Sound Synthesis Based on Physical Models

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CIRMMT Distinguished Lecture
McGill University

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Overview

Early Ideas

Physical Modeling

Recent CCRMA Work

Acoustic Guitar Models

Haptic Instruments

Harpsichord Models

Microphone Array

ASLP Special Issue

Summary
Outline

- Early Ideas
- Physical Modeling Synthesis and Effects
- Recent Work at CCRMA
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- Early Ideas
- Physical Modeling Synthesis and Effects
- Recent Work at CCRMA

Emphasis:

- Sound examples
- Block diagrams
- Historical notes
The Knoll, Stanford University
Early Ideas
Daniel Bernoulli (1733): Physical vibrations can be understood as a superposition of “simple modes” (pure sinusoidal vibrations):

\[ y(t, x) = \sum_{k=0}^{\infty} A_k \sin\left(\frac{k\pi x}{L}\right) \cos\left(k\pi \nu t\right) \]

(displacement of length \( L \) vibrating string at time \( t \), position \( x \))

D’Alembert (1747): String vibration can be understood as a pair of traveling-waves going in opposite directions at speed \( c \):

\[ y(t, x) = y^+ \left( t - \frac{x}{c} \right) + y^- \left( t + \frac{x}{c} \right) \]
D’Alembert’s Derivation

D’Alembert’s derivation (1747) consisted of plugging Taylor’s restoring force $Ky''$ for the vibrating string into Newton’s law of motion “$f = ma$” to obtain the first partial differential equation

$$K \frac{\partial^2 y}{\partial x^2} = \epsilon \frac{\partial^2 y}{\partial t^2}$$

(in modern notation), where

$$K = \text{string tension}, \quad \epsilon = \text{string mass density}.$$ 

D’Alembert also derived the general solution as a superposition of two traveling waves:

$$y(t, x) = y^+(t - \frac{x}{c}) + y^-(t + \frac{x}{c}), \quad c = \sqrt{\frac{K}{\epsilon}}$$
Mathematical Paradoxes

Reasonable question of the day:

How can a superposition of standing waves give you a propagating wave?

\[ y(t, x) = \sum_{k=0}^{\infty} A_k \sin\left(\frac{k\pi x}{L}\right) \cos(k\pi vt) \]

Another reasonable question of the day:

How can an infinite sum of sinusoids give an arbitrary (e.g., discontinuous) function?
Euler, d’Alembert, and Lagrange agreed that tonal sound was a periodic pulse train (pulse shape noncritical)

- Musical consonance = “pulse coincidence”

- Pipe organs did a kind of “additive synthesis” by mixing non-sinusoidal periodic waveforms (reeds, flue pipes, etc.)

- Sums of sinusoids had no physical meaning in their opinion
Bernoulli, on the other hand, understood sound as a superposition of sinusoidal motions with separate physical existence.

- D’Alembert thought this was impossible due to “intermodulation” (This remains a valid criticism of loudspeakers today)
- Helmholtz (1863) established much later that the ear was a kind of Fourier analyzer (so evolution agreed with Bernoulli)

**Reference:** Darrigol:

“The Acoustic Origins of Harmonic Analysis”

*Archive for History of the Exact Sciences, 2007*
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Sound According to Bernoulli

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Bernoulli’s and D’Alembert’s Contradictory Views

- Bernoulli saw a superposition of harmonic vibrations
- D’Alembert saw traveling waves
- We now know these are interchangeable descriptions!
  - Project initial state onto standing-wave “basis functions”
  - Standing-wave = sum of opposite-going traveling waves
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Animations:
- [Standing waves on a string]
- [Standing wave as two traveling waves]
Digital D’Alembert Synthesis
Kelly-Lochbaum Vocal Tract Model
(Discrete-Time Transmission-Line Model)

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Recent CCRMA Work

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Microphone Array

John L. Kelly and Carol Lochbaum (1962)
“Bicycle Built for Two”: (WAV) (MP3)

- Vocal part by Kelly and Lochbaum (1961)
Sound Example

“Bicycle Built for Two”: (WAV) (MP3)

