Surveillance Tracking System Using Passive Infrared Motion Sensors in Wireless Sensor Network

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***Abstract*— Wireless Sensor Networks for surveillance systems in home, office, or factory environment require correct tracking of intruders. For such systems, passive infrared motion sensors (PIR sensors) are ideal because they do not require any signal or devices on the object to be tracked and they can work in dark environment as well. This paper first analyzes the performance and the applicability of the PIR sensors for security systems. Then, we propose a region-based human tracking algorithm with actual implementation and experiment in real environment. From the experiments, we show that the human tracking algorithm based on the PIR sensors performs very well with proper sensor deployment.**

I. INTRODUCTION

Wireless sensor network is a very useful system for monitoring and interacting with environment because it consists of small senor nodes with wireless communication capability which enables easy integration with environment. Moreover, they can be automated so no human intervention is required. There are a lot of monitoring applications based on wireless sensor network technology and they are interested in monitoring specific events or objects. Not only they need to figure out the occurrence or existence of such events or objects, but also they need to find out where the events have occurred or the objects are present. Examples of that kind of application include fire monitoring systems, surveillance systems, livestock monitoring and protection systems, and so on. The target application aimed by this paper is surveillance systems for home, office, or factory. In surveillance systems, it is very important to detect undesired intrusion by foreign people while nobody is present in office, home, or factory. Wireless sensor network is ideal for such application because it is a fully automated system which does not require any human intervention and easily connected to external network such as the Internet or the cellular network so it can notify the user about the undesired situation.

To find out not only the existence of intruders but also the location of them, we propose a region-based human tracking algorithm using passive infrared motion sensors (PIR sensors). There are several reasons why we use PIR sensors as base sensing tool for tracking human in surveillance systems. First, PIR motion sensors do not require any device or signal from detecting object unlike sound, ultrasound, or RSSI based localization schemes. This fact is very important in surveillance applications because intruders usually do not have such characteristics. Second, PIR motion sensors can work in dark whereas vision-based system cannot. They detect a change in temperature so human body's movement can be detected because body temperature makes a change in temperature in PIR sensor's view. Third, PIR sensors are cheap and easy to use. Processing data from PIR sensor is much easier than those from microphone, ultrasound, or vision device. Therefore, scaling security systems based on PIR sensors to large systems does not cost much and not require huge computational power. [4]

Given that PIR sensors have several advantages over other sensors in surveillance applications, we propose region-based human tracking algorithm. First, we discuss about the performance and the characteristics of the passive infrared motion sensor used in this paper. In addition, issues related to the deployment of sensors are discussed because the performance of the algorithm is highly dependent on how the sensors are deployed in monitored space. Then, we provide mathematical abstraction of the detection region of PIR sensor which is a building block for the region-based tracking algorithm. Finally, we propose the algorithm with actual implementation and experiments in real environment.

II. BACKGROUND AND RELATED WORKS

A simple approach determining direction to the position of human was proposed by A. S. Sekmen for human-robot interaction.[4] In A.S. Sekmen's research, PIR sensors are attached to a robot and used to find out relative direction of human from the current position of robot. Several PIR sensors were attached together making a circle and the relative direction of human is the position of PIR sensor which detects the human. The advantages of PIR sensors were also discussed. Moreover, the intensity-based localization scheme is proposed by M. Waelchli.[5] It has been shown that event-localization based on signal intensities gathered by sensor nodes is mathematically possible and the actual implementation and proof of applicability are discussed in later publication.[6] In addition, a fully distributed object tracking framework, DELTA was also introduced by M. Waelchli.[7] This framework tracks and localizes light using photo sensors. DELTA maintains groups of nodes that are dynamically formed and a group leader is elected by a measurement-based election algorithm. The group leaser is in charge of group maintenance, data gathering and processing, as well as reporting to the base station.

Human tracking method proposed in this paper uses PIR (Passive infrared) sensors. PIR sensors detect changes in infrared radiation which is caused by movement of a person (or object) which has different temperature from the surroundings. Because PIR sensors detect temperature differences, it is ideal for detecting the motion of people by detecting the difference of their body temperature and the surroundings. In addition, PIR sensor used in the experiment of the method proposed in this paper has wide sensing area of 10m with about 90°. Therefore, we have decided to use PIR sensors with region-based tracking algorithm for detecting human movement.

A. Characterization of PIR sensor

According to the datasheet [8] of the PIR sensor, it has detection distance of maximum 10m (32.808ft) and detection range of 110° in horizontal and 93° in vertical. We performed a simple lab test to identify actual performance of the PIR sensor and obtained similar results to those in the datasheet. However, we found that the actual detection region with high reliability is a little smaller than the detection region specified in the datasheet. Table 1 shows the comparison between the performance of PIR sensor provided in the datasheet and the real performance obtained by our lab test.

