Design and analysis of the cost-effective wireless sensor network for Energy and Resource optimization

Abstract:

In today's world, sensors are everywhere! This paper proposes the use of motion sensors with Internet of Things (IoT) enabled devices to create smart Wireless Sensor Network (WSN). Normally, motion sensors act discretely to turn ON/OFF devices based on human/animal detection in the Field of View (FoV) of the sensor. However, by examining analog movement pattern from the sensor can reveal important information such as direction of travel and other valuable information about the underlying object movement. The analog wave pattern is processed via signal processing and time-series algorithm. Later, the processing outcomes fed machine learning algorithm to reveal the direction of a travel. The direction of movement is estimated with more than 95% of accuracy. In a test building site, multiple of such sensor modules are distributed throughout a building. These modules send incoming and outgoing movement data to the sensor fusion node connected to the data logging computer. The data pattern is carefully analyzed to optimize the energy usage of university hallways lights and other appliances. Furthermore, data analysis and automatic building lighting control is explored as a part of an upcoming summer scholarly activities.

This project is involving group of undergraduate senior level students of our engineering technology program. Students got the exposure of prototyping a sensor module, 3-D printing, deployment consideration, embedded programming, and the sensor data management.

Keywords: Wireless Sensor Network, Pyroelectric Infrared Sensor, Internet of Things, Signal Processing, Classification, Detection

I. INTRODUCTION:

The Pyroelectric Infrared (PIR) motion detectors are pervasive in our digital society [1]. Their use can create a smart system which otherwise, require plenty manual control or in some cases, it is almost impossible by human end. Smart systems incorporate the function of sensing, actuation, and control to analyze the surrounding environment and situation and make appropriate decisive actions based on available resources. Smart sensors and associated circuits are available at very affordable price due to the historical growth of a chip design industry. Therefore, it is very common to visualize these sensor systems at industrial environments, buildings, offices, public places, vehicles, and even at home.

Often smart home and buildings have motion sensors [2]. These tiny pieces of electronic modules are often used to surveillance and control the electrical appliances, lights in the vicinity of a human presence. Thus, their presence optimizes the electricity usage. More often, these sensor modules are discretely located and controlling the local devices. True potential can be released if

they communicate with each other for collaborative decisions. Therefore, it is necessary to have sensor network. Sensors do not have well defined protocols and capabilities to work together unlike the computer network. In addition, it is not generally feasible to connect geographically displaced sensors via cable. Fortunately, today's microcontrollers are digitally smart, smaller in size, cost-effective, and often equipped with wireless modules. Thus, combining sensors to the radio capable controllers is a most predominant approach to build wireless sensors network.

This project involves group of a senior engineering technology students. Student gain multidisciplinary knowledge in practical systems design, deployment, and underlying analysis which are among the most important skills expected from the recent graduates by the current industry. Student utilize their 3D modeling skills to build a custom shape, used smart controllers and programmed to address application needs, build a wireless sensor network and know more on RF propagation, collect and manage the raw data to in cloud, and exposed to use high level statistical analysis and machine learning concepts for energy resource optimization.

The paper is organized as follows. In Section II, the basic PIR operation is presented. The subsequent Section III summarize the system design hardware and the deployment architecture. The Section IV is depicting overall Distributed Sensor Network (DSN) architecture. The Section V is focusing on mobility detection methods employed in this paper. Finally, student learning experience, conclusion and future work are briefly explained followed by useful references.

II. BASIC OPERATION:

Motion sensors use pyroelectric infrared (PIR) sensors to sense bodily heat emitted by the humans or animals when they are observed in a close distance from the sensor. Usually, an ambient temperature is different compared with the body temperature which in-tern momentarily create the temperature difference in the field of view (FoV) of a PIR sensor. The sensor converts the resulting change of infrared heat radiation into the change in its output voltage, thus triggers the detection. However, output voltage from the PIR sensor is very low requiring multiple amplifying stages. The PIR sensors are available in variety of configurations to make them suitable in a typical application. Most of the PIR modules are designed with cost-effective plastic Fresnel Lens which extends the effective sensing range from few feet to tens of meters and viewing angle from few degrees to about half a circle [3], [8].

