2020 embedded VISION summit

Structures as Sensors: Smaller-Data Learning in the Physical World

Pei Zhang
Associate Research Professor
Electrical and Computer Engineering
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Carnegie Mellon University

How do we understand the physical world?

Growth of Large-Scale Sensing Applications


Tracking


Traffic Congestion


Air Pollution

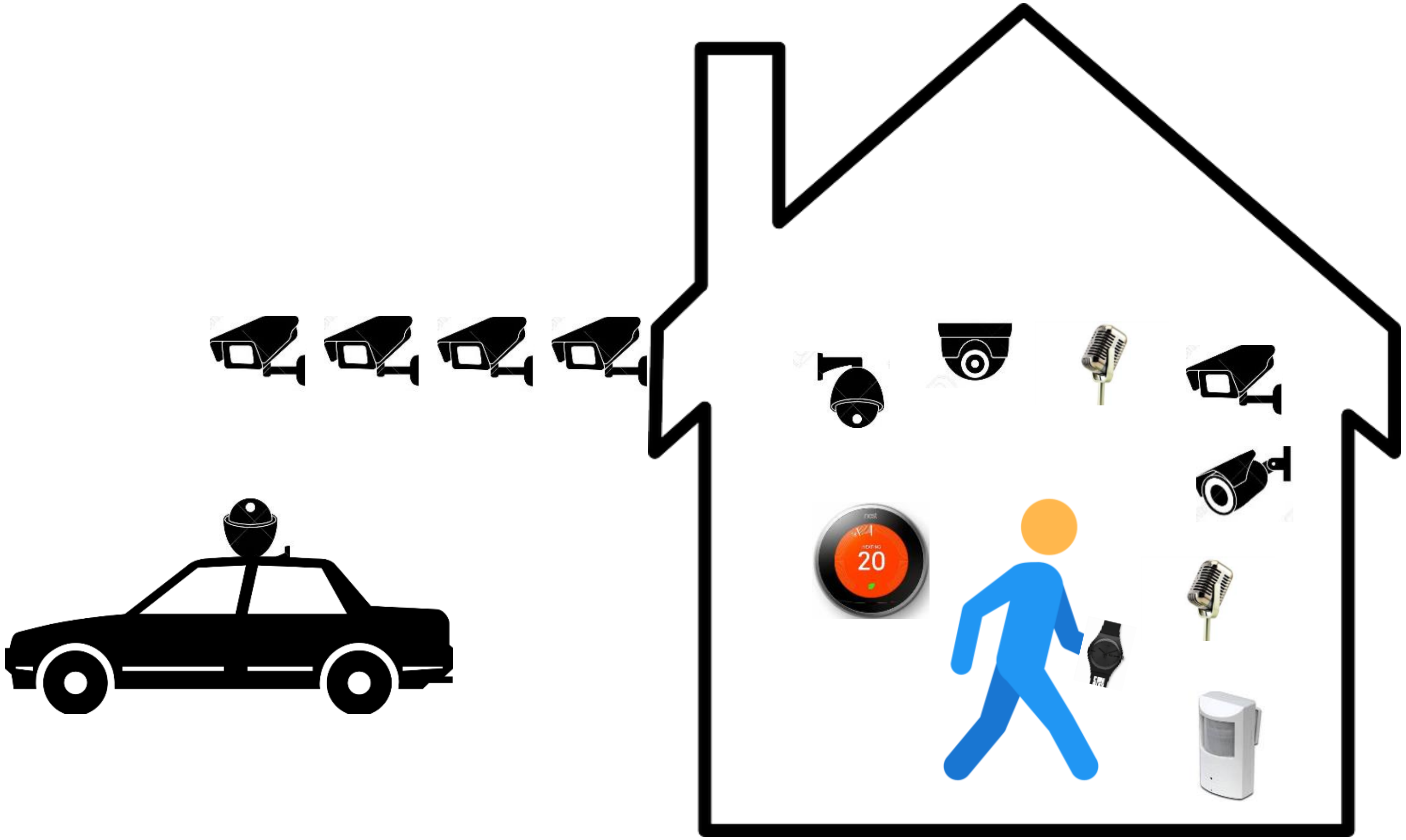