- Vocal part by Kelly and Lochbaum (1961)
- Musical accompaniment by Max Mathews
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- Musical accompaniment by Max Mathews
- Computed on an IBM 704
- Based on Russian speech-vowel data from Gunnar Fant’s book
- Probably the first digital physical-modeling synthesis sound example by any method
- Inspired Arthur C. Clarke to adapt it for “2001: A Space Odyssey” — the computer’s “first song”
Digital Waveguide Models (1985)

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**Lossless digital waveguide** $\triangleq$ **bidirectional delay line** at some **wave impedance** $R$

$z^{-N}$

Useful for *efficient* models of

- strings
- bores
- plane waves
- conical waves
Signal scattering is caused by a change in wave impedance $R$:

$$k_1 = \frac{R_2 - R_1}{R_2 + R_1}$$

If the wave impedance changes every spatial sample, the Kelly-Lochbaum vocal-tract model results (also need reflecting terminations)
**Ideal Plucked String (Displacement Waves)**

- Load each delay line with \textit{half} of initial string displacement
- Sum of upper and lower delay lines = string displacement
Hammer strike = momentum transfer = velocity step:

\[ m_h v_h(0^-) = (m_h + m_s)v_s(0^+) \]
Karplus-Strong (KS) Algorithm (1983)

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**Recent CCRMA Work**

- Acoustic Guitar Models
- Haptic Instruments
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**Discovered (1978) as “self-modifying wavetable synthesis”**

- Wavetable is preferably initialized with random numbers

**Mathematical Representation**

\[ y(n) = \frac{1}{2} y(n-N) + \frac{1}{2} \]

\[ y(n) = y(n-N) + z^{-1} \]

\[ y(n) = \frac{1}{2} y(n-N) + \frac{1}{2} \]

Output \( y(n) \) is delayed by \( N \) samples and fed back to the input with a gain of \( \frac{1}{2} \).
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EKS Algorithm (Jaffe-Smith 1983)

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Haptic Controls

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Haptic Controls

\[ H_p(z) = \frac{1 - p}{1 - p z^{-1}} = \text{pick-direction lowpass filter} \]

\[ H_\beta(z) = 1 - z^{-\beta N} = \text{pick-position comb filter, } \beta \in (0, 1) \]

\[ H_d(z) = \text{string-damping filter (one/two poles/zeros typical)} \]

\[ H_s(z) = \text{string-stiffness allpass filter (several poles and zeros)} \]

\[ H_\rho(z) = \frac{\rho(N) - z^{-1}}{1 - \rho(N) z^{-1}} = \text{first-order string-tuning allpass filter} \]

\[ H_L(z) = \frac{1 - R_L}{1 - R_L z^{-1}} = \text{dynamic-level lowpass filter} \]
EKS Sound Examples

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Haptic Instruments

Plucked String: (WAV) (MP3)

- Plucked String 1: (WAV) (MP3)
- Plucked String 2: (WAV) (MP3)
- Plucked String 3: (WAV) (MP3)

(Computed using Plucked.cpp in the C++ Synthesis Tool Kit (STK) by Perry Cook and Gary Scavone)
EKS Sound Example (1988)

Bach A-Minor Concerto—Orchestra Part: (WAV) (MP3)

- Executed in real time on one Motorola DSP56001 (20 MHz clock, 128K SRAM)
EKS Sound Example (1988)

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- Solo violin part was played live by Dan Kobialka of the San Francisco Symphony
Digital Waveguide Single Reed, Cylindrical Bore Model (1986)

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Acoustic Guitar Models

Haptic Instruments

Digital waveguide clarinet

- Control variable = mouth half-pressure
- Total reed cost = two subtractions, one multiply, and one table lookup per sample
Digital Waveguide Single Reed, Cylindrical Bore Model (1986)

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Mouth Pressure

\[ \frac{p_m(n)}{2} \]

\[ h_m \]

\[ p_b(n) \]

Reed to Bell Delay

Output Filter

Reflection Filter

Bell to Reed Delay

Embouchure Offset

\[ h^+_\Delta \]

\[ p_b^+(n) \]

Reed Table

\[ \rho \]

\[ h_m \]

\[ p_b(n) \]

