Rendering Realistic Contact with Virtual Surfaces
Via Event-Based Haptic Feedback

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Outline for Today

- Tool-Based Contact with Real Objects
- Typical Haptic Rendering Schemes for Hard Virtual Objects
- Event-Based Haptic Rendering Techniques
- Conclusion and Questions
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How can you best judge the material of hard objects?

Pressing

Tapping

Tapping generates high-frequency accelerations that efficiently convey material properties.
Tapping Enables Better Material Discrimination

Mechanoreceptors in Glabrous Human Skin

Pacinian corpuscles act as biomechanical accelerometers and are especially suited to detecting vibrations through hand-held tools.

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<thead>
<tr>
<th>Adaptation Speed</th>
<th>Receptive Field Size</th>
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<tr>
<td></td>
<td>Small</td>
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<tr>
<td>Fast</td>
<td>FA I</td>
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<td>Meissner Corpuscle</td>
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<td>8 to 64 Hz</td>
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<td>Spatial Deformation</td>
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<tr>
<td>Slow</td>
<td>SA I</td>
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<td>Merkel Complex</td>
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<td>2 to 32 Hz</td>
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<td>Spatial Curvature</td>
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<td>Large</td>
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<td>FA II</td>
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<td></td>
<td>Pacinian Corpuscle</td>
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<td>Greater than 64 Hz</td>
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<td>Non-localized Vibration</td>
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<td>SA II</td>
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<td>Ruffini Ending</td>
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<td>DC to 8 Hz</td>
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<td>Directional Stretch</td>
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Stylus with Accelerometer
Demonstration of Contact Acceleration Transients
**Salient Observations from the Demonstration**

- Contact with hard objects creates high-frequency, short-duration acceleration transients.

- Contact transients tend to resemble exponentially decaying sinusoids; they vary by frequency, magnitude, and duration.

- Faster taps create larger acceleration transients.

- Stiffer materials generate higher-frequency transients.

- The dynamics of the human hand play a key role in determining the shape of the contact transient.
Modeling Real Contact Dynamics

- A user tapped 250 times with a stylus on a wood surface.
- Transient frequency and duration were very consistent, but magnitude varied significantly between trials.
- What factors affect the magnitude of the contact transient?

Linear Correlation Between Incoming Contact Velocity and Peak Contact Force

This finding is consistent with a simple mass model: the contact force scales to cancel the linear momentum of the hand and stylus.

\[ L_1 - L_0 = 0 - m v_{in} = \int_0^{t_1} F_c(t) \, dt, \]

\[ F_c(t) = -m v_{in} \hat{f}_c(t) \]
A More Sophisticated Dynamic Model Predicts Decaying Sinusoid Transients

Equation of Motion
\[ m \ddot{x}_m + (b + b_s) \dot{x}_m + (k + k_s) x_m = b \dot{x}_d + k x_d \]

Desired Motion Trajectory
\[ \dot{x}_d(t) = v_{in} + a_{in} t \quad x_d(t) = v_{in} t + \frac{1}{2} a_{in} t^2 + \frac{m a_{in}}{k} \]

Contact Force Response
\[ F_c(t) = -\beta \sin(\omega t + \phi)e^{-\alpha t} - c_2 t^2 - c_1 t - c_0 \]

Analysis of this model shows approximately linear correlations from incoming acceleration and grip force to peak contact force.
Experimental Data Shows Dominance of Incoming Velocity, Small Influences of Incoming Acceleration and Grip Force
Tapping on real objects creates contact transients that are shaped like decaying sinusoids and scaled by incoming velocity.
Questions about tool-based contact with real objects?
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Haptic Interfaces for Virtual Environments: Scope of This Talk

User Grounded Impedance-Type Haptic Interface

Position Measurements

Force Commands

Computerized Environment Model of Firm (Nondeformable) Objects
Proxy-Based Haptic Rendering

The proxy is a virtual tool that always stays outside the object being contacted.

The haptic interface creates a virtual spring to pull the user’s hand toward the proxy.

The haptic feedback force is proportional and opposite to the penetration vector.

\[ \vec{F} = -k \vec{x}_{\text{penetration}} \]

Typical Haptic Rendering Scheme: A Unilateral Spring

- Position
- Proportional
- Force
Virtual Objects All Feel Like Springs

- Recall that most real objects do not behave as simple springs, so tapping will never feel correct, regardless of the stiffness.

- If we can match the stiffness of the virtual spring to that of a certain real object, they will feel identical during slow pressing.

- Problem: simulating a high stiffness spring by reading position and outputting force requires an ideal haptic interface.
Common Impedance-Type Haptic Interfaces

- SensAble Phantom Premiums
- Force Dimension Omega
- Immersion Impulse Engine
- SensAble Omni
- MPB Freedom6S
- Novint Falcon
Nonidealities of Impedance-Type Haptic Interfaces

Wide Range of Hand Dynamics

Position Sensor Quantization

Flexible Cables and Linkage Elements

Friction at Pivots and Sliders

Limited Current Output Bandwidth

Current Command Quantization

Discrete Time Processing

Lengthy Computations
Nonidealities of Impedance-Type Haptic Interfaces

- All of these effects combine to severely limit the closed-loop stiffness that can be rendered in virtual environments.

- What happens when one programs a stiffness that is relatively high for the selected device / computer / user configuration?

- Sustained contact vibrations severely detract from the user experience because real objects never behave like this.

- Higher resolution position sensors and a faster computer can help, but there will always be an upper limit on stiffness output.