Smart Buildings


Retail


Medical

Enable "Small Data" for Learning through Integration of Physical Understanding

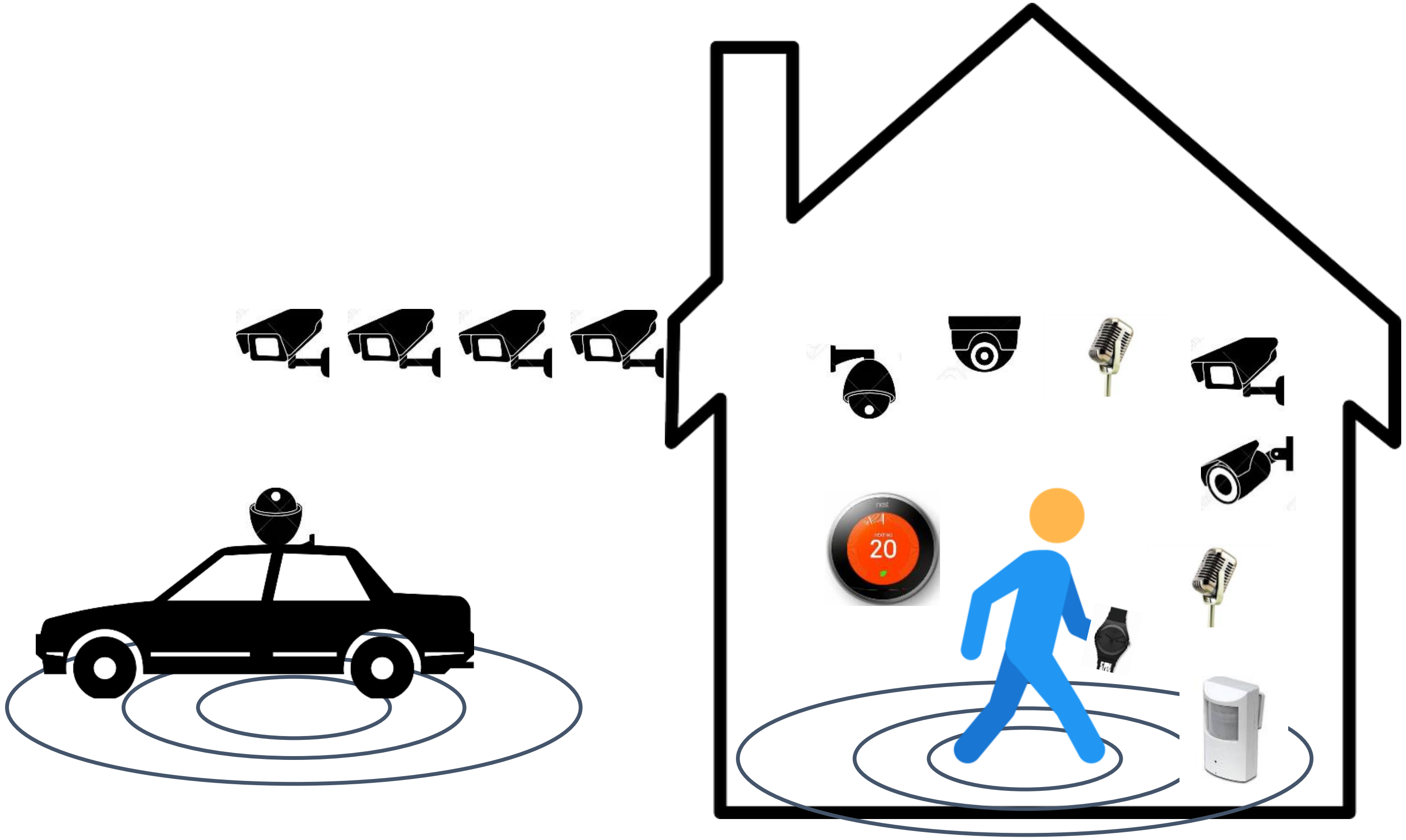
Mobile Sensors **Static Sensors**



- Deploy different sensors everywhere to collect data
- Challenges
  - Difficult to deploy and maintain

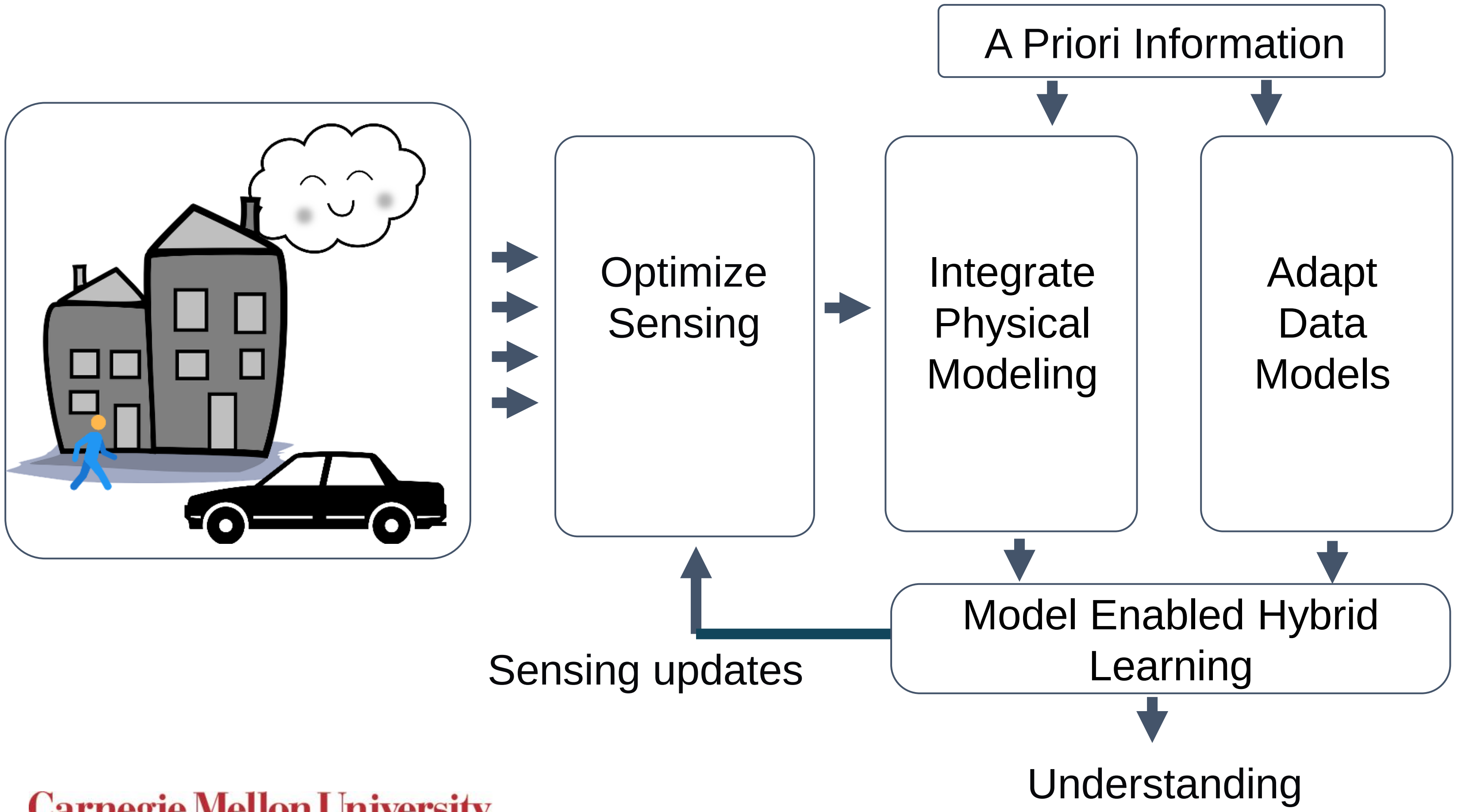
Enable "Small Data" for Learning through Integration of Physical Understanding

