Effective Near-Field Haptics in Virtual Environments

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Overview

- **Motivation**
- **Near-field haptic approaches**
- **Our prototype**
- **Empirical studies**
- **Application areas**
Problem Statement

- **Virtual environments are typically limited to visual and audio cues**
  - Do not faithfully recreate reality
  - Sensorially-deprived environments
  - Do not take advantage of human bandwidth capacity
  - Users only receive cues produced by the system
  - Difficult to manipulate objects effectively
Problem Statement (cont.)

- **Virtual contact**
  - What should we do when we know that contact has been made with a virtual object?
  - The output of collision detection is the input to virtual contact
  - Cues for understanding the nature of contact with objects is typically over-simplified
## Some Cueing Options

<table>
<thead>
<tr>
<th>Cueing Technique</th>
<th>Modality</th>
<th>Mapped to…</th>
</tr>
</thead>
<tbody>
<tr>
<td>Color change</td>
<td>Visual</td>
<td>Location/depth of penetration</td>
</tr>
<tr>
<td>Vector glyphs</td>
<td>Visual</td>
<td>Force and direction of contact</td>
</tr>
<tr>
<td>Texture distortion</td>
<td>Visual</td>
<td>Location/depth of penetration</td>
</tr>
<tr>
<td>Shape distortion</td>
<td>Visual</td>
<td>Location/depth of penetration</td>
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<tr>
<td>Contact illumination</td>
<td>Visual</td>
<td>Location of collision</td>
</tr>
<tr>
<td>Pitch change</td>
<td>Auditory</td>
<td>Depth of penetration</td>
</tr>
<tr>
<td>Amplitude change</td>
<td>Auditory</td>
<td>Force of collision</td>
</tr>
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<td>Spatialization</td>
<td>Auditory</td>
<td>Location of collision</td>
</tr>
<tr>
<td>Vibrotactile amplitude</td>
<td>Haptic/Tactile</td>
<td>Location/velocity/depth of penetration</td>
</tr>
</tbody>
</table>
The Nature of Near-Field Haptics

- **Vehicular vs. personal contact**
- **Object properties**
  - Surface (texture)
  - Compliance
  - Physical makeup
- **Contact properties**
  - Velocity
  - Location(s) on the object
  - Location(s) on the person
Active- vs. Passive-Haptic Feedback

- **Active-haptic feedback**
  - Typically, force-reflecting devices under computer control
  - Expensive
  - Cumbersome

- **Passive-haptic feedback**
  - Inherent properties of objects
  - Cheap
  - High fidelity
  - Limited amount and type of feedback
Active-Haptic Feedback: Ex. 1 - SensAble PHANToM

http://www.sensable.com/
Active-Haptic Feedback: Ex. 2 - Immersion CyberGrasp

http://www.immersion.com/
Passive-Haptic Feedback:
Ex. 1 - GW Hand-Held Windows

http://www.seas.gwu.edu/~gogo/
Passive-Haptic Feedback: Ex. 2 - UNC *Being There* Project

http://www.cs.unc.edu/~lowk/beingthere/
Vibrotactile Cueing Devices

Vibrotactile feedback has been incorporated into many devices

- Used for decades for the hearing impaired
- Widely used in cell phones and pagers
  - "Manner" button
- Console controllers from Sony, MS, Nintendo
- PC joysticks from MS, Logitech, etc.
- Research devices from Immersion Corp., Virtual Technologies, etc.
Technologies for Producing Vibrotactile Cues

- **Called tactors**
- **Arm linkages**
- **Pin arrays**
- **Voice coils**
  - Speakers
- **Pager motors**
  - DC motor with an eccentric mass
Vibrotactile Feedback: Ex. 1 - Navy TSAS Project

http://www.namrl.navy.mil/accel/tsas/
Vibrotactile Feedback: Ex. 2 - Purdue *Haptic Vest*

http://www.ecn.purdue.edu/HIRL/projects_vest.html
The GW TactaBoard Design

**Design goals**
- Low cost
- Low power
- High update rate
- Many form factors
- Scalable
- Different tactors
- Individual control
- Simple Interface
- Wearable

**Design decisions**
- Use COTS
- Use PWM
- Low number of tactors
- Flexible design
- Communication bus
- External power supply
- Multiple PWM signals
- ASCII command set
- Small footprint
Current TactaBoard Prototype

http://www.vibrotactile.org/tactaboard/
System Structure

Host

Serial Line

CAN Bus

TactaBoard$_1$

Tactor$_1$

Tactor$_2$

Tactor$_n$

TactaBoard$_2$

Tactor$_1$

Tactor$_2$

Tactor$_n$

TactaBoard$_m$

Tactor$_1$

Tactor$_2$

Tactor$_n$
Pulse-Width Modulation (PWM)

