PIR Probability Model for a Cost/Reliability Tradeoff Unobtrusive Indoor Monitoring System

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Abstract. PIR (Pyroelectric InfraRed) sensors can be used to detect the presence of humans without the need for them to wear any device. By construction, the fields of view of the sensors are not uniform both in terms of vision space and of sensitivity. The aim of this work is twofold: to provide a probabilistic model of the sensors' detection sensitivity with respect to the movement of the person and of his/her emission surface, and to identify the probability of detection within an area covered by multiple PIR sensors. This allows the computation of the coverage of the PIRs and their optimal arrangement that maximizes the probability of detection of the person.

Keywords: Pyroelectric infrared sensors · PIR sensor model · Presence detection

1 Introduction

The 2010 United Nations report of the department of economic and social affairs population division [1] states that ageing population is one of the most distinctive demographic events of the twentieth century. The slow, but steady, increase of the average population age has a deep, but unavoidable, impact on the social, economic and political conditions of all countries. In particular, the inter-generational social support systems will be unsustainable in the long-term.

One way to develop sustainable solutions in such a forthcoming scenario, consists in enforcing the autonomous and independent life of elderly through social support and the use of technologies, by monitoring the elderly at home and let the caregivers know in which condition the person is.

Methods proposed in the literature range from user location and biological monitoring using wearable devices to the gathering of data from environmental sensors. The cost of the system and the level of required cooperation from the person are key factors. Other not negligible aspects are system reliability and fault tolerance related to both devices and human. This paper provides a model for PIRs stochastic characterization (focusing on real industrial devices) and discusses the effect of their placement and interaction.

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The paper is organized as follows: next section reports previous works regarding PIR modelling. Then, we introduce our stochastic model for PIRs and show how PIR models are merged to characterize, from a probabilistic point of view, the sensitivity of interacting sensors. Finally, we validate our model by presenting experimental results of two industrial products and discuss its application in a real environment.

2 Previous Works

Most of literature on PIR devices describe them through very simple and deterministic models: the approaches in [2–4] adopt a 0/1 model, where the activation is “1” if a person crosses the sensible area of the sensor, otherwise it is “0”. The authors in [5, 6] propose a “simplified imperfect binary sensing” model for a ceiling-mounted sensor, where the target is always detected within an inner disk of radius R_{in} and is detected with some nonzero probability in an annulus between this inner disk and the outer disk of radius R_{out}. This model improves the 0/1 model since it considers the distance from the sensitive element. However, it ignores factors like the speed of movement of the person, the size of his/her emitting surface, the period of insensitivity of the sensor. Indeed, in real physical devices, the activation value is a function of such factors: however, the parameters of the corresponding relationship can be only roughly estimated due to the uncertainty condition of the system: therefore, [7] propose an approach to represent, experimentally and using fuzzy sets, the detection distance as a function of the other parameters.

A stochastic model considering the Euclidean distance between the sensor and the object is proposed in [8], but it does not take into account the speed of the object and the inactivity time. The authors in [9] propose a motion-tracking pyroelectric detector: by using multiple sensor clusters in different orientation, they are able to track a human motion. Unfortunately, their approach requires a detailed sensor model for sensible elements and lenses, and is not general. However, they show that the detector sensitivity can be increased by using four sensors, one at each corner of the room; that the spatial sensitivity is not uniform at different distances and for different walking speed; and that there are dead points where the detection sensitivity is very low.

In this paper we propose a general stochastic model, experimentally calibrated for the detection of a moving person, which takes into account the speed, the direction of movement, and the distance from the sensing element. The model is used to evaluate the sensor position (location and orientation) in the different rooms of the house with the aim to identify a tradeoff between increasing the probability of detection and reducing the cost of the proposed solution.

3 Model and Characterization of a Single PIR

A Pyroelectric Infrared Sensor (PIR) is a passive device that measures the changes in the infrared (IR) radiation levels emitted by surrounding objects and returns “1” when it detects a variation within its viewing range. A PIR can detect any object emitting IR radiation, heat or changes in the background IR level, and is generally used for motion detection.

A PIR sensor is characterized by a, so called, *detection degradation*, which is a function of the direction (radial or tangential) and speed of the moving object, distance from the sensible element, the environment temperature, and the surface of the object. To detect people in their houses, our model becomes independent from the emitting surface (moving object are persons) as well as from the environment temperature (houses and apartments).