Mobile Sensors **Static Sensors**



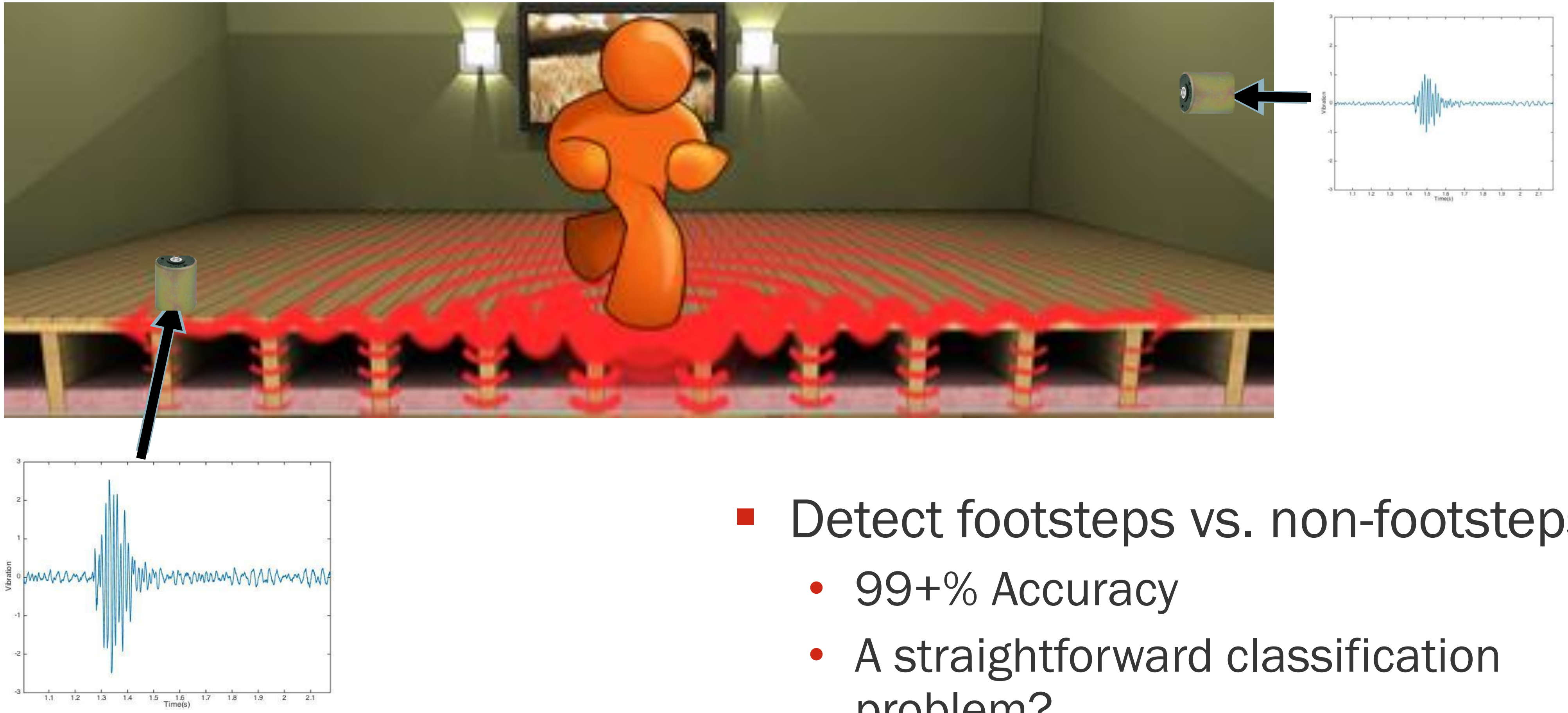
- Using the building as the physical sensor
  - Reduces sensor maintenance
- Challenges
  - More variability
  - Capture a lot of activities

Enable "Small Data" for Learning through Integration of Physical Understanding



1. **Optimize sensing** through sensor hardware adaptation.
2. **Integrate physical models** to offset data needs
3. **Adapt data models** using the physical understanding to transfer data from different applications

Buildings as Sensors



- Detect footsteps vs. non-footsteps
  - 99+% Accuracy
  - A straightforward classification problem?

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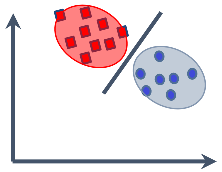
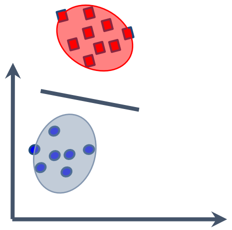
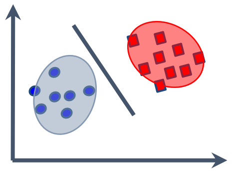
What Happens in Different Buildings?

63% accuracy => Structure-dependent vibration signal characteristics







Structure Effect

$$Y = H \cdot X$$

Vibration Freq Response

Excitation Effect

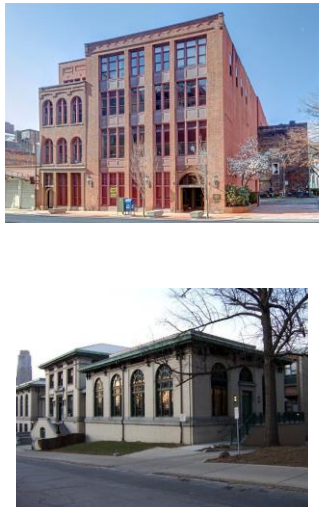
Need to calibrate/train data in every building!

How Can We Minimize Training?

Question: How do we reduce the amount of labeled training data needed?

