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

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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

- Deploy different sensors everywhere to collect data
- Challenges
  - Difficult to deploy and maintain
Enable “Small Data” for Learning through Integration of Physical Understanding

- 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?
What Happens in Different Buildings?

63% accuracy => Structure-dependent vibration signal characteristics

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

Available Labelled Data

Target Structures

No Labelled Data

Model Transfer
How Can We Minimize Training?

Our Solution: Structure-Informed Model Transfer

[Diagram showing source and target structure data with group A and group B, and arrows indicating excitation and structure effects.]
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.

\[
\begin{align*}
\min_W & \text{tr}(W^T \tilde{K} L \tilde{K} W) + \mu \text{tr}(W^T W) + \frac{\lambda}{n^2} \text{tr}(W^T \tilde{K} L \tilde{K} W) \\
\text{s.t.} & \quad W^T \tilde{K} H \tilde{K} y y H \tilde{K} W = I
\end{align*}
\]

- Structural Effect
- Regularization Term
- Distribution Shape Preserving
- Label Information

• 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

- Center of Gravity kept center
- Small angle of foot and floor

- Center of Gravity kept back
- Large angle of foot and floor
People walk differently

Person A

Person B
Same Person Walks the Same

Trace 1

Trace 2

Trace 3
4 Hardware Versions
- Increase sensitivity (dynamic sensing range)
- Optimize settings for maximum signal resolution
- Reduce structural variation
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%
Person Characteristics
- Inference using footstep vibration
- Identity, Balance, Muscular Dystrophy, Dementia, etc.
- Performance: 99% identity

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

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
Ongoing Deployment

Eldercare deployment
- Walk balance
- Activity monitoring
- Vital monitoring
- Fall prediction
- Stroke recovery
Select Real-world Deployments

- 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

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  – Mr. Ray Washburn (Vincentian)
  – Brian Sadler (Army Research Lab)
  – Steve Gu (AiFi)
Papers and Resources on Structure as Sensors

Identification


Localization


Structure as Sensors in Popular Media

Scientific American: Footstep Sensors Identify People by Gait
Thanks! Questions?

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