On the Effect of Sensing-holes in PIR-based Occupancy Detection Systems

Abdelraouf Ouadjaout, Noureddine Lasla, Djamel Djenouri and Cherif Zizoua
CERIST Research Center, Ben-Aknoun, Algiers, Algeria

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Abstract: Sensing-holes in PIR-based motion detection systems are considered, and their impact on occupancy monitoring applications is investigated. To our knowledge, none of prior works on PIR-based systems consider the presence of these holes, which represents the major cause for low precision of such systems in environments featured with very low mobility of occupants, such as working offices. We consider optimal placement of PIRs that ensures maximum coverage in presence of holes. The problem is formulated as a mixed integer linear programming optimization problem (MILP). Based on this formulation, an experimental study on a typical working office has been carried out. The empirical results quantify the effects of the holes on the detection accuracy and demonstrate the enhancement provided by the optimal deployment of the solution.

1 INTRODUCTION

Detecting user occupancy in buildings is a fundamental step for reducing wastage of energy and improving users' comfort. In fact, in many cases, buildings have a set of predefined actuation schedules for managing electrical appliances, such as HVAC and lights. These schedules have a coarse-grained time dependability that is generally related to static issues such seasons, days of the week, etc.. However, by dynamically detecting vacant places, more optimized context-aware schedules can be implemented that can help shortening the actuation durations everyday without compromising the users convenience.

Many of the proposed solutions for tracking the presence of persons in buildings are based on the use of passive infrared (PIR) sensors (Delaney et al., 2009; Agarwal et al., 2010; Marchiori and Han, 2010; Lu et al., 2010; Beltran et al., 2013; Kazmi et al., 2014). These sensors are made from inexpensive pyroelectric materials that react to the change of infrared emissions in the environment, which helps in capturing the presence of humans in a specific space. The low cost and low energy consumption of such sensors enable their large use in battery-operated systems. Further, they do not affect the privacy of people and do not require the presence of an existing infrastructure. This makes them an appropriate candidate for monitoring private spaces such as offices, meeting rooms, etc., where other technologies, such as cameras, cannot be used.

However, a major drawback of PIR sensors is their false negatives (non-detection) in some situations. The first reason behind this shortcoming is that these sensors are only capable of detecting motion, and not static bodies. Whilst this does not represent any problem in some typical places of a building, such as corridors and near the doors where people are generally moving, it prevents the accurate monitoring in places such as offices where workers tend to stay immobile for relatively long periods. To tackle this problem, some solutions have been proposed in the literature that complement the PIRs with information provided by additional sensors. For example, the occupancy detection system proposed by Agarwal et al. (Agarwal et al., 2010) is enhanced with a magnetic reed switch sensor to track the open/close events of an office door and match them with the output of the PIRs. ThermoSense (Beltran et al., 2013) employs, in addition to a PIR sensor, a thermal sensor array that can measure temperatures of a $2.5\,m \times 2.5\,m$ area discretized as a 8×8 grid. Alternatively, some other solutions use other sensing techniques, such as (Nguyen and Aiello, 2013).

The second problem is that the sensing area of a typical PIR module is not a contiguous volume, but it is featured with the presence of several spaces where changes of infrared emissions are not captured by the sensor. We refer to these uncovered spaces by the term of *sensing-holes*. The dimensions of

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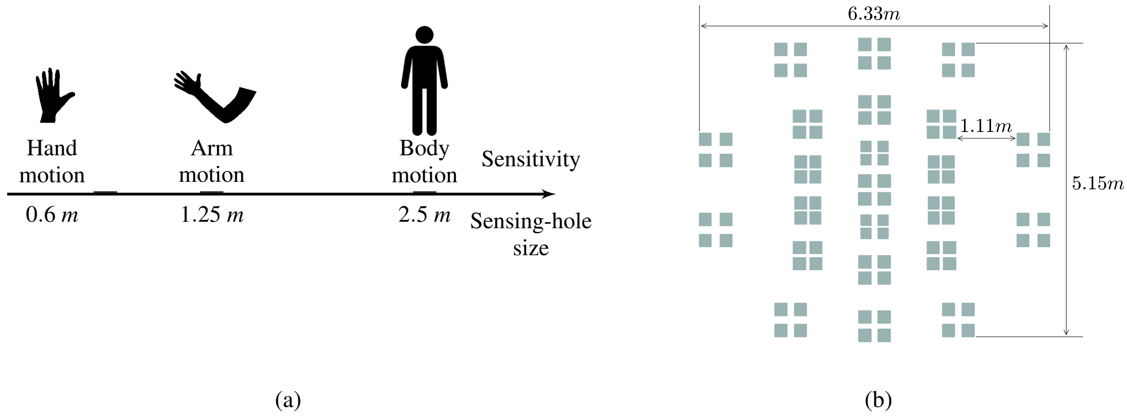


