Toward Tracking Multiple Building Occupants by Footstep Vibrations

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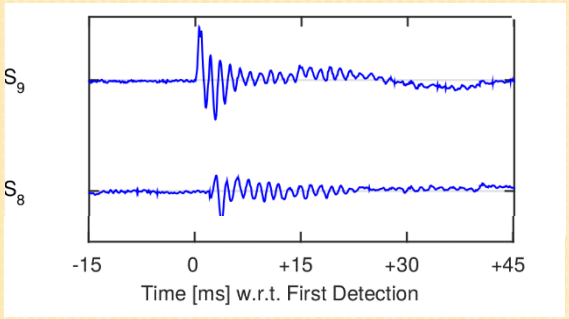

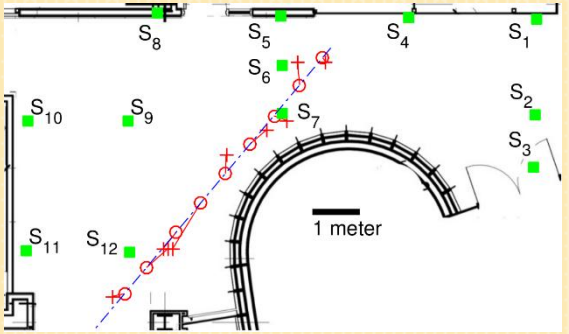

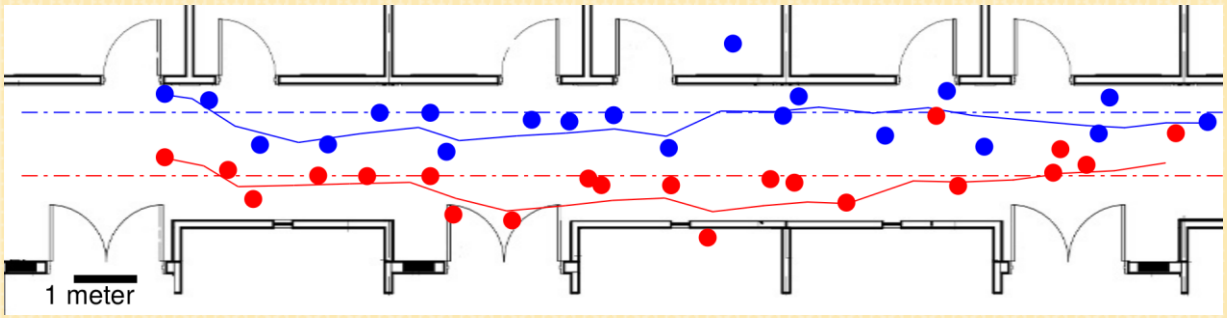

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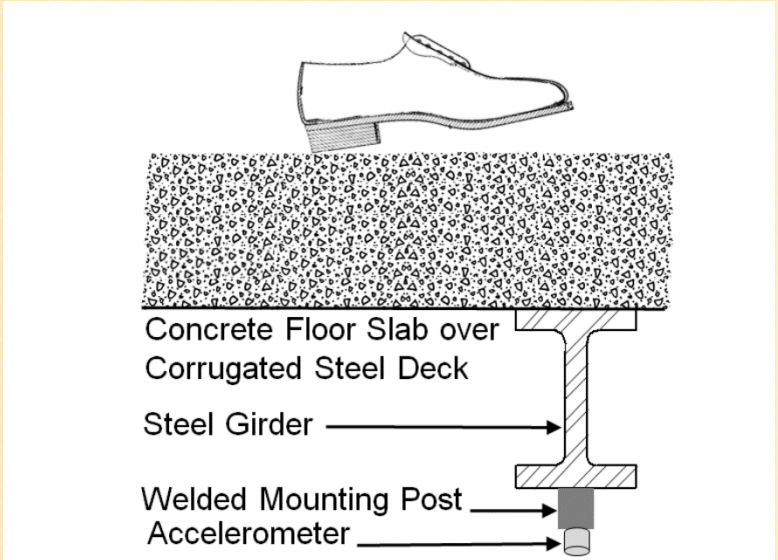
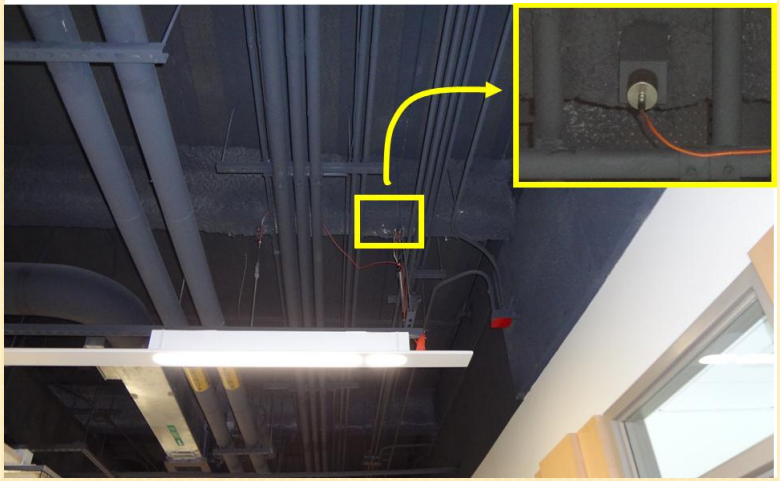