Our Solution: Structure-Informed Model Transfer

Source Structures



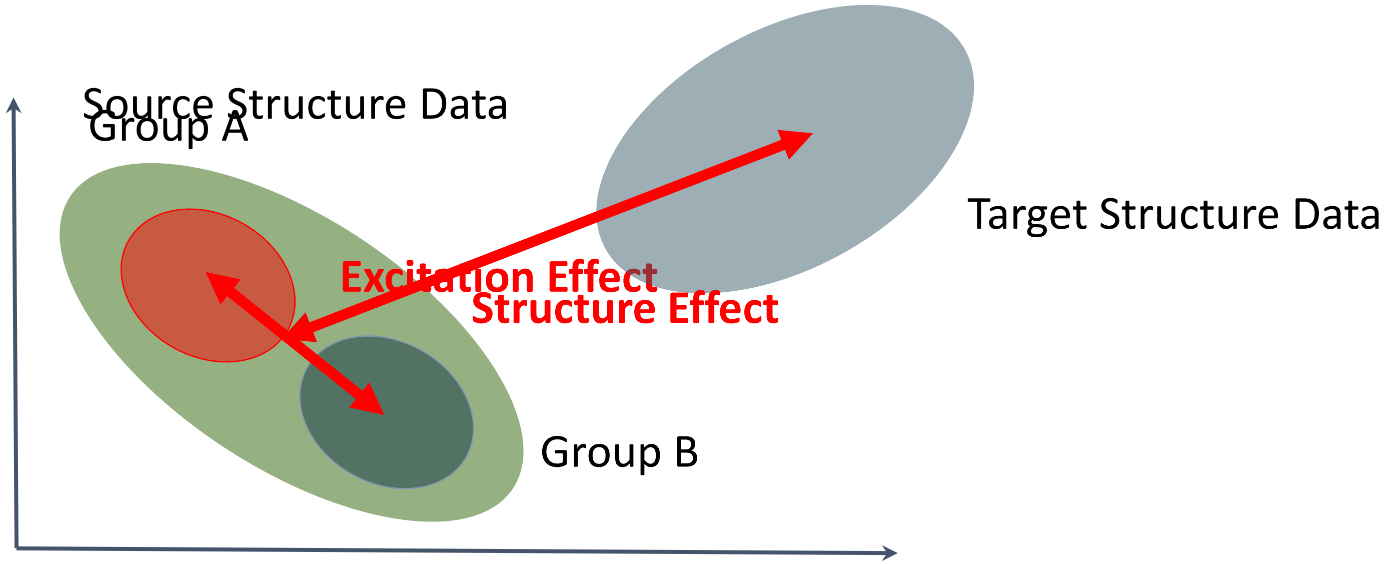
Model Transfer →

Target Structures

Available Labelled Data

No Labelled Data

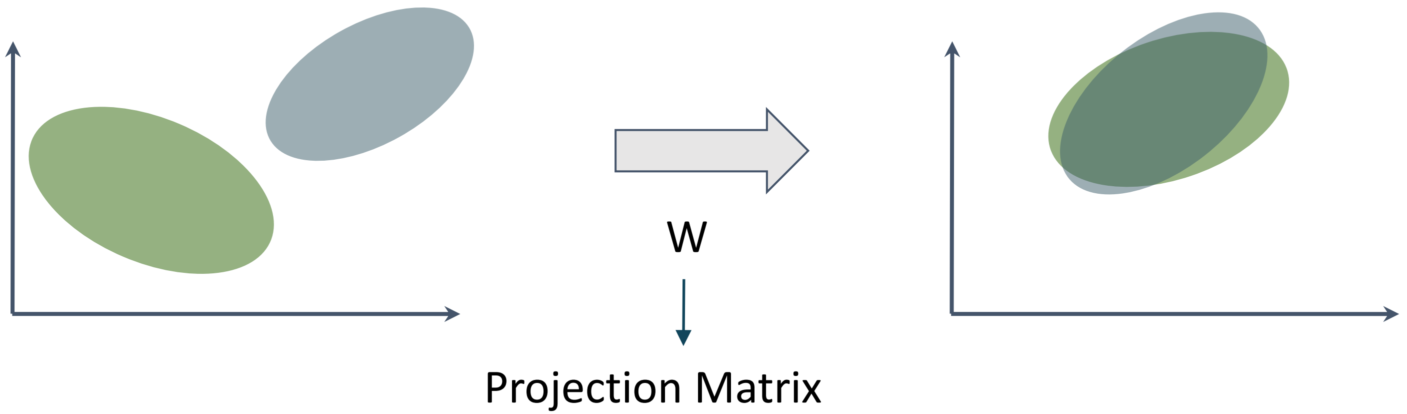
Our Solution: Structure-Informed Model Transfer



How Can We Minimize Training?

Our Solution: Structure-Informed Model Transfer

- We look for projection with lower structural effect.



Low Structural Effect
i.e. building structures has reduced effect on the signal

How can we minimize training?

Our Solution: Structure-Informed Model Transfer

- Write in the form of transductive component analysis.

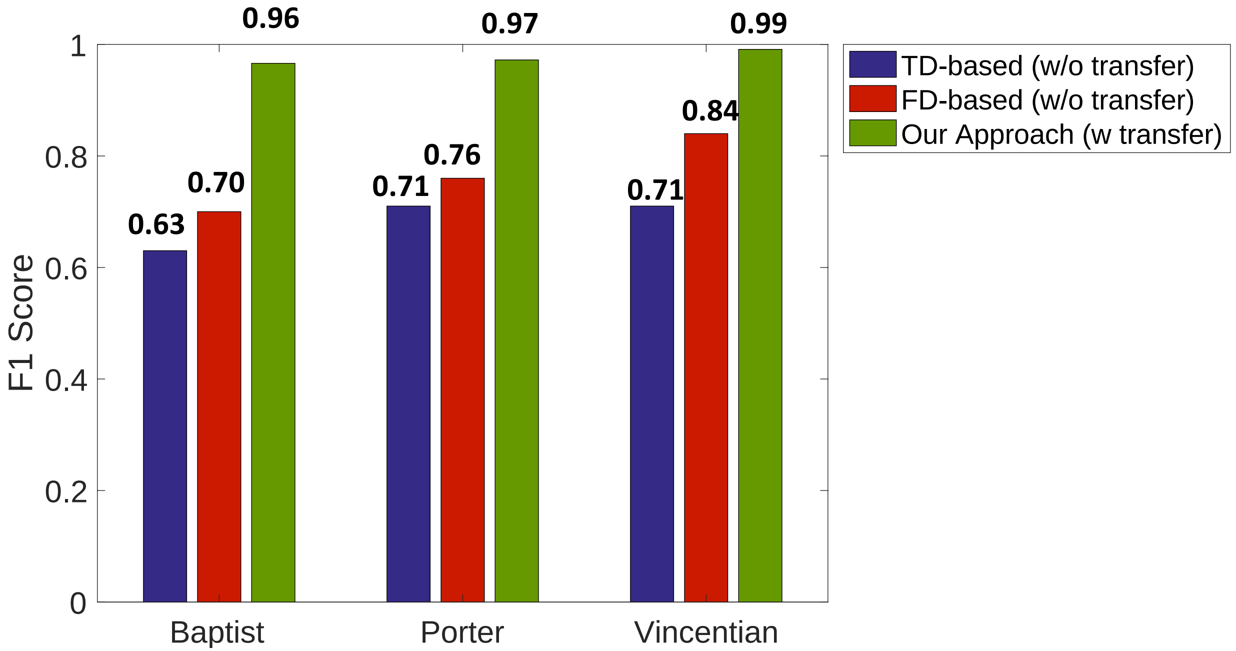
$$min_W tr(W^T \bar{K} L \bar{K} W) + \mu tr(W^T W) + \frac{\lambda}{n^2} tr(W^T \bar{K} \mathcal{L} \bar{K} W)$$

$$s.t. \quad W^T \bar{K} H \widetilde{K}_{yy} H \bar{K} W = I$$

- $tr(W^T \bar{K} L \bar{K} W)$: Structural Effect
- $W^T \bar{K} H \widetilde{K}_{yy} H \bar{K} W = I$: Label Information
- $\mu tr(W^T W)$: Regularization Term
- $\frac{\lambda}{n^2} tr(W^T \bar{K} \mathcal{L} \bar{K} W)$: Distribution Shape Preserving

