WHISPER: A Spread Spectrum Approach to Occlusion in Acoustic Tracking

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Under the supervision of Gary Bishop
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Outline

- Motivation
- Thesis Statement
- Previous Work
- Algorithm
- System Performance
- Conclusion
What is tracking?

• Determination of the position and/or orientation of a target object

• There is a nearly ubiquitous tracking device you are all familiar with…
The Mouse!

Motivation - Thesis Statement - Previous Work - Algorithm - Performance - Conclusion
Virtual Environments

- Need high quality tracking information

Motivation - Thesis Statement - Previous Work - Algorithm - Performance - Conclusion
Head Tracking

• Focus of the majority of past VE tracking research
Body Tracking

• Growing interest due to quality head tracking

• Uses:
  – Avatars
  – Mine style interaction [Mine 1997]

• Goals:
  – Occlusion-tolerant
  – Body-centered

Motivation - Thesis Statement - Previous Work - Algorithm - Performance - Conclusion
Spread spectrum technology applied to acoustic tracking produces a robust tracking device with better performance than existing acoustic systems. Extending the frequency range of the signal down into the audible range enables tracking in the presence of occlusions.
Spread Spectrum Concepts

- What is spread spectrum?
- Multipath = echoes
- Multiple access techniques
  - Frequency Division (FDMA) – Radio & TV
  - Time Division (TDMA) – Ethernet
  - Code Division (CDMA) – Sprint PCS
Spread Spectrum Advantages

• When applied to acoustic tracking:
  – Continuous signal allows frequent updates
  – Robust to noise and multipath
  – CDMA allows multiple simultaneous ranges
Also... Diffraction is now usable!

- Using audible frequencies in the spread spectrum signal allows for more diffraction

- System can function while occluded!
Previous Work (body-centered)

• Gypsy (& ShapeTape)
Previous Work (body-centered)

- Gypsy (& ShapeTape)
- WearTrack [Foxlin 2000]
Previous Work (body-centered)

- Gypsy (& ShapeTape)
- WearTrack [Foxlin 2000]
- Magnetic [Insko 2001]
Previous Work (acoustic)

• Acoustic system features
  – Sound speed is convenient
  – Low-cost, easily available transducers

• Poor performance of previous systems:
  – Not robust in noisy environments
  – Slow update rates
Previous Work (acoustic)

- Phase coherent [Sutherland 1968]
- Lincoln Wand [Roberts 1966]
- Modern systems:
  - Intersense Constellation [Foxlin 1998]
  - Nintendo Powerglove [1989]
  - Logitech 3D mouse [circa 1992]
WHISPER vs. Other Acoustic Systems

- Pulsed trackers
  - Faster update rate
  - Multiple simultaneous range measurements
  - More robust to echoes and noise
- Phase coherent trackers
  - Much more robust to echoes & interference
Previous Work (spread spectrum)

- Global Positioning System (GPS)
- Aetherwire [Fleming 1995]
- Spatiotrack [Palovuori 2000]
- Acoustic/Optical system [Girod 2001]
- VTT Automation [2000]
WHISPER Overview

Motivation - Thesis Statement - Previous Work - Algorithm - Performance - Conclusion
Pseudonoise and Correlation

- Pseudonoise – known noise-like signal
- Autocorrelation has large value at 0 delay
Correlation Demo

Motivation - Thesis Statement - Previous Work - Algorithm - Performance - Conclusion
Correlation is Expensive!

- Assuming 1000 sample window, 500 Hz computation rate:
  - 1000 multiply-adds per delay
  - 1000 possible delays
  - 500 times per second

Total Cost = 1 billion operations per second!
**WHISPER’s Algorithm**

- Limit delay search range
- Limit computation cost per delay

Initialize with Correlation

Kalman filter
- Predict

Kalman filter
- Correct

Reduced Correlation search around prediction + interpolation

Motivation - Thesis Statement - Previous Work - **Algorithm** - Performance - Conclusion
Kalman Filter Basics

• Predictor/Corrector

• Three components:
  – State estimate with variances
  – Process Model
  – Measurement Model

Motivation - Thesis Statement - Previous Work - Algorithm - Performance - Conclusion
Correlation with Computation Reuse

100 kHz Sampling rate

1 kHz update rate

= 100 samples between Kalman filter iterations
Correlation with Computation Reuse

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1 kHz update rate

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Input signal
(chunks of 100 samples):

Motivation - Thesis Statement - Previous Work - Algorithm - Performance - Conclusion
Correlation with Computation Reuse

100 kHz Sampling rate

1 kHz update rate

= 100 samples between Kalman filter iterations

Input signal
(chunks of 100 samples):