Key Idea: Footstep Vibrations are a Novel Source of Information for Localization and Tracking

- 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





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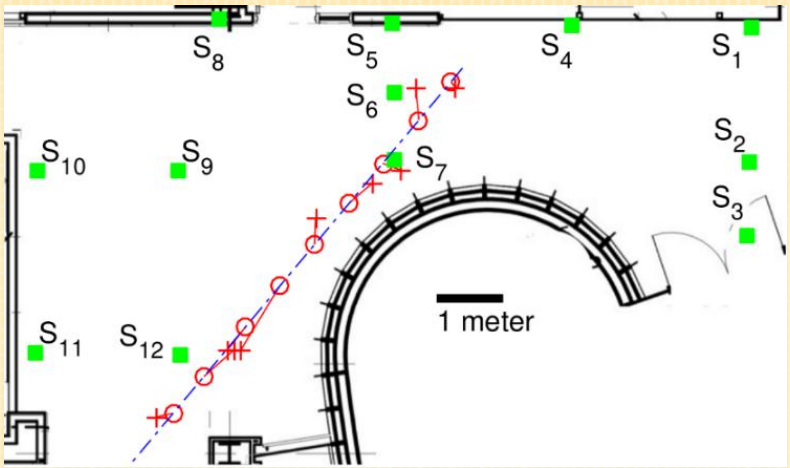
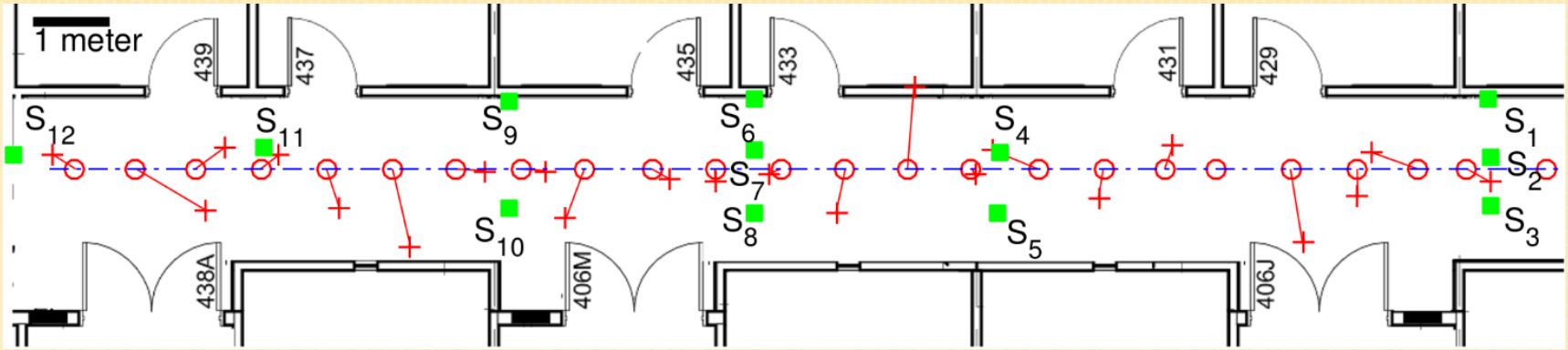
Prior Work Addressed Complex Wave Interactions with I LoViT Algorithms for Sub-meter Localization Accuracy

