A Domain Adaptation Technique for Fine-Grained Occupancy Estimation in Commercial Buildings

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Overview – Problem Definition

- How to **reliably** estimate the **number of occupants** in the many rooms of a commercial building?

Estimated Binary State:  **UnOccupied**
Estimated Occupancy Count:  **3**
Overview – Applications of Occupant Count Determination

Demand-Driven HVAC Control  Security  Space Utilization  Many other applications in occupant-centred buildings
Overview – Problem Definition

- How to **reliably** estimate the number of occupants in the many rooms of a commercial building?
- Well-studied problem at the room level, but how about a large building?
Overview – Domain Adaptation

- How to build a general model that can be reused in multiple rooms/buildings?
- How to build a black-box model for a room/building with no/limited available labeled data

Solution: modify a well-tuned model for one room/building to adapt it to the target room/building leveraging some information
Overview – Experiments

- Data collected from two buildings located in Canada and Denmark
- Buildings have different room sizes, types, and sensing modalities

Ground truth data collected using cameras

Ground truth data extracted from room calendars

Building A
- CO₂
- Damper Position
- Outside Temperature
- Cloud Coverage

Building B
- Room Temperature
- Air Flow
- Outside Temperature
- Cloud Coverage
Outline

- Challenges and previous work
- Methodology
- Results
- Takeaways and future work
Challenges

- Multiple sensing modalities

<table>
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<th>Cameras</th>
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<th>Door Sensors</th>
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<td>[Agarwal 11]</td>
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- Grid-EYE sensors
- Damper Position Sensors
- CO₂, Temp & Humidity Sensors
- Magnetic Reed Switches

https://hackaday.com/2017/06/05/diy-grid-eye-i-camera/
http://csr200.blogspot.com/2016/03/damper-position-sensors.html
https://www.tempoon.co.uk/shop/hobo-mx1102-bluetooth-co2-temp-rh-data-logger
### Different sensing modalities

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## Different sensing modalities

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- **Cameras [Erickson 13]**: High cost, high privacy, high accuracy.
- **Wireless Network [Zou 17]**: Low cost, low privacy, high accuracy.
- **Thermal Arrays [Beltran 13]**: High cost, low privacy, high accuracy.
- **HVAC Sensors [Ardakanian 18]**: Zero-cost sensors, low privacy, high accuracy.
- **Door Sensors [Agarwal 11]**: Low cost, low privacy, low accuracy.
Wait... Can HVAC sensors be used for occupancy estimation?
Challenges

- Multiple sensing modalities, some are less correlated with occupancy (HVAC sensors)
- Several sensor data fusion algorithms
  - Physics-based model to quantify heat gain due to occupancy
    - Have to customize for each room/building. Too complex to build high-order models.
  - Black-box model
    - Easier to build, but requires large amounts of labelled data for training
Challenges

- Multiple sensing modalities, some are less correlated with occupancy (HVAC sensors)
- Different sensor data fusion algorithms (black-box model)
  - Time-series models (using a sequence of data to predict)
    - RNN / NARX
  - Single snapshot prediction models (using one data point to predict)
    - SVR / SVM / Random Forest
Challenges

- Multiple sensing modalities, some are less correlated with occupancy (HVAC sensors)
- Different sensor data fusion algorithms (black-box model)
- Ground truth data is often sparse or nonexistent (expensive to collect)
Our hypothesis is...

models that are built in a controlled environment (source domain) can be reused in a new environment (target domain) after some adaptation

and that the adapted model has higher accuracy than a model built from scratch for the target domain
Domain Adaptation

Basic Idea: transform a well-trained model from a source domain to a related target domain after performing some modifications on the model.
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Domain Adaptation

How is it applied to our problem?

• Train a well-suited model in a room equipped with a high-accuracy occupancy monitoring system (source domain)
• Adapt it to another room within the same building (target domain) using some information about the apparent differences between the rooms

• Main benefit: we do not need a lot of labeled data in the target domain; hence, it can be widely applied to the many rooms in a given building
Assumptions

- Occupancy influences measured quantities in both source and target domains in a similar way.
- The same types of sensors are deployed in both domains (same feature space)
Why domain adaptation is necessary?

Source and target domains may have different distributions

Room 1 in Building A

Room 2 in Building A
Why domain adaptation is necessary?

Source and target domains may have different distributions

Room 1 in Building A

Room 2 in Building A
Why domain adaptation is necessary?
Why domain adaptation is necessary?
Domain Adaptation Techniques

Unsupervised learning model (training step)

Semi-supervised learning model (training step)

Supervised learning model (training step)
Domain Adaptive Recurrent Neural Networks

• Re-weighting (may be carried out for semi-supervised and unsupervised domain adaptation):
  • Adjust the weights of output layer based on the maximum occupancy
  • Adjust the weights of input layer corresponding to the CO$_2$ values based on the size of the room and the ventilation power of the room

• Re-training (only for semi-supervised domain adaptation):
  • Use the limited labeled data from the target domain to calibrate the weights
Methodology

Domain Adaptive NARX Network

Domain Adaptive LSTM Cell
Applying Domain Adaptation
Applying Domain Adaptation
Applying Domain Adaptation

Re-weighting
Applying Domain Adaptation

Room 1 in Building A

Room 2 in Building A
The whole process...

Source data + labels

Source Model

Source Domain Estimation Model

Transfer Knowledge

Re-weighting

Target Model

Calibrated Model

Target Domain Estimation Model

Target data + labels

Re-training
Results

![Bar chart showing RMSE (no. people) for different re-weighting methods and supervision types. The chart includes supervised, unsupervised, and semi-supervised methods. The re-weighting options are labeled as 'x' and '✓', with corresponding RMSE values: 6.11 (supervised), 4.25 (unsupervised), 4.11 (semi-supervised), 4.21 (LSTM re-weighting with x), and 4.06 (LSTM re-weighting with ✓).]
Results

- Domain-adaptation improves the accuracy

![Graph showing RMSE (no. people) for different re-weighting and supervision settings]
Results

• Domain-adaptation improves the accuracy

• Semi-supervised performs better (re-training is useful)
• Domain-adaptation improves the accuracy

• Semi-supervised performs better (re-training is useful)

• Re-weighting can help reduce the RMSE, BUT requires the knowledge of the differences between the two domains

Results
Results

![Graph showing RMSE (no. people) for different amounts of ground truth data from the target domain. The graph compares Semi-supervised (LSTM), Unsupervised (LSTM), and Supervised (SVR) models. The RMSE values are indicated for 1 hour, 3 hours, and 1 day amounts of ground truth data.](https://via.placeholder.com/150)
Results

![Graph showing RMSE (no. people) for different methods and amounts of ground truth data from the target domain. The methods compared are Semi-supervised (LSTM), Unsupervised (LSTM), and Supervised (SVR). The graph illustrates the RMSE for 1 hour, 3 hours, and 1 day of ground truth data.]
Results

two rooms in Building A
Takeaways

- Time-series black-box model can estimate the number of occupants accurately
- Domain-adaptation techniques can be applied to occupancy estimation task to improve the performance
- Domain-adaptation can significantly reduce the amount of ground truth data required in the target domain
Directions for future work

- What if the source and target domains are in two different geographies?
- What if the feature spaces are different?
- Can we apply domain adaptation to other types of models (e.g., heat transfer models, occupant comfort models, etc.)?
Questions?