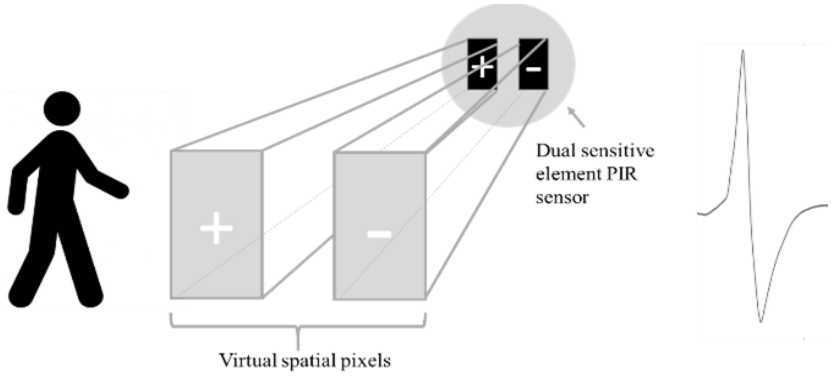


Fig.1 Typical human movement pattern by the motion sensor.

III. HARDWARE DESIGN:

The PIR sensor module design carrying many components including PIR sensor, driving amplifier interface circuit, microcontroller with radio access module, battery backup to continuously supply power to the entire module, and custom designed housing case to fit all the above components. The module design involves commercially available IRA-S210ST01 PIR sensor [11]. An objective here is to accurately determine the direction of the travel in the Field of View (FoV) of the sensor. Therefore, the multizone dome or curtain lenses are not well suited here. For this reason, the system is equipped with IML-0686 curtain lens on a small form factor [12]. This lens directly fit on the top of a steel case of the PIR sensor.

An output of the sensor needed to be amplified by two operational amplifier stages. The system is designed with LM324 general purpose amplifier with the collective gain of 65 dB at the mid-band frequency. The bandwidth of this slow varying systems is typically set from 0.1Hz to 10Hz to accommodate both fast as well as slow human movements in the sensing zone. Typically, the amplifier stage output is given to analog comparator circuit to detect the threshold levels. However, in this design the analog output is directly connected to the microcontroller built in Analog to Digital Convertor (ADC). The proposed system developed using Adafruit Feather© M0 with RFM95 LoRa Radio platform [9]. Some key features of the controller module are:

- Microchip© ATSAMD21G18 controller @ 48MHz, 256 KB flash memory, 32KB SRAM
- Hardware Serial, I2C, and SPI support, 8 PWM , 11 analog I/O, built in LiON charger
- SX1278 LoRa© Radio module with SPI interface uses ITU USA 915MHz ISM band
- Packet radio with ready to go Arduino libraries

The module block diagram is shown in the following figure.

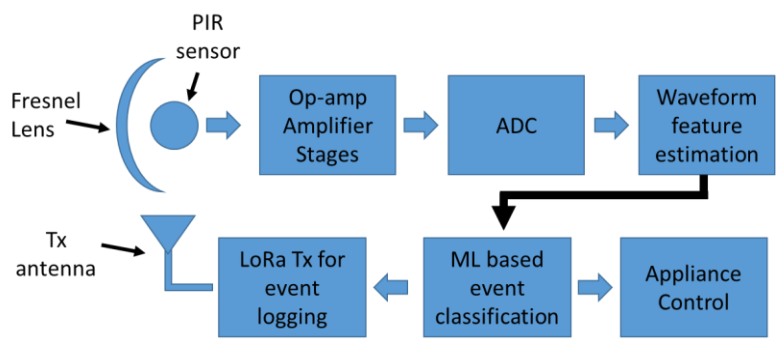
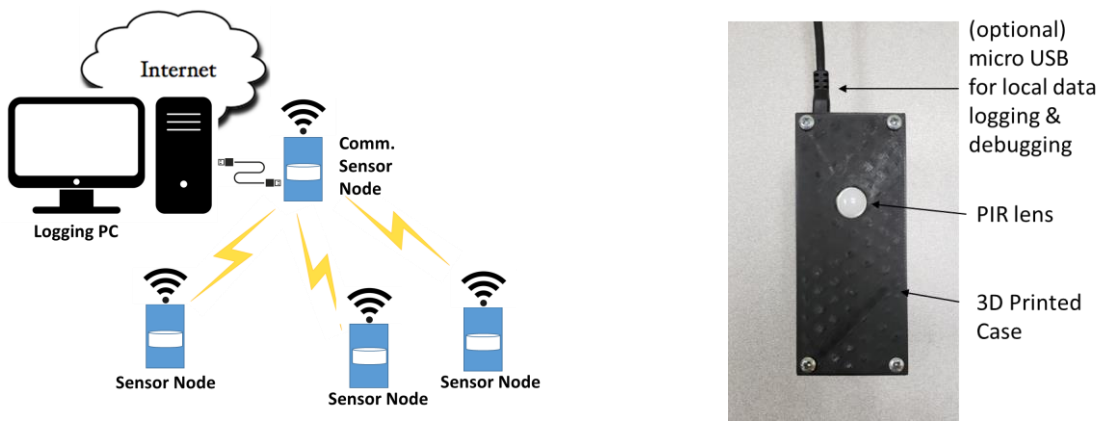


