Shuttered Passive Infrared Sensor for Occupancy Detection: Exploring a Low Power Electro-Mechanical Driving Approach

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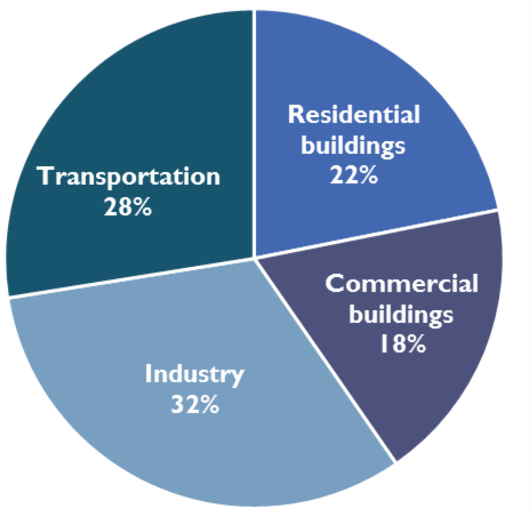
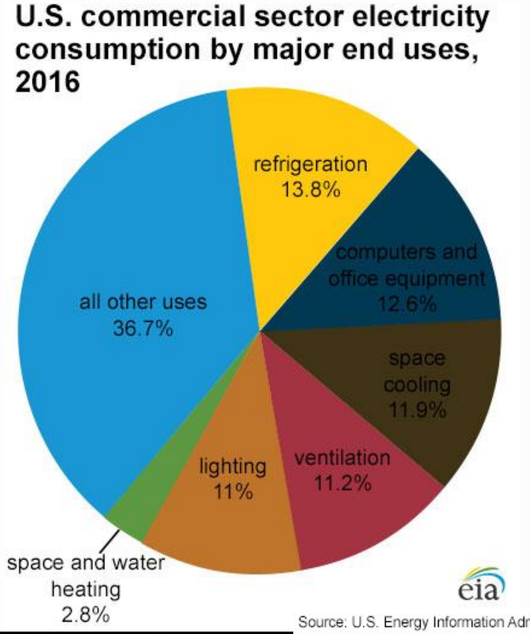
Outlines

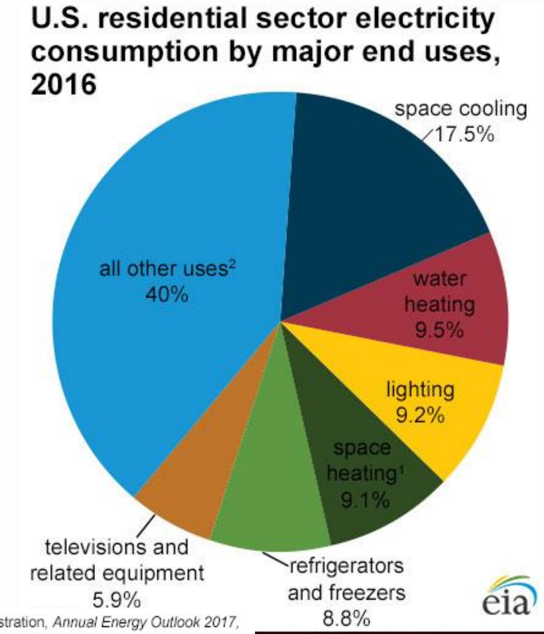
- Motivation
  - Background introduction
  - Issues with existing PIR sensors
  - Our proposed solution
- Shuttered Passive Infrared Sensor
  - Working principle
  - Optimization
  - Results and analysis
- Summary and Conclusions

Background Introduction

- Residential and commercial buildings consume over 13 quads of energy.
- HVAC and lighting consume 50% of it.
- Thermostats are not used efficiently.







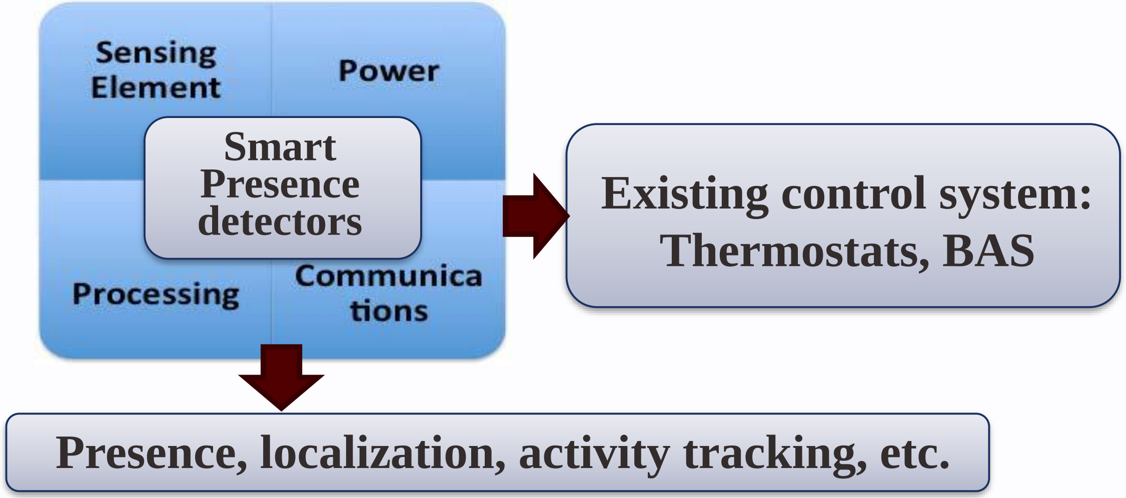
Source: U.S. Energy Information Administration, *Annual Energy Outlook 2017*, Table 5, January 2017

Issues with existing PIR sensors

- PIR sensors: widely used in buildings for lighting control.
- PIR sensors: motion sensors in nature, only response to moving occupants.
- They face high failure rate when occupants are not moving, causing uncomfortable light/temperature swing, short lifetime of equipments and the waste of energy.

Our Solution

- Use HDPE optical shutter to modulate received energy for both stationary and moving occupants.
- PIR sensor receives variate energy.
- PIR sensor is able to detect stationary occupants.
- More indoor detection functionalities can be explored:
  - Presence, localization, tracking, identification, etc.

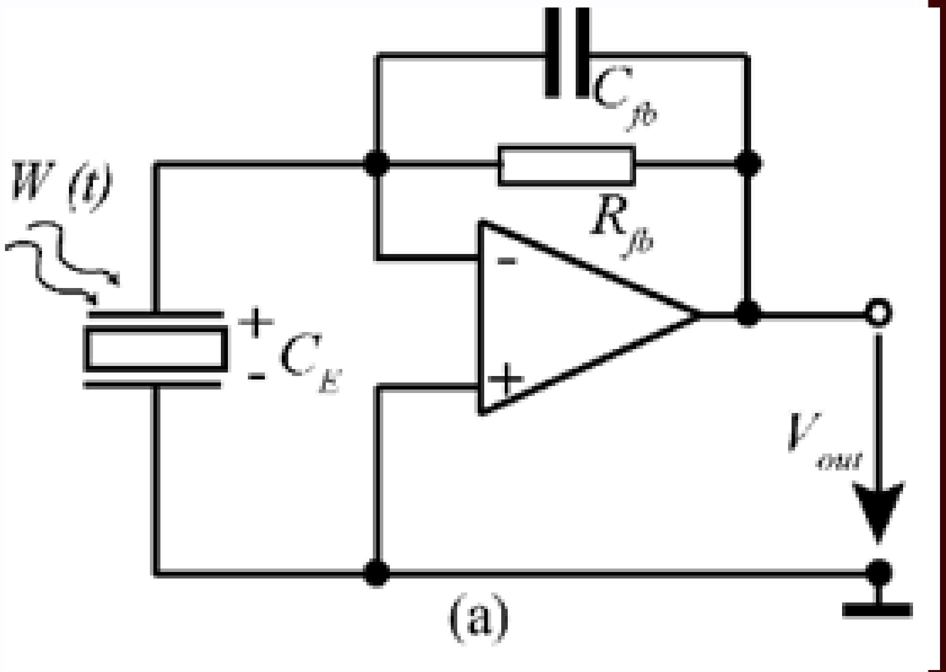


Working Principle

- The circuit consists of an op-amp, feedback, and a pyroelectric sensing element.
- Output voltage can be written as:

$$-V_{out}(t) = \frac{R_{fb}\eta p' A\omega}{G_T\left(1+\omega^2\tau_T^2\right)^{1/2}\left(1+\omega^2\tau_E^2\right)^{1/2}} W(t)$$

- Output voltage V_{out} is proportional to received energy $W(t)$.
- Modulation frequency ω (shuttering period) is also essential.