Bell to Reed Delay

Bore

Bell

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Digital Waveguide Wind Instrument Sound Examples

- STK Clarinet: (WAV) (MP3)
  Google search: STK clarinet
- See also Faust-STK Clarinet (new)
  Staccato Systems Slide Flute
  (based on STK flute, ca. 1995): (WAV) (MP3)
- Yamaha VL1 “Virtual Lead” synthesizer demos (1994):
  - Shakuhachi: (WAV) (MP3)
  - Oboe and Bassoon: (WAV) (MP3)
  - Tenor Saxophone: (WAV) (MP3)
Digital Waveguide Wind Instrument Sound Examples

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Digital Waveguide Bowed Strings (1986)

- Reflection filter summarizes all losses per period (due to bridge, bow, finger, etc.)
- Bow-string junction = *memoryless* lookup table (or segmented polynomial)
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Amplifier Distortion + Amplifier Feedback

Sullivan 1990

Distortion output signal often further filtered by an *amplifier cabinet filter*, representing speaker cabinet, driver responses, etc.
Distortion Guitar Sound Examples

(Stanford Sondius Project, ca. 1995)

- Distortion Guitar: (WAV) (MP3)
- Amplifier Feedback 1: (WAV) (MP3)
- Amplifier Feedback 2: (WAV) (MP3)
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Acoustic Guitar Models

Haptic Instruments

Schematic diagram of a stringed musical instrument.
Commuted Synthesis of Acoustic Strings (1993)

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Haptic Instruments

Microphone Array

Schematic diagram of a stringed musical instrument.

Equivalent diagram in the linear, time-invariant case.
Commuted Synthesis of Acoustic Strings (1993)

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CIRMNT Lecture, McGill University – 28 / 60

Schematic diagram of a stringed musical instrument.

Equivalent diagram in the linear, time-invariant case.

Use of an aggregate excitation given by the convolution of original excitation with the resonator impulse response.
**Commuted Components**

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Haptic Instruments

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**Aggregate Excitation**

```
Trigger → Aggregate Excitation → String → Output
```

“Plucked Resonator” driving a String.

```
s(t) → Bridge Coupling → Guitar Body → Air Absorption → Room Response → y(t)
```

Possible components of a guitar resonator.
Sound Examples

Electric Guitar (Pick-Ups and/or Body-Model Added) (Stanford Sondius Project → Staccato Systems, Inc. → ADI, ca. 1995)

- Example 1: (WAV) (MP3)
- Example 2: (WAV) (MP3)
- Example 3: (WAV) (MP3)
- Virtual “wah-wah pedal”: (WAV) (MP3)
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STK Mandolin

- STK Mandolin 1: (WAV) (MP3)
- STK Mandolin 2: (WAV) (MP3)
Sound Examples

More Recent Acoustic Guitar

- Bach Prelude in E Major: (WAV) (MP3)
- Bach Loure in E Major: (WAV) (MP3)
- More examples
- Yet more examples

Virtual performance by Dr. Mikael Laurson, Sibelius Institute
Sound Examples

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Virtual performance by Dr. Mikael Laurson, Sibelius Institute

Virtual guitar by Helsinki Univ. of Tech., Acoustics Lab

1http://www.acoustics.hut.fi/
Commuted Synthesis of Linearized Violin

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Microphone Array

Assumes ideal Helmholtz motion of string

Sound Examples (Stanford Sondius project, ca. 1995):
- Bass: (WAV) (MP3)
- Cello: (WAV) (MP3)
- Viola 1: (WAV) (MP3)
- Violin 1: (WAV) (MP3)
- Viola 2: (WAV) (MP3)
- Violin 2: (WAV) (MP3)
- Duet: (WAV) (MP3)
**Commuted Synthesis of Linearized Violin**

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### Assumptions

- Assumes *ideal Helmholtz motion* of string
- Sound Examples (Stanford Sondius project, ca. 1995):
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**Commuted Synthesis of Linearized Violin**

**a)**

Amplitude\(n\) → **Impulse Train** → String → Resonator → Output \(x(n)\)

Amplitude\(n\) → Frequency\(n\) → e\(n\) → **Impulse Train** → String → Resonator → Output \(x(n)\)

