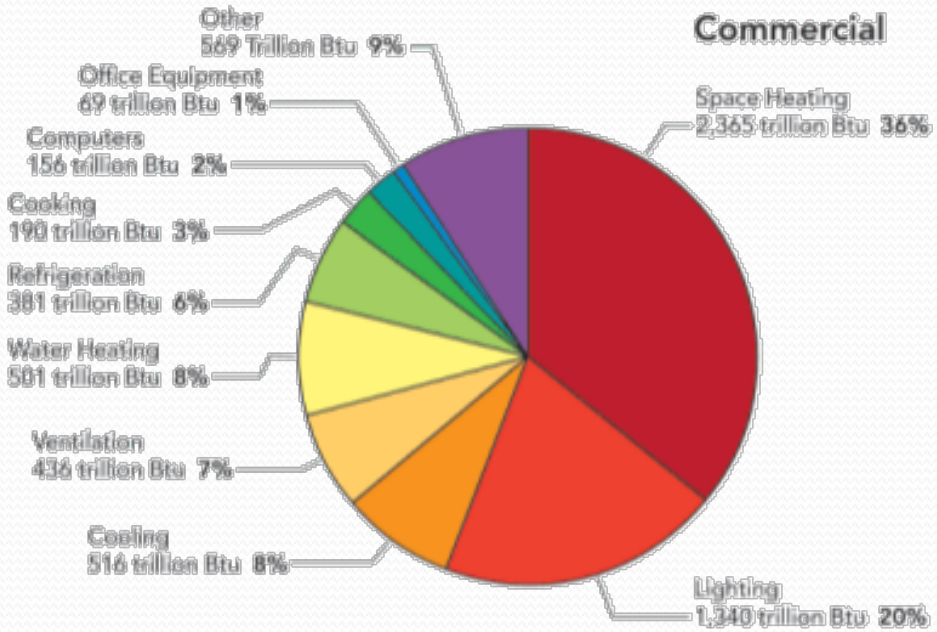
SPOT*
A Smart Personalized Office Thermal Control System

Peter Xiang Gao
Alimohammad Rabbani
S. Keshav

12 November, 2014

HVAC Energy use

- Buildings use 1/3 of all energy
- 30-50% of building energy is for HVAC



Percentage of energy use for commercial facilities (EIA)

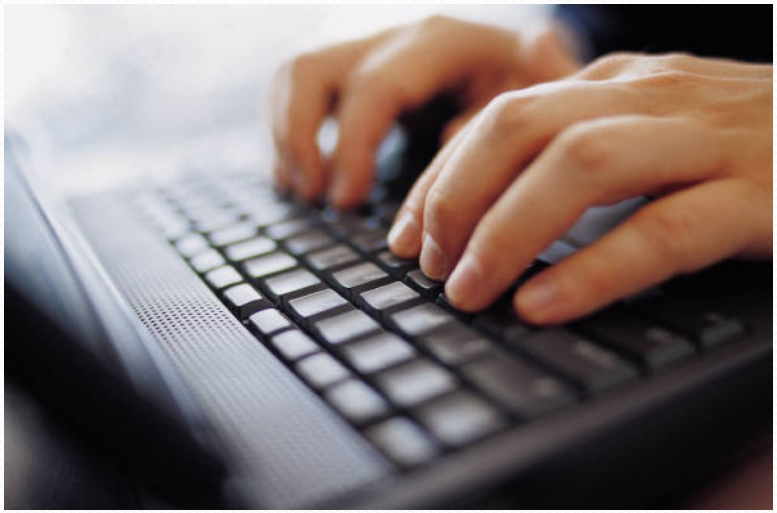
Can we improve efficiency?

- Yes!

- Change temperature setpoint:
  - 1°C higher when cooling ≈ 10% saving
  - 1°C lower when heating ≈ 2-3% saving
- But this can reduce comfort

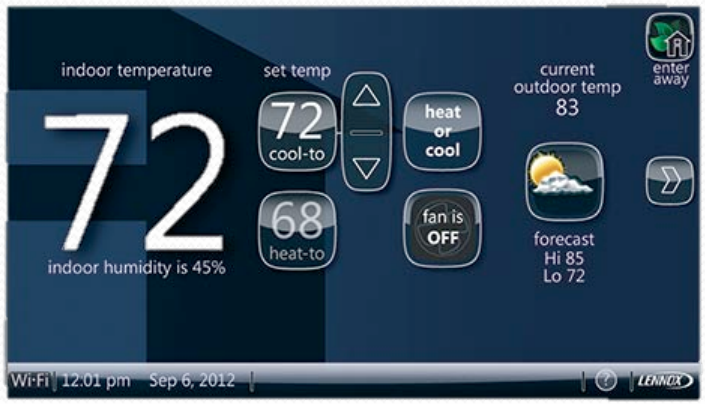
Focus of this work

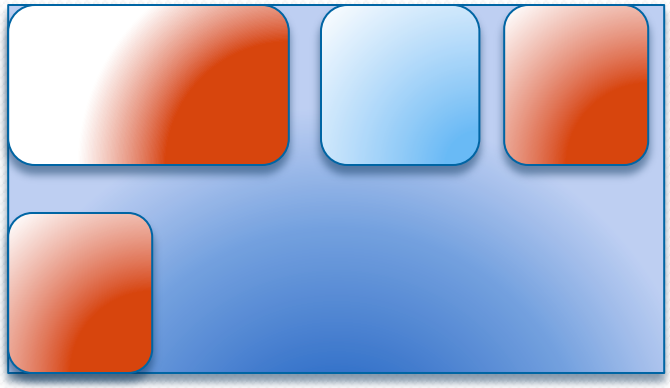
How to keep office workers comfortable while reducing energy use?



Option 1: Tweak Status Quo

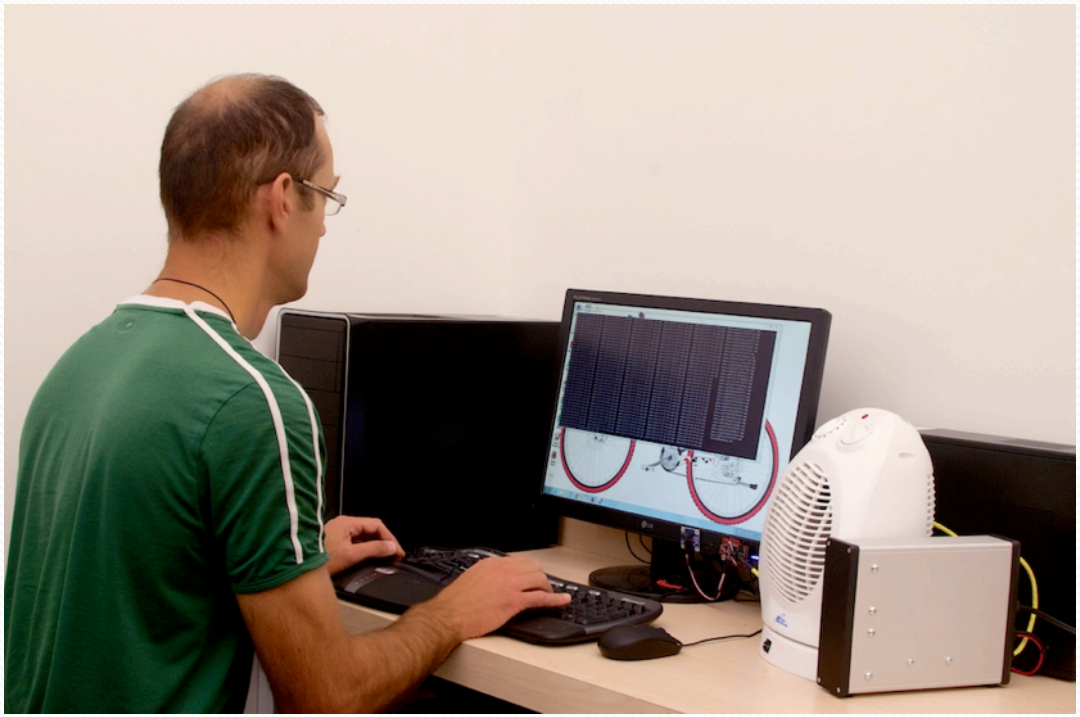
- Problem: centralized control and management
  - ignores workers
    - or has minimal input from them
  - invades privacy





Our insight

Option 2: Decentralize!



