Toward Tracking Multiple Building Occupants by Footstep Vibrations

Jeffrey D. Poston

poston@vt.edu

Copyright © 2018 by Jeffrey D. Poston. All rights reserved.
Key Idea: Footstep Vibrations are a Novel Source of Information for Localization and Tracking

- Vibration sensors (accelerometers) are in some buildings now

- For example, Virginia Tech’s Goodwin Hall has 200+ sensors

- Sensors are mounted to steel girders; the original intent was to study structural dynamics
Prior Work Addressed Complex Wave Interactions with I LoViT Algorithms for Sub-meter Localization Accuracy

- Figures from “I-LoViT: Indoor Localization by Vibration Tracking,” (J. Poston, GlobalSIP 2016)
Tracking Multiple Building Occupants must Resolve the Footstep-to-Occupant Data Association Problem

- The radar community’s multiple hypothesis tracking (MHT) relevant here (e.g., the “Track Tree” of Kurien’90), but there are important distinctions for this research:
  - *Walking gait* versus radar-style “gating” (i.e., error ellipse)
  - *Event-driven* processing of footsteps, not periodic radar scans
  - Both *conjectured miss* and *confirmed miss* distinguishable in footstep-based localization
The Track Tree Holds Hypothesized Footstep-to-Track Assignments; Then Tree Pruning Reduces Complexity

- One tree $\mathcal{T}_n$ for each active or new track
- Footsteps are $f_1, \ldots, f_k$
- Space-time windowing around the root finds footsteps consistent with human gait

A miss $\emptyset$ is always possible; consecutive misses $\rightarrow$ unlikely track
This also suppresses new tracks from false alarms
Example for Active Tracks $\mathcal{T}_1$, $\mathcal{T}_2$ and New Steps $\{f_5, f_6, f_7, f_8\}$
Kalman Filtering Provides a Trajectory Prediction for each Branch and Gives Likelihood of Footsteps

- First, there is a state estimate $\hat{x}$ that gives a predicted position $\hat{z}$

- The windowed footsteps $\{f_5, f_6\}$ have position uncertainty too

- The Mahalanobis distance distribution informs the likelihood calculation
  $$(z_j - \hat{z}_i)^T S_i^{-1} (z_j - \hat{z}_i)$$
  $S$ is residual or innovation covar.

Also, Kalman filtering with missing observations handed in a principled way (B. Sinopoli et al., 2004)
Constrained Optimization Enforces Globally Consistent Assignment of all Footsteps

\[
H_{\mathcal{T}_1} = \begin{bmatrix}
1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
1 & 1 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 1 & 1 & 1 & 0 & 0 & 0 \\
1 & 0 & 0 & 1 & 0 & 0 & 1 & 0 & 0 \\
0 & 1 & 0 & 0 & 1 & 0 & 0 & 1 & 0 \\
0 & 1 & 0 & 0 & 1 & 0 & 0 & 1 & 0
\end{bmatrix}
\]

One tree branch

Branch’s track membership

Footsteps in branch

\[b^* = \arg\min \mathbf{c}^\top \mathbf{b}, \text{ subject to } H\mathbf{b} = 1\]

branch \( b_i \) cost: \( c_i = -\log \text{likelihood}(h_i) \)

\( h_{i,j} \in \{0, 1\}, \quad b_j \in \{0, 1\} \)
Solving the Constrained Optimization Guides Tree Pruning and Trajectory Updating
This Algorithm for Multi-Target Tracking is Believed to be the First that Incorporates Walking Gait

- Example results from Goodwin Hall experiments with ground truth established by lidar

Tracking performance (RMSE): 0.37 m (top track), 0.36 m (bottom)

Tracking performance (RMSE): 0.23 m (top track), 0.36 m (bottom)
This Research Demonstrated Localization and Tracking of Building Occupants Solely from Footstep Vibrations

Benefits

- This approach offers a device free capability
- Camera-based tracking poses privacy concerns as does device-based tracking
  - Nordstrom admitted to tracking shoppers by their smartphone’s Wi-Fi (Clifford & Hardy, NYT 2013); this could be linked to facial recognition

Privacy

Future Directions

- This research would benefit from more experiments with a range of movement patterns
- Individuals may be distinguished by walking gait, thus assisting the data association task