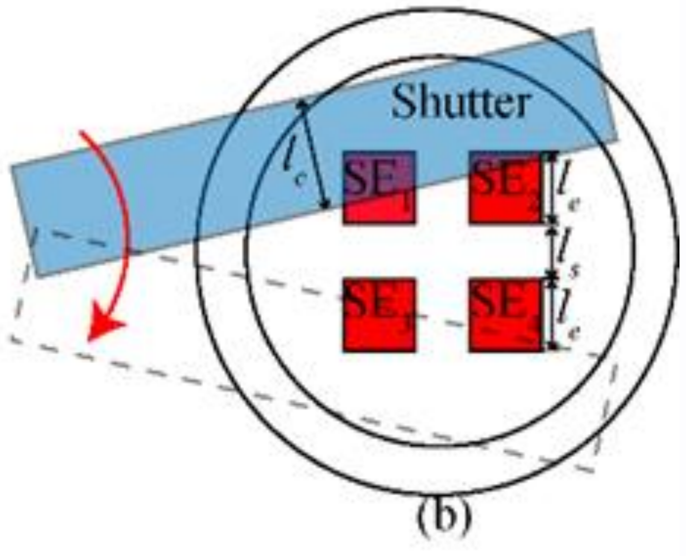


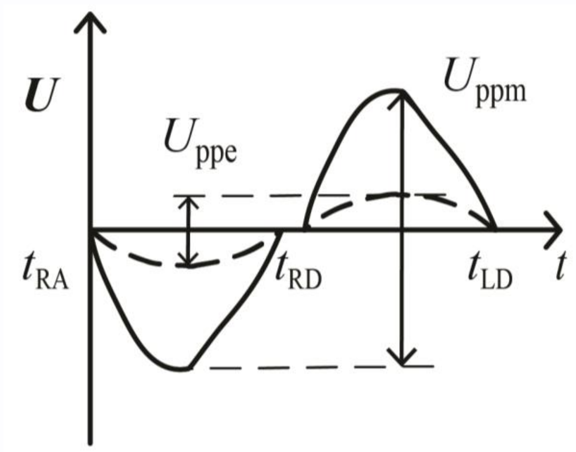
Working Principle

- A PIR sensor consists of 2 or 4 sensing elements.
- Shutter covers sensing elements by sequence.
- Variant energy can be written as:

$$\Delta W(t) = \Phi {l_e}^2 (1 - \kappa) \sin(2\pi t / T)$$

- Output voltage V_{out} is in sinusoid shape. Peak-to-peak V_{pp} value is one feature to indicate occupancy presence.

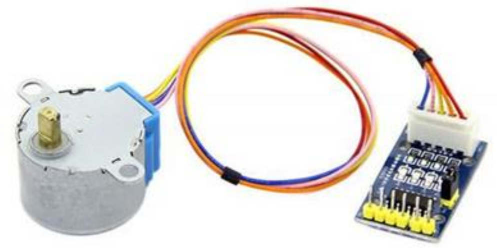




Source: Haili Liu, et al. *Applied Physics Letter*, VOL. 111 No. 24 (2017): pp. 243901.

Optimization: Driving Approach

- Shutter is driven by a motor.
- What we should consider when designing:
  - Power? Size? Cost?
- In previous work, we used servo motor/stepper motor (C-PIR/Ro-PIR)
  - Large weight and size, high power consumption, large noise, high cost.

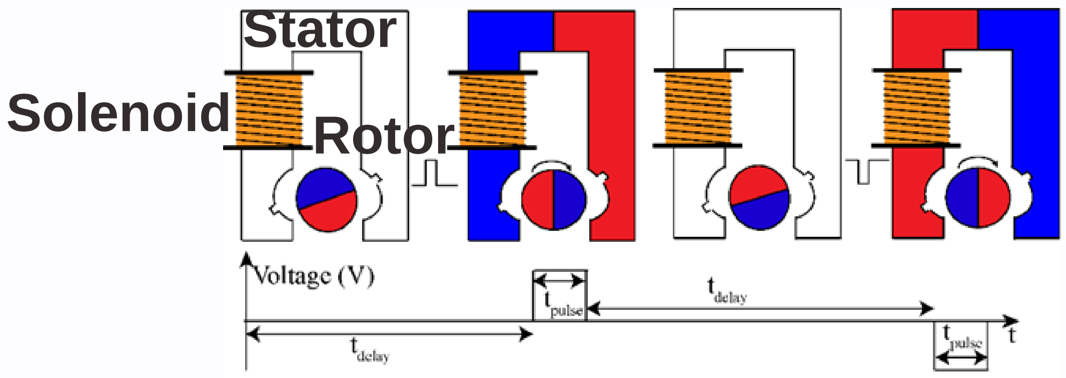


[1] H. Liu, Y. Wang, K. Wang, and H. Lin, Appl. Phys. Lett. **111**, 243901 (2017).
[2] L. Wu, Y. Wang, and H. Liu, IEEE Sensor Journal, 2018 (Accepted).

Image: https://robu.in/product/towerpro-sg90-9gm-1-2kg-180-degree-rotation-servo-motor-good-quality/