The proposed PIR model is obtained by combining a *geometric model* and a *motion model*.

The *geometric model* is characterized by the maximum detection angle (field of view), the discretization of the detection angle into sectors, and the detection depth with its discretization into traces. Figure 1 depicts an example of a PIR sensor (radial) model which takes into account the maximum angle of view (for ceiling-mounted sensors this is 360° and for wall-mounted sensors it is a parameter provided by the producer), the angle discretization (sectors) and the maximum detection distance from the sensing element discretized over the distance (traces).

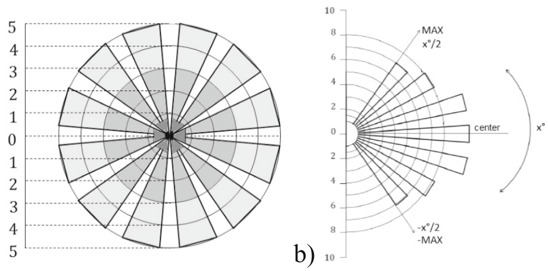

Fig. 1. The PIR radial geometric model - (a) the ceiling-mounted and (b) the wall mounted.

The *motion model* is characterized by the direction of the movement (radial or tangential) and the user speed. Each elementary geometric area, i.e., sector, is characterized by a probability to detect a movement with respect to the movement direction and speed. The proposed model considers 4 speed intervals (slow movement, slow step, normal step and quick step - see Table 1), and computes the activation probabilities by series of experiments.

Table 1. The four speeds models with their minimum, maximum and average speeds.

#	Name	Speed [m/s] min-avg-max
1	Slow Movement (SM)	0.2–0.3–0.4
2	Slow Step (SS)	0.4–0.6–0.8
3	Normal Step (NS)	0.8–1.2–1.6
4	Quick Step (QS)	1.6–2.0–2.4

By repeating the same compatible movement (speed in the interval and direction) several times, we can estimate activation probabilities for any cell in the planar geometric model, obtaining 8 probabilistic models, i.e., one for each speed for each movement direction. The combination of the geometric and motion models becomes the functional model of the sensors; an example of such model for a wall-mounted sensor is depicted in Fig. 2: slow motion is detected with lower probability.

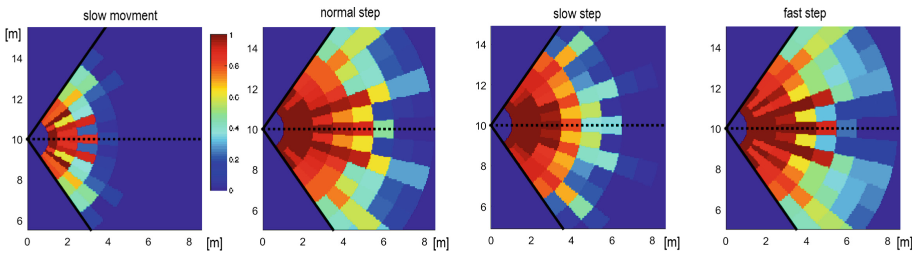

Fig. 2. Sensor functional model for a wall-mounted detector (horizontal direction) located at (0,10) obtained for the four speed models.

4 PIR Sensitive Estimation for an Arbitrary Motion

Based on the functional model of the sensor, a probabilistic model is extracted for arbitrary movement in the single and a multiple sensors scenario.

Arbitrary Motion Detection – 1 Detector: The functional model of a sensor combines a geometric model and a motion model. More general movement patterns could be modeled by considering that a generic movement direction can be always decomposed in two components: the radial and tangential directions:

$$P_{ics} = P_{\|ics}(1 - |\sin(\beta_c)|) + P_{\perp ics}|\sin(\beta_c)| \quad (1)$$

where P_{ics} is the probability of activation in the c-th cell of the i-th sensor with a subject speed of s, $P_{\|cs}$ and $P_{\perp ics}$ are the radial and tangential probabilities at cell c, and β_c is the angle between the motion direction and crossed sector (see Fig. 3(a)).

Figure 3 depicts an example where the detection probabilities are shown for a quick step movement (b) along the central axis, and (c) at an angle of 45° with respect to the central sensor axis.