Temperature or comfort?

Most current systems maintain temperature

Why not control comfort instead?

Comfort according to ASHRAE

Cold	Cool	Slightly Cool	Neutral	Slightly Warm	Warm	Hot
-3	-2	-1	0	1	2	3

…can be predicted!

- Predicted Mean Vote (PMV) model (ISO 7730)
- Six input parameters
  - Air Temperature
  - Background Radiation
  - Air Velocity
  - Humidity
  - Metabolic Rate
  - Clothing Level

- Developed by P.O. Fanger in 1970
  - Extensively validated

… and personalized

- PMV model represents the average
  - for a single office, only the occupant's vote matters

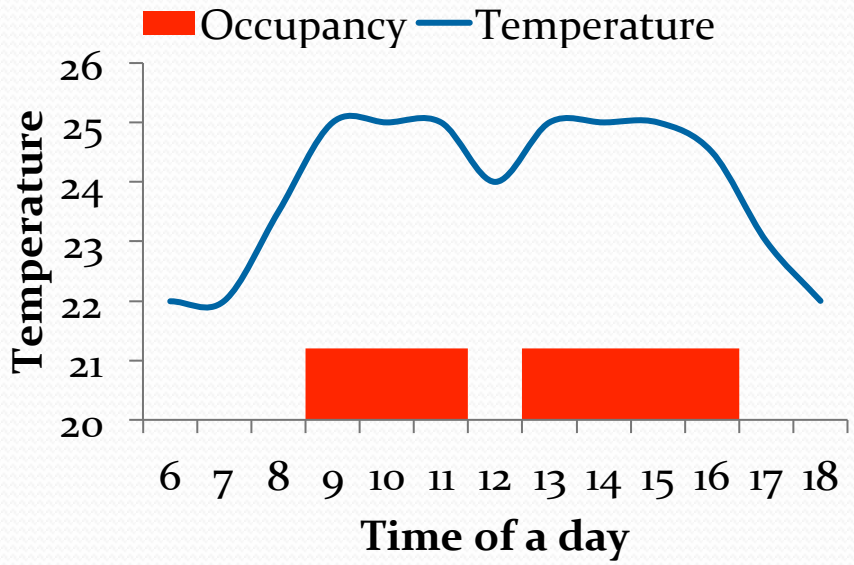
- Predicted Personal Vote (PPV) Model

$$ppv = f_{ppv}(pmv)$$

where $f_{ppv}(\bullet)$ is a linear function

Our idea in a nutshell

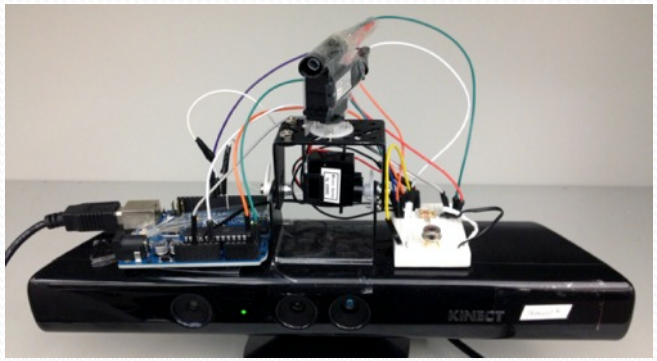
- Measure occupancy and comfort
- When occupied, keep office comfort at the minimum acceptable level
- When vacant, turn heating/fan off
  - but pre-heat if needed



Two systems

SPOT (2011-2013)

- Extreme sensing
- In office only
- Expensive
- Reactive or pro-active



SPOT* (2014)

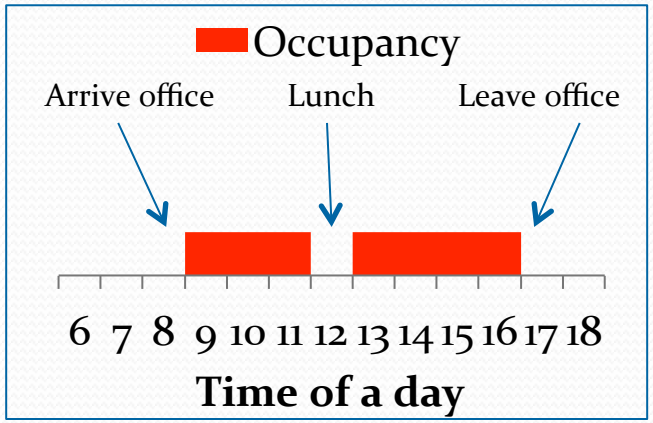
- Minimal sensing
- Flexible location of functionality
- Low-cost
- Reactive

