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Bachelor Thesis

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

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With my signature below, I assert that the work in this thesis has been composed by myself independently and no source materials or aids other than those mentioned in the thesis have been used.

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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.

Contents

Chapter 1

Introduction

Scanning a textured surface with a tool generates rich high-frequency signals that demonstrate mainly microscopic roughness of a surface. These captured vibrations are called vibrotactile or acceleration signals which is considered synonymous as in [SHNS18]. To achieve full distal attribution, sensed vibrations must correspond to the user inputs in a physically appropriate manner [Loo92].

A reasonable idea is that varying one's exploratory speed and normal force must significantly alter the realism. However, studies (e.g. [CK15]) show that removing force responsiveness does not have a significant effect on the perceived realism, whereas removing speed responsiveness is more salient to users. Therefore, vibration signals in this thesis include speed responsiveness and not force responsiveness.

Allowing texture vibrations to respond to user speed is a valuable part of creating realistic haptic textures, nonetheless can be a challenging and time consuming part of the implementation, if real recorded acceleration signals are displayed for every speed level. Some research [JMRK10] elucidate mathematical models as an alternative solution for representing a vibration texture under specific probe-surface interaction conditions.

This thesis has fine texture features as its center of focus and aims to evaluate the prediction results obtained from mathematical models, namely LPC and major frequency analysis to be able to display realistic vibrations at different speed levels through interpolated audio signals.

Chapter 2

Haptic texture rendering

The human haptic perception system relies on kinesthetic and cutaneous sensory information provided by several receptors during probe-surface interactions [LK09].

The kinesthetic sense focuses on the perception of forces and torques acting on the human body. Kinesthetic stimulation is sensed by mechanoreceptors located in the muscles. Kinesthetic mechanoreceptors include muscle spindles in parallel with muscle fibers and Golgi tendon organs in series with them at the connection with the skeleton [Cha15]. In some mainly kinesthetic tasks, the tactile sense only indicates a contact.

Tactile perception is stimulated by cutaneous receptors. There are four kinds of mechanoreceptors in the glabrous skin: The Merkel cells (Braille dots and sharp edges), Meissner corpuscles (low-frequency vibrations), Pacinian corpuscles (high frequency stimuli), Ruffini endings (still unknown).

Friction, hardness, macroscopic roughness, microscopic roughness and thermal conductivity are the main dimensions to build haptic texture models. All of these aspects should be well considered in order to increase immersion into a virtual environment. In the following of this thesis, microscopic roughness is our main focus as a vibrotactile feature.

2.1 Roughness

As an abstract feature roughness plays an important role in haptic signal perception.The roughness dimension may be divided into two dimensions: macro and fine (micro) roughness as in [SOY13].

2.1.1 Macroscopic Roughness

Due to the duplex nature of roughness, macroscopic roughness should strictly be considered in order to understand fine roughness. Coarse roughness is mainly represented by the "uneven", "relief", or "voluminous" labels and mediated by different mechanisms from micro roughness. For coarse surface roughness, the spatial distribution of SAI units is related to roughness perception [SOY13].

2.1.2 Fine Roughness

In the mechanism of fine roughness perception, FAI and FAII units contribute and is mainly represented by the "rough" label. During surface-tool or surface-finger sliding motions, high frequency vibrations can be extracted using an accelerometer mounted on a human finger. Microscopic roughness impressions can be characterized by these vibrations. The macro and fine roughness dimensions can be separated according to the mentioned aspects but can intersect each other during the process of perception. Figure 2.1 illustrates the process of texture production with an accelerometer.