TABLE I
THE COMPARISON OF THE PERFORMANCE OF THE PIR SENSOR

Items		**Datasheet**	**Lab Test**
Detection Distance		10m (32.808ft)	9m (29.528ft)
Detection Range	Horizontal	110°	90°
	Vertical	93°	90°

According to the datasheet of the PIR sensor, the detection region of the sensor is not continuous. Instead, it is divided into several “detection zones”. Detection zone is a small region within the whole detection region of the PIR sensor. Objects would not be detected by the PIR sensor if they are not in the detection zone although they are in the whole detection region. Following figures show the detection zones according the datasheet of the PIR sensor. Figure 2 is a cross-sectional view of detection zones where X and Y axis are showed in dotted lines of Figure 1.

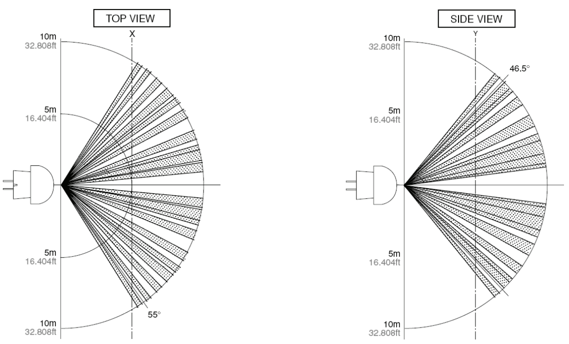


Fig. 1. Horizontal and vertical view of detection zones of the PIR sensor according the datasheet.

As we can see in those figures about detection zones, there is a possibility that the PIR sensor can not detect human within detection region because detection zones are spatially distributed in the region. However, this situation is very unlikely to occur. We have performed extensive lab test to make this situation occur but it was impossible for human not to be detected by the PIR sensor within the detection range. The reason is that the size of human is relatively big enough so human is always detected by at least one detection zone.

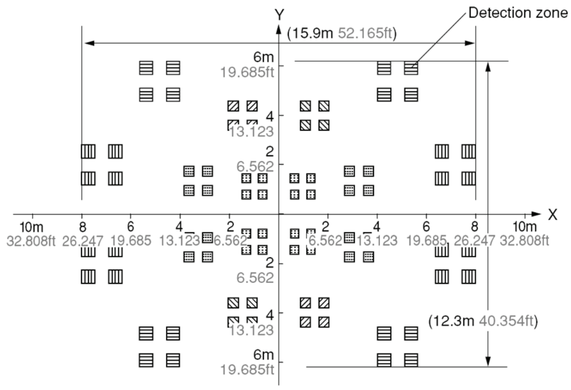
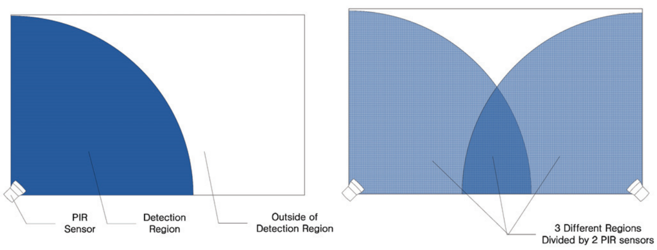


Fig. 2. X-Y cross-sectional view of detection zones of the PIR sensor according the datasheet.

III. THE PROPOSED DEPLOYMENT SCHEME

How the PIR sensors are deployed is very important for localizing an object when region-based tracking algorithm is used because the performance of tracking is highly dependent on the deployment of the sensors. When we use only one PIR sensor, the only information we can obtain is existence of an object (technically, the motion of an object) within the detection region of that one sensor as shown in Figure 3 (i). However, if we deploy 2 PIR sensors, we can divide a space into 3 different regions as shown in Figure 3 (ii).



(i) (ii)

Fig. 3. Sensor deployment with only one PIR sensor (i) and two PIR sensors (ii).

Here we propose a simple example of sensor deployment in a small room with 10 sensors. Suppose the width of the small room is 14.25m and the height is 9.0m. Figure 4 shows a possible deployment of 10 sensors which divide the small room into approximately 39 different regions. Maximum error is 4.5m and minimum error is 0.27m.