Figure 1: (a) The relation between the size of sensing-holes and motion sensitivity. (b) 2D view of a PIR Field-of-View. Solid rectangles represent detection zones.

these sensing-holes become larger as we move far from the sensor, e.g., it reaches the scale of a human body movements at a distance of 2 *m* to 3 *m*, typical hight of ceiling at offices, where PIRs are usually installed. Consequently, a PIR cannot detect a person within the sensing-hole even when he performs small movements (e.g., in the office scenario, moving his arms, rotating the chair when sitting, etc.). While it seems infeasible to detect static body only with PIRs (the first problem), we think it is possible to tackle the second one by investigating the sensing-holes and their impact, and using optimal deployment of PIRs to eliminate/minimize such holes. This represents the subject of this work. To the best of our knowledge, this problem has not been considered previously in the literature.

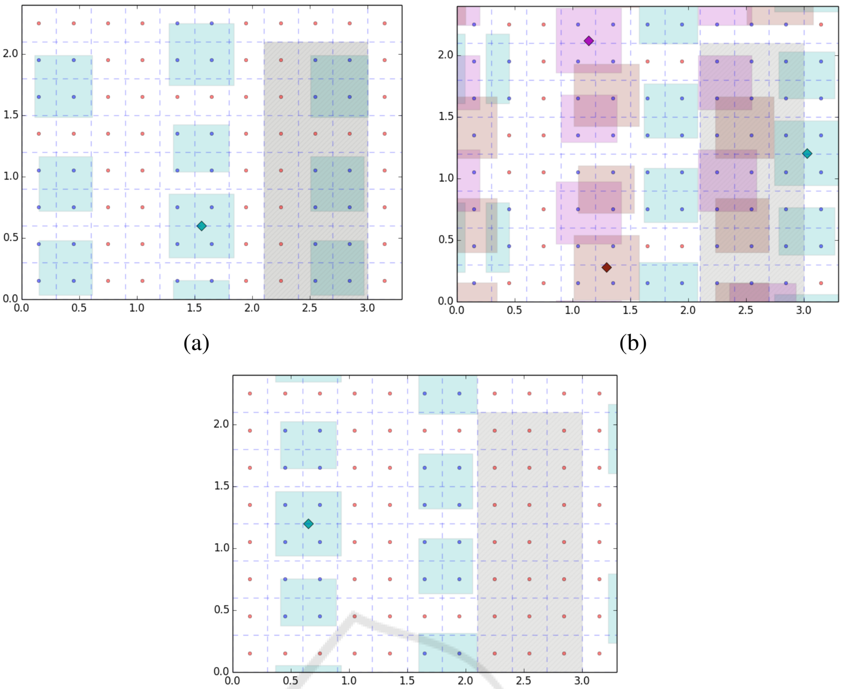
The remaining of the paper is organized as follows, Sec. 2 presents the problem formulation where the problem of sensing-holes is introduced and PIR deployment for optimal coverage is modeled as a mixed integer linear program (MILP). Solution of this MILP is used in the experimentations, which are presented in Sec. 3. Finally, Sec. 4 draws the conclusions and sketches the perspectives.