Amplitude\(n\) → Frequency\(n\) → **Impulse-Response Train** → String → Output \(x(n)\)

- Assumes *ideal Helmholtz motion* of string
- Sound Examples (Stanford Sondius project, ca. 1995):
  - Bass: (WAV) (MP3)
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  - Violin 1: (WAV) (MP3)
  - Violin 2: (WAV) (MP3)
  - Duet: (WAV) (MP3)

Hammer-string interaction pulses (force):

![Graph showing hammer-string interaction pulses](image-url)
Faster collisions correspond to narrower pulses (*nonlinear filter*).

For a *given velocity*, filter is linear time-invariant.

Piano is “linearized” for each hammer velocity.
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Synthesis of Hammer-String Interaction Pulse

- Faster collisions correspond to *narrower* pulses (*nonlinear filter*)

- For a *given velocity*, filter is linear time-invariant

- Piano is “linearized” for each hammer velocity

![Diagram](image-url)
Synthesis of Hammer-String Interaction Pulse

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- Faster collisions correspond to *narrower* pulses *(nonlinear filter)*

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Synthesis of Hammer-String Interaction Pulse

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- Acoustic Strings
- Sound Examples
- Linearized Violin
- Commuted Piano
- Pulse Synthesis
- Complete Piano
- Sound Examples

Recent CCRMA Work
- Acoustic Guitar Models
- Haptic Instruments
- Microphone Array
- Haptic OmMa
- Pulse Synthesis

- Faster collisions correspond to narrower pulses (nonlinear filter)
- For a given velocity, filter is linear time-invariant
- Piano is “linearized” for each hammer velocity

Impulse
Time

Lowpass Filter

Impulse Response
Time
Multiple Hammer-String Interaction Pulses

Superimpose several individual pulses:

\[
\begin{align*}
\text{Impulse 1} & \xrightarrow{\delta_1} \text{LPF1} \\
\text{Impulse 2} & \xrightarrow{\delta_2} \text{LPF2} \\
\text{Impulse 3} & \xrightarrow{\delta_3} \text{LPF3} \\
\end{align*}
\]

\[
\begin{align*}
+ & \rightarrow \text{String} \\
\text{Input} & \\
\end{align*}
\]

Force

Time

\[
\begin{align*}
\delta_1 & \\
\delta_2 & \\
\delta_3 & \\
\end{align*}
\]
Multiple Hammer-String Interaction Pulses

Overview

Early Ideas

Physical Modeling

- KL Voice
- "Daisy"
- Digital Waveguide
- Signal Scattering
- Plucked String
- Struck String
- Karplus Strong
- EKS Algorithm
- Clarinet
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- **Pulse Synthesis**
- Complete Piano
- Sound Examples

Recent CCRMA Work

Acoustic Guitar Models

Haptic Instruments

Haptic Instruments

Superimpose several individual pulses:

As impulse amplitude grows (faster hammer strike), output pulses become *taller and thinner*, showing less overlap.
Complete Piano Model

Natural Ordering:

\[ v_c \]

Trigger → Impulse Generator → θ₁ → Tapped Delay Line → δ₁ → LPF1 → θ₁ → LPF2 → θ₂ → LPF3 → θ₃ → String → Sound Board & Enclosure → Output

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Recent CCRMA Work

Acoustic Guitar Models

Haptic Instruments

Microphone Array
Complete Piano Model

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Commuted Ordering:

- Sound Board & Enclosure
- Impulse Response
- Tapped Delay Line
- LPF1
- LPF2
- LPF3
- String
- Output
Complete Piano Model

Natural Ordering:

Commuted Ordering:

- Soundboard and enclosure are *commuted*
Complete Piano Model

Natural Ordering:

Commuted Ordering:

- Soundboard and enclosure are *commuted*
- Only need a stored recording of their *impulse response*
Complete Piano Model

Overview

Early Ideas

Physical Modeling
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Recent CCRMA Work

Acoustic Guitar Models

Haptic Instruments

Natural Ordering:

\[ v_C \]

\[ \delta_1 \]
\[ \delta_2 \]
\[ \delta_3 \]