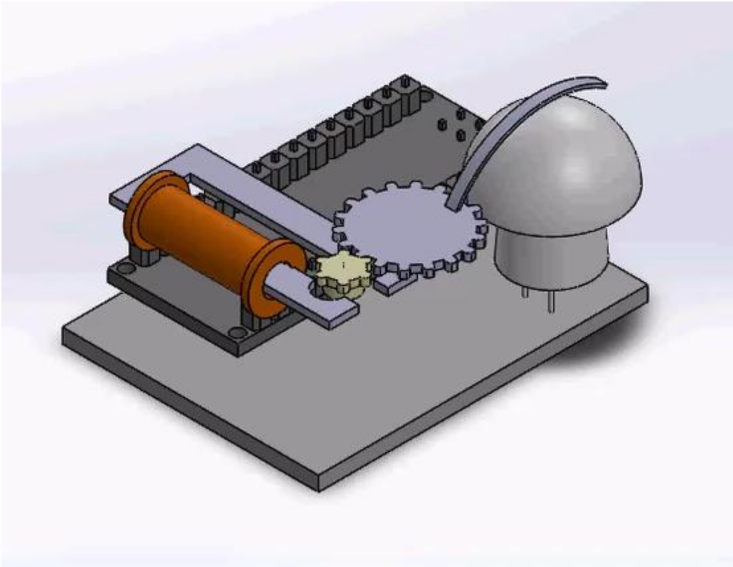
Optimization: Driving Approach

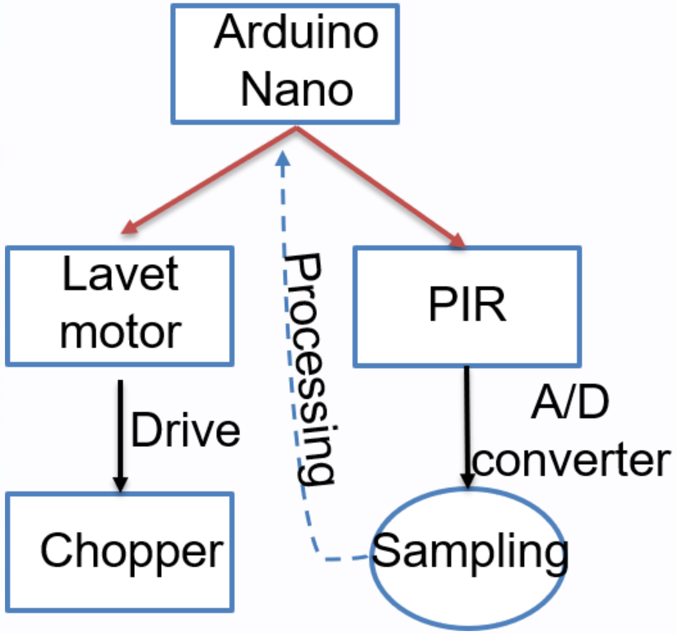
- Lavet type motor is widely used in clock and wrist watch due to its low power consumption, small size.
- When provided **pulse signal**, the energized stator forces rotor moving to corresponding position.
- One positive pulse, one no current state, one negative pulse and another no current state, will make the rotor rotating 360°.

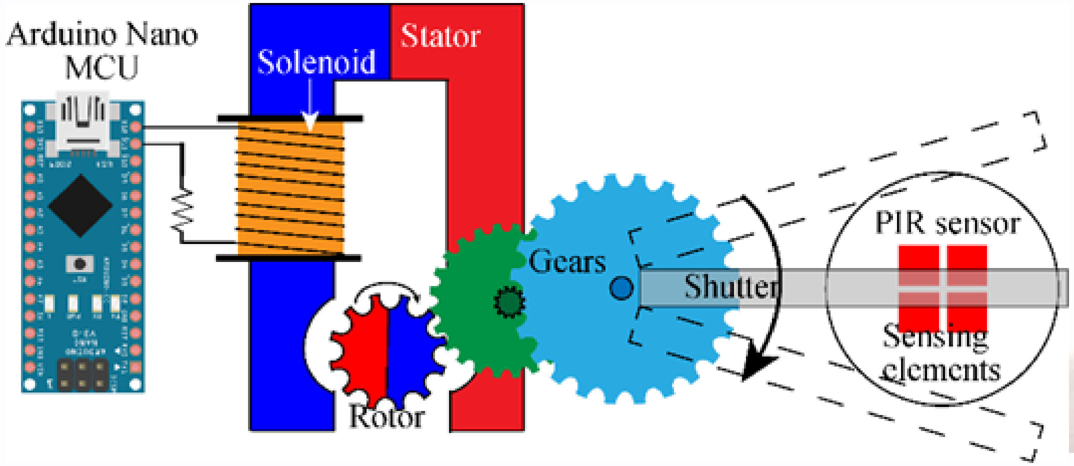


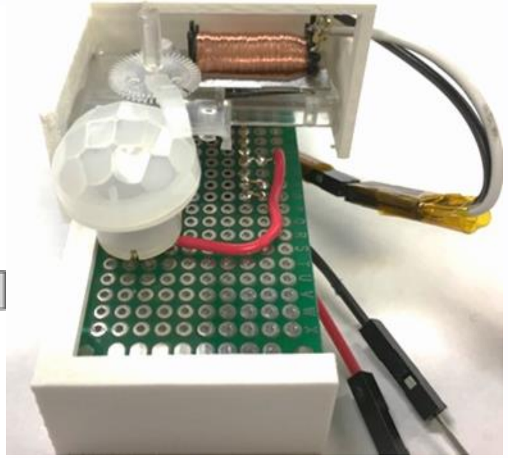
Lavet Motor PIR (LAMPIR) Node Design

- MCU controls motor and PIR.
- Motor drives shutter.
- PIR acquires analog data.



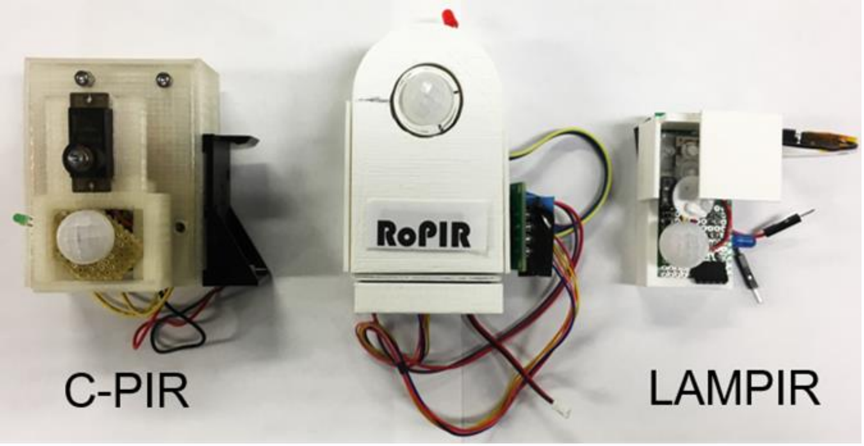






LAMPIR Node Advantage

- Smaller, lighter
- Lower Cost
- Less power consumption
- Higher detection range

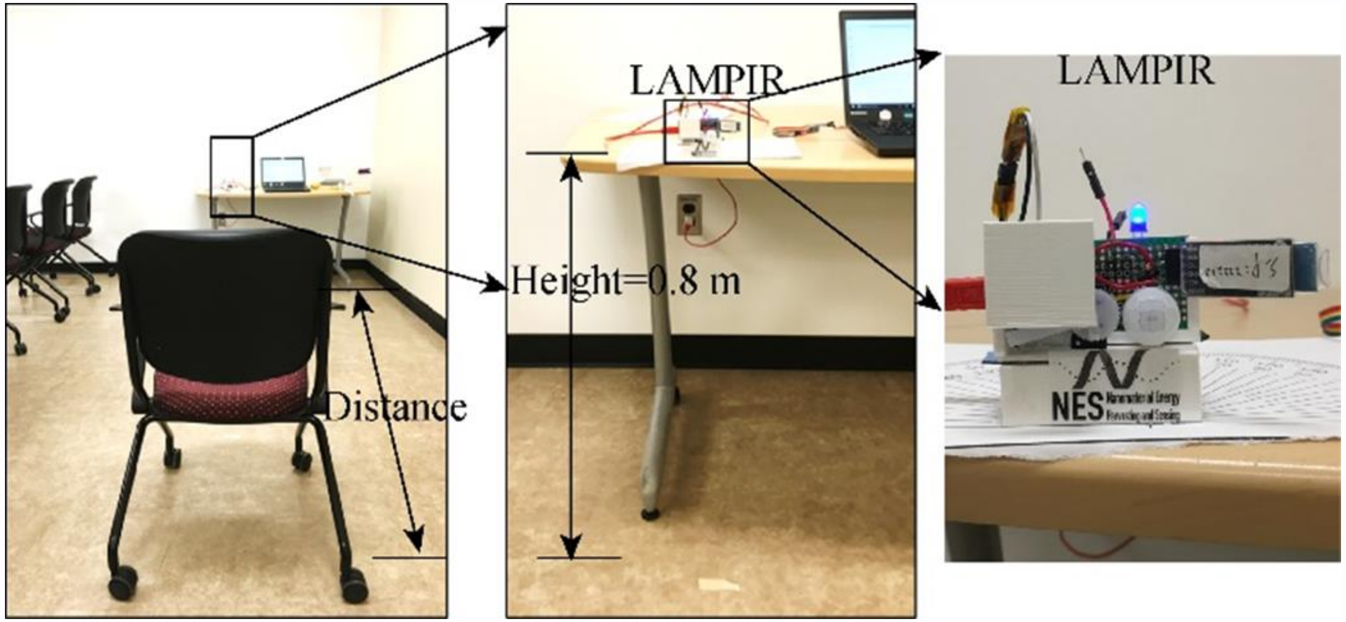


	Weight (g)	Size(mm)	Power (W)	Cost ($) Vol. 10k	Detection range(m) Stationary / Moving
C-PIR[1]	130	80×63×60	1.05	4.06	4 / 8
Ro-PIR[2]	160	100×60×45	1.68	4.99	3 / 8
LAMPIR	40	65×43×45	0.19	3.46	4.5 / 10
Comparison to C-PIR	- 70%	- 60%	- 82%	- 15%	+11% / +25%
Comparison to Ro-PIR	- 75%	- 55%	- 89%	- 31%	+50% / +25%