2 PROBLEM FORMULATION

PIRs use pyroelectric transducers that convert infrared radiations into electrical signals. To increase the PIR sensitivity, a Fresnel lens is used which concentrates infrared radiations onto the detector. This results in a field-of-view (FoV) that is more like a discrete set of beams or cones, including many *sensing-holes*. To be detected, the movements of the person should take place within the FoV. Fig. 1(a) illustrates the different types of motion made by a human and the corresponding maximum sensing-hole size for which the motion can be detected by a PIR (California Energy Commision, 1993). The sensing-holes should not be more than 0.6 *m* to ensure an efficient detection by the PIR of a sitting person's movements caused by hand motions.

The size and distribution of the holes impact the granularity of the PIR detections. Fig. 1(b) illustrates the projection of the actual FoV of a Panasonic EKMB PIR sensor on a two dimensional plane (Panasonic, 2012). The PIR is placed at the ceiling of an office and the projection is performed on the plane parallel to the ground and elevated at a typical height of desks, where most of persons' low movement activities take place (e.g. arm and hand movement when sitting). The figure shows the presence of several sensing-holes that represent more than 87% of the total monitored office area, and their sizes vary from one region to another within the PIR's FoV and can exceed 1 *m* in some places. These large sensing-holes can affect PIR-based occupancy detection systems and cause incorrect decisions to be taken, such as turning off a light or HVAC in the presence of a person, which limit the credibility of the system.

To alleviate the negative impact of the sensing-holes, we define the *Maximal PIR Coverage* (MPC) problem that finds the optimal positions of the PIRs for maximum coverage in the area of interest. To simplify the problem, we do not consider the 3*D* coverage but the study herein is limited to the projection of the covered area on a two dimensional plane as explained before. Even with such simplification, the computation of the union of the detection zones for a given set of PIRs is difficult to formulate mathematically. Therefore, we discretize the monitored area and consider it as a set of points, where a point will be considered covered iff it is within the coverage zone of



(a) (b) (c)

Figure 2: Three deployments scenarios considered during the experimentation. Circle points represent the discrete grid of the deployment area and diamond points represent the PIRs. The gray zone delimits the place of the office's desk, which has been given a greater weight in Φ. (a) Optimal deployment with one PIR. (b) Optimal deployment with three PIRs ensuring full coverage of the desk's area. (c) Hole-unaware deployment where the desk area is completely uncovered.

at least one PIR. Formally, let D denotes the two dimensional space to be monitored by a set, S, of PIRs. For the sake of simplicity, we assume that D has a rectangular shape with width W and length L. Without loss of generality, we discretize D by dividing its sides with a step l, which results in a grid of points $\tilde{D} = \{(i.l + \frac{l}{2}, j.l + \frac{l}{2}) \mid 0 \leq i \leq \lfloor \frac{W}{l} \rfloor \wedge 0 \leq j \leq \lfloor \frac{L}{l} \rfloor\}$.

In general, the density of persons in the space $\tilde{D}$ is not homogeneously distributed and obstacles (e.g., bookshelf, desks, table, etc.) may also be present. Therefore, we introduce a weighting matrix $\Phi_{(x,y)\in\tilde{D}}$ that enriches the geometric deployment space with a semantic dimension indicating the places where people are more likely to be detected. This is by given a high weight to areas where people are likely to stay and thus exhibit low movement activity once there (e.g., area of a desk chair, meeting table chairs), zero weight at obstacles (e.g., bookshelf, table, etc.), and regular weight elsewhere where people are likely to move. We assume that PIRs are placed on the ceil of the deployment area without any rotation. Consequently, the detection zones of any PIR $s \in S$ will have a rectangular shape and can be modeled by a set $Z_s \subseteq \mathbb{R}^4$, where a tuple $(x_0^i, x_1^i, y_0^i, y_1^i) \in Z_s$ denotes the boundaries of a single detection zone, z_i, on the X and Y, when s is placed at the origin $(0,0)$. The consequence of a change in the PIR coordinate from the origin, say to the position (X_s, Y_s), is a simple translation of the zone, z_i, on the abscissa and ordinate axes, by, X_s, and Y_s, respectively.