- Figures from
  "I-LoViT: Indoor Localization by Vibration Tracking,"
  (J. Poston, GlobalSIP 2016)



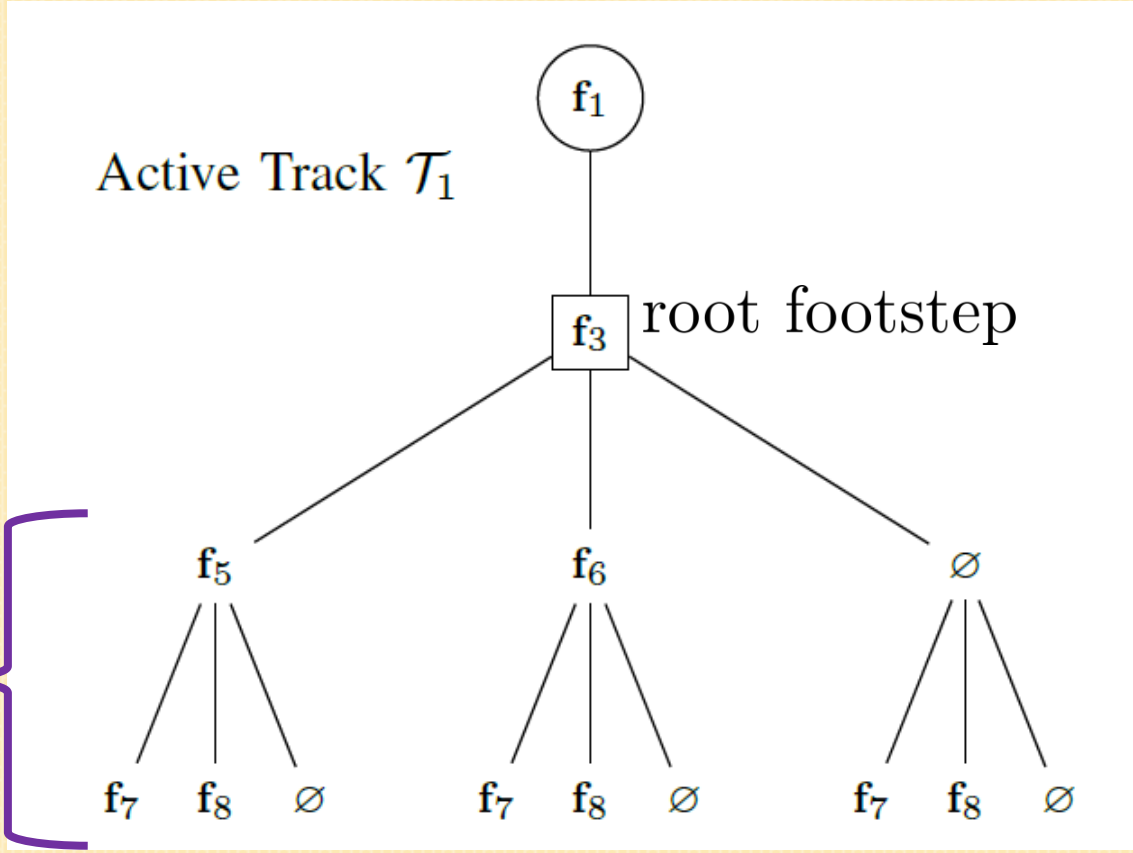


Tracking Multiple Building Occupants must Resolve the Footstep-to-Occupant Data Association Problem

