quad (2.3)$$

$$a_g(l) = e_g(l) + \vec{h}^T \vec{a}_g(l-1) \quad (2.4)$$

The value $\vec{e}_g(l)$ is a randomly generated Gaussian white noise but its average signal power must be equal to that of the average signal power remaining in the residual, $P\{\vec{e}(k)\}$ after filter optimization.

The definition of power is as in the following equation:

$$P\{\vec{a}(l)\} = \frac{1}{N} \sum_{n=0}^{N-1} |a(n)|^2 \quad (2.5)$$

This is equivalent to signal variance σ^2 , because our signals are zero-mean signals. Now, we have to determine the order of our prediction filter, which affect the accuracy of the prediction. The higher we choose the order, the smaller the residual gets. It means we have a better prediction with higher orders, but then the calculation gets more complicated. It is possible to calculate the success of the synthetic result with a cost function defined as the RMS error as follows [JMRK10]:

$$C\{\vec{a}_g(l)\} = \frac{RMS(DFT_s\{\vec{a}(l)\} - DFT_s\{\vec{\hat{a}}_g(l)\})}{RMS(DFT_s\{\vec{a}(l)\})} \quad (2.6)$$

Using this equation, where $DFT_s\{\vec{a}\}$ represents the discrete Fourier transform of vector \vec{a} , it is possible to obtain the optimal order of the filter. In our case we choose $length(\vec{a}(l)) - 1$ as the order for the best quality of results.

Now that we have generated our prediction filter with two unique variables \vec{h} vector and $e_g(l)$, it comes to interpolate between our synthesized signals to create new signals. Bilinear interpolation of both the vector \vec{h} and $e_g(l)$ of two signals in different velocities and applying

these new values to our prediction filter result in new synthesized signals, so that we create signal data for audio signals at different force and velocities.

2.1.2 Signal Generation from Major Frequencies

The other method for signal generation is using rich and valuable information of signals' high frequencies. The frequency of the vibration must change as the users change their force and so that their velocity. This is one of the realistic methods for interpolation between signals recorded under different velocities.

At first we determine the number of the frequencies we are going to deal with for synthesizing new signals. This is done in a similar way to order selection of a prediction filter in the previous section. For our case we choose 10 for the optimum frequency value.

In order to find the major frequencies, we calculate the discrete Fourier transform of the two recorded data and find ten highest amplitudes of the transformed signals. It is important here to ensure that selected frequencies should not be close to each other because the superposition of two pure tones with slightly different frequencies can lead to beats. Therefore we remove frequencies among selected ones with a difference less than 5 and choose new others under this condition.

We synthesize from the highest ten amplitudes and their phases a new signal according to the following equation:

$$z = z + \max A(k) * (\cos(2 * \pi * t * \max F(k) + \max P(k)) + i * \sin(2 * \pi * t * \max F(k) + \max P(k))) \quad (2.7)$$

where $\max A(k)$ represents the amplitude of selected frequencies and $\max F(k)$ the place order of them, $\max P(k)$ represents the phase of selected frequencies and z is zero at the beginning and

— Human-user studies form an integral part of the evaluation of haptic virtual systems. However, the drawback of these approaches is that they are tedious, time consuming and highly expensive.

We explain how to apply the mathematical principles of Linear Predictive Coding (LPC) to develop a discrete transfer function that represents the acceleration response under specific probe-surface interaction conditions. We then use this predictive transfer function to generate unique acceleration signals of arbitrary length. In order to move between transfer functions from different probe-surface interaction conditions, we develop a method for interpolating the variables involved in the texture synthesis process. Finally, we compare the results of this process with real recorded acceleration signals, and we show that the two correlate strongly in the frequency domain.

Dragging a tool across a textured surface produces vibrations that convey important perceptual information about the interaction and the underlying qualities of the surface. These vibrations depend on the motions of the tool and respond to both normal force and tangential speed. This paper explores various methods of simulating haptic texture interactions by rendering tool vibrations that are based on recorded data. We designed and ran a human-subject study (N=15) to analyze the importance of creating virtual texture vibrations that respond to user force and speed. Our analysis of data from fifteen textures showed that removing speed responsiveness did cause a statistically significant decrease in perceived realism, but removing force responsiveness did not. This result indicates that virtual textures aiming to simulate real surfaces should vary the rendered vibrations with user speed but may not need to vary them with user force. that represents the acceleration response under specific probe- surface interaction conditions. We then use this predictive

2.2 Beispiel für eine Abbildung



Figure 2.1: Beispiel für eine Beschriftung.

$$mRG = \beta \cdot \sum_{k=1}^K \sum_{l=1}^L \hat{\mathbf{X}}(k, l) \quad (2.8)$$

Durch die `\label` kann auf die Bilder mit `\ref` verwiesen werden (z.B. Abbildung 2.1).

2.3 Beispiele für Referenzen

Die Literaturhinweise werden im Text z.B. folgendermaßen verwendet:

“..., wie in gezeigt, ...” oder “... es gibt mehrere Ansätze [Arn99, GLL90] ...”

2.4 Schrifttypen

Als Schrifttyp wird Arial oder Roman empfohlen. Bitte beachten, daß Größen und Einheiten eine eigene Schreibweise haben:

Kursivschrift: physikalische Größen (z.B. U für Spannung), Variablen (z.B. x), sowie Funktions- und Operatorzeichen, deren Bedeutung frei gewählt werden kann (z.B. $f(x)$)

Steilschrift: Einheiten und ihre Vorsätze (z.B. kg, pF), Zahlen, Funktions- und Operatorzeichen mit feststehender Bedeutung (z.B. sin, lg)

2.5 Archivierung

Für die Archivierung sind alle Dateien der Arbeit (auch der Vorträge) dem Betreuer zur Verfügung zu stellen. Weiterhin soll noch ein BibT_EX-Eintrag der Arbeit erstellt werden (die Felder in eckigen Klammern sind dabei auszufüllen):

```
@MastersThesis{<Nachname des Autors><Jahr>,  
  type =      {<Art der Arbeit>},  
  title =     {{<Thema der Arbeit>}},  
  school =    {Institute of Communication Networks~(LKN),  
              Munich University of Technology~(TUM)},  
  author =    {<Nachname des Autors>, <Vorname des Autors>},  
  annote =    {<Nachname des Betreuers>, <Vorname des Betreuers>},  
  month =     {<Monat>},  
  year =      {<Jahr>},  
  key =       {<Mehrere Suchschlüssel>}  
}
```

Chapter 3

Zusammenfassung

Am Schluß werden noch einmal alle wesentlichen Ergebnisse zusammengefaßt. Hier können auch gemachte Erfahrungen beschrieben werden. Am Ende der Zusammenfassung kann auch ein Ausblick folgen, der die zukünftige Entwicklung der behandelten Thematik aus der Sicht des Autors darstellt.

Appendix A

Ein Beispiel für einen Anhang

Beispiel für eine Tabelle:

Table A.1: Beispiel für eine Beschriftung. Tabellenbeschriftungen sind üblicherweise über der Tabelle platziert.

left	center	right
entry	entry	entry
entry	entry	entry
entry	entry	entry

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