Arbitrary Motion Detection – k Detectors: in case of *K* interacting PIR sensors, the detection probability is obtained by combining the detection probabilities of all the sensors according to the following formula:

$$P_{cs} = 1 - \Pi_{j=1..k}\left(1 - P_{jcs}\right) \quad (2)$$

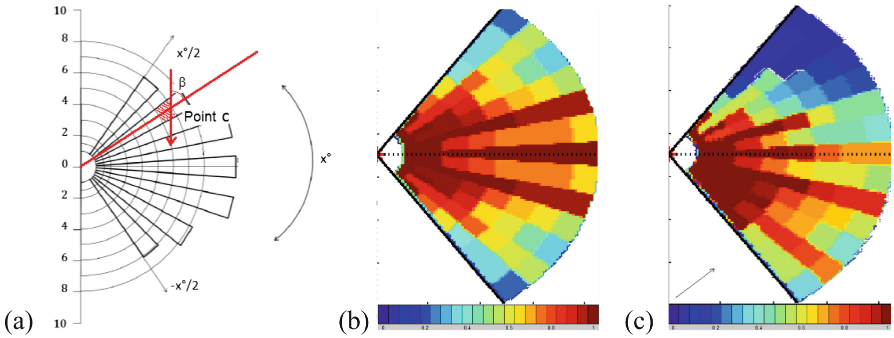

Fig. 3. (a) Angle with respect to the movement trajectory calculated at point c; (b) probability of detection along the central axis, and (c) at an angle of 45°.

where P_{cs} is the detection probability in the cell c with subject speed s, while P_{jcs} (j = 1..k) is the detection probability at the same speed in the same cell for sensor j.

The example in Fig. 4 depicts the detection probability for 3 sensors for the four motion models, at an angle of 45° with respect to the central sensor axis. The dotted lines represent the central axes of the PIRs. The dimension of the room is $8 \times 6\ m^2$ - sensor sensitivity in the center axes is 8 m.

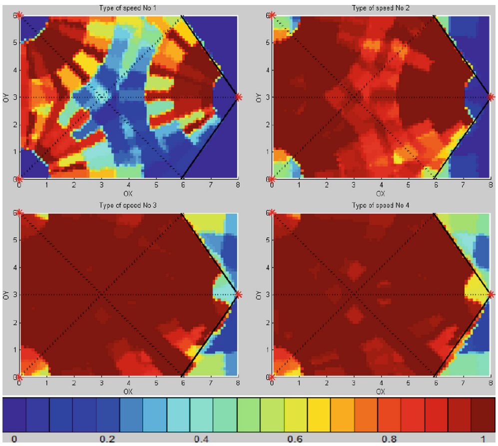

Fig. 4. Detection probability with 3 sensors at an angle of 45°, for each motion model.

5 Experimental Results

To evaluate the model we used the following figure of merit:

$$\varepsilon = \sum\nolimits_{i=1..4} \left(A_{iexp} - P_{imod} \right) \quad (3)$$

where each i represents one of the four speed models, $A_{i\ exp}$ is the experimental average detection activity, and $P_{i\ mod}$ is the detection probability derived from the model.

For the experimental data, given a point in the room, we carried out a series of 25 measurements for the four speed models and along 4 directions (0°, 45°, 90° and 135°) for a total of 400 measures. The approach was validated using a SP814-1 sensor from Everspring [11] and FGMS-001 V2.4 from Fibaro [12]. The former was placed at the recommended height of 1.8 m: its viewing angle is 110° and the maximum detection distance is 10 m. The latter was mounted at the recommended height of 2.4 m: its viewing angle is 98° and its detection depth is 7 m. Results are reported in Table 2 and Fig. 5, where d_i = (x,y,α) denotes the position of each PIR sensor d_i, where (x,y) are the coordinates with respect to the origin of the axis (0,0) and α is the angle between the middle ray of the detector and the horizontal axis. P(x,y) is the position of the measurement point. L and W represent the length and the width of the room, respectively. Notice that in case of large rooms the limited detection depth of the FIBARO sensor does not allow to detect P.

Table 2. Model validation with sensor type everspring – SP814-1 and FIBARO.