- 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 $\mathbf{f}_1, \ldots, \mathbf{f}_k$
- Space-time windowing around the root finds footsteps consistent with human gait



A miss $\varnothing$ is always possible; consecutive misses → unlikely track

This also suppresses new tracks from false alarms

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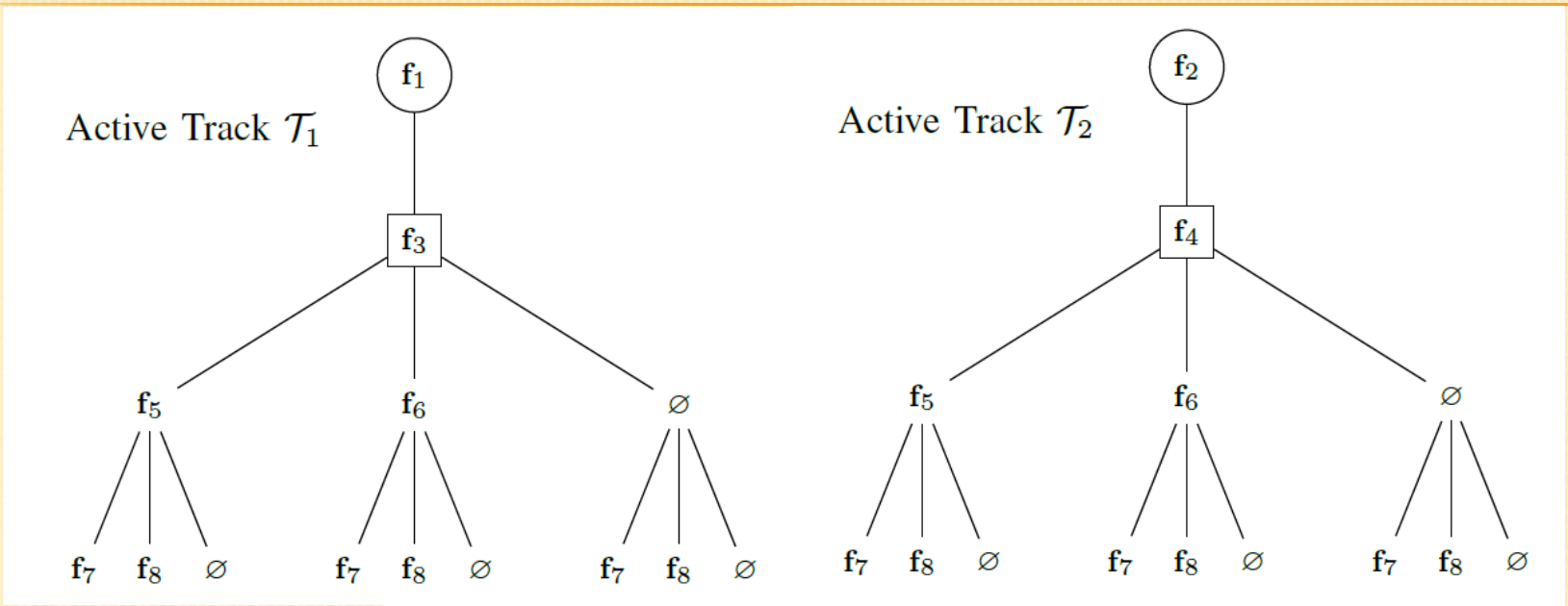
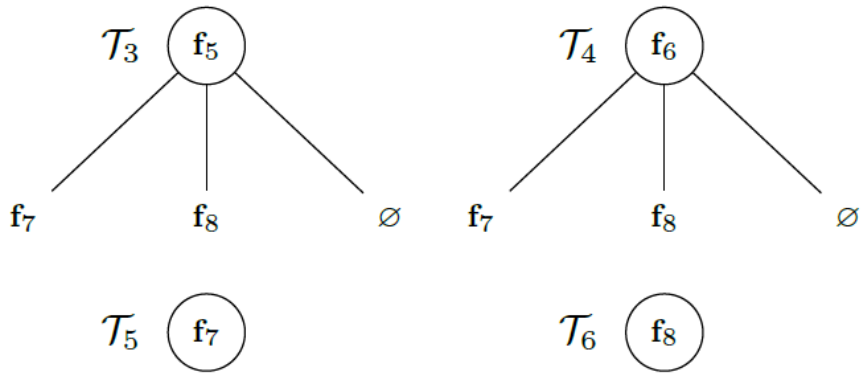
Example for Active Tracks $\mathcal{T}_1, \mathcal{T}_2$ and New Steps $\{f_5, f_6, f_7, f_8\}$