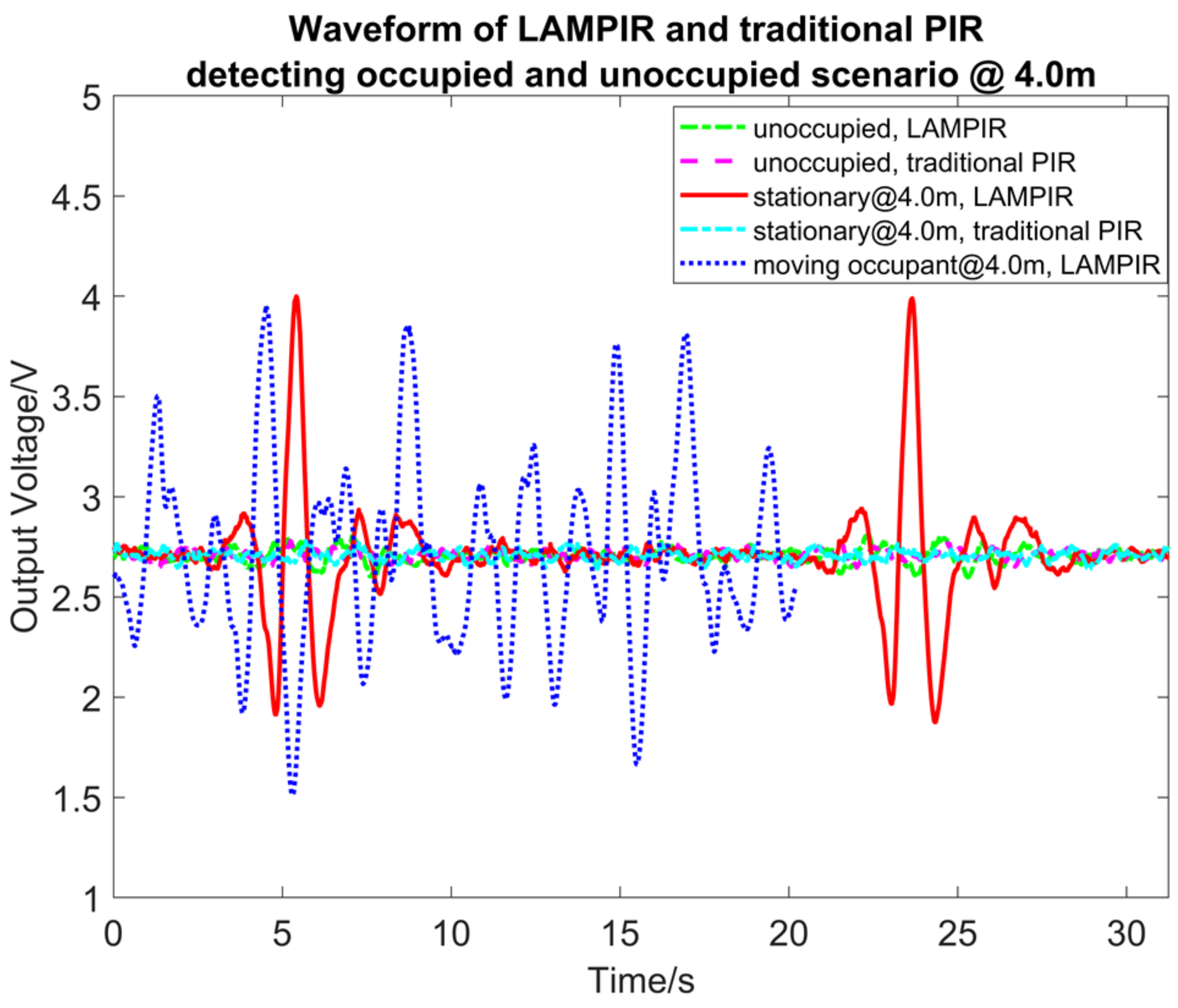
[1] H. Liu, Y. Wang, K. Wang, and H. Lin, Appl. Phys. Lett. **111**, 243901 (2017).
[2] L. Wu, Y. Wang, and H. Liu, IEEE Sensor Journal, 2018 (Accepted).

Experimental Setup

- The test is conducted in a conference room, under room temperature=26.6 °C and 24.6 °C.
- LAMPIR is placed on a table with height H=0.8m.
- Occupant is sitting in front of the device.