- **Shortening the duty cycle reduces the output voltage**

![Diagram of Pulse-Width Modulation](image)
Varying the Cues

- **Individual tactors**
  - Frequency
  - Amplitude
  - Temporal delay
  - Pulses

- **Groups of tactors**
  - Waveform
  - Tactor placement
  - Interpolation method
Empirical Studies

- 21 subjects
- 3 seated tasks
  - Location Discrimination
  - Visual Search
  - Intensity Matching
- 6 cm spacing
- Mouse input
Experiment 1: Location Discrimination Task
Experiment 1: Experimental Design

- **Independent variable**
  - Each row/column combination
    - Thirty-six trials
- **Dependent variable**
  - Perceived vs. actual location
- **One-second, vibrotactile pulse at 91 Hz**
## Exp. 1 - Results:
Mean Accuracy (percent)

<table>
<thead>
<tr>
<th>Stimulus Row</th>
<th>Stimulus Column</th>
<th>Mean</th>
<th>Std. Dev.</th>
<th>N</th>
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<tr>
<td>Upper</td>
<td>Left</td>
<td>0.83</td>
<td>0.37</td>
<td>84</td>
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<tr>
<td></td>
<td>Center</td>
<td>0.70</td>
<td>0.46</td>
<td>84</td>
</tr>
<tr>
<td></td>
<td>Right</td>
<td>0.82</td>
<td>0.39</td>
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<td></td>
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<tr>
<td>Middle</td>
<td>Left</td>
<td>0.83</td>
<td>0.37</td>
<td>84</td>
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<tr>
<td></td>
<td>Center</td>
<td>0.88</td>
<td>0.33</td>
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<tr>
<td></td>
<td>Right</td>
<td>0.88</td>
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<td>Row Total</td>
<td>0.87</td>
<td>0.34</td>
<td>252</td>
</tr>
<tr>
<td>Lower</td>
<td>Left</td>
<td>0.88</td>
<td>0.33</td>
<td>84</td>
</tr>
<tr>
<td></td>
<td>Center</td>
<td>0.80</td>
<td>0.40</td>
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<td>Right</td>
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<td></td>
<td>Row Total</td>
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<td>252</td>
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<td>Column Totals</td>
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<td>252</td>
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<td></td>
<td>Center</td>
<td>0.79</td>
<td>0.41</td>
<td>252</td>
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<tr>
<td></td>
<td>Right</td>
<td>0.88</td>
<td>0.32</td>
<td>252</td>
</tr>
<tr>
<td>Overall Total</td>
<td></td>
<td>0.84</td>
<td>0.36</td>
<td>756</td>
</tr>
</tbody>
</table>

- **119 mis-idents.**
- Mostly vertical
- Mostly downward

![Diagram]
Experiment 2: Visual Search Task
Experiment 2: Experimental Design

- **Within-subjects design**
- **Independent variables**
  - Visual cue type
  - Vibrotactile waveform
- **Dependent variables**
  - Trial time
  - Correct letter identified
- **Fifty trials per treatment**
**Experiment 2: Treatments**

- **Seven treatments**
  - None-None
  - None-Square
  - Single-Square
  - Multi-Square
  - Multi-None
  - Multi-Sawtooth
  - Multi-Triangle

<table>
<thead>
<tr>
<th>Visual Cue Levels</th>
<th>Vibrotactile Cue Levels</th>
</tr>
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<tbody>
<tr>
<td></td>
<td>None</td>
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<tr>
<td><strong>None</strong></td>
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<tr>
<td><strong>Single</strong></td>
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<tr>
<td><strong>Multi</strong></td>
<td>X</td>
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</table>
### Exp. 2 - Results: Mean Trial Time (seconds)