Potential New Tracks $\mathcal{T}_3, \ldots, \mathcal{T}_6$



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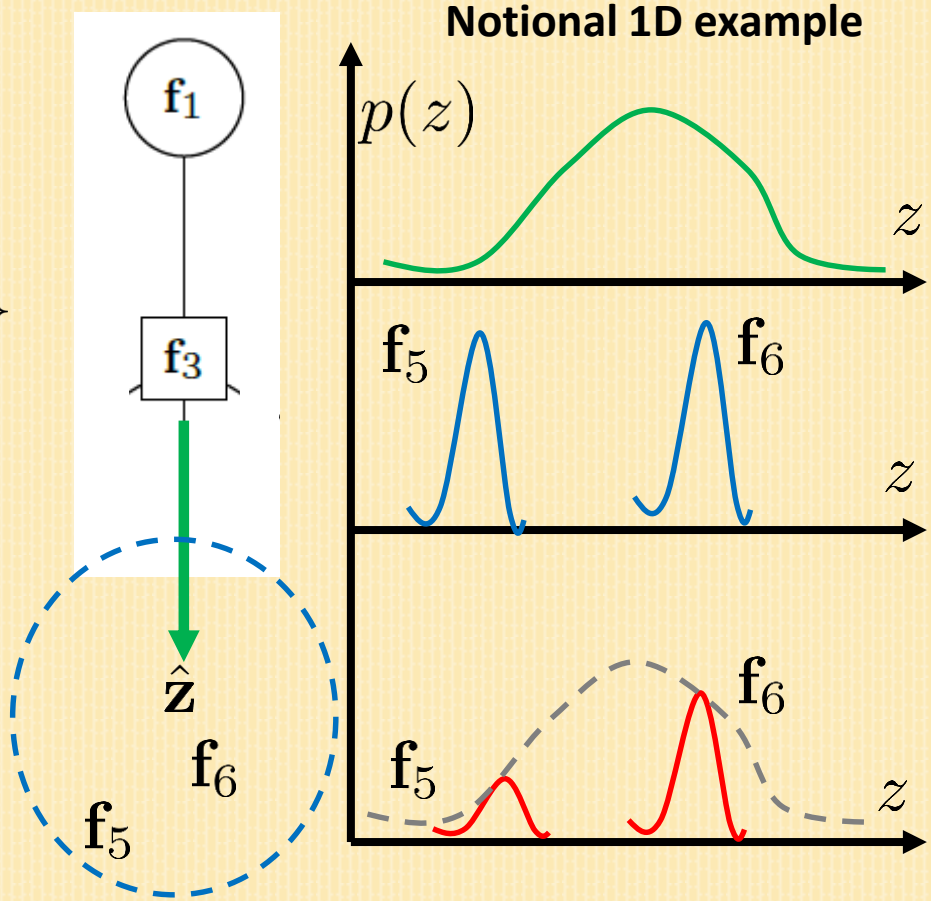
Kalman Filtering Provides a Trajectory Prediction for each Branch and Gives Likelihood of Footsteps