Impulse Generator
Tapped Delay Line
LPF1
LPF2
LPF3
Plus
String
Sound Board & Enclosure
Output

Commuted Ordering:

\[ v_C \]

Impulse Response
Tapped Delay Line
LPF1
LPF2
LPF3
Plus
String
Output

- Soundboard and enclosure are *commuted*
- Only need a stored recording of their *impulse response*
- An enormous digital filter is otherwise required
Piano and Harpsichord Sound Examples

(Stanford Sondius Project, ca. 1995)

- Piano: (WAV) (MP3)
- Harpsichord 1: (WAV) (MP3)
- Harpsichord 2: (WAV) (MP3)
More Recent Harpsichord Example

- Harpsichord Soundboard Hammer-Response: (WAV) (MP3)
- Musical Commuted Harpsichord Example: (WAV) (MP3)
- More examples

References:

- “Sound Synthesis of the Harpsichord Using a Computationally Efficient Physical Model”,
- by Vesa Välimäki, Henri Penttinen, Jonte Knif, Mikael Laurson, and Cumhur Erkut, JASP-2004
- Forthcoming dissertation by Jack Perng (Stanford, Physics/CCRMA)
Recent CCRMA Research related to Virtual Musical Instruments
Recent Research on Virtual Musical Instruments at CCRMA

Overview

Early Ideas

Physical Modeling

Recent CCRMA Work

- CCRMA
- Outline

Acoustic Guitar Models

Haptic Instruments

Harpsichord Models

Microphone Array

ASLP Special Issue

Summary

CCRMA building: The Knoll, Stanford University
Outline

- Virtual Acoustic Guitar — Nelson Lee
  (Computer Science PhD student)
- Haptic Virtual Instruments — Ed Berdahl
  (Electrical Engineering PhD student)
- Virtual Harpsichord — Jack Perng
  (Physics PhD student)
- Acoustic Space Modeling — Consulting Professor Jonathan Abel, Music PhD student Nick Bryan, EE graduate student Travis Skare, and others
- IEEE-ASLP Special Issue on Virtual Analog Audio Effects & Musical Instruments, edited by Välimäki, Fontana, Zölzer, & Smith
- Software Tools in the Faust Language, with Plans for STK Extensions
Virtual Acoustic Guitar Models
Submitted paper based on recent CCRMA/CS thesis by Nelson Lee:

“Analysis and Synthesis of Coupled Vibrating Strings Using a Hybrid Modal-Waveguide Synthesis Model”

by Nelson Lee, Julius Smith, and Vesa Välimäki.

Accepted for publication in the IEEE special issue on Virtual Analog Audio Effects and Musical Instruments, May 2010 (est.)
String excitation (for commuted waveguide synthesis) is highpass filtered to avoid exciting first $N$ partials.

Lowest $N$ partials are replaced by fourth-order resonators (which can independently beat and give two-stage decay).

Similar to Balázs Bank formulation which adds second-order resonators to existing partials of the filtered-delay-loop.

New analysis methods (in thesis) for estimating partial parameters, as well as other results.
Sound Examples of Individual Effects

From Nelson Lee’s thesis defense:

- Original waveform: (WAV) (MP3)
- Simple lossless, reflectively terminated digital waveguide (DWG): (WAV) (MP3)
- Add loop filter: (WAV) (MP3)
- Add interpolation filter: (WAV) (MP3)
- Add excitation (ICMC07): (WAV) (MP3)
- Add body response: (WAV) (MP3)
- Add hybrid modal/waveguide model: (WAV) (MP3)
- Exaggerate pitch glide due to tension modulation: (WAV) (MP3)
Virtual Acoustic Guitar Sound Examples

More Nelson Lee examples:

- Original 1: (WAV) (MP3)
- Synthesized 1: (WAV) (MP3)
- Original 2: (WAV) (MP3)
- Synthesized 2: (WAV) (MP3)
- Original 3: (WAV) (MP3)
- Synthesized 3: (WAV) (MP3)
- Original 4: (WAV) (MP3)
- Synthesized 4: (WAV) (MP3)
- Original 5: (WAV) (MP3)
- Synthesized 5: (WAV) (MP3)
- Original 6: (WAV) (MP3)
- Synthesized 6: (WAV) (MP3)
- Synthesized Chord Demo: (WAV) (MP3)
Overview