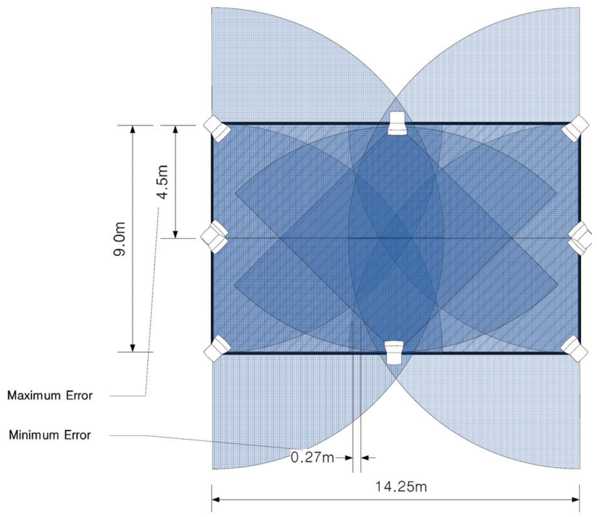


Fig. 4. A possible deployment example for a small room with 10 PIR sensors.

IV. The Proposed Region Based Tracking Algorithm

The purpose of region-based tracking algorithm proposed in this paper is finding out which region an object is located by using output signal of several sensors. For example, there are 39 different regions in the example of Figure 4. If the output signals of the all PIR sensors are high, which means they are detecting an object in their own detection region, the object is in the center region of the small room because it is intersection of the detection regions of each sensor. Therefore, in general, region-based tracking algorithm can be summarized as following equation.

$$R_{object} = R_1 \cap R_2 \cap \ldots R_{i-1} \cap R_i \cap R_{i+1}^C \cap R_{i+2}^C \cap \ldots \cap R_{j-1}^C \cap R_j^C \quad \textbf{(1)}$$

where Robject is a region where an object exists,
R1…i are detection regions of each sensor that detects the object,
and Ri+1…j are detection regions of each sensor that do not detect the object.

A. *Abstraction of the Detection Region of a PIR Sensor*

To find out R_i or r_j^C in (1), we need to model the detection region of sensor. There are three important properties about detection region of PIR sensor. First, the shape of detection region of PIR sensor is a sector form according to Figure 1. Second, the sector form has a constant radius which is a maximum detection distance of PIR as shown in Table 1. Third, the sector form also has a central angle which is a detection range of PIR sensor as shown in Table 1. To model the detection region of PIR sensor, let's say the width of the rectangle in Figure 4 as X axis and height of the rectangle as Y axis. Now we can consider the detection region as a sector form on plane coordinates. Therefore, a detection region of PIR sensor can be modeled as following equations. Figure 5 shows the definition of starting angle, θ and position, (x_1, y_1) of a sector form.

The detection region of a PIR sensor is a region defined by *x* and *y* coordinates which satisfy following equations.

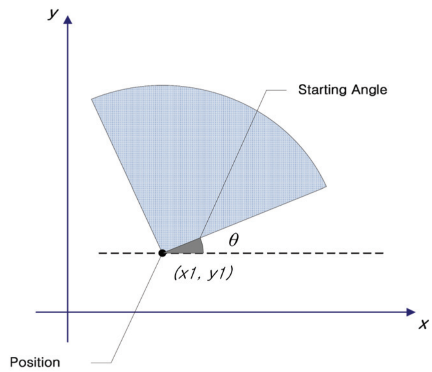


Fig. 5. Definition of starting angle and position of a sector form.

i) $0 + 2n\pi \le \theta < \pi/2 + 2n\pi$, where θ is starting angle of a sector form

$$\begin{cases} (x-x_1)^2 + (y-y_1)^2 \le r^2 \ldots & \textbf{(2)} \\ y - y_1 \ge \tan\theta \cdot (x - x_1) & \textbf{(3)} \\ y - y_1 \ge -\tan(\pi/2 - \theta) \cdot (x - x_1) & \textbf{(4)} \end{cases}$$

where $-r \cdot \cos(\pi/2 - \theta) + x_1 \le x \le r \cdot \cos\theta + x_1$

, $y_1 \le y \le r + y_1$

, (x_1, y_1) is a position of PIR sensor

, and r is detection distance which is a constant value, 9m.

ii) $\pi/2 + 2n\pi \le \theta < \pi + 2n\pi$

$$\begin{cases} (x-x_1)^2 + (y-y_1)^2 \le r^2 & \textbf{(5)} \\ y - y_1 \le -\tan(\pi - \theta) \cdot (x - x_1) & \textbf{(6)} \\ y - y_1 \ge \tan(\theta - \pi/2) \cdot (x - x_1) & \end{cases}$$

where $-r + x_1 \le x \le x_1$ **(7)**

and $-r \cdot \cos(\pi - \theta) + y_1 \le y \le r \cdot \cos(\theta - \pi/2) + y_1$.