- Typical approach is to make the virtual spring as stiff as possible, achieving marginal stability and a “Nerf World” feel.

Human Subject Study on Contact Realism

- 16 subjects
- Blind tapping to isolate haptic sense
- 3 real and 9 virtual samples
- Realism rating (1-7)

How much does it feel like real wood?

Tapping on a Real Surface
Tapping on a Virtual Surface
Five of the Samples

Real Foam
\( k \approx 220 \text{ N/m} \)

Soft Virtual Spring
\( k \approx 340 \text{ N/m} \)

Firm Virtual Spring
\( k \approx 680 \text{ N/m} \)

Very Firm Virtual Spring
\( k \approx 1020 \text{ N/m} \)

Real Wood
\( k \approx 70,000 \text{ N/m} \)

Haptic feedback based on virtual springs cannot authentically recreate the feel of real hard objects.

Representative Contact Transients

Real Wood
$k \approx 70,000 \text{ N/m}$

Real Foam
$k \approx 220 \text{ N/m}$

Real Foam
$k \approx 220 \text{ N/m}$

Soft Virtual Spring
$k \approx 340 \text{ N/m}$

Firm Virtual Spring
$k \approx 680 \text{ N/m}$

Very Firm Virtual Spring
$k \approx 1020 \text{ N/m}$
Key Finding: Haptic feedback based on parallel springs and dampers makes surfaces feel harder and more distinct than springs alone.

Observation: The abrupt changes in force that occur at contact act like step inputs to the haptic interface, so all virtual surfaces generate similar high-frequency contact transients.
Virtual spring rendering methods cannot adequately imitate the feel of real hard objects, but increasing force output at contact seems promising.
Questions about typical haptic rendering schemes for hard virtual objects?
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At the event of contact with a virtual object, add a short-duration (<100 ms) high-frequency force transient to the typical virtual-spring force.


How should these open-loop transients be designed?
For EBH tapping, you need contact velocity and the resulting transient.

You can use either force or acceleration transients.

Accelerometers are much cheaper and smaller than force sensors, and they compare well with Pacinian Corpuscles.

Acquire Experimental Data

Use transients directly or parameterize Haptograph
A Natural Choice for a Parametric Model: 
Exponentially Decaying Sinusoids

\[ F(t) = A \left| v_{in} \right| e^{\ln p t / d} \sin(\omega t) \quad \text{for} \quad 0 < t \leq d \]

- \( A \): Amplitude Scale, \( \text{N}/(\text{m/s}) \)
- \( v_{in} \): Incoming Velocity, \( \text{m/s} \)
- \( d \): Transient Duration, \( \text{s} \)
- \( \omega \): Transient Frequency, \( \text{rad/s} \)
- \( p \): Transient Proportion at \( t = d \), e.g., 0.01
**Event-Based Haptic Transient Tips**

- Keep track of real time in your program by sampling the processor’s clock every cycle.

- If re-playing recorded data, linearly interpolate between adjacent transients by incoming velocity.

- If using a parametric model, choose $d$ to be an integer multiple of the sinusoid’s half period so $F(t)$ goes to zero at $t = d$.

- Latch contact state and don’t re-trigger on the same constraint surface until the transient has finished playing.
The system’s computational, electrical, mechanical, and biomechanical dynamics distort the feel of high-frequency haptic feedback.
Dynamic Response of a Phantom Premium 1.0

Motor Current (A) to Handle Acceleration (g)

![Graph showing the relationship between motor current and handle acceleration for different current command levels.](image)

- **Frequency (Hz)**
- **Magnitude**
- **Phase (degrees)**

<table>
<thead>
<tr>
<th>Current Command</th>
<th>Low</th>
<th>Medium</th>
<th>High</th>
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<tr>
<td>1 to 500 Hz</td>
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<tr>
<td>500 to 1 Hz</td>
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How Can You Generate Transients That Feel Good?

1. **User Judgment:** Hand-tune the playback gain or the model’s parameters via informal or formal user testing (better with direct comparisons to real objects).

2. **Dynamic Compensation:** Explicitly identify the dynamics of your haptic system and condition your desired acceleration outputs by the inverse of these dynamics (also called “Acceleration Matching”).

3. **Dedicated Actuator:** Add a vibration actuator to the tool to achieve high performance without requiring extensive nonlinear time-varying system identification.
16 subjects

Blind tapping to isolate haptic sense

3 real and 9 virtual samples

Realism rating (1-7)

How much does it feel like real wood?

Tested Samples

Real Objects

Pulses

Decaying Sinusoids

Acceleration Matching

Virtual Springs
Full Realism Rating Results

Realism Rating
Soft    Firm

Very
Firm
Foam
Proportional
Decaying
Sinusoid
Fixed-Width
Pulse
Acceleration
Matching
Wood on Foam
Wood

1 2 3 4 5 6 7
The underlying softness of the virtual spring makes it more natural to recreate the feel of wood on foam than that of wood.
Adding **short-duration high-frequency transients** at contact events is a simple way to make virtual surfaces feel significantly more realistic than a virtual spring ever will.
Questions about event-based haptic rendering techniques?
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Summary

- Human haptic perception of hard objects depends on high-frequency contact transients.
- The virtual spring rendering method does not feel realistic.
- Adding event-based transients at contact initiation can significantly increase the realism of virtual contact.
- Design the transients to match the real experience being emulated, and tune them to feel correct on your system.
Questions?

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