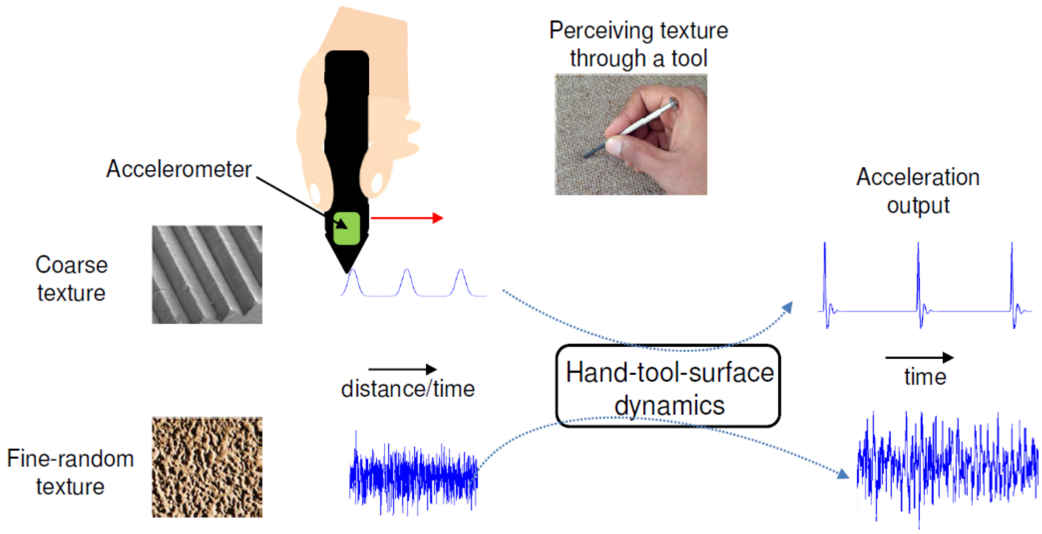

Figure 2.1: Mechanism of texture production. A hand-held tool is used to stroke a textured surface. An acceleration sensor signal mounted on the tool measures the response of the hand-tool system as it hits surface features. Figure reproduced from [Cha15]

The recorded acceleration signals depend on the scan speed and force, nonetheless we ignore the force dependencies as mentioned in the introduction part. Thereby, our approach in this thesis is generating vibrotactile signals based on the recorded acceleration data for different absolute scan speed. They are then displayed via a voice coil actuator.

Chapter 3

Interpolation of vibrotactile signals

Priori model designs have recently been evolved into data-driven haptic textures. The apparent concept is simply displaying recorded texture acceleration signals, where the exploratory speed dependency is disregarded. However, this is not a sufficient way of representing acceleration response. Therefore, user speed should be incorporated into the feedback signal.

One way of

[CRC+12] Interpolate audio signals for different velocities.

There are methods: lpc and major frequency.

3.1 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 $H(z) = [-h_1 z^{-2} - h_2 z^{-1} ... - h_n z^{-n}]$. 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:

$$\frac{\vec{e}(k)}{\vec{a}(k)} = 1 - H(z) = P(z) \tag{3.1}$$

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

$$\vec{e}(k) = a(k) - \hat{a}(k) = a(k) - \vec{h}^T \vec{a}(k-1) \tag{3.2}$$

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 (3.1) and (3.2) as follows:

$$\frac{\vec{a_g}(l)}{\vec{e_g}(l)} = \frac{1}{1 - H(z)} = \frac{1}{P(z)} \tag{3.3}$$

$$a_g(l) = e_g(l) + \vec{h}^T \vec{a_g}(l-1) \tag{3.4}$$

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:

$$P\{\vec{a}(l)\} = \frac{1}{N} \sum_{n=0}^{N-1} |a(n)|^2 \tag{3.5}$$

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]:

$$C\{\vec{a_g}(l)\} = \frac{RMS(DFT_s\{\vec{a}(l)\} - DFT_s\{\vec{a_g}(l)\})}{RMS(DFT_s\{\vec{a}(l)\}} \tag{3.6}$$

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.

3.2 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:

$$z = z + maxA(k) * (cos(2 * \pi * t * maxF(k) + maxP(k)) + i * sin(2 * \pi * t * maxF(k) + maxP(k))) \tag{3.7}$$

where $maxA(k)$ represents the amplitude of selected frequencies and $maxF(k)$ the place order of them, $maxP(k)$ represents the phase of selected frequencies and z is zero at the beginning and

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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.

statistically significant decrease in realism this study elucidated the conditions necessary to create realistic haptic textures. a process of synthesizing probe-surface interactions from data recorded from real interactions. via automated analysis of real recorded data. While haptic feedback is known to increase the immersion into a virtual environment (VE), most haptic feedback devices lack the ability to display multidimensional tactile impressions. To provide a more efficient and robust method of building haptic texture models from tool-surface interaction data...

The perception of displayed haptic information typically varies across different human subjects [7]. Experiments with human participants are thus an integral part of the research in haptics. In our case, the tactile properties of the real and the artificially displayed surface materials for individual subjects need to be compared and evaluated.

$$mRG = \beta \cdot \sum_{k=1}^{K} \sum_{l=1}^{L} \hat{\mathbf{X}}(k, l) \tag{3.8}$$

Durch die `\label` kann auf die Bilder mit `\ref` verwiesen werden.

3.3 Beispiele für Referenzen

Die Literaturhinweise werden im Text z.B. folgendermaßen verwendet:
"..., wie in gezeigt, ..." oder "... es gibt mehrere Ansätze [Arn99, GLL90] ..."

3.4 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)

3.5 Archivierung

Für die Archivierung sind alle Dateien der Arbeit (auch der Vorträge) dem Betreuer zur Verfügung zu stellen. Weiterhin soll noch ein BibTeX-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 4

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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