Early Ideas

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Acoustic Guitar Models

**Haptic Instruments**

Harpsichord Models

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ASLP Special Issue

Summary

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**Haptic Feedback Control for Virtual Instruments**
Haptic Virtual Musical Instruments

Recent CCRMA/EE PhD graduate Ed Berdahl is working on

_Haptic Feedback Control for Virtual Instruments_

Goals:

- Assist and/or augment _gestures_
- Assist with _accurate playing_
- Recent projects:
  - Haptically plucked virtual string
  - Active drumhead (one-handed rolls, etc.):

http://ccrma.stanford.edu/~eberdahl/Projects/HapticDrum/
Virtual Harpsichord
CCRMA/Physics PhD student **Jack Perng** is working on

1. Built a harpsichord jack and monochord
2. Measuring position and velocity data, etc.
3. Developed a novel, more accurate plectrum model
4. Presently working on interfacing the new plectrum to a digital waveguide string

Prof. Tom Rossing collaborating
Harpsichord Jack and Monochord

Overview
Early Ideas
Physical Modeling
Recent CCRMA Work
Acoustic Guitar Models
Haptic Instruments
Harpsichord Models
- Harpsichord
- Harpsichord Jack
Microphone Array
ASLP Special Issue
Summary
Acoustically Transparent and Configurable Microphone Array
- Adjustable geometry (software calibrated)
- Sixteen microphones (Countryman B6 Omni Lavalier):
  - 2 mm diameter capsules
  - 1 mm diameter flexible mounting wire
  - Acoustically transparent over most of the audio band
“A Configurable Microphone Array with Acoustically Transparent Omnidirectional Elements”

Jonathan Abel, Nicholas Bryan, Travis Skare, Patty Huang, Darius Mostowfi, Miriam Kolar, and Julius Smith

AES-2009, New York

Current Application:

Recording and modeling acoustic properties of underground galleries at pre-Inca archeological site Chavín de Huántar in Peru
Special Issue of the IEEE ASLP
IEEE ASLP Special Issue

The May 2010 issue of the IEEE Transactions on Audio, Speech, and Language Processing (ASLP) was a special issue devoted to Virtual Analog Audio Effects and Musical Instruments.

Editors:

- Vesa Välimäki
- Federico Fontana
- Udo Zölzer
- Julius Smith

Check it out!
Special-Issue Papers on Virtual Musical Instruments

- “Tubular Bells — A Physical and Algorithmic Model” by Rabenstein, Koch, and Popp
- “A Block-Based Physical Modeling Approach to the Sound Synthesis of Drums” by Marogna and Avanzini
- “A Virtual Model of Spring Reverberation” by Bilbao and Parker
- “Analysis and Synthesis of Coupled Vibrating Strings Using a Hybrid Modal-Waveguide Synthesis Model” by Lee, Smith, and Välimäki
- “A Modal-Based Real-Time Piano Synthesizer” by Bank, Zambon, and Fontana
Summary of a quick look at recent acoustic-modeling research at CCRMA:

- Coupled Strings Analysis and Synthesis — Nelson Lee (CS) — Fourth-order modes for low partials, waveguide model for upper partials; new analysis techniques

- Haptic Virtual Instruments — Ed Berdahl (EE) — Real controllers (with force feedback) for virtual instruments

- Virtual Harpsichord — Jack Perng (Physics) — Monochord+jack measurements toward improved harpsichord synthesis models

- Microphone Array — Jonathan Abel et al. — Acoustically transparent, configurable, software-calibrated microphone array for sampling the 3D sound field

- Special Issue on Virtual Analog Audio Effects and Musical Instruments — Vesa Välimäki et al., eds.
Summary
We have reviewed a “CCRMA-biased slice” through the history of sound synthesis based on physical modeling, spanning

- Bernoulli’s superposition of simple modes of vibration
- d’Alembert’s superposition of traveling waves
- Physical Modeling Synthesis
- Recent Research at CCRMA