- Derived from Physical equations => Interpretable

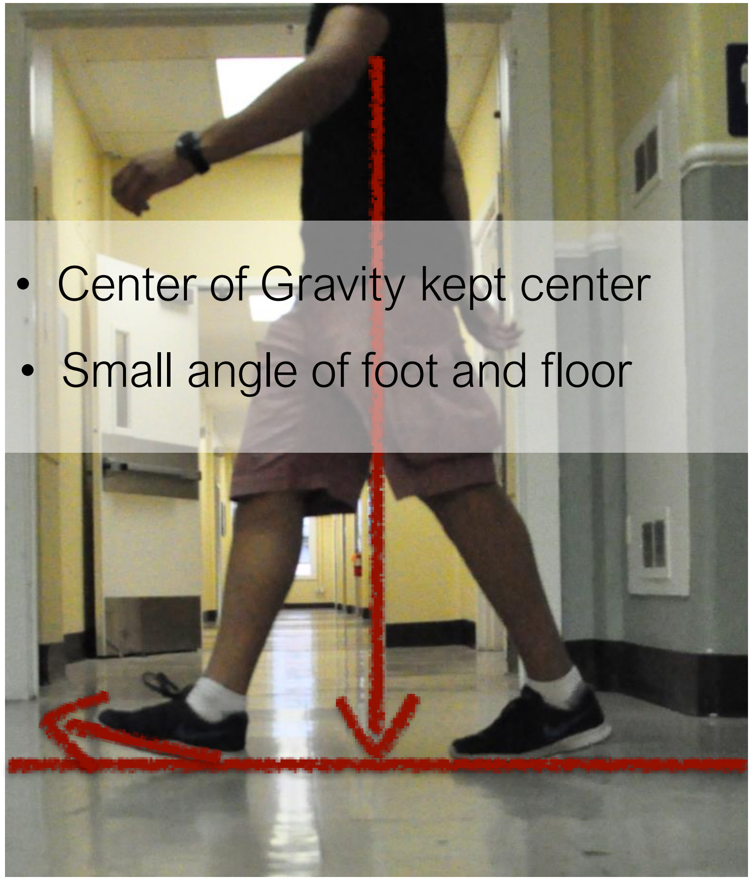
Footstep Detection Evaluation

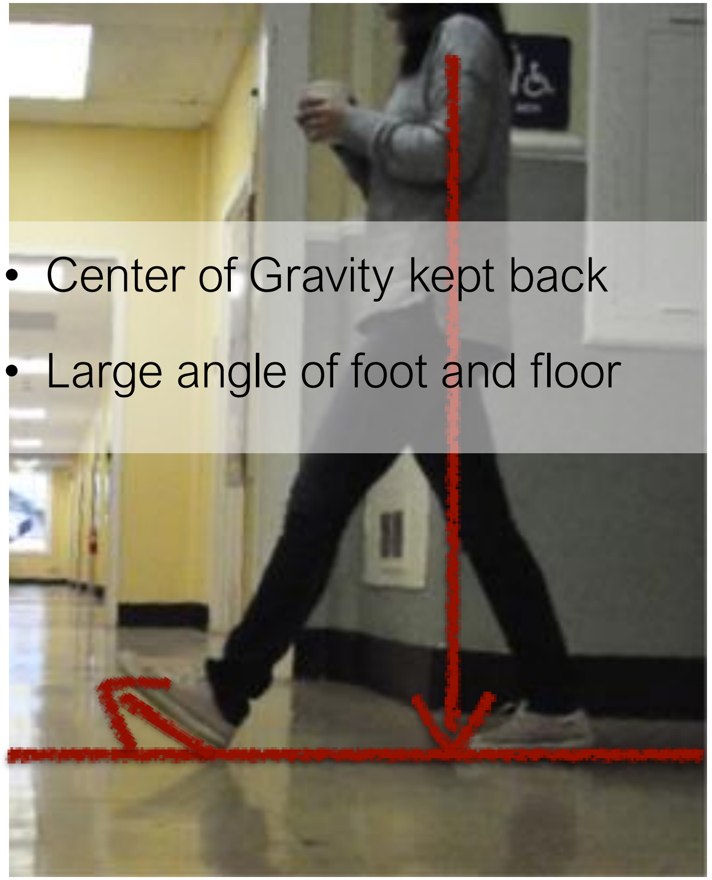


- 9.25X, 9.7X, and 29X reduction in error for TD-based
- 7.5X, 8X, and 16X reduction in error for FD-based

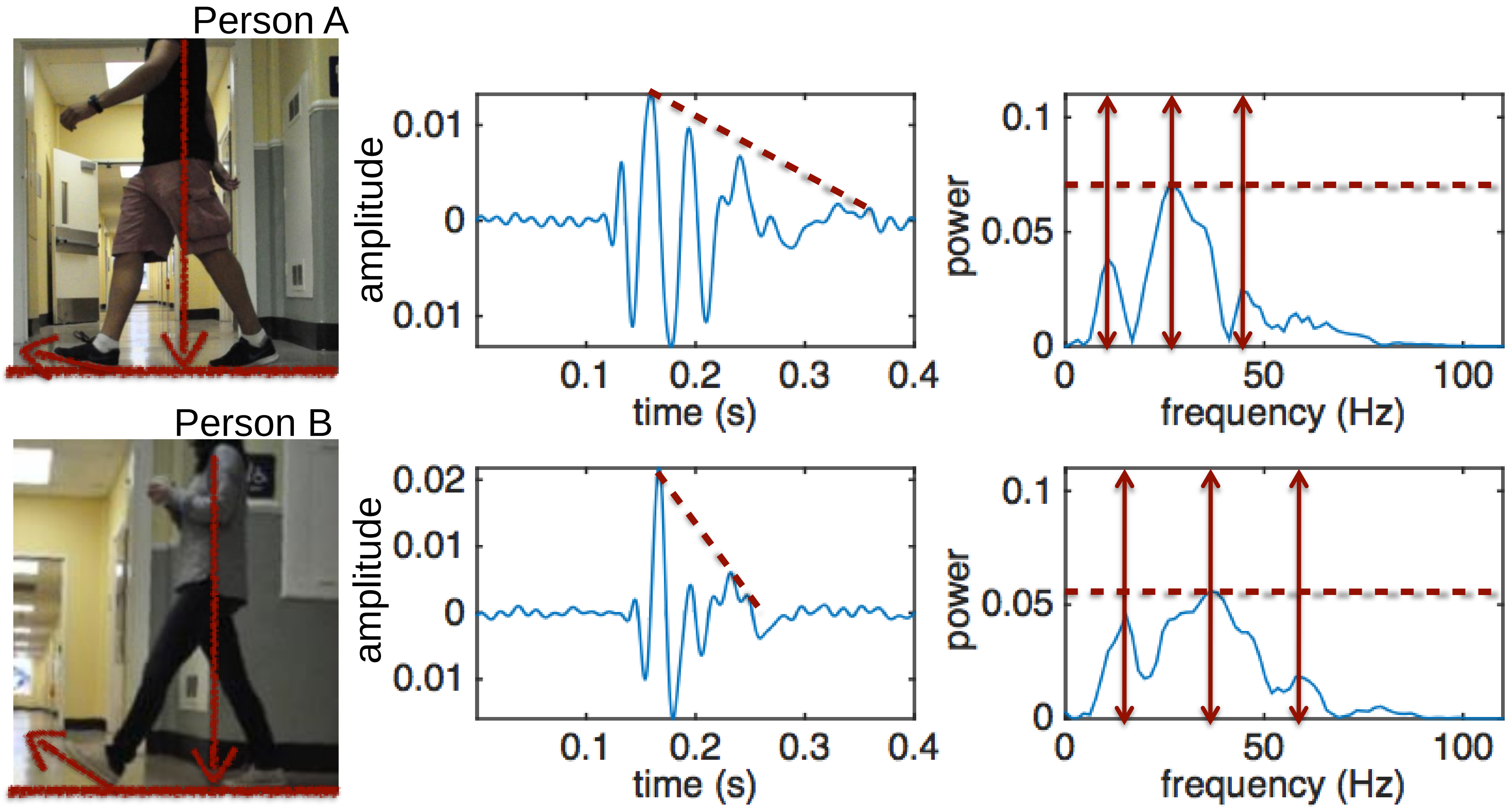
Example Application:
Using Structure Vibrations to Identify People