The MPC problem can then be formalized as a mixed integer linear problem (MILP) as follows. We define the decision variables X_s and Y_s for denoting the coordinates of a PIR $s \in S$, and the binary decision variables $C_{(x,y)}$ that indicate wether the point $(x,y) \in \tilde{D}$ is covered by at least one PIR or not. The objective function can therefore be defined as:

$$\max \sum_{(x,y)\in\tilde{D}} C_{(x,y)} \times \Phi_{(x,y)}, \tag{1}$$

with the following two constraints:

$$\begin{aligned} &\forall (x,y) \in \tilde{D}: \\ &\quad C_{(x,y)} = 0 \vee \\ &\quad \exists s \in S, \exists (x_0^i, x_1^i, y_0^i, y_1^i) \in Z_s : \ l \\ &\qquad (X_s + x_0^i \leq x \leq X_s + x_1^i) \wedge \\ &\qquad (Y_s + y_0^i \leq x \leq Y_s + y_1^i) \end{aligned} \tag{2}$$

and,

$$\begin{aligned} &\forall s \in S: \\ &\quad (0 \leq X_s \leq W) \wedge (0 \leq Y_s \leq L). \end{aligned} \tag{3}$$

The first constraint formalizes that $C_{(x,y)} = 1$ in the solely case of the existence of at least one detection zone of a sensor s that covers the point (x,y), while the second restricts the coordinates of the sensors within the deployment area. To eliminate the operators $\exists$ and $\vee$ in (2), and transform the MILP into a standard form that can be handled by solvers, the big-M method can be used.

3 EXPERIMENTS

We have deployed an experimental PIR-based occupancy detection system to monitor an office and quantify the impact of the sensing-holes on the performances of the system. The experiments were performed using the EKMB PIR sensors from Panasonic. The data acquisition mechanism was implemented on an nRF51-based hardware platform manufactured by Nordic Semiconductors featuring a low-power SoC that embeds an ARM Cortex-M0 MCU, along with a 2.4 GHz wireless transceiver.

The considered deployment area has a rectangular shape of size $3.3 \times 2.4\ m^2$. Most of occupants activity is concentrated over the office desk that received greater weights in the matrix Φ. The discretization step l was fixed to 0.3 m resulting in a grid of 11×8 points.

We have tested three deployments scenarios. The first one corresponds to the optimal solution of the MPC problem when using one PIR. As shown in Fig. 2(a), this deployment covers nearly 63% of the desk's area. Optimal full coverage of this space is ensured with 3 PIRs, which corresponds to our second deployment scenario depicted in Fig. 2(b). In the third scenario, a single PIR was placed in a way to put the largest holes at the desk area as shown in Fig. 2(c). It shows the real impact of sensing-holes on the performances of the detection system. It is worth noting that existing solutions, by ignoring the presence of the sensing-holes, consider such deployment as optimal since the overall sensing range of a single PIR fully covers the office area.

The deployed motes actively monitor the state of the PIR and notify a central base station about any detection event. The latter maintains a database for logging the incoming sensory data along with ground truth presence/absence intervals, which are provided manually by occupants. The experiments were performed over a period of three days. The obtained results are depicted in Fig. 3(a) that summarizes, for the three deployment scenarios, the proportions of all possible detection cases: true presence (TP), true absence (TA), false presence (FP), and false absence (FA). We can clearly see that taking into consideration the presence of sensing-holes helps in reducing the FA, i.e., the system is able to capture more occupant movements. However, these results represent the distribution of the *raw data* collected from PIRs and can not be used as a reliable indication of absence. As the PIR signal fluctuates significantly when occupants are moving, detection systems generally implement a filtering mechanism to smooth the collected raw data. The filter is based on a timeout mechanism that is launched when no motion is detected, which delays the decision about absence detection to overcome FA.

To evaluate the performance of the system in the different deployment scenarios and under different timeout values, we have measured two metrics, (i) the *comfort level*, and (ii) the *waste in energy usage*. The first metric quantifies the ability of the system to preserve the convenience of users, that is, the ability not to disturb the occupants by keeping office energy supply on when they are present in the target area (i.e., ability to overcome FA). The second one reflects the proportion of time the system fails to effectively detect (or react to) the absence of occupants, which implies a missed opportunity to reduce the energy consumption.