iii) $\pi + 2n\pi \le \theta < 3\pi/2 + 2n\pi$

$$\begin{cases} (x-x_1)^2 + (y-y_1)^2 \le r^2 & \textbf{(8)} \\ y - y_1 \le \tan(\theta - \pi) \cdot (x - x_1) & \\ y - y_1 \le -\tan(3\pi/2 - \theta) \cdot (x - x_1) & \textbf{(9)} \end{cases}$$

where $-r \cdot \cos(\theta - \pi) + x_1 \le x \le r \cdot \cos(3\pi/2 - \theta) + x_1$ **(10)**

and $-r + y_1 \le y \le y_1$

iv) $3\pi/2 + 2n\pi \le \theta < 2\pi + 2n\pi$

$$\begin{cases} (x-x_1)^2 + (y-y_1)^2 \le r^2 & \textbf{(11)} \\ y - y_1 \ge -\tan(2\pi - \theta) \cdot (x - x_1) & \textbf{(12)} \\ y - y_1 \le \tan(\theta - 3\pi/2) \cdot (x - x_1) & \end{cases}$$

where $x_1 \le x \le r + x_1$ **(13)**

and $-r \cdot \cos(\theta - 3\pi/2) + y_1 \le y \le r \cdot \cos(2\pi - \theta) + y_1$

B. *Algorithm for Finding the Object Region*

Given that the set of equations, **(2)** ~ **(13)** model detection region of a PIR sensor, we can define a function, $f_i(x, y)$ which is evaluated to 0 if the coordinate *(x, y)* is not in the detection region of *i*th sensor and 1 if the coordinate *(x, y)* is in the detection region of *i*th sensor. Then, we can now define R_i and R_i^C of equation (1).

$$R_i = \{x, y \mid f_i(x, y) = 1\} \tag{14}$$

$$R_i^C = \{x, y \mid f_i(x, y) = 0\} \tag{15}$$

Now, we can find a region where an object in our PIR sensor field exists using equation (1).

V. Implementation of Surveillance Tracking System

To verify the applicability of region-based tracking algorithm proposed in this paper and the performance of the PIR sensors, we implemented the algorithm, developed a program which gathers information from the PIR sensors and finds out the location of an object based on region, and performed an experiment.

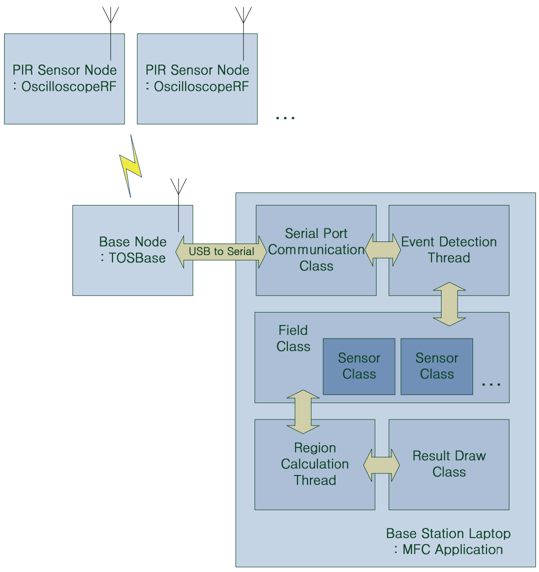


Fig. 6. Architecture of surveillance tracking system.

Figure 6 shows the structure of surveillance tracking system developed in this paper. We used TmoteSky[9] for PIR sensor nodes and base node. TmoteSky is equipped with 8 MHz MSP430 microcontroller, 10k RAM, 48k Flash, CC2420 IEEE 802.15.4 Wireless Transceiver. Moreover, PIR sensor boards are equipped with a number of sensors such as PIR, microphone, and visual light sensor.

Our system consists of mainly three different parts. First, a number of PIR sensor nodes which are deployed into interested space or room and send its PIR sensor information to the base node. Second, the base node which is connected to the base station laptop and receives/forwards sensor information. Third, the base station laptop which gathers sensor information and performs the region-based tracking algorithm. The result will be displayed on the screen of the laptop using MFC windows application. The sampling interval of the PIR sensor nodes is 100ms and they wait until 10 samples are gathered and send them to the base node in one packet. Therefore, they send their sensor information every one second.