Fig.2. PIR sensor module block diagram

The waveform received from the sensor is continuous in nature. It encompasses several samples in a specific movement pattern. However, the controllers have limited processing resources. Therefore, it is predominantly important to estimate the necessary wave-pattern features from the real-time movement specific waveform. Later, these features are fed to the Machine Learning (ML) algorithms for classifying underlying event pattern [4]-[6], [13]. Finally, the estimated event results can be directly used to exercising lighting/appliance control or sent to the master logging station for offline statistical analysis and resource management.

IV. WIRELESS SENSOR NETWORK

The system is designed as Distributed Sensor Network (DSN). The sensors are placed at the building doorways. It the perfect place to monitor incoming and outgoing traffic. These sensors are capable to control the hallway lights. They drive the general-purpose relay control modules for exercising response to the local presence. Additionally, these distributed sensor nodes are registering movement information to the sensor fusion node. The fusion node is an identical to the LoRa module except it is directly connected to the logging PC as showing in the following Fig. 3-(a). In this DSN system, individual sensor modules are processing raw-data received from the PIR sensor and map it into the feature vector. As said before, the feature vector is passed to learning algorithm to determine movement direction in the PIR sensing zone. This is considerably reducing the data processing complexity as decision is taken at the node level. Only event specific date is sent to the fusion node.



(a) (b)

Fig. 3 Surveillance system architecture (a) and PIR system module (b)

V. MOBILITY DETECTION

The movement detection in a sensitive viewing area of the PIR sensor can reveal a sinusoidal wave pattern. A slow varying DC level is always centered around the half analog reference voltage. This random voltage variation is translating the local ambient temperature environment. Also, the human walking is typically about 5 Kmph. This is resulting into less than a few Hz frequency in the output waveform. Therefore, the system is designed to avert high frequency noise more than 10 Hz. Typically, 0.5 Hz to 10 Hz system bandwidth allow very slow to fast motion detection.

A. Peak to peak Variation in the wave

The peak to peak variation in the resulting sinusoidal wave pattern is directly proportional to lateral movement in the FoV of sensor and underlying Fresnel Lens pattern. Factors such as a distance from the sensor, slow/fast movement, and ambient temperature condition dominate on a waveshape. Following Fig.4 indicate a typical human movement at 3 ft in FoV of the PIR sensor module.

B. Direction of the movement estimation

The analog output from the sensor reveal the direction of a travel in the sensitive zones of a motion sensor. The first peak in the movement wave pattern reveal information about the direction of the travel in FoV of the sensor