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Mean</th>
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<th>N</th>
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</thead>
<tbody>
<tr>
<td><strong>By Visual Cue Type</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>None-None</td>
<td>1924.30</td>
<td>984.54</td>
<td>1050</td>
</tr>
<tr>
<td>None-Square</td>
<td>1693.51</td>
<td>702.45</td>
<td>1050</td>
</tr>
<tr>
<td>Single-Square</td>
<td>1336.76</td>
<td>349.54</td>
<td>1050</td>
</tr>
<tr>
<td>Multi-Square</td>
<td>1301.46</td>
<td>342.33</td>
<td>1050</td>
</tr>
<tr>
<td>Total</td>
<td>1564.01</td>
<td>701.45</td>
<td>4200</td>
</tr>
<tr>
<td><strong>By Vibrotactile Cue Type</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>None-None</td>
<td>1924.30</td>
<td>984.54</td>
<td>1050</td>
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<tr>
<td>Multi-None</td>
<td>1338.64</td>
<td>375.68</td>
<td>1050</td>
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<tr>
<td>Multi-Square</td>
<td>1301.46</td>
<td>342.33</td>
<td>1050</td>
</tr>
<tr>
<td>Multi-Sawtooth</td>
<td>1337.26</td>
<td>423.55</td>
<td>1050</td>
</tr>
<tr>
<td>Multi-Triangle</td>
<td>1308.05</td>
<td>381.31</td>
<td>1050</td>
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<tr>
<td>Total</td>
<td>1441.94</td>
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<td>Overall Total</td>
<td>1462.85</td>
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<table>
<thead>
<tr>
<th>Treatment</th>
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<th>3</th>
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<tbody>
<tr>
<td>Multi-Square</td>
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<td></td>
</tr>
<tr>
<td>Single-Square</td>
<td>1336.76</td>
<td>1693.51</td>
<td>1924.30</td>
</tr>
<tr>
<td>None-Square</td>
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</tr>
<tr>
<td>None-None</td>
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<td></td>
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</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Treatment</th>
<th>1</th>
<th>2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Multi-Square</td>
<td>1301.46</td>
<td></td>
</tr>
<tr>
<td>Multi-Triangle</td>
<td>1308.05</td>
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</tr>
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<td>Multi-Sawtooth</td>
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<tr>
<td>Multi-None</td>
<td>1338.64</td>
<td>1924.30</td>
</tr>
<tr>
<td>None-None</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Exp. 2 - Results:
Discussion

- **Visuals dominated**
- **Vibrotactile helped in the absence of visuals**
- **Latency of our apparatus**
- **No difference for different waveforms**
Experiment 3: Intensity Matching Task
Experiment 3: Experimental Design

- **Eighty-one trials**
- **Independent variables**
  - Frequency
  - Location
- **Dependent variable**
  - Numerical difference between the actual and perceived intensity
- **Ten frequencies (Hz)**
  - 38, 54, 65, 68, 69, 72, 75, 78, 81, 83
Exp. 3 - Results: Mean Difference (Hz)

<table>
<thead>
<tr>
<th>Stimulus Comparison</th>
<th>Mean</th>
<th>Std. Dev.</th>
<th>N</th>
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</thead>
<tbody>
<tr>
<td>By Location</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Upper-Left</td>
<td>12.84</td>
<td>9.87</td>
<td>189</td>
</tr>
<tr>
<td>Upper-Center</td>
<td>24.76</td>
<td>18.67</td>
<td>189</td>
</tr>
<tr>
<td>Upper-Right</td>
<td>20.18</td>
<td>17.12</td>
<td>189</td>
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<tr>
<td>Middle-Left</td>
<td>14.80</td>
<td>10.75</td>
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<tr>
<td>Middle-Center</td>
<td>16.68</td>
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<td>Middle-Right</td>
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<td>12.89</td>
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<td>Lower-Left</td>
<td>13.23</td>
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<td>Lower-Right</td>
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<td>By Reference Frequency (Hz)</td>
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<td>38 (1)</td>
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<td>54 (2)</td>
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<td>65 (3)</td>
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<td>68 (4)</td>
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<td>69 (5)</td>
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<td>72 (6)</td>
<td>19.05</td>
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<td>75 (7)</td>
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<td>78 (8)</td>
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<tr>
<td>81 (9)</td>
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<td>210</td>
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<tr>
<td>83 (10)</td>
<td>10.70</td>
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<td>84</td>
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<tr>
<td>By Row</td>
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<td>By Reference/Adjustable Relationship</td>
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<td>Same Tactor</td>
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<td>Distance of 13.42</td>
<td>18.86</td>
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<tr>
<td>Overall Total</td>
<td>17.11</td>
<td>14.22</td>
<td>1701</td>
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</tbody>
</table>
Exp. 3 - Results: Discussion

- **Complex relationship**
  - Location and frequency
  - 7 Hz difference at the same location is encouraging
  - No clear mapping from one location to another

- **Higher frequencies seem to lead to better performance**

- **Close to spine was worse**
  - Vertical confusion
Applications

- **Data perceptualization**
  - Map variables to tactors

- **Spatial awareness**
  - Driver warning system (vibrotactile Bott's dots)

- **Navigational aid**
  - Firefighter guidance

- **Non-verbal communication**
  - Map hand signals to vibrotactile patterns
Acknowledgments

- ONR VIRTE project
- DARPA
- ATR, Japan

For more info. on the TactaBoard:
- http://www.vibrotactile.org/