Mathematical basis

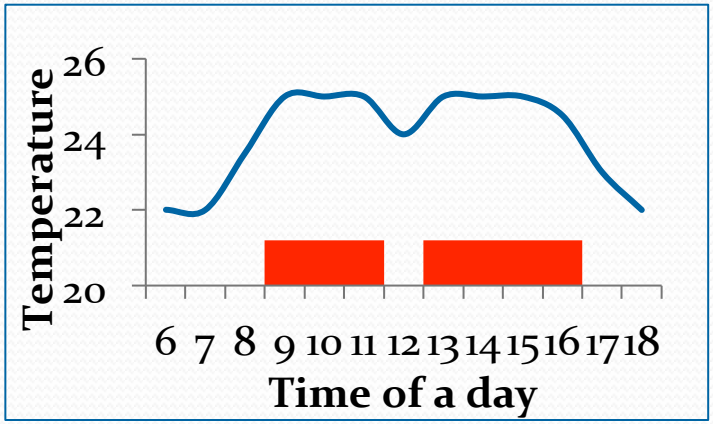
Personal Thermal Comfort Evaluation

Cold	Cool	Slightly Cool	Neutral	Slightly Warm	Warm	Hot
-3	-2	-1	0	1	2	3

Learning-Based Modeling



Occupancy Prediction



Optimal control

Mathematical basis

Personal Thermal Comfort Evaluation

Cold	Cool	Slightly Cool	Neutral	Slightly Warm	Warm	Hot
-3	-2	-1	0	1	2	3

Learning-Based Modeling

Occupancy Prediction

Setpoint Scheduling

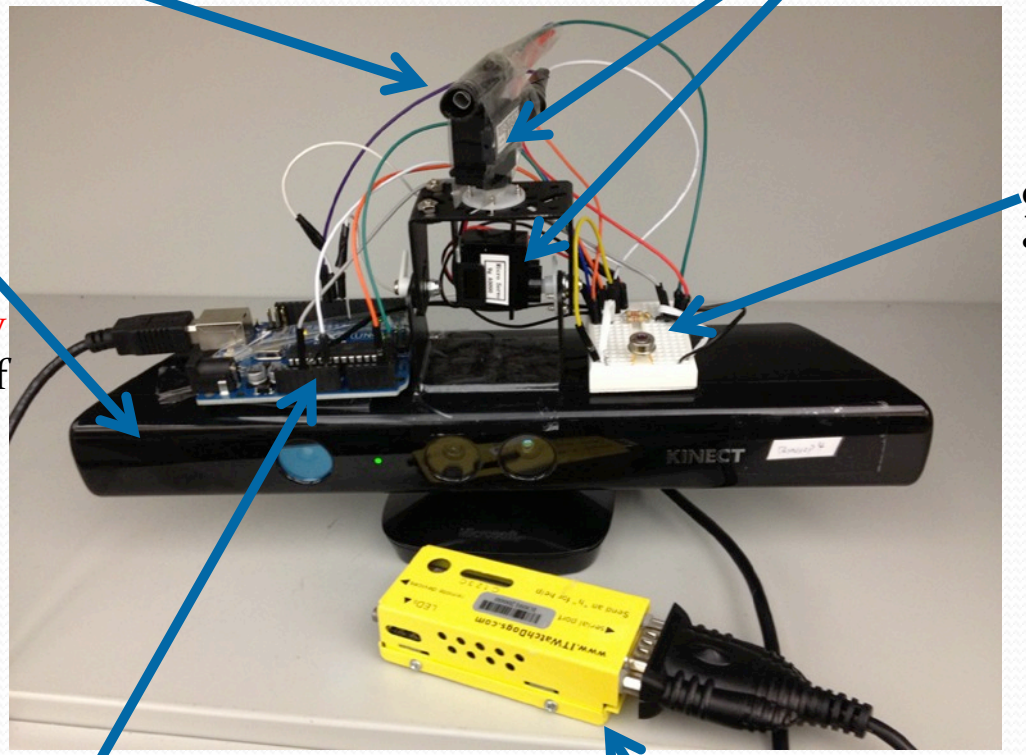
Monitoring PMV

Air Temperature	Measured by sensor
Background Infrared Radiation	Measured by sensor
Air Velocity	Measured by sensor
Humidity	Measured by sensor
Metabolic Rate	Constant for indoor activity
Clothing Level	Estimated

SPOT+: extreme sensing

Servos:
- Controls the direction of the 5° infrared sensor

5° infrared sensor:
- Detects users' clothing surface temperature



90° infrared sensor:
- Detects background radiant temperature

Microsoft Kinect:
- Detects occupancy
- Detects location of the user

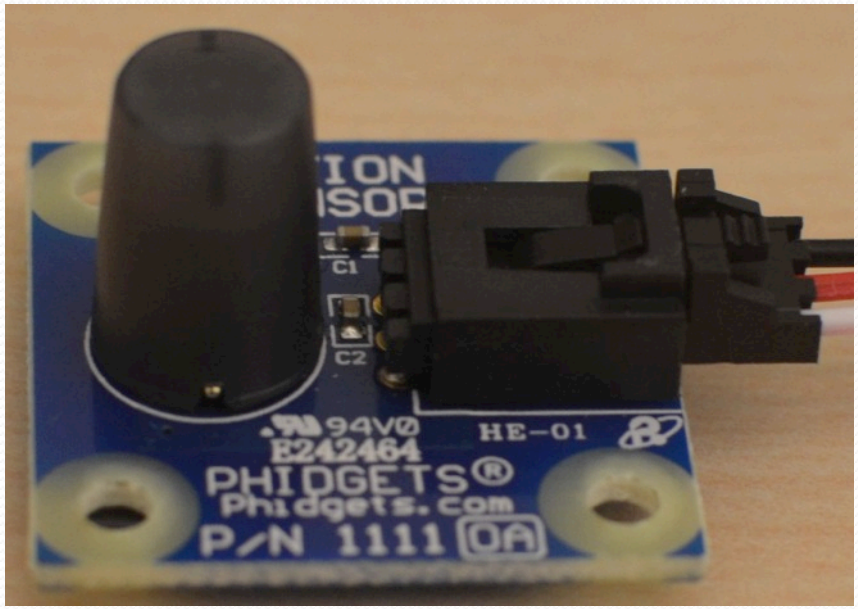
Microcontroller:
- Pull data from the sensors
- Control the rotation angle of the servos

Weatherduck sensor:
- Detects air temperature, humidity, air velocity

SPOT*: minimal sensing

Occupancy/temperature sensor

- Passive IR



Clothing level estimation (SPOT+)

- Estimate clothing by measuring emitted infrared
  - More clothing => lower infrared reading

$$Clo = k * (t_{clothing} - t_{background}) + b$$

- $t_{clothing}$ is the infrared measured from human body
- $t_{background}$ is the background infrared radiation
- k and b are estimated by regression

Learning PPV

- Training phase
  - SPOT knows PMV
  - Occupant votes periodically = PPV
  - PMV -> PPV relation learnt by linear regression

Mathematical basis

Personal Thermal Comfort Evaluation

Cold	Cool	Slightly Cool	Neutral	Slightly Warm	War m	Hot
-3	-2	-1	0	1	2	3

Learning-Based Modeling

Occupancy Prediction

Setpoint Scheduling

Forecasting comfort

- Heating: Learning-Based Predictive Control (LBMPC) predicts the temperature given heating minutes
  - plug into PMV equation
- Cooling: fan speed lowers perceived temperature
  - plug into PMV equation

Thermal model

rate of thermal loss

$$P_{loss} = k(T_{in} - T_{out})$$

net heat input

$$P = eP_{hvac} - P_{loss} = eP_{hvac} - k(T_{in} - T_{out})$$

$$P = \frac{dQ}{dt} = C\frac{dT_{in}}{dt}$$

$$\frac{dT_{in}}{dt} = \frac{eP_{hvac} - k(T_{in} - T_{out})}{C}$$

Discrete time model

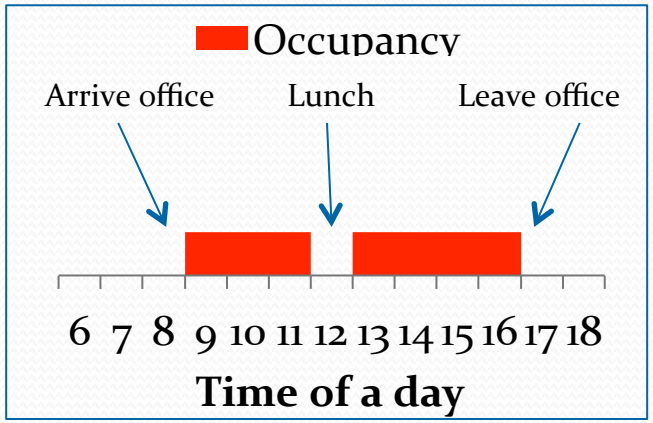
$$T_{in}(s+1) = T_{in}(s) + \frac{eP_{hvac}(s) - k(T_{in}(s) - T_{out}(s))}{C}$$

