SurfaceVibe: Vibration-Based Tap & Swipe Tracking on Ubiquitous Surfaces

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Touch Inputs

- People rely on touch to interact with everyday objects
- Touch enables intuitive human-machine interactions
We Touch Surfaces Beyond Touch Screens

People touch various surfaces in life
# Ubiquitous Touch Sensing

<table>
<thead>
<tr>
<th>Feature</th>
<th>Capacitive-based</th>
<th>Vision-based</th>
<th>Vibration/Acoustic-based</th>
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<tbody>
<tr>
<td><strong>Accuracy &amp; Resolution</strong></td>
<td>High</td>
<td>Medium</td>
<td>Low</td>
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<tr>
<td><strong>Sensing Requirements</strong></td>
<td>Require high density / expensive sensor</td>
<td>Require line-of-sight</td>
<td>Low cost vibration sensors</td>
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<td><strong>Applicable Surface Types</strong></td>
<td>Capacitive screens</td>
<td>Multiple surfaces</td>
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</tr>
</tbody>
</table>

- **Capacitive-based**
  - High accuracy and resolution
  - Require high density/ expensive sensor
  - Applicable surface types: Capacitive screens

- **Vision-based**
  - Medium accuracy
  - Require line-of-sight
  - Applicable surface types: Multiple surfaces

- **Vibration/Acoustic-based**
  - Low accuracy
  - Low cost vibration sensors
  - Applicable surface types: Multiple surfaces
Vibration/Acoustic-Based Touch Sensing

- Touch inputs cause object surfaces to vibrate
- The vibrations travel through solids and can be detected by vibration sensors
- Vibration sources (touch inputs) can be localized/recognized
Related Work

Gesture Classification
- Need large amount of training data
- Limited by gesture set

TDoA-based Zone Level Localization
- Zone number is limited
- Low resolution

TDoA-based Multilateration
- Limited scenarios (materials, size, etc.)
- Lack robustness & accuracy

Challenges and Objectives

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<th>Challenges</th>
<th>Our Objectives</th>
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<td>Distortion during propagation</td>
<td>Handling dispersion and reflection (use physics knowledge on wave)</td>
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<tr>
<td>Surface material variation</td>
<td>Characterizing multiple surface conditions (material, size, sensor placement, etc.)</td>
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<tr>
<td>Interaction variation (tap &amp; swipe)</td>
<td>Localizing taps and tracking swipes (with cm level accuracy)</td>
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Our Approach: SurfaceVibe

Interactions induce vibration

- Sensing
- Interaction Detection
- Tap or swipe?
- Tap Localization
- Initial Tap Localization
- Swipe Tracking
- Location
- Trajectory
- Touch inputs
Interaction 1: Tap

The impact induces waves dominated by Rayleigh–Lamb waves.

gif credit: http://web.ics.purdue.edu/~braile/edumod/waves/WaveDemo.htm
Interaction 2: Swipe

The friction induces waves dominated by Shear waves

gif credit: http://web.ics.purdue.edu/~braile/edumod/waves/WaveDemo.htm
Vibration Signal Sensing

- Four vibration sensors cover a sensing area
- Sensors are synchronized to each sampling point
- Raw signals are amplified before ADC
- Surfaces’ edges are mounted by weights *(optional)*
Interaction Detection & Characterization

Tap and swipe induce waves with different characteristics. Different methods targeting these characteristics are carried out.

- Tap
  - More complicated frequency domain
  - More affected dispersion effects

- Swipe
  - More focused frequency domain
  - Less affected dispersion effects
Tap Localization

Wave Propagation Property: Dispersion

different propagation length

Wavelet: Decompose the Impulse Signal

use first peak to estimate TDoA (avoid reflection)
Swipe Tracking

- The segments contain ‘slip-pulses’ caused by stick-slip motions
- Each segment shows correlation and time shift through sensor pairs → cross correlation to get TDoA
- The initial contact point can be used to correct trajectory
- There is no ‘first peak’ → mount loose edge to reduce reflection
Experiment

- **Reflection Reduction -- damping with sand-filled weights**
  - enhance the coupling and dampen the wave reflection at the **loose edges**
  - represent real-world table/wall conditions

- **Investigating Parameters**
  - **5 materials**
    - wood, iron, cement, stone, ceramic tile
  - 4 different board sizes
    - size = 40/60/80/100cm
  - 5 different distance between sensors
    - distance = 40/50/60/70/80cm

- **Evaluating Interactions**
  - Tap: 16 points → location
  - Swipe: 8 directions → trajectory length/angle

(a) Wood board baseline
(b) Wood board damped
Tap Localization Example

- Filtering allows consistent TDoA estimation
- Band and velocity calibration allows accurate location estimation
Tap Localization Evaluation

- SurfaceVibe improves the localization accuracy on 5 different materials compared to baseline.
- Average localization accuracy through 5 materials is improved by 6X.
Swipe Tracking Example

System output ‘slip-pulse’ locations
Ground truth trajectory
Swipe Tracking Evaluation

- Wood surface avg. length error
- Baseline (only use slip-pulse locations): -8.15 cm
- Reflection reduction: -5.83 cm
- Initial point correction: -5.9 cm
- SurfaceVibe: -2.67 cm (error ↓ 3X)
Swipe Tracking Evaluation

- SurfaceVibe improves the length estimation accuracy on 4 different materials
- Exception: ceramic
  - only available in 40cmX40cm
  - different dampening boundary conditions
- Avg. length over 5 materials error ↓ 3X
- SurfaceVibe improves the average angle error as well
Conclusion

- SurfaceVibe turns common surfaces in life into touch inputs.
- We study waves properties and design the system to reduce dispersion and reflection, thereby enabling accurate localization of taps and swipes.
- We characterize different surface materials and settings to evaluate the accuracy and robustness of the system.
- Our algorithm achieves up to 6X improvement in tap localization and 3X improvement in swipe length estimation.
Thanks!

Questions?

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