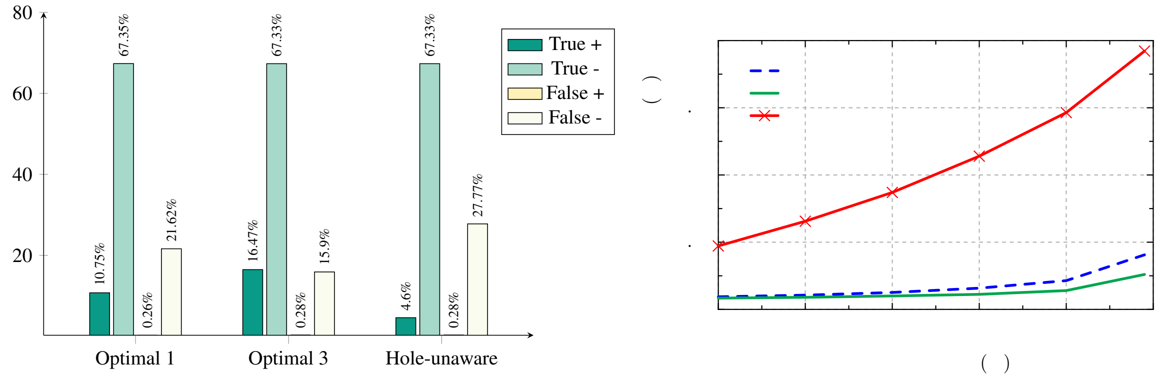
Formally, the comfort level $\mathcal{C}$ and the energy usage waste $\mathcal{W}$ are computed as follows:

$$\mathcal{C} = \frac{\mathbb{T}_P}{\mathbb{T}_P + \mathbb{F}_A}, \mathcal{W} = \frac{\mathbb{F}_P}{\mathbb{F}_P + \mathbb{T}_A},$$

where $\mathbb{T}_P$ (respectively $\mathbb{F}_P$) denotes the total durations of TP (respectively FP), and $\mathbb{T}_A$ (respectively $\mathbb{F}_A$) denotes the total durations of TA (respectively FA).

For every deployment scenario, the value of the absence timeout has been varied, and $\mathcal{C}$, $\mathcal{W}$ have been measured for every case. Fig. 3(b) shows the variation of the observed usage waste for different levels of comfort. We observe that the performances of the hole-unaware deployment are remarkably lower than our proposed solution, which means that the presence of holes significantly affects the waste of energy usage, specially when requiring a high level of users' comfort. In fact, to ensure a high level of comfort in the presence of sensing-holes, absence decisions need to be delayed for long periods (high timeout). This is explained by the fact that these zones hamper the proper capture of small movements, which increases the time required to catch such rare events. The consequence of high values of the timeout is that occupants leaving the office are not timely detected (reported), which causes energy waste.

We can also notice from Fig. 3(b) that the performances of the optimal solution using only one PIR are



(a) (b)

Figure 3: Experimental results for the three scenarios. (a) Time proportion for the different cases of detection based on raw data. (b) The variation of the energy waste for different levels of users' comfort using a timeout smoothing.

very close to the optimal full coverage solution using three PIRs. This is due to the fact the first deployment covers an important proportion of the chair-side of the office desk. Consequently, covering the remaining spaces of the desk, as in the second deployment scenario, does not help capturing more occupants activity. This result demonstrates that it is important to properly construct the Φ matrix in order to focus the optimization problem on the most relevant spaces which helps reducing the number of required sensors.

4 CONCLUSIONS

In this paper, we have investigated the impact of sensing-holes on the performances of typical PIR-based occupancy detection systems. To our knowledge, our work represents the first study that (i) investigates how this intrinsic property affects the accuracy of detection and (ii) proposes a deployment method to alleviate its negative effects and enable the system to optimize energy usage. The problem has been formulated with mixed integer linear programming (MILP), where the positions of a set of PIRs are sought out in a way to maximize the effectively covered area. Based on this formulation, several experiments have been carried out to evaluate the performances of the obtained solutions in