Example: Identification

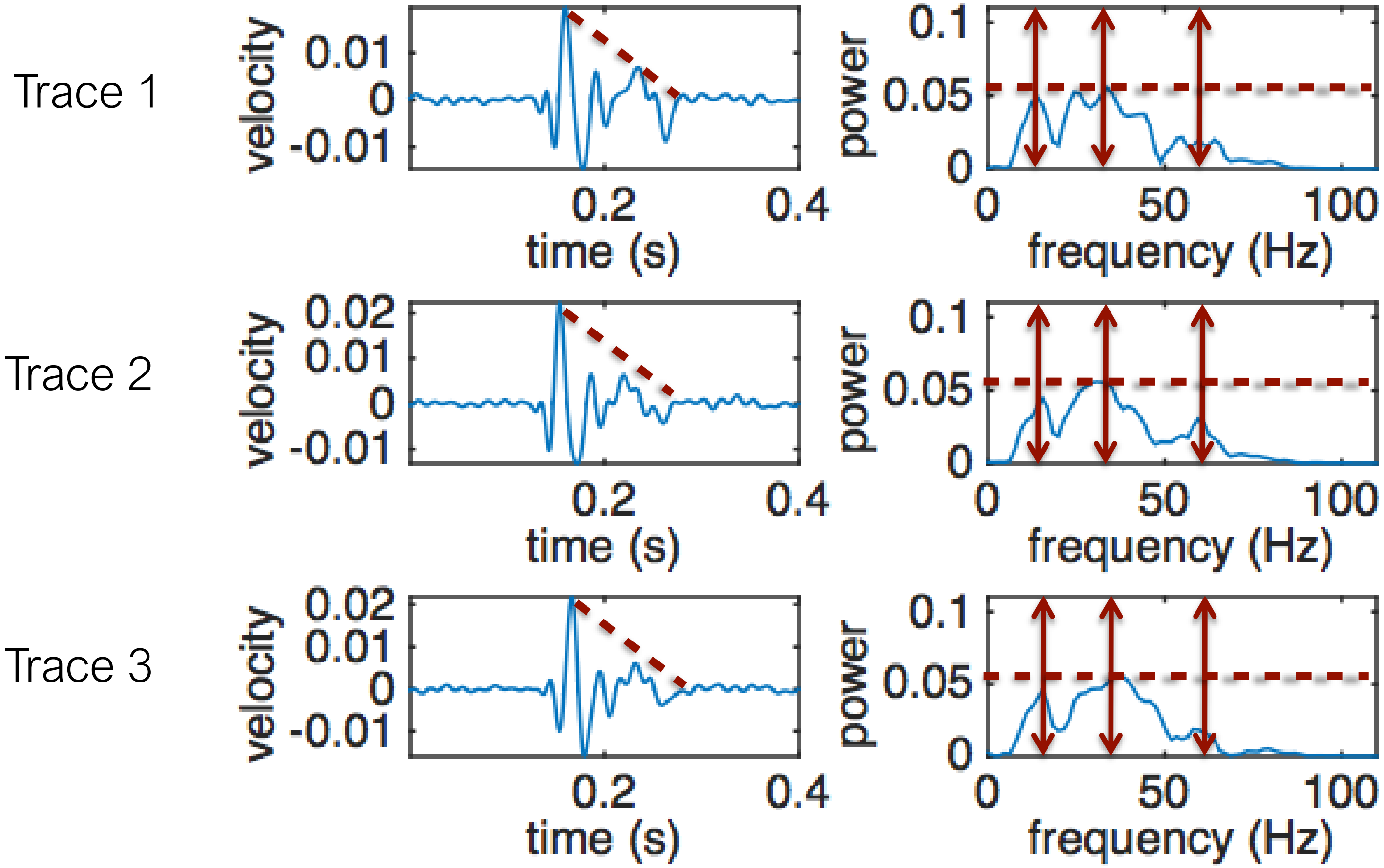




People walk differently

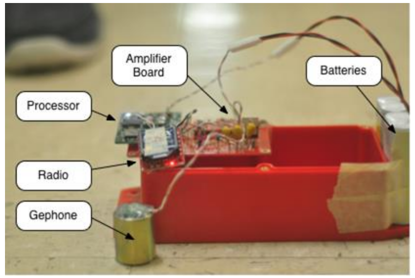


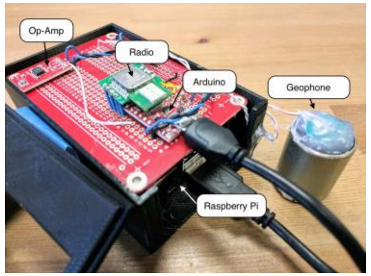
Same Person Walks the Same

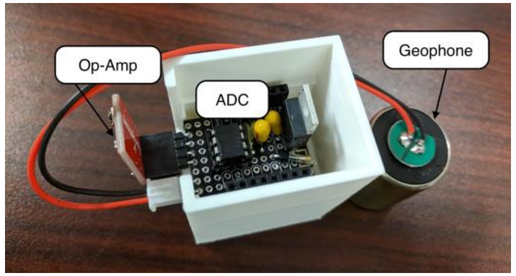


Hardware for Human-Induced Floor Vibration

Building Occupant Monitoring Box







4 Hardware Versions

- Increase sensitivity (dynamic sensing range)
- Optimize settings for maximum signal resolution
- Reduce structural variation

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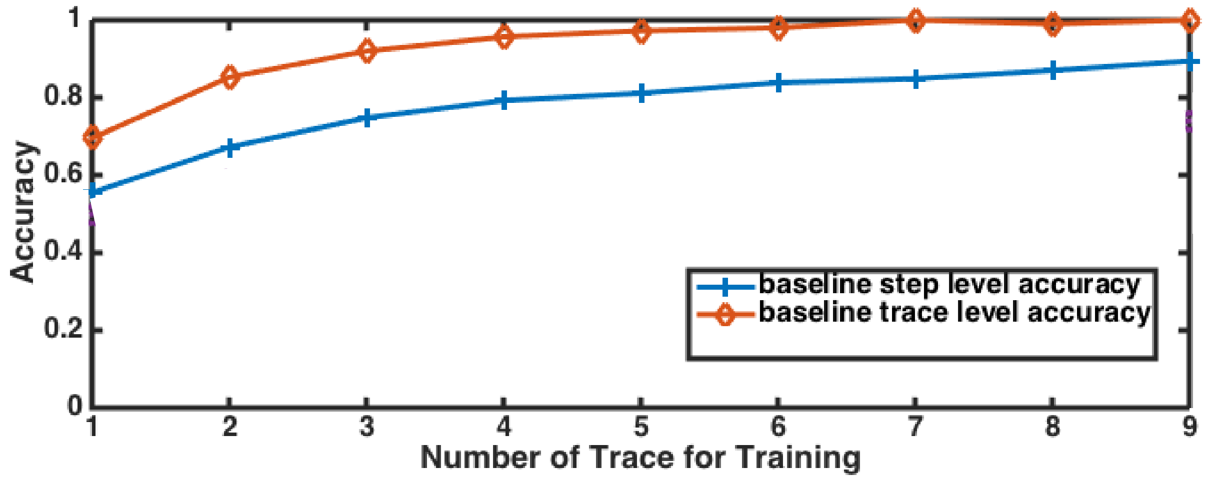
Identify: Evaluation Results