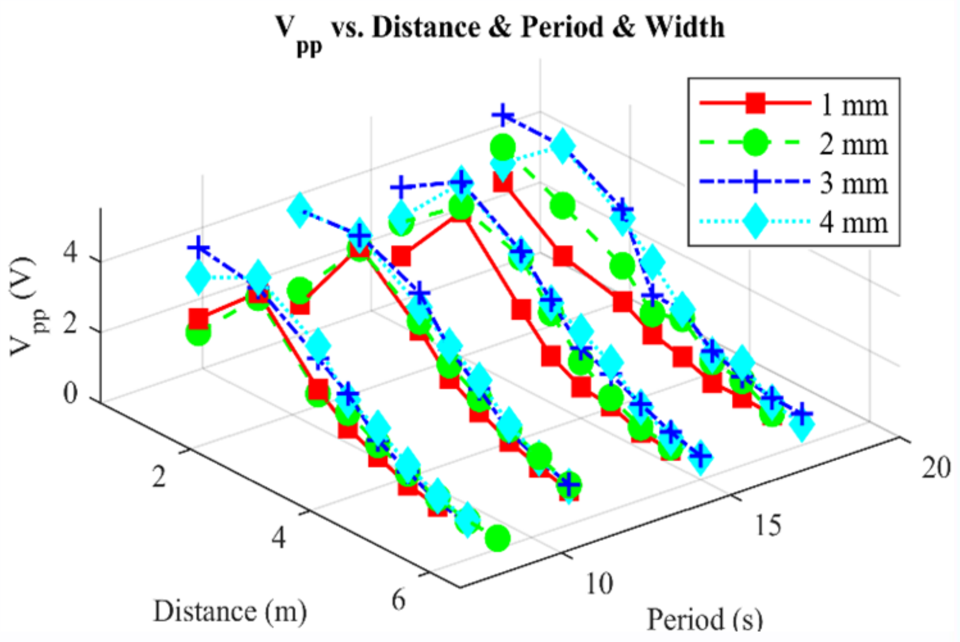


Waveform of LAMPIR Sensor



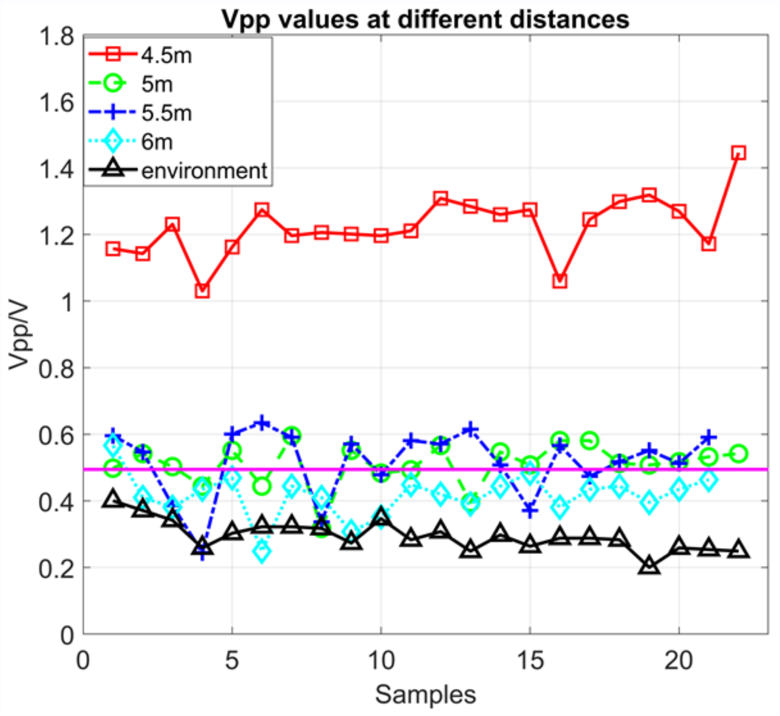
Parametric Optimization

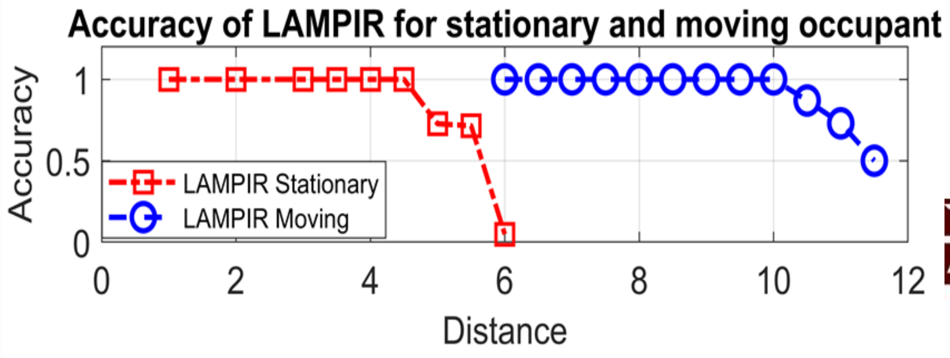
- Two parameters are considered: shutter width w and shuttering period T.
- Shutter width: 1.0/2.0/3.0/4.0 mm.
- Shutter period: 9/12/15/18 seconds.
- Occupant sits at different distance: 1.0-6.0m.
- We use $\boldsymbol{w}$ **= 4 mm** width and $\boldsymbol{T}$ **= 18 seconds** for further tests.



Occupancy Detection Accuracy

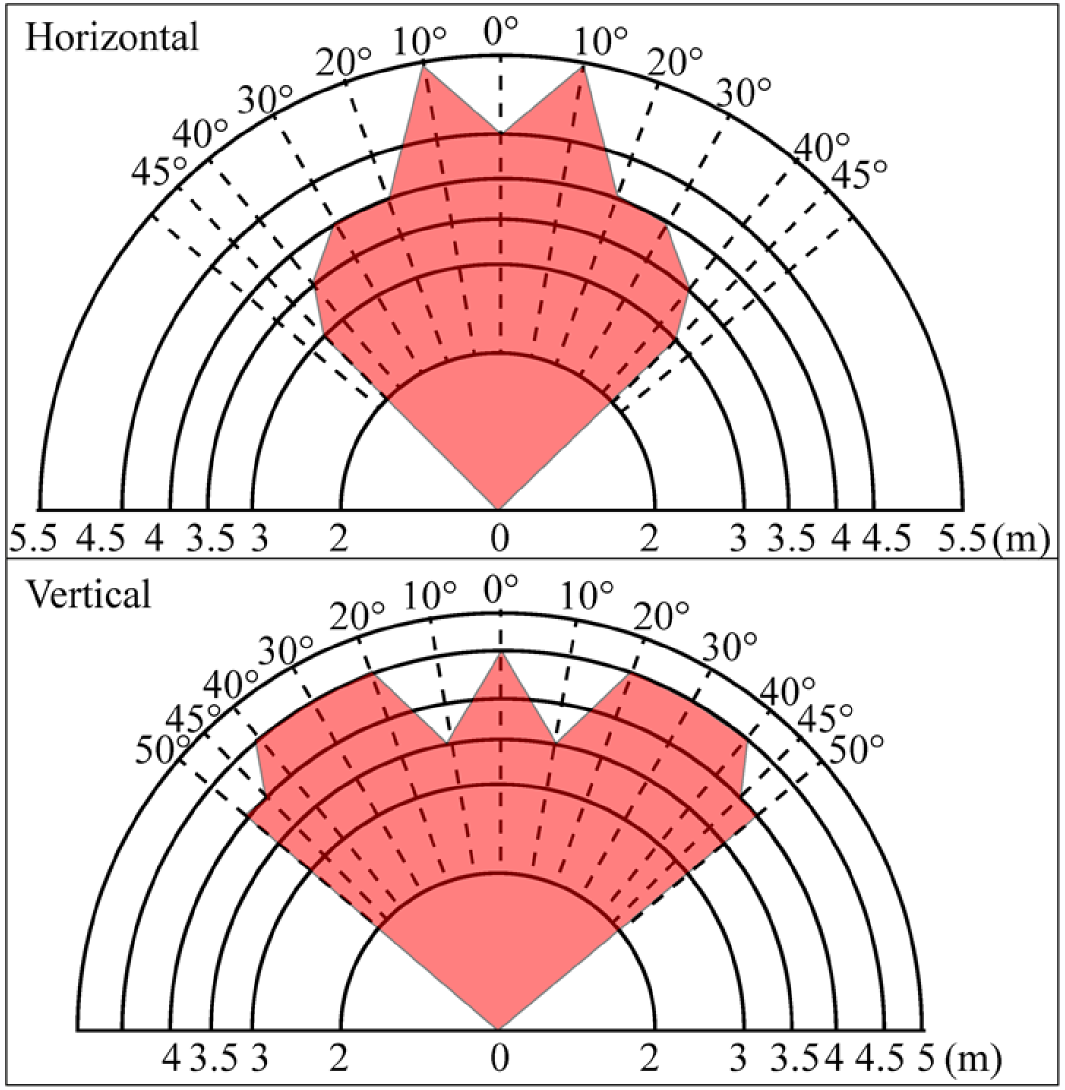
- A threshold *Vth* value is used.
- *Vppe* is maximum-minimum value of unoccupied environmental waveform.
- Choose $V_{th}=\max(1.6\times V_{ppe}, V_{ppe}+0.2\text{V})$.
- *Vpp* of distance =4.5/5.0/5.5/6.0 m and environment is plotted.
- Find that **D= 4.5m** has 100% accuracy.
- Accuracy drops when D>4.5m.