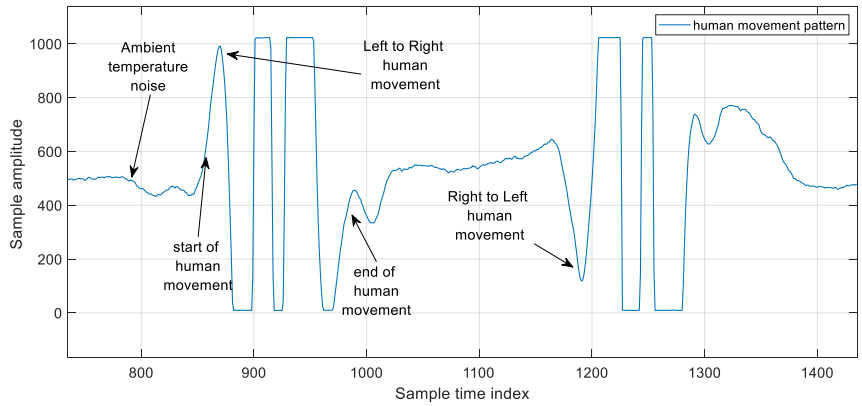


Fig.4. PIR sensor module output of a normal walking pattern at 3 ft from the sensor.

. This is marked in Fig.4. However, it the ambient heat source often randomly introduce the bias. In addition, it is strictly associated with the Fresnel lens pattern. Therefore, one cannot only rely on the first peak to determine the direction of the movement. Several other wave parameters such as peak to peak variation, average peak duration, bias level before and after the movement, and frequency of the sinusoidal pattern are carefully analyzed and to improve the estimation accuracy of the direction of a movement. Therefore, this experiment utilizes some of the mentioned parameters and fed it to the machine learning algorithm. The supervised machine learning models rely on the tagged data, meaning, a movement patterns with associated actual physical direction information. Fig.5. show snapshot of the direction estimation performance by the ML algorithm.

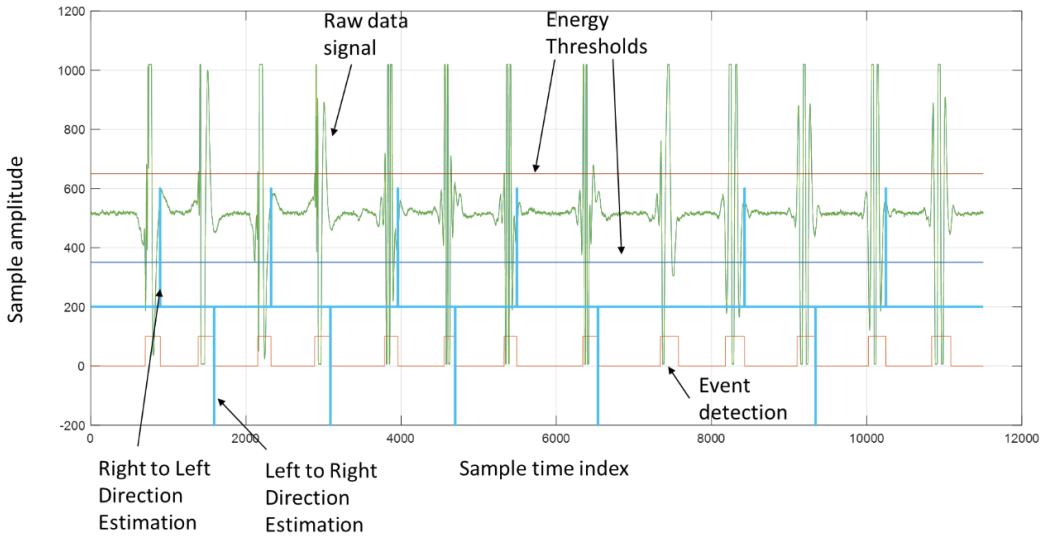


Fig.5. movement direction estimation using ML model

VI. STUDENT LEARNING EXPERIENCE

This work is designed as a part of the capstone project of a group of senior students. They gained enormous cross-discipline knowledge by utilizing skills on mechanical, computing, and statistical analysis. Specifically, this capstone activity involves cross-discipline students in Electrical and Computer Engineering Technology, Mechanical Engineering Technology, and Electro-mechanical Engineering Technology domains. Collectively it can be a part of educational activities which can address almost all the newly designed ABET-ETAC student outcomes 2019-2020 [15].

The 3D printing layout on a CAD tool is designed by senior students of the local engineering technology department. Later, they created a prototype the design using ABS plastic-based 3D printer. Subsequently, they have integrated the battery, LoRa Feather module, PIR sensor and interfacing circuit, and Fresnel lens into the customized model. In addition, students collected the hallway movement data at appropriate distances from the sensor module and tagged it with the event ID. Students have done an excellent effort in modeling raw data vectors into the formatted vector suitable for processing in machine learning models. Finally, students have deployed it to the entrance of the buildings and verified the wireless data exchange at the fusion node. Firstly, the obtained data is analyzed in Matlab or Python based higher level system designed software. Secondly, the observed working of the classification algorithm is converted into real-time C program on controllers.