Mathematical basis

Personal Thermal Comfort Evaluation

Cold	Cool	Slightly Cool	Neutral	Slightly Warm	War m	Hot
-3	-2	-1	0	1	2	3

Learning-Based Modeling



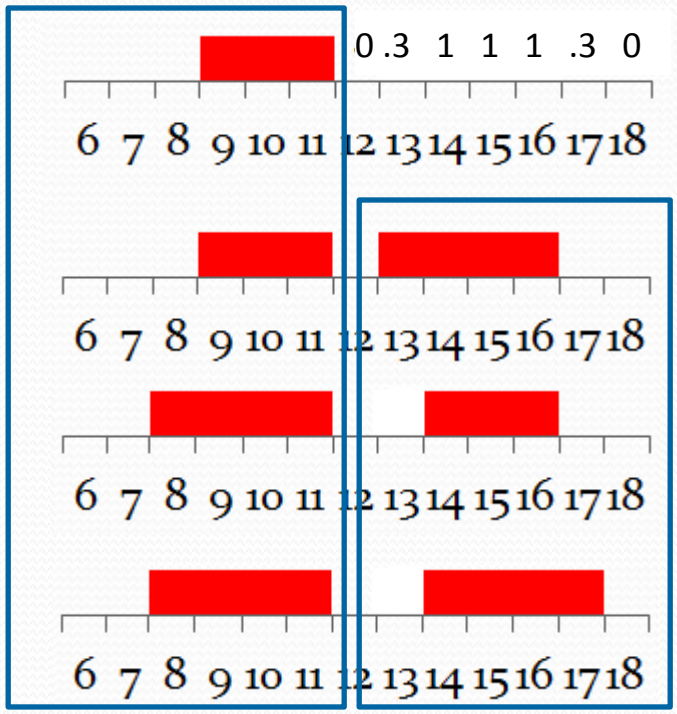
Occupancy Prediction

Setpoint Scheduling

Occupancy Prediction

- Predict occupancy using historical data
  - (only needed for pre-heating)

Match Previous similar history



Predict using matched records

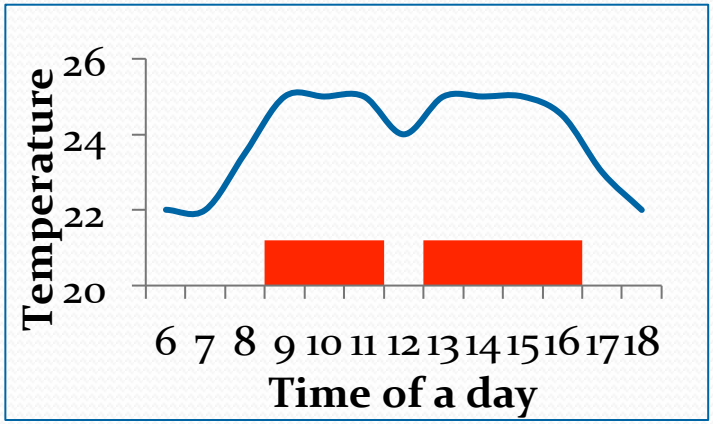
Mathematical basis

Personal Thermal Comfort Evaluation

Cold	Cool	Slightly Cool	Neutral	Slightly Warm	War m	Hot
-3	-2	-1	0	1	2	3

Learning-Based Modeling

Occupancy Prediction



Setpoint Scheduling

Reactive control

- When occupant is present
  - if comfort is not in [-0.5, 0.5]
  - either heater + max fan
  - or fan speed control

Optimal Control

- Forecasts occupancy as well as effect of heating

$$min \sum_{s=1}^{S} P_{hvac}(s) + \lambda \sum_{s=1}^{S} m(s)(\beta_c(s) + \beta_h(s))$$

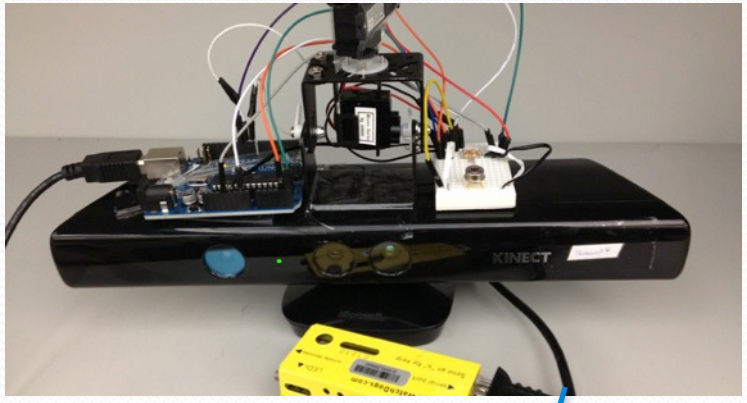
Overall energy consumption in the optimization horizon S

Weight of comfort, set to large value to guarantee comfort first

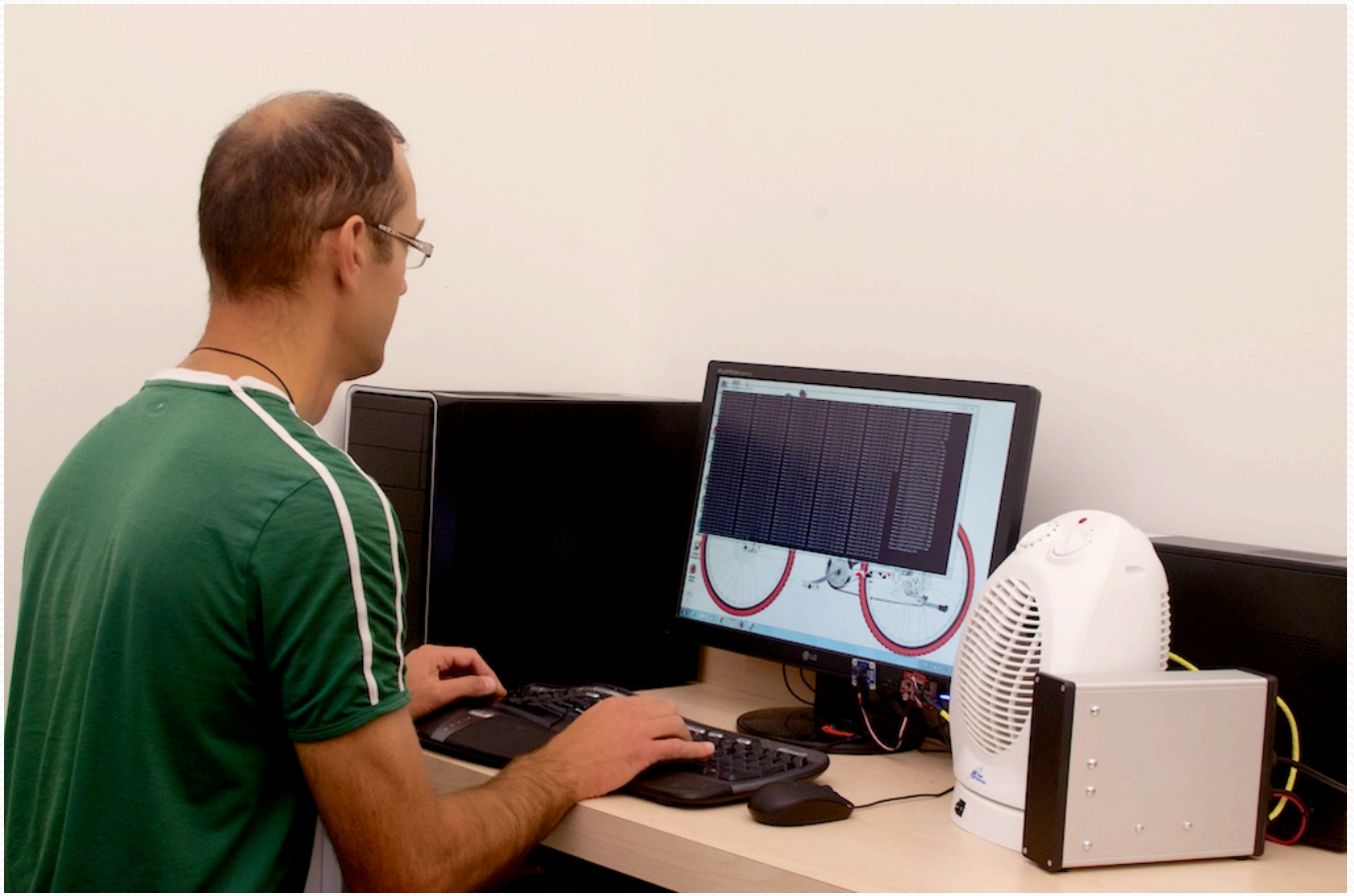
Predicted occupancy, we only guarantee comfort when occupied i.e., when m(s) = 1