- First, there is a state estimate $\hat{\mathbf{x}}$ that gives a predicted position $\hat{\mathbf{z}}$
- The windowed footsteps $\{\mathbf{f}_5, \mathbf{f}_6\}$ have position uncertainty too
- The Mahalanobis distance distribution informs the likelihood calculation

$$\left(\mathbf{z}_j - \hat{\mathbf{z}}_i\right)^{\mathrm{T}} \mathbf{S}_i^{-1} \left(\mathbf{z}_j - \hat{\mathbf{z}}_i\right)$$

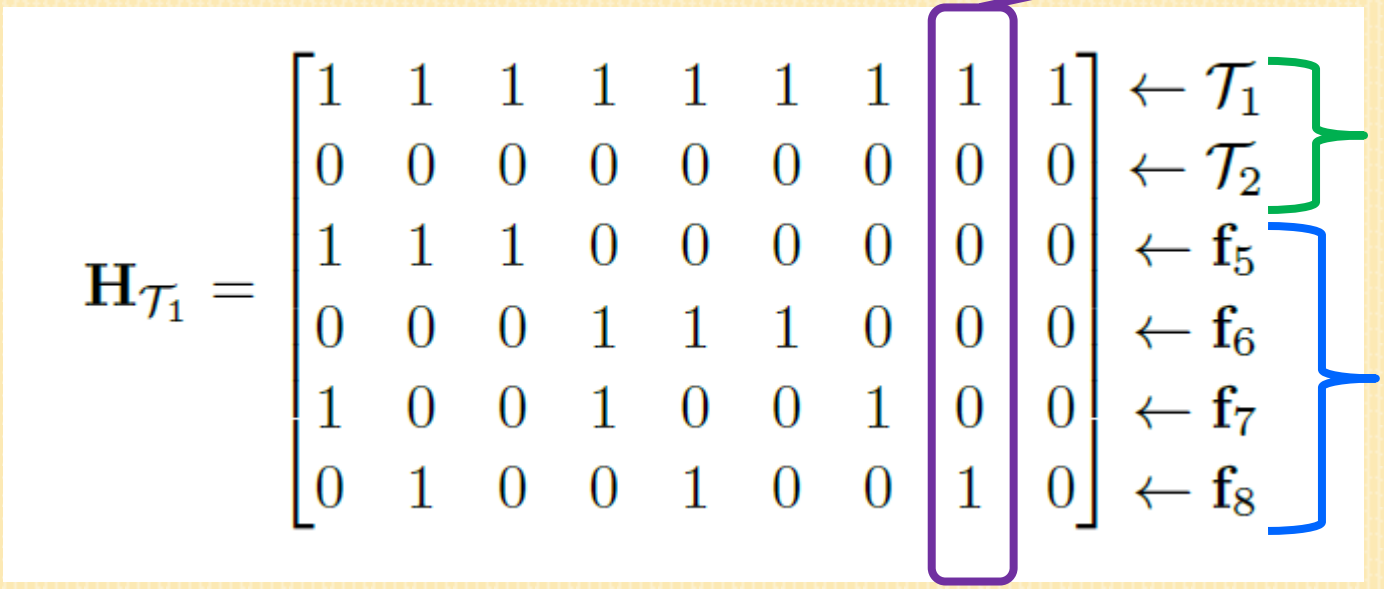
$\mathbf{S}$ is residual or innovation covar.



Also, Kalman filtering with missing observations handled in a principled way (B. Sinopoli *et al.*, 2004)

Constrained Optimization Enforces Globally Consistent Assignment of all Footsteps