Experiment setting	Error everspring	Error FIBARO
L = 9 m–W = 6 m; d_1(0,3,0°), d_2(9,3,180°); P(4.5,1.2)	0.033	Not detected
L = 6 m–W = 5 m; d1(0,2.5,0°), d2(6,2.5,180°); P (3,0,1.3)	0.052	0.038
L = 7 m–W = 4 m; d1(0,1,0°), d2(0,3,180°); P(6,2)	2.540	1.590
L = 6 m–W = 2.5 m; d1(0,0.5,0°), d2(0,2, 0°); P(5,1.2)	0.709	0.280
L = 5 m–W = 5 m; d1(0,4,0°), d2(4,0,90°); P(4,4)	0.587	0.125
L = 8 m–W = 5 m; d1(0,3,0°), d2(6,0,90°); P(7,4)	0.218	Not detected

Figure 5 depicts the results of the model in a 9 × 6 m^2 room with a sensor placed at d_1 = (0,3,0°), and a second one at d_2 = (9,3,180°); the point is in position x = 4.5 m and y = 1.2 m (P(4.5, 1.2)).

It is worth noting that, as reported in the tables, the model always underestimates the real behavior of the system; thus, the proposed approach is suitable for a worst case analysis.

Finally, models and method can be used to determine the optimal positioning of PIRs. Figure 6 reports two different coverage scenarios using two PIRs: (a) is slightly better than (b) with respect to the entire room coverage.

Currently, the model is under test in a real situation where a person with a mild cognitive disability is experimenting his autonomy. The tradeoff between the cost (given by the number of PIRs used to detect the position) and the system's ability to detect the person's position was considered.

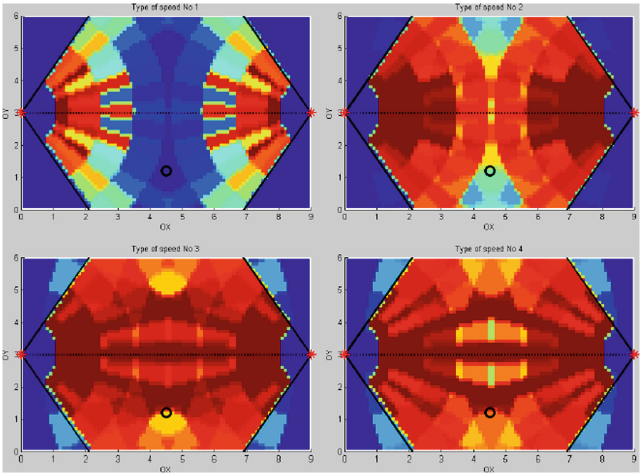

Fig. 5. Detection probability with 3 PIR sensors and 45° motion direction, for each speed model.

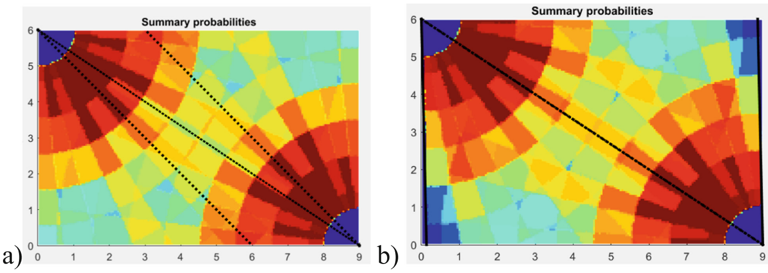

Fig. 6. Two scenarios with 2 PIR for covering a 6×9 m^2 room: (a) 97.03% coverage, 0.67 avg. probability detection, (b) 95.50% coverage, 0.64 avg. probability detection.

Figure 7 shows the final configuration: in the bed room (left-hand side room) two PIRs (PIR1 and PIR2) have been placed, even if PIR1 alone could cover the entire room; their combined effect increases the detection probability to detect the presence of the person near the door and in the center of the room. In the kitchen (in the upper/right part of the map) two different situations can be discriminated with the combination of PIR4 and PIR5: the user is in the kitchen but not at the table (only PIR4 is active) and the user is in the kitchen (both PIRs are active). It is worth noting that the duplication of PIRs allows also the identification of a PIR failure without losing the complete control of the “status” of the person.

Fig. 7. An apartment instrumented with PIR using the proposed model.

6 Conclusions and Future Work

In this paper we have described a probabilistic model of the sensors' detection sensitivity that considers factors such as the speed of movement of the person and the distance from the sensitive element. The approach can be applied to identify the probability of detection within an area covered by multiple PIR sensors. The model has been validated against the real behavior of different motion detectors with different room settings: experiments show that our model can be effectively used to approximate the worst case of real behaviors.

As future work we plan to develop algorithms for optimal positioning of detectors considering the characteristics of the area to be covered, which may be non-uniform in terms of detection needs. Moreover, we plan to extend the approach to multi-user detection.

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