The student group is awarded Armin J. Fleck scholarship award by Fleck foundation to fully support the underlying cost involve in the capstone project [14]. Overall, student group expressed a very positive learning outcome. Students are willing to extend their capstone design in a professional proposal for observing human traffic at key university buildings and public/private sector buildings.

VII. CONCLUTIONS AND FUTURE DIRECTIONS

This paper illustrates a cost-effective surveillance method by employing distributed motion sensors modules. These sensor modules are equipped with the low-cost wireless engine to communicate with the master fusion node and log various movement events on to the computer/server. The computer can initiate lightening or appliance control based on the past-learned events from the distributed sensors. The distributed sensor network not only optimize the energy usage but also it can allow a better statistical view of a public/private building usage with secured and privacy-protective human surveillance. There are many techniques in Machine learning and Deep learning can be exploited with the wisdom of conventional time-series prediction methods to optimized pattern classification performance. An author would like to explore more wave features to extend this problem in the multiclass classification level.

This is one of the good examples of research collaboration between professor and students. Students learned by multi-discipline design, programming, and data management. Administratively, this allows the department to get ABET student outcomes. In addition, researchers get the raw-data to work on algorithm analysis and optimization.

REFERENCES

[1] R. Whatmore, "Pyroelectric devices and materials," J. Rep. Prog. Phys., vol. 49, no. 12, 1986, Art. no. 1335.

[2] A. Hossain andM. H. Rashid, "Pyroelectric detectors, and their applications," IEEE Trans. Ind. Appl., vol. 27, no. 5, pp. 824–829, Sep./Oct. 1991.

[3] Pyroelectric infrared detectors. [Online]. Available: http://www.fuji-piezo.com/prodpyro.htm. Accessed: May 14, 2018.

[4] H. Gami, "Movement Direction and Distance Classification Using a Single PIR Sensor," IEEE Sensors Letters, vol. 2, no. 1, pp. 529–551, Mar 2018.

[5] J. Yun and S. Lee, "Human movement detection and identification using pyroelectric infrared sensors," Sensors, vol. 14, pp. 8057–8081, 2014.

[6] Shankar, M.; Burchett, J.B.; Hao, Q.; Guenther, B.D.; Brady, D.J., "Human-tracking systems using pyroelectric infrared detectors". Optical Engineering, vol. 45, no. 10, Oct. 2006

[7] SmartDetect Project Team, "Wireless sensor networks for human intruder detection," J. Indian Inst. Sci., vol. 90, no. 3, pp. 347–380, 2010.

[8] Zilog Inc., "ZMOTION lens and pyroelectric sensor product specification," Zilog Inc., San Jose, CA, USA, 2013. [Online]. Available: www.mouser.com/ds/2/450/ps0286-8752.pdf Accessed May 14, 2018.

[9] Adafruit Feather M0 with RFM95 LoRa Radio., [Online] Available: https://www.adafruit.com/product/3178 Accessed: Feb 28, 2019.

[10] "Machine Learning," [Online]. Available: https://www.coursera.org/learn/machine-learning Accessed: Feb. 28, 2019.

[11] Dual-element Pyroelectric Sensor. [online] https://www.murata.com/en-us/products/productdetail?partno=IRA-S210ST01 Accessed: Feb 28, 2019

[12] Curtain Fresnel Lens. [online] https://www.murata.com/en-us/products/productdetail?partno=IML-0686 Accessed: Feb 28, 2019

[13] R. O. Duda, P. E. Hart, and D. G. Stork, Pattern Classification, 2nd ed. New York, NY, USA: Wiley, 2017.

[14] Department of Engineering Technology – Miami University [online] Available: https://miamioh.edu/regionals/academics/departments/ent/index.html Accessed: Mar 25, 2019

[15] Engineering Technology Accreditation Commission (ETAC) [online] Available: https://www.abet.org/etac/ Accessed: Mar 25, 2019