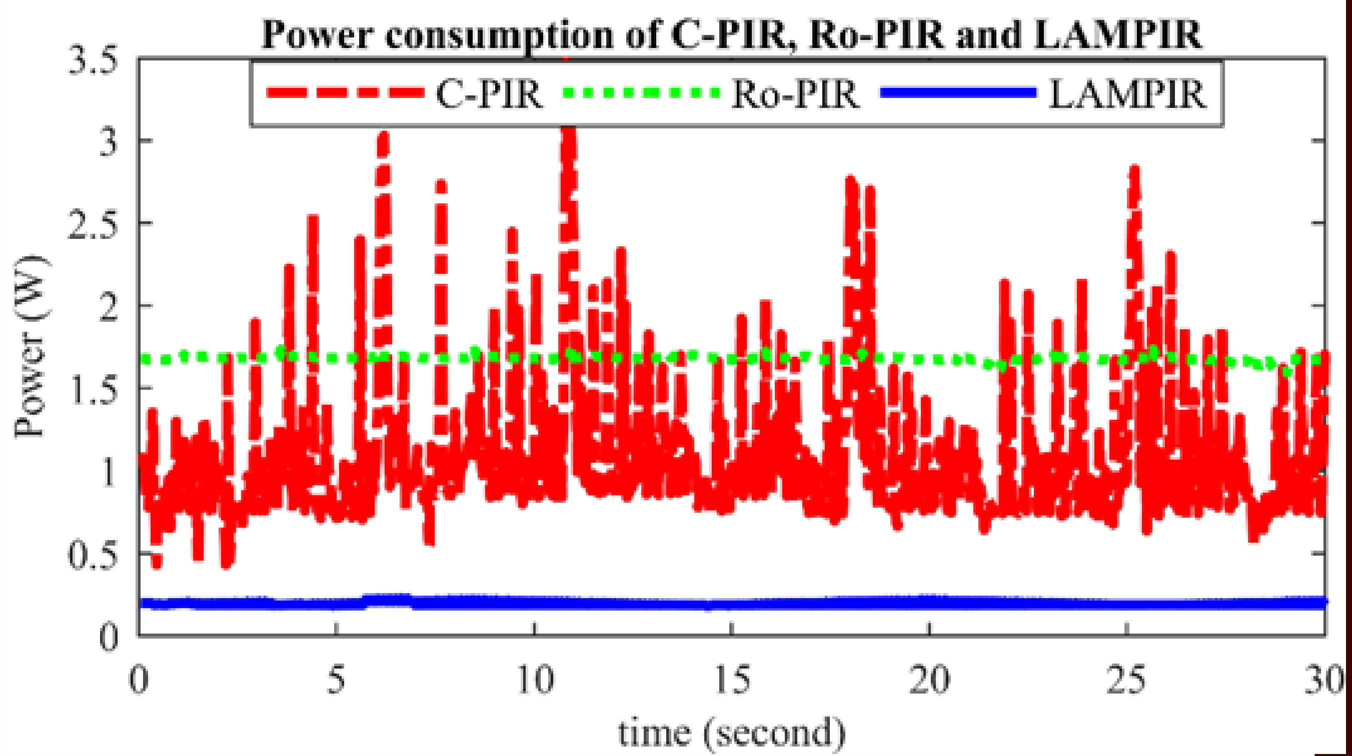
LAMPIR Field of View

- FOV is $\mathbf{90°}(\boldsymbol{Hor}) \times \mathbf{100°}(\boldsymbol{Ver})$.
- Compared to on board PIR sensor: $93°(Hor) \times 110°(Ver)$.
- LAMPIR has reasonable FOV for most applications.



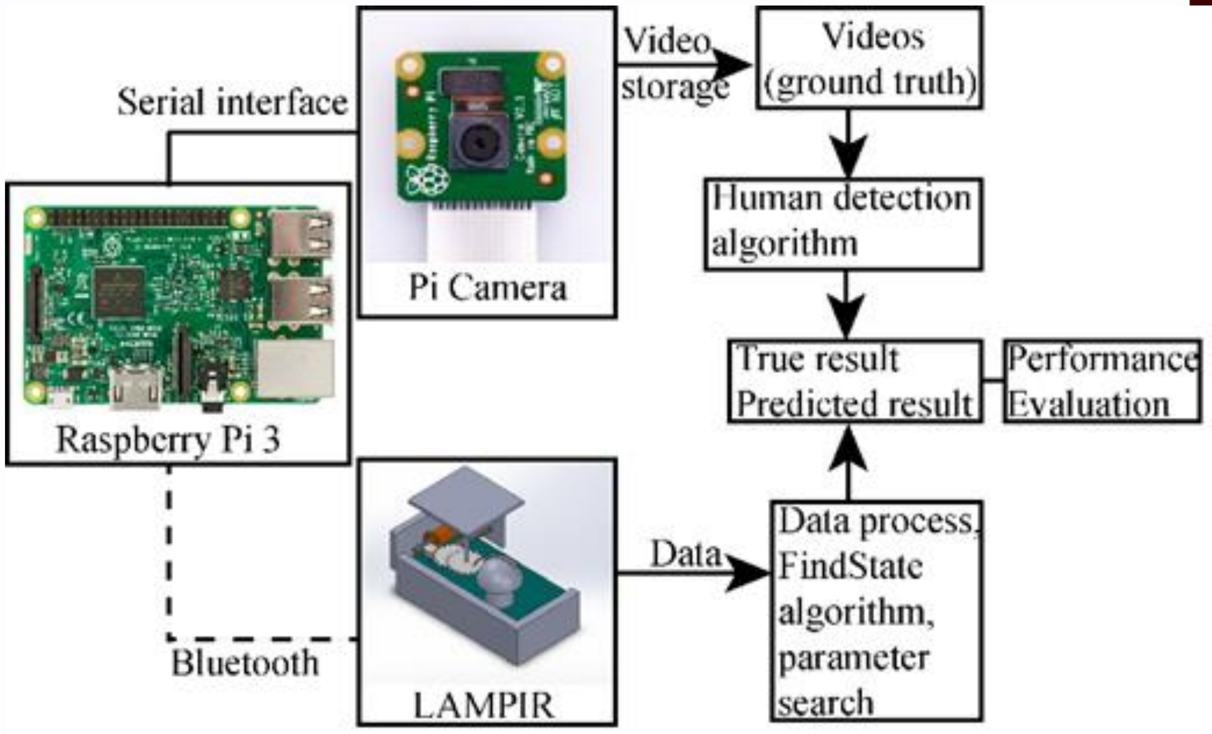
Power Consumption

- The Lavet vibrator only consumes power when the pulse voltage is applied.
- The comparison of a power consumption of the C-PIR, Ro-PIR and LAMPIR sensor is shown in the figure.