Thermal comfort penalty. Both term equal o when the user feels comfortable

SPOT+ system



SPOT* system

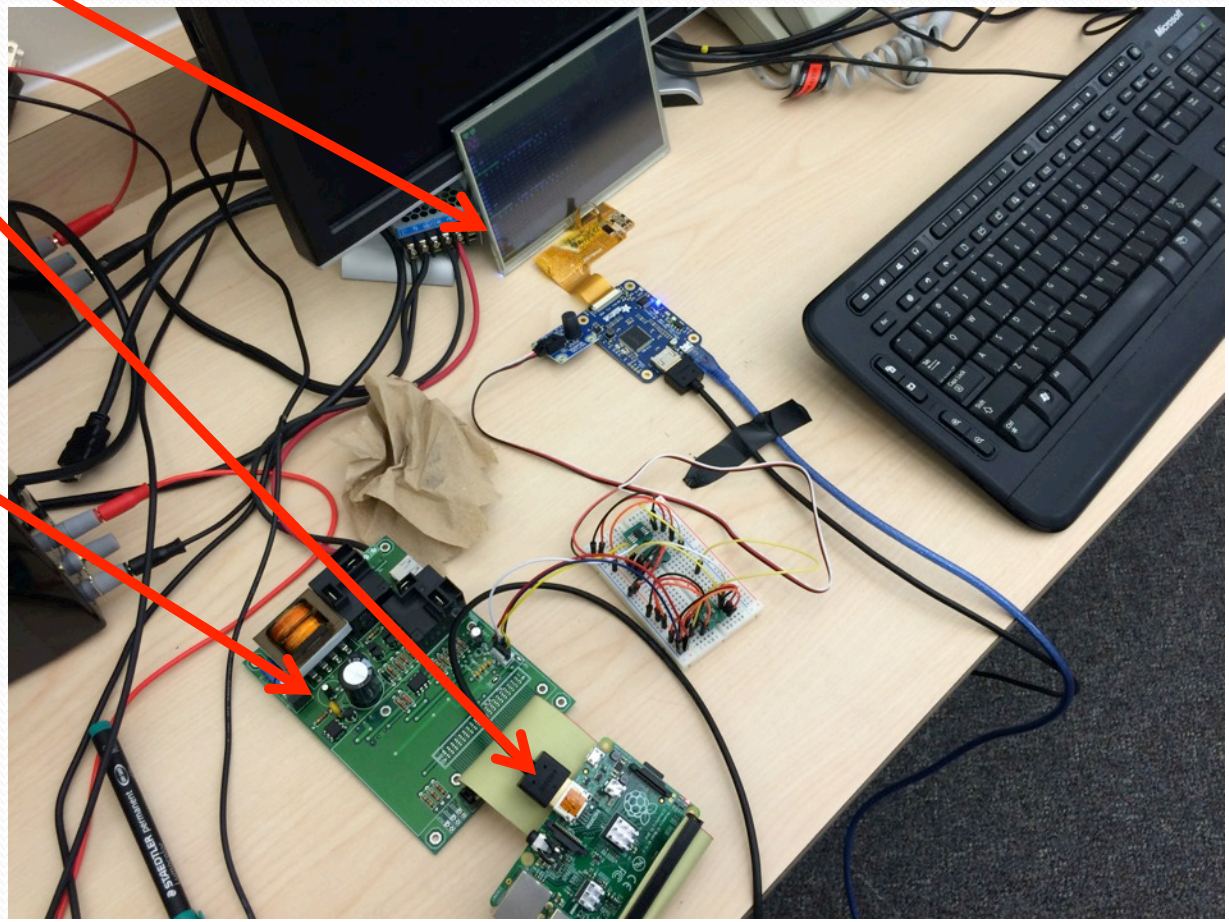


SPOT* control

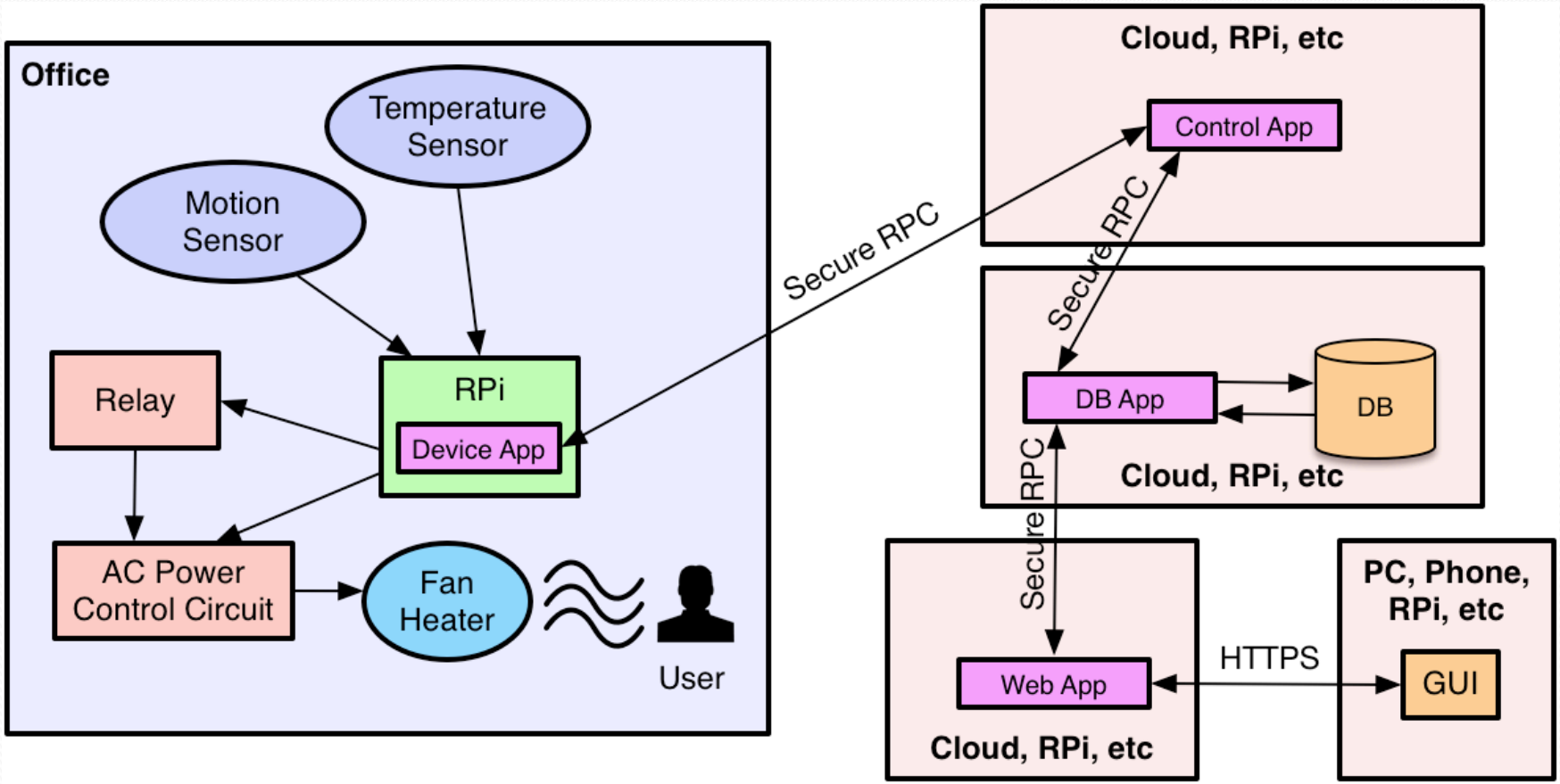
Display
- For local control

Raspberry Pi Microcontroller
- Pulls data from the sensors
- Controls heat and fan speed