- 10 people
- 10 traces per person
- SVM
- Single sensor in hallway



- Step level identity classification reaches 90%
- Trace level identity classification reaches 99%

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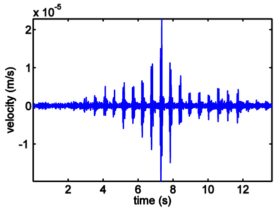
Building as Sensor Summary



Identity/ Characteristics

Person Characteristics

- Inference using footstep vibration
- Identity, Balance, Muscular Dystrophy, Dementia, etc.
- Performance: 99% identity

Location

Inference of Location

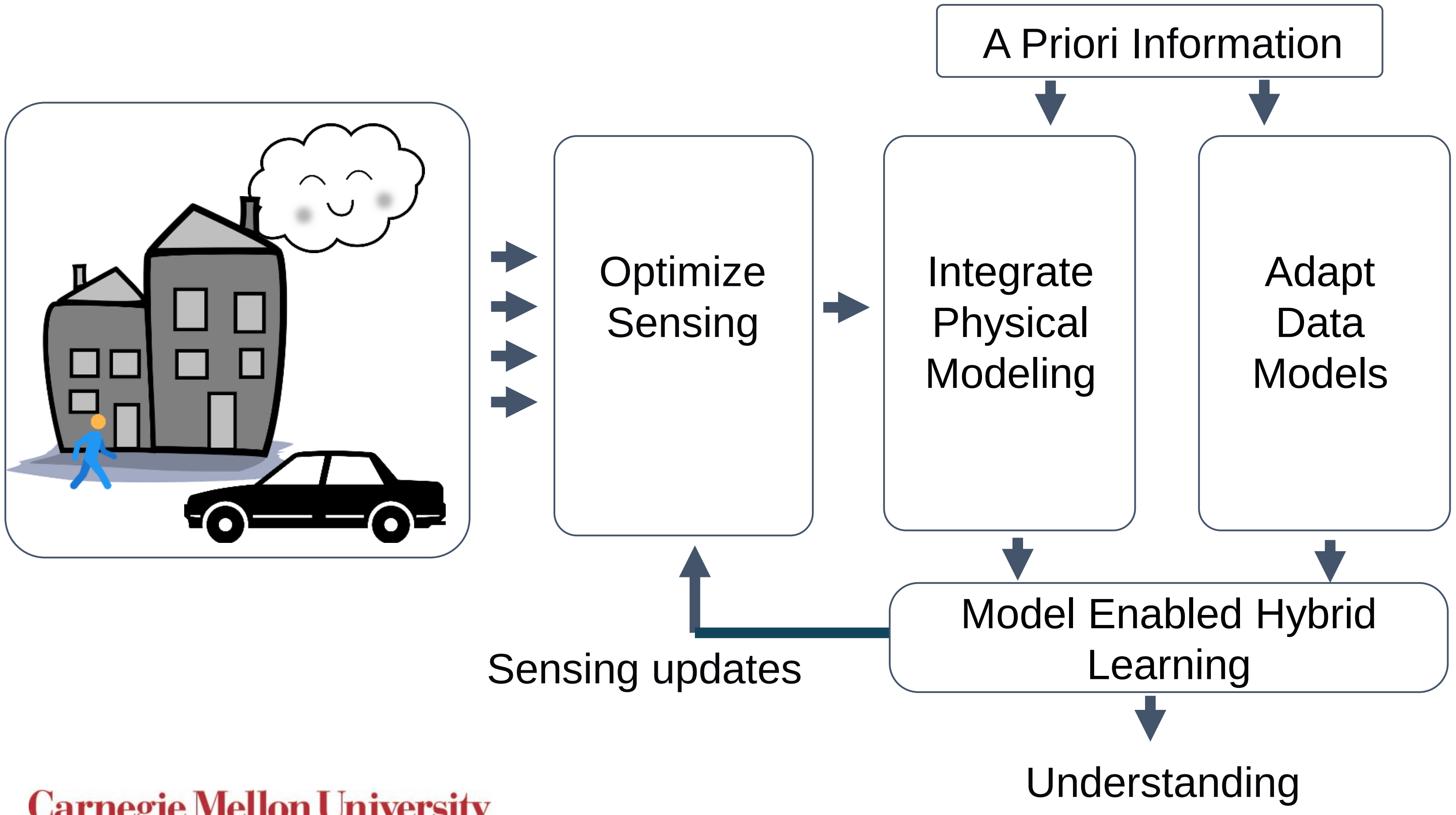
- Identify and infer location of walkers and devices
- Multi-Source Separation (Multi-walkers)
- Inference using footstep and sequence events Performance: ~0.2m

Learning

Machine Learning with Physical Knowledge

- Transfer models through physical understanding (buildings, persons, environments)
- Interpretable learning through physical models