Constraint matrix for branches in Track Tree #1



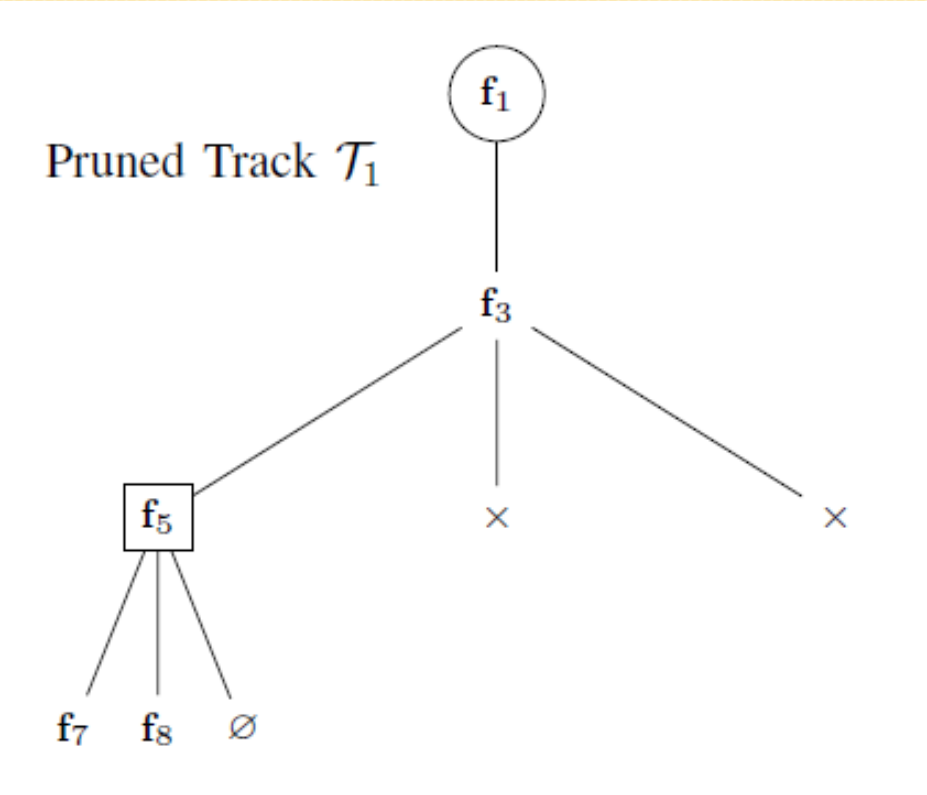
$$\mathbf{H}_{\mathcal{T}_1} = \begin{bmatrix} 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 1 & 1 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 1 & 1 & 0 & 0 & 0 \\ 1 & 0 & 0 & 1 & 0 & 0 & 1 & 0 & 0 \\ 0 & 1 & 0 & 0 & 1 & 0 & 0 & 1 & 0 \end{bmatrix} \begin{matrix} \leftarrow \mathcal{T}_1 \\ \leftarrow \mathcal{T}_2 \\ \leftarrow \mathbf{f}_5 \\ \leftarrow \mathbf{f}_6 \\ \leftarrow \mathbf{f}_7 \\ \leftarrow \mathbf{f}_8 \end{matrix}$$

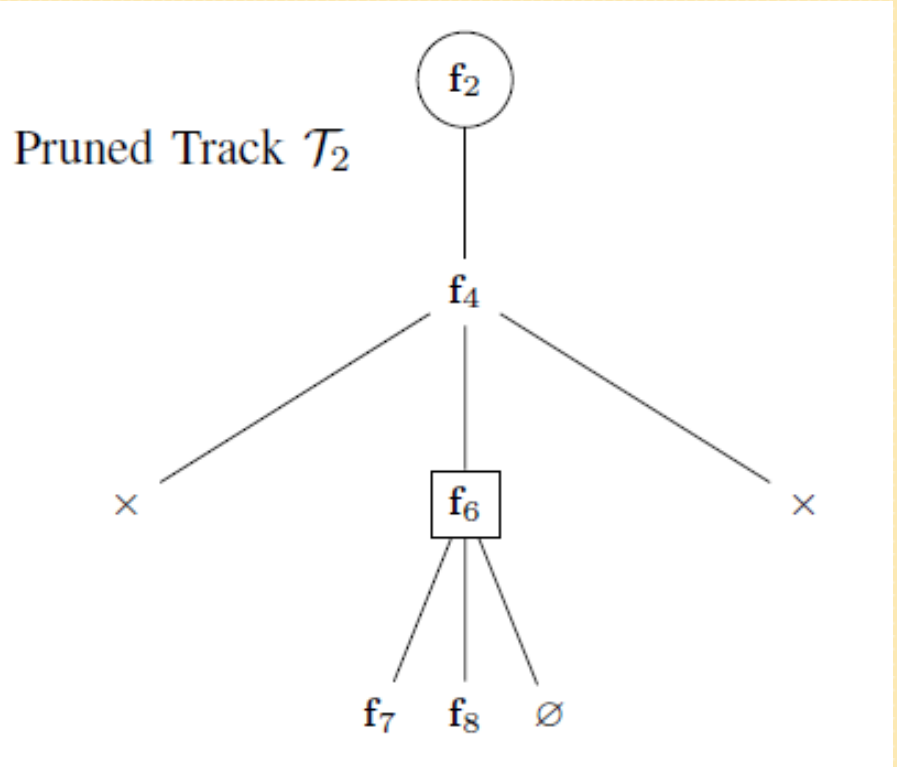
$$\mathbf{b}^\star = \operatorname{argmin} \mathbf{c}^\top \mathbf{b}, \text{ subject to } \mathbf{Hb} = \mathbf{1}$$