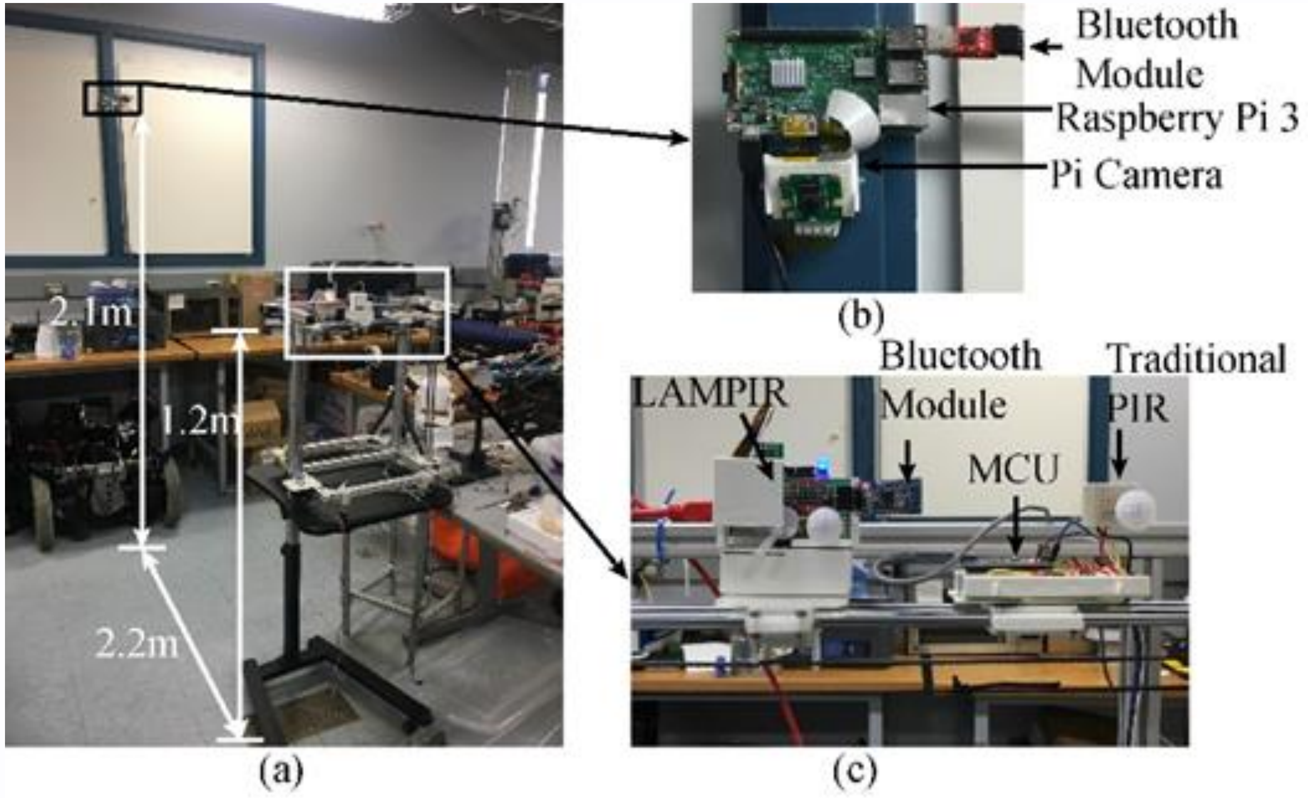


Long-term Occupancy Detection

- A video is recorded and processed by an human detection algorithm.
- Three states are classified.
  - Unoccupied
  - Moving
  - Stationary
- By comparing the predicted states and the true states, the evaluation is made for LAMPIR sensor



Long-term Experimental Setup



Video Processing

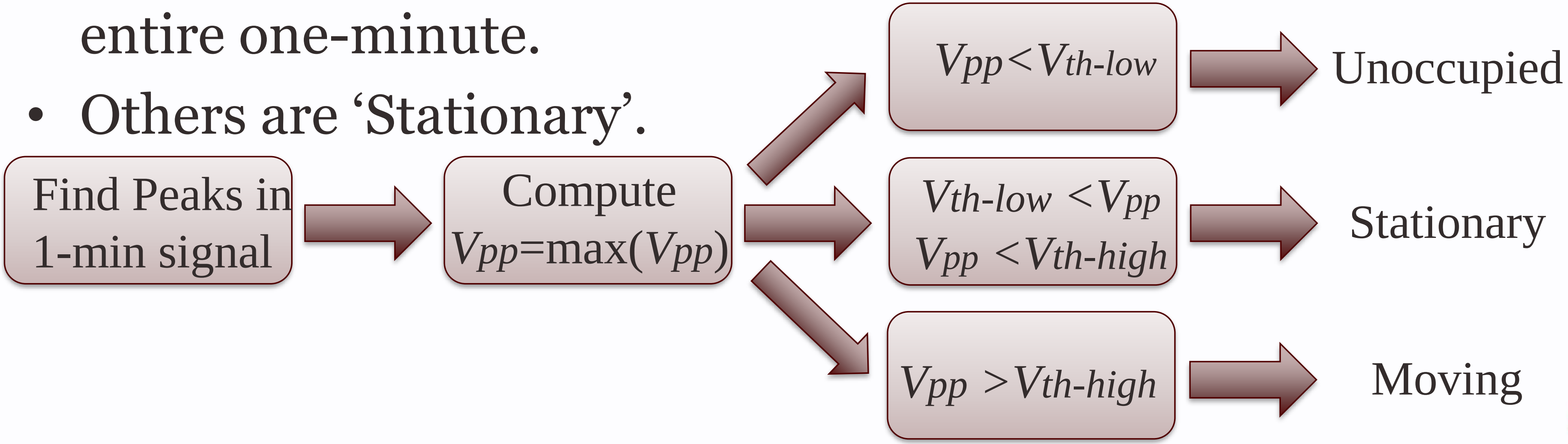
- Use a background threshold-dilation fused with a dense optical flow approach.
- Algorithms can reach 99.6% accuracy by comparing with manually labeled result from a data set of size 450.

Background subtraction → Dilation → Optical flow

(a) (b) (c)

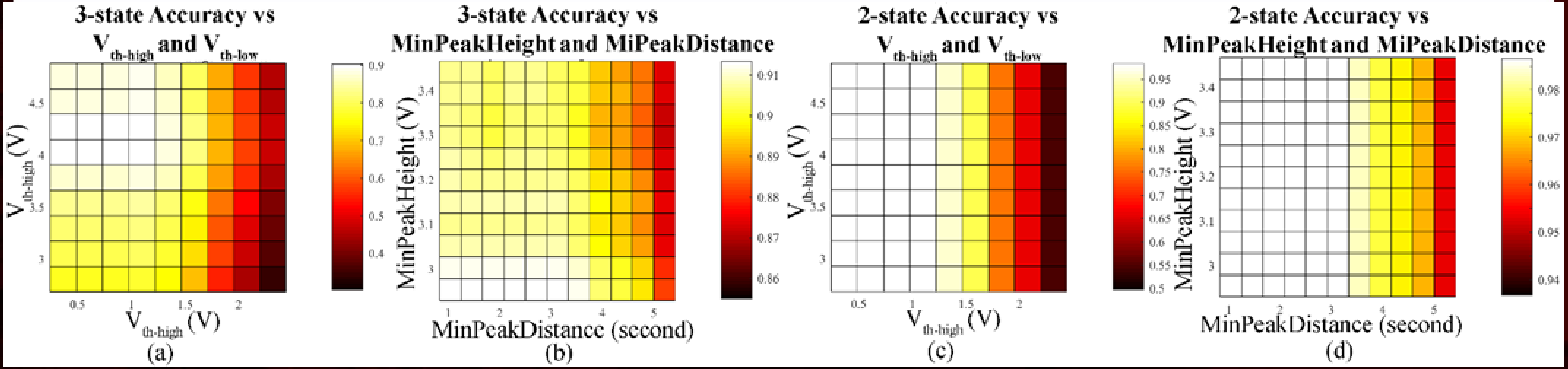
Long-term Presence Detection

- Predict state for each 1-minute interval.
- State is ‘moving’ when there exists one moment that the human is moving.
- ‘Unoccupied’ state happens when no occupants within the entire one-minute.
- Others are ‘Stationary’.