Iteration

k

Correlation window (1000 samples)
Correlation with Computation Reuse

100 kHz sampling rate

\[ \begin{align*}
1 \text{ kHz update rate} & \quad = 100 \text{ samples between Kalman filter iterations} \\
\end{align*} \]

Input signal (chunks of 100 samples):

\[ \begin{array}{c}
\text{Iteration} \\
\begin{array}{c}
\text{k} \\
\text{k+1}
\end{array}
\end{array} \]

Correlation window (1000 samples)

Motivation - Thesis Statement - Previous Work - **Algorithm** - Performance - Conclusion
Calculating Position from Range

• Easiest to look at 2D example:
Calculating Position from Range

- Easiest to look at 2D example:
Easiest to look at 2D example:
Prototype Configuration

Microphone 1

Microphone 2  30.5 cm  Microphone 3

30.5 cm

Speaker on target

Motivation - Thesis Statement - Previous Work - Algorithm - Performance - Conclusion
Error Sources

- Noise
- Local environmental conditions
- Directionality of transducers
- Geometric dilution of precision
Geometric Dilution of Precision

Motivation - Thesis Statement - Previous Work - **Algorithm** - Performance - Conclusion
3D, 2 Target Demonstration

Motivation - Thesis Statement - Previous Work - Algorithm - Performance - Conclusion
Overall 3D Performance

- 1000 updates per second
- Static Performance:
  - 0.46 to 0.91 mm standard deviation
- Latency
  - 18-49 ms depending on signal-to-noise ratio
Noise Performance (Range)

Motivation - Thesis Statement - Previous Work - Algorithm - Performance - Conclusion
## Static 3D Performance

<table>
<thead>
<tr>
<th>Rail Orientation</th>
<th>Measured Rail Distance</th>
<th>WHISPER Distance</th>
</tr>
</thead>
<tbody>
<tr>
<td>X</td>
<td>300 ± 1 mm</td>
<td>300.0 mm</td>
</tr>
<tr>
<td>Y</td>
<td>300 ± 1 mm</td>
<td>300.7 mm</td>
</tr>
<tr>
<td>Z*</td>
<td>300 ± 1 mm</td>
<td>302.6 mm</td>
</tr>
<tr>
<td>Arbitrary</td>
<td>300 ± 1 mm</td>
<td>300.2 mm</td>
</tr>
<tr>
<td>Arbitrary</td>
<td>300 ± 1 mm</td>
<td>300.6 mm</td>
</tr>
</tbody>
</table>

* Rail was not rigidly supported
Dynamic Performance

\[ \sigma = 2.0 \text{ mm} \]

\[ \text{mean} = 202.7 \text{ mm} \]
## Occluded Range Performance

<table>
<thead>
<tr>
<th>Sphere Radius mm</th>
<th>Direct (a) mm</th>
<th>Calculated (b) mm</th>
<th>Measured (b) mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>25.4</td>
<td>642.8</td>
<td>644.8</td>
<td>645.3</td>
</tr>
<tr>
<td>50.8</td>
<td>642.8</td>
<td>650.8</td>
<td>652.0</td>
</tr>
<tr>
<td>76.2</td>
<td>642.8</td>
<td>661.0</td>
<td>663.0</td>
</tr>
<tr>
<td>101.6</td>
<td>642.8</td>
<td>675.2</td>
<td>676.8</td>
</tr>
</tbody>
</table>
Occluded 3D Performance

Error caused by occlusion of one range measurement

Motivation - Thesis Statement - Previous Work - Algorithm - Performance - Conclusion
Occluded 3D Performance

Error caused by occlusion of three range measurements, 5 cm from speaker
• Interesting computational approach to a spread spectrum ranging system
• Compared to existing acoustic systems:
  – More robust to noise and multipath
  – Better performance (rate, simultaneous targets)
• Diffraction allows tracking during occlusions
Applications

- Body tracking
- HCI device (like mouse)
- Lab-mounted (ceiling) tracker
Future Work

• Filtering & Auto Gain Control (AGC) on input
• Miniaturization and “wearability” of system
• Adaptations abound:
  – Output volume to background noise
  – Output spectrum to occlusion (ultrasonic?)
• Use kinematic structure of human body
Acknowledgements

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- My family
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THE END!
No, really. That was the end.
Spectrogram
Dual Target Velocities

Target velocities for interspeaker measurements

- Target 1
- Target 2

speed (m/s) vs. time (seconds)
Dual Target Velocity Differences

Speed difference between the two targets during interspeaker measurements

- **x-axis:** time (seconds)
- **y-axis:** speed difference (m/s)