Enable “Small Data” for Learning through Integration of Physical Understanding



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Marauder's Map

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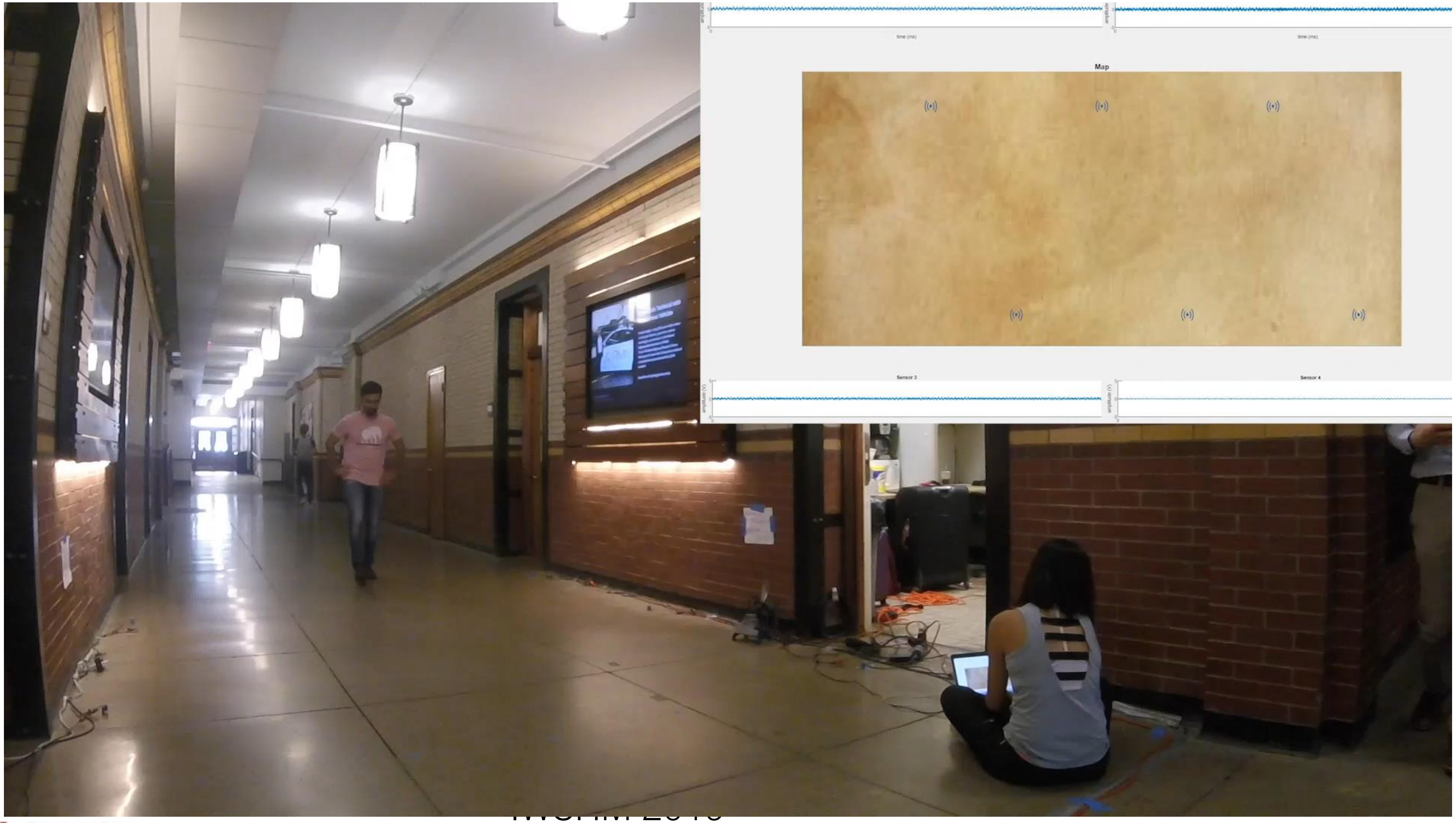
Marauder's Map



Ongoing Deployment

Eldercare deployment

- Walk balance
- Activity monitoring
- Vital monitoring
- Fall prediction
- Stroke recovery

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Baptist HOMES

Select Real-world Deployments

Mobile Sensing

Building as Sensors

- Research Competitions
  - @CPS-IoT Week
- Data for the research community
- 3 Startups

- ZebraNet: first mobile sensor net
- Autonomous retail stores in 5 countries
- 600 million pollution data collected on 500,000 km taxi traces
- Extended life expectancy for children with LGMD by 50% => 10 years.

Collaborators and Funders

- Ph.D. Students
  - Adeola Bannis
  - Amelie Bonde
  - Jonathon Fagert
  - Joao Diogo Falcao
  - Jesse Codling
- Past Ph.D.
  - Aveek Purohit
  - Zheng Sun
  - Frank Mokaya
  - Xinlei Chen
  - Shijia Pan
  - Susu Xu
  - Carlos Ruiz Dominguez
  - Mostafa Mirshekari

- Electrical engineering
  - Prof. John Shen (CMU)
  - Prof. Ian Lane (CMU)
  - Prof. Bob Iannucci (CMU)
  - Prof. Lin Zhang (Tsinghua)
  - Prof. Shijia Pan (UC Merced)
- Civil Engineering:
  - Prof. Hae Young Noh (Stanford)
  - Prof. Mario Berges (CMU)
- Robotics
  - Prof. Stefano Carpin (UC Merced)
- Computer Science
  - Prof. Jorge Sa Silva (U Coimbra)
  - Prof. Lizhong Zheng (MIT)
  - Prof. Margaret Martonosi (Princeton)
- Government/Industry/Medical
  - Dr. Linda Lowes (Nationwide Children's Hospital)
  - Dr. Trevor Pering (Google)
  - Dr. Eve Schooler (Intel)
  - Mr. Ray Washburn (Vincentian)
  - Brian Sadler (Army Research Lab)
  - Steve Gu (AiFi)

Google AIFI BETAGRO NSF USGS science for a changing world intel traffic21 a transportation research initiative of Carnegie Mellon University NATIONWIDE CHILDREN'S When your child needs a hospital, everything matters. VINCENTIAN COLLABORATIVE SYSTEM HIGHMARK Baptist HOMES NOKIA

Papers and Resources on Structure as Sensors

Identification

Pan, S., Yu, T., Mirshekari, M., Fagert, J., Bonde, A., Mengshoel, O. J., ... & Zhang, P. (2017). Footprintid: Indoor pedestrian identification through ambient structural vibration sensing. Proceedings of the ACM on Interactive, Mobile, Wearable and Ubiquitous Technologies, 1(3), 1-31.

Han, J., Pan, S., Sinha, M. K., Noh, H. Y., Zhang, P., & Tague, P. (2018). Smart home occupant identification via sensor fusion across on-object devices. ACM Transactions on Sensor Networks (TOSN), 14(3-4), 1-22.

Pan, S., Wang, N., Qian, Y., Velibeyoglu, I., Noh, H. Y., & Zhang, P. (2015, February). Indoor person identification through footstep induced structural vibration. In Proceedings of the 16th International Workshop on Mobile Computing Systems and Applications (pp. 81-86).

Localization

Mirshekari, M., Pan, S., Fagert, J., Schooler, E. M., Zhang, P., & Noh, H. Y. (2018). Occupant localization using footstep-induced structural vibration. Mechanical Systems and Signal Processing, 112, 77-97.

Mirshekari, M., Pan, S., Zhang, P., & Noh, H. Y. (2016, April). Characterizing wave propagation to improve indoor step-level person localization using floor vibration. In Sensors and Smart Structures Technologies for Civil, Mechanical, and Aerospace Systems 2016 (Vol. 9803, p. 980305). International Society for Optics and Photonics.

Mirshekari, M., Fagert, J., Pan, S., Zhang, P., & Noh, H. Y. (2020). Step-Level Occupant Detection across Different Structures through Footstep-Induced Floor Vibration Using Model Transfer. Journal of Engineering Mechanics, 146(3), 04019137.

Structure as Sensors in Popular Media

Scientific American: Footstep Sensors Identify People by Gait
https://www.scientificamerican.com/article/footstep-sensors-identify-people-by-gait/

Thanks! Questions?

http://www.peizhang.com
peizhang@cmu.edu