The base station laptop runs the MFC Windows application which contains code for region-based tracking algorithm mentioned above. There are 5 components in this application. Serial Port Communication class is in charge of communication between laptop and base node through USB to serial port. It performs parsing the message structure from base node and storing the sensor values into in-memory data structure. Event Detection Thread continuously monitors those stored sensor values and determine whether an event occurs or not. The meaning of event is state transition of a PIR sensor which means the existence or non-existence of an object in the detection region of the sensor. If an event is detected, Event Detection Thread updates relevant data fields of Field Class. Field Class is an abstraction of a space or a room that is monitored by our system. Field Class contains some properties such as length and width of a monitored space or a room as well as a number of Sensor Classes which are also an abstraction of PIR sensors. Each Sensor Class implements a function f(x, y) mentioned in section 5 and provides a method for determining whether a given coordinate (x, y) is in its detection region or not. Sensor Class also includes several properties of PIR sensor such as maximum detection distance, detection range, and its position and starting angle. The states of each Sensor Class are updated by Event Detection Thread in real time. Region Calculation Thread is in charge of finding out the region where a detected object exists using equation (1). It implements the equation (1) and let Result Draw Class display the region detected by PIR sensors.

VI. Performance Evaluation

Figure 7 shows the indoor experimental setup and corresponding divided regions. As mentioned in the datasheet[9] of the PIR sensor, if object enters from Z-direction to the detection region, the detection distance will be shortened as in Figure 8. Therefore, we have installed the PIR sensors on the ceiling, so any object can not approach the sensor from Z-direction.

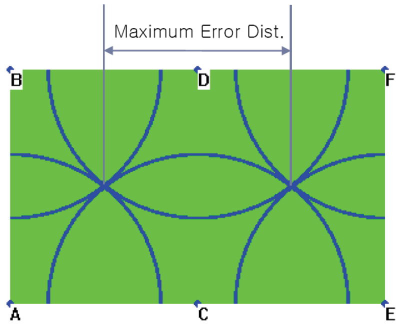


Fig. 7. The indoor experimental setup and divided regions.

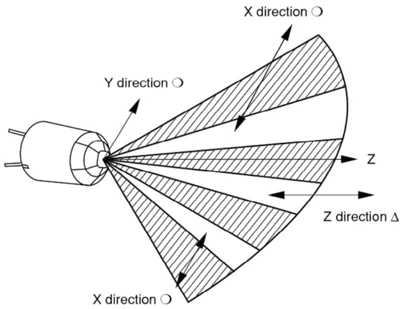


Fig. 8. Various directions from which an object can approach.

We deployed 6 PIR sensors in 10.5m by 6.6m sized room so the room is divided into 13 different regions as shown in Figure 7. This deployment and the divided regions have maximum error of 5.25m. In this experiment, a person moved around in the room as shown in Figure 7 with a red arrow and the result is depicted in Figure 9.

In indoor experiment, we have obtained very good performance of human localization. Since the object does not enter the PIR sensors from Z-direction so the assumption which is a basis for the region-based tracking algorithm is correct. Therefore, with an appropriate deployment and installation of PIR sensors, the region-based tracking algorithm using PIR sensors performs very well.

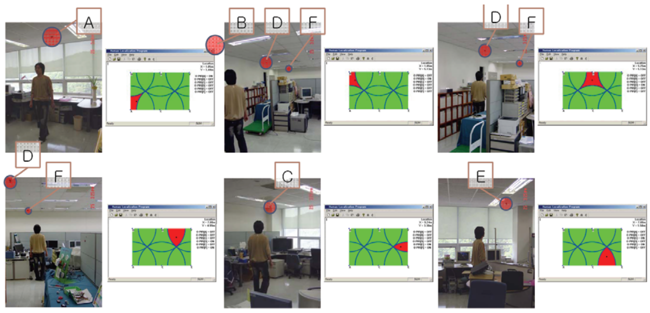


Fig. 9. Result of the indoor experiment.

VII. Conclusions and Future Work

This paper introduces a region-based human tracking algorithm with its actual implementation and experiments in real environment. The surveillance tracking system based on the PIR sensors proposed in this paper demonstrates a way to implement surveillance systems using currently available wireless sensor network technology. An evaluation of PIR sensor for surveillance systems and the effect of sensor deployment to the performance of algorithm are discussed. In addition, a mathematical abstraction of PIR sensor as a building block for the algorithm is provided and a region-based human tracking algorithm is proposed. Finally, the actual implementation with currently available hardware and experiments and evaluations of the performance of the algorithm are discussed. More research is needed to track multiple humans in a single PIR sensor field in case that one or more intruders exist. Moreover, to extend the life time of the system, a method for low rate sampling with event time calculation for low power operation.

VIII. Acknowledgement

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