Fan speed controller
- Pulls data from the sensors
- Controls heat and fan speed



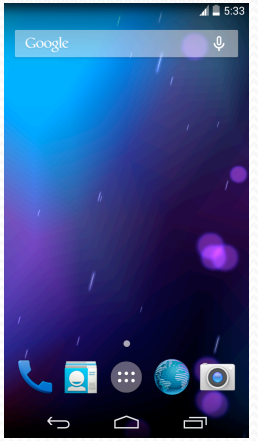
SPOT* system

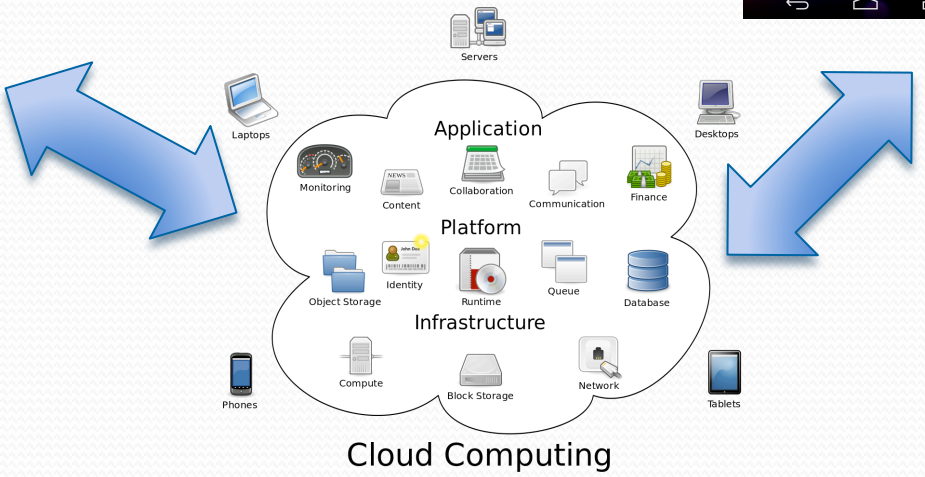

Office
Temperature Sensor
Motion Sensor
Relay
RPi
Device App
AC Power Control Circuit
Fan Heater
User
Secure RPC
Cloud, RPi, etc
Control App
Secure RPC
DB App
DB
Cloud, RPi, etc
Secure RPC
Web App
Cloud, RPi, etc
HTTPS
PC, Phone, RPi, etc
GUI

SPOT* flexibility

Flexible location of functionality:

- sensing
- actuation
- user input
- data storage
- control logic

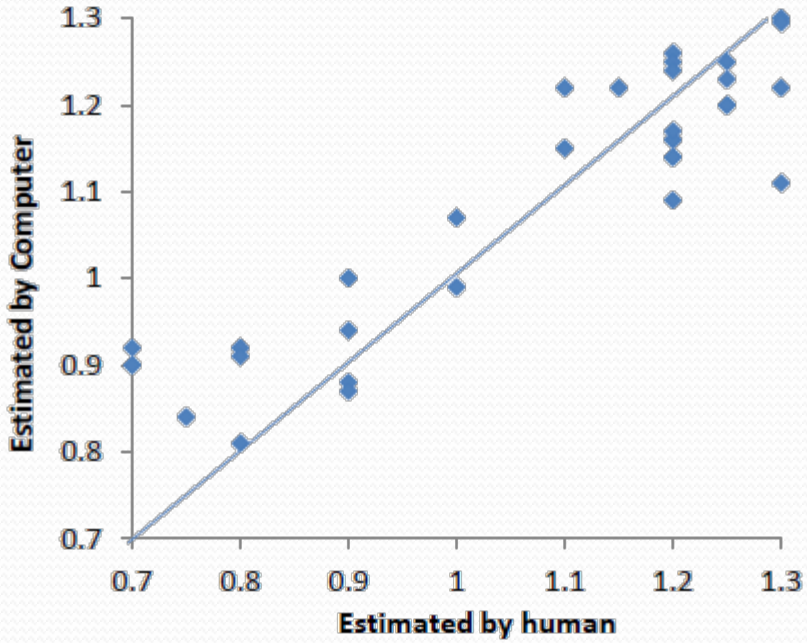




Results

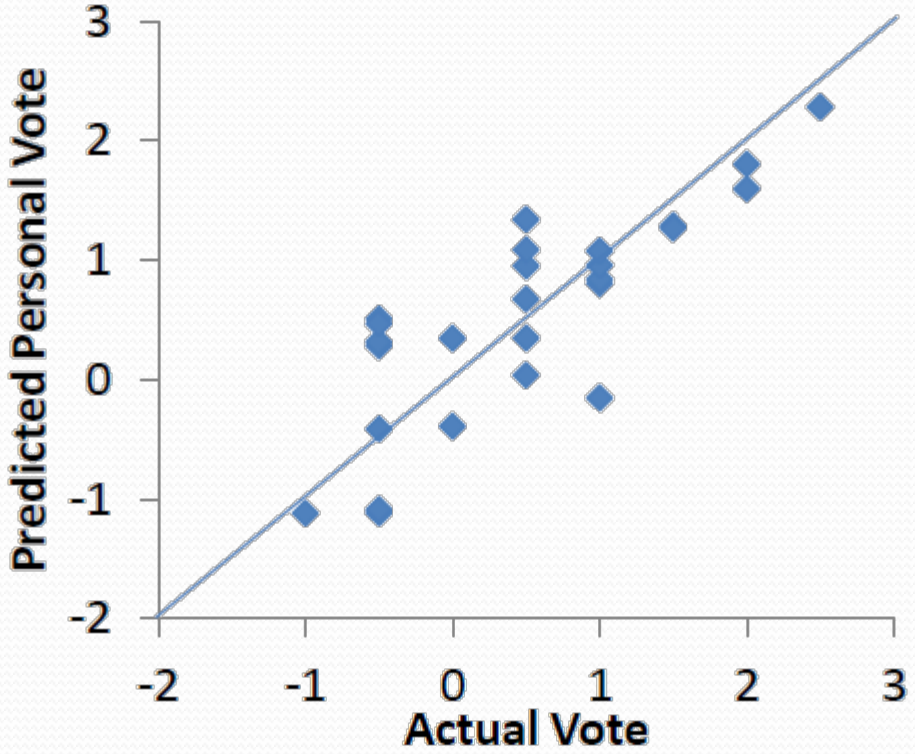
Sensing accuracy

Clothing level estimation



- Root mean square error (RMSE) = 0.0918
- Linear correlation = 0.92

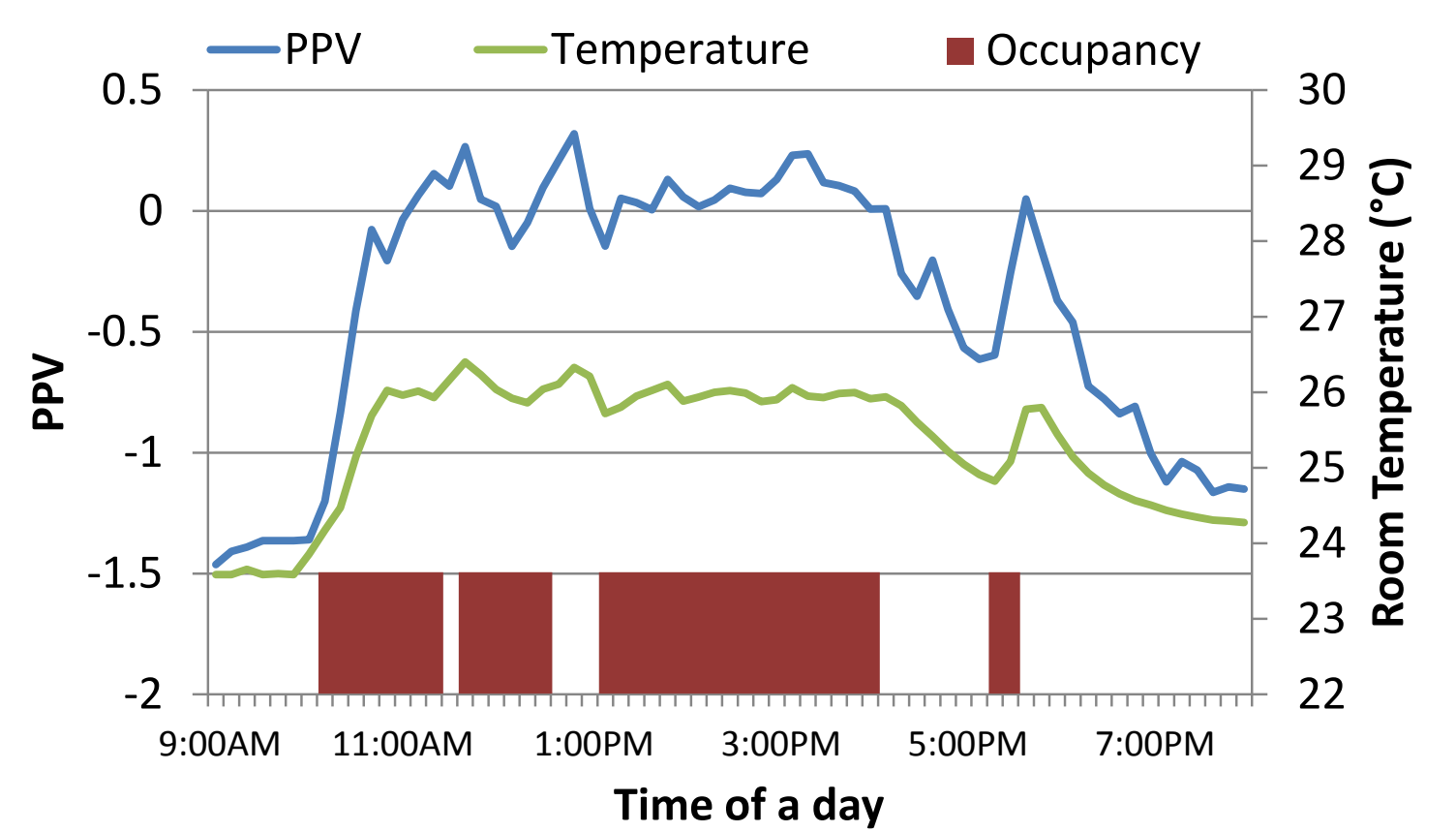
PMV Estimation



- Root mean square error (RMSE) = 0.5377
- Linear correlation = 0.8182

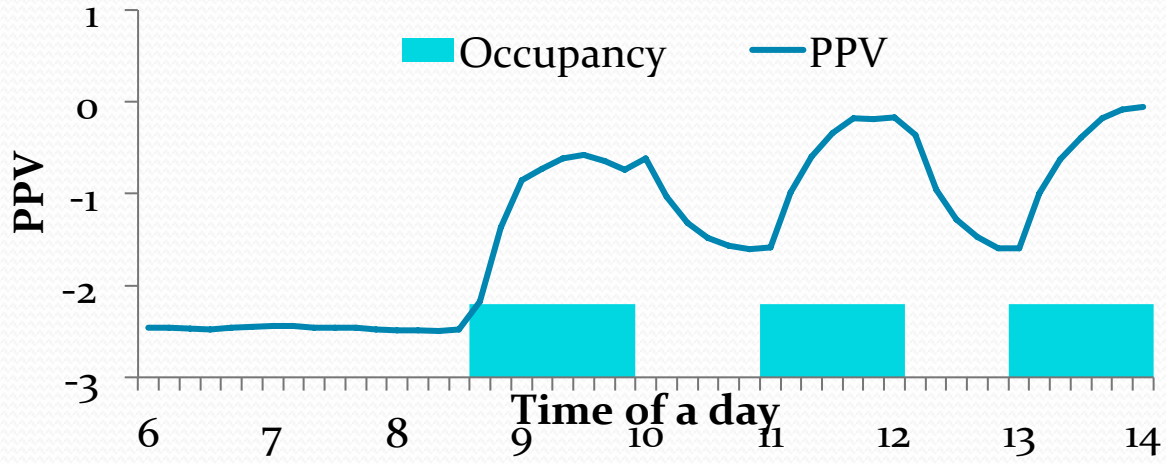
Reactive Control

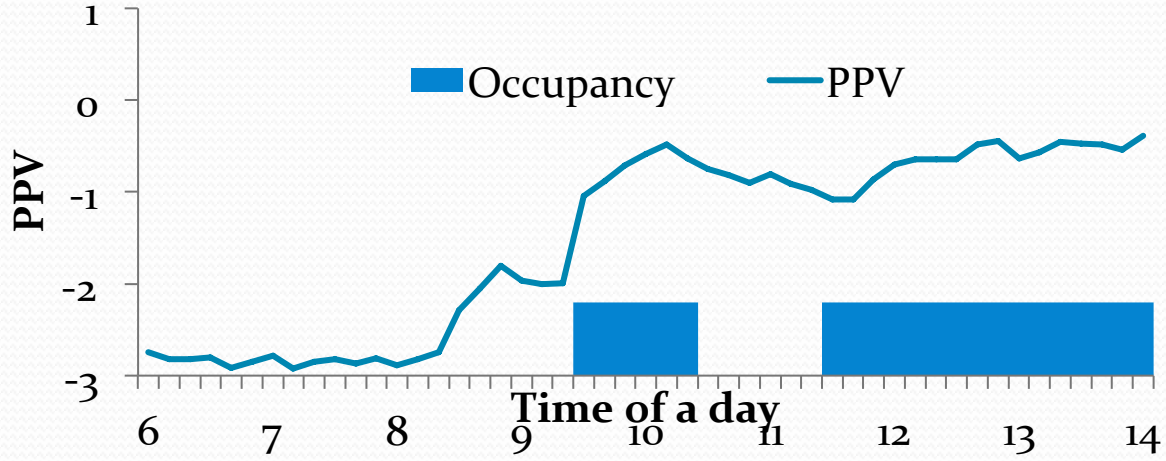
Room temperature and PPV



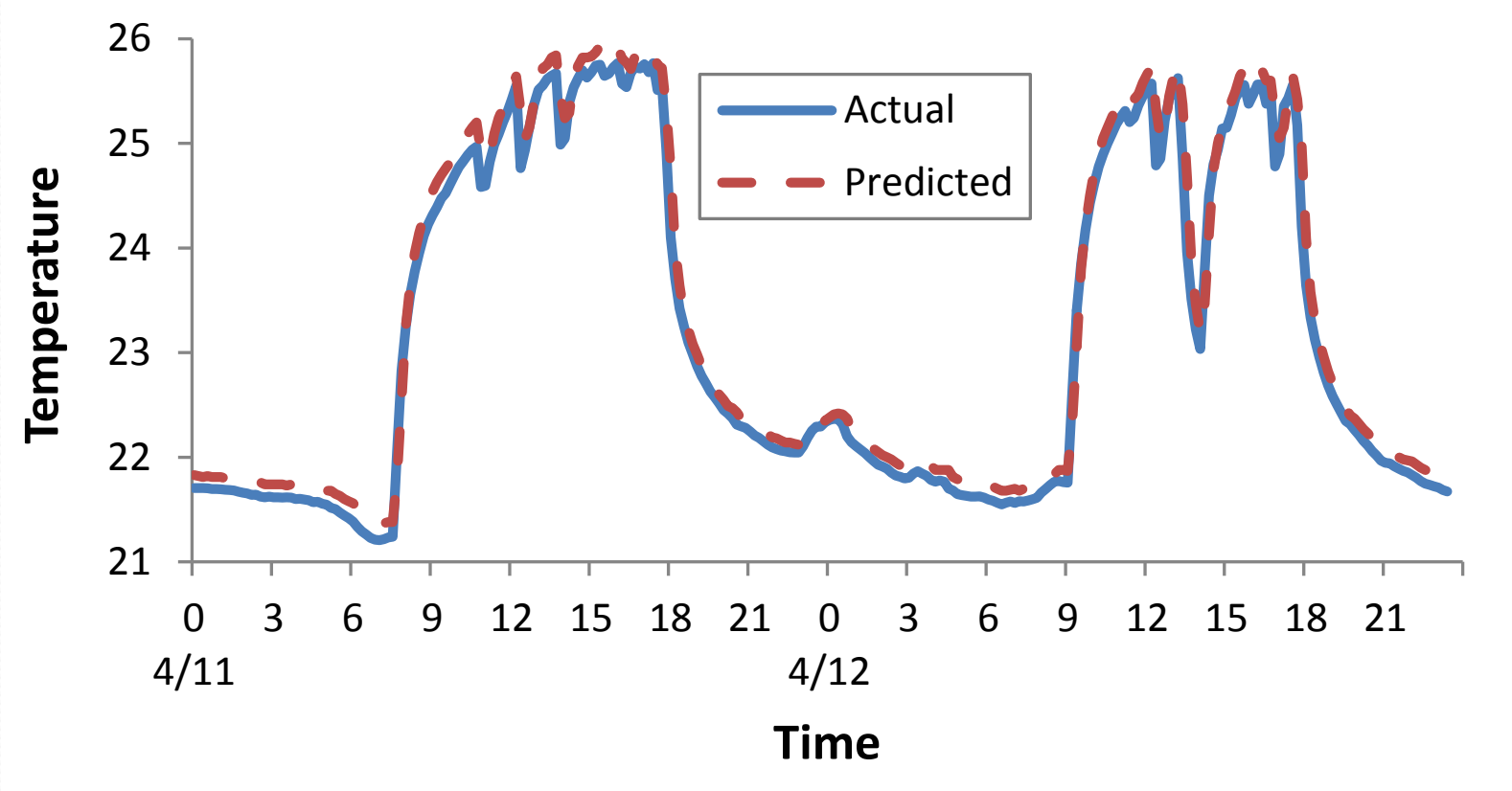
Optimal Control

Reactive Control vs. Optimal Control



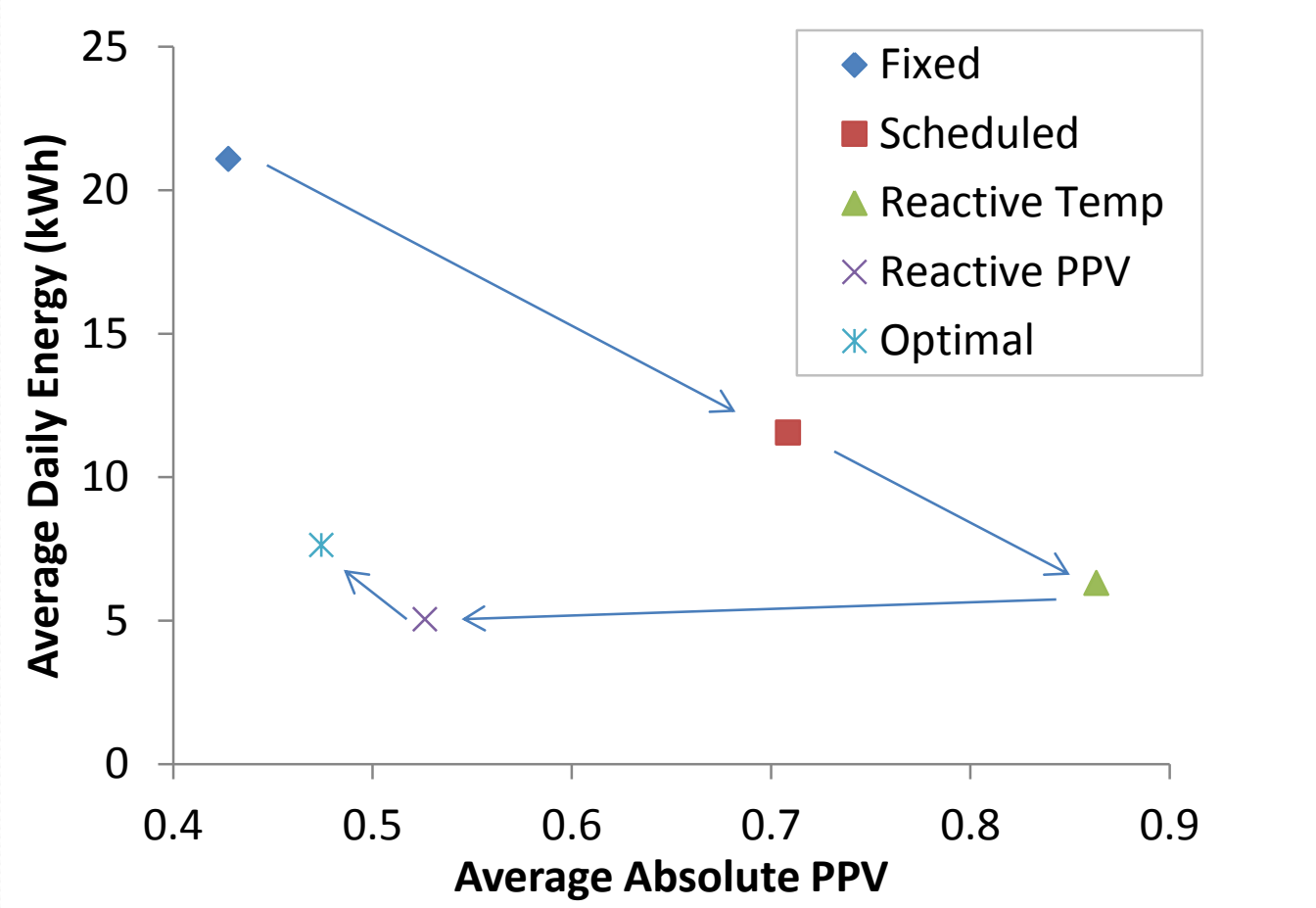


Accuracy of LBMPC



- The RMSE over a day is 0.17C.

Comparision of schemes



Conclusions

- We extended PMV model for personalized thermal control
- We design and implement SPOT+ and SPOT*
- SPOT can accurately maintain personal comfort despite environmental fluctuations
- Legacy and privacy compatible