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

$$h_{i,j} \in \{0, 1\}, \; b_j \in \{0, 1\}$$

Solving the Constrained Optimization Guides Tree Pruning and Trajectory Updating





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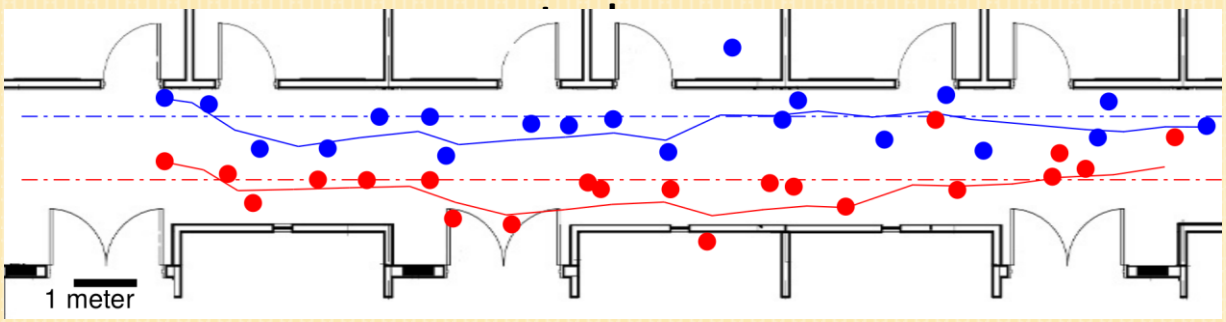
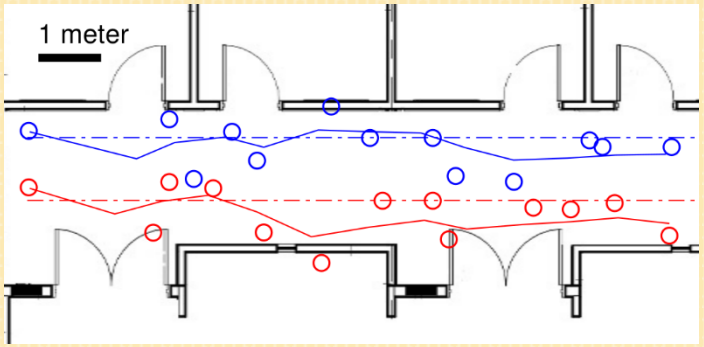
This Algorithm for Multi-Target Tracking is Believed to be the First that Incorporates Walking Gait

- 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)

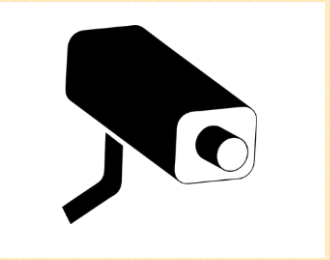


This Research Demonstrated Localization and Tracking of Building Occupants Solely from Footstep Vibrations

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

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