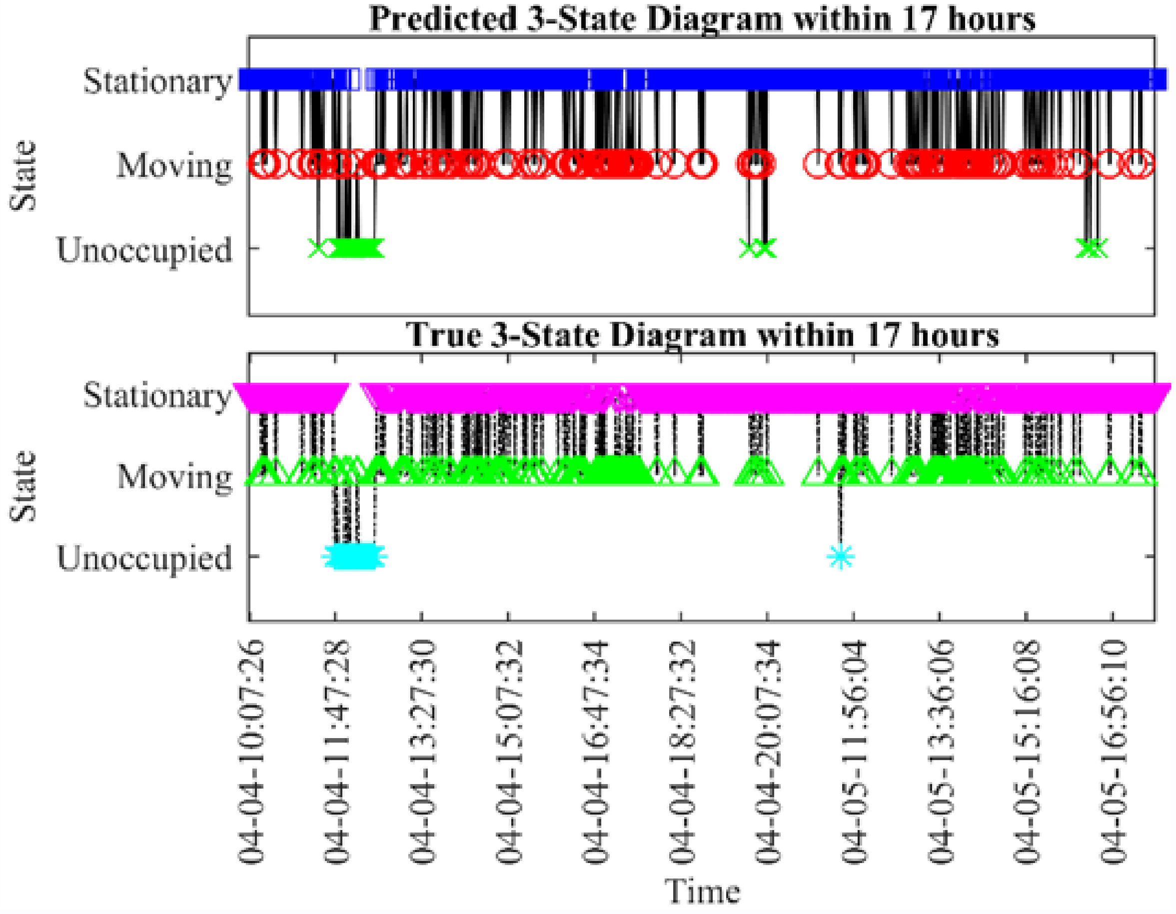
Long-term Presence Detection

- Four parameters in the prediction process:
  - MinPeakHeight and MinPeakDistance when finding peaks in signals.
  - $V_{th\text{-}high}$, $V_{th\text{-}low}$ when determining state.
- Grid search approach is used.
- 3-state accuracy is to predict 3 states: unoccupied, moving, stationary.
- 2-state accuracy is to predict 2 states: unoccupied, occupied.



Long-term Presence Detection

- 17-hour experiment.
- Parameters to predict 3-state accuracy.
  - $V_{th\text{-}high}$ = 4.150 V, $V_{th\text{-}low}$ = 0.976 V
  - MinPeakHeight = 2.929 V, and MinPeakDistance = 2.083 seconds
  - 93.52% accuracy.
- Parameters to predict 2-state accuracy.
  - $V_{th\text{-}low}$ = 0.976 V, MinPeakDistance = 2.083 seconds
  - 98.76% accuracy.



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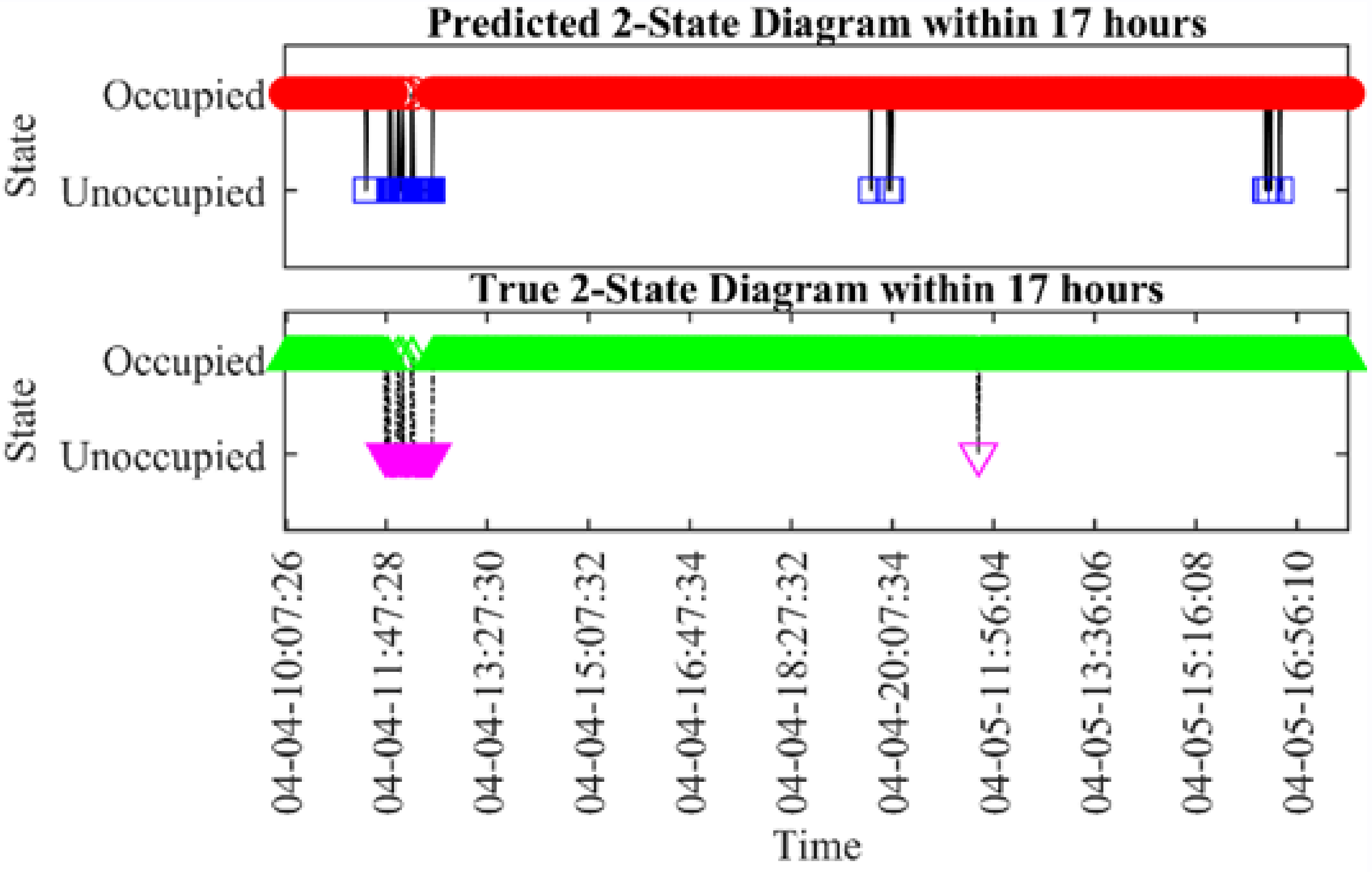

Summary

- A Lavet motor PIR (LAMPIR) sensor is designed.
- Optimal parameters are found.
- Power consumption is reduced to 0.19 W, much lower (82% and 89% lower) than other driving approach (1.05 W for servo motor, 1.68 W for stepper motor).
- A long-term (17h) occupancy detection reaches 93.52% (3-state) and 98.76% (2-state).

Future Work

- Collect data over 10000 minutes (approximately one week) to evaluate the long-term performance.
  - More efficient video processing algorithm.
- Reduce the error rate when predicting the states.
  - Add a peak counting number to predict.
  - Use a moving window to reduce the impossible transition between ‘unoccupied’ state to ‘stationary’ state.
- Real time prediction.
  - Onboard parameter learning.

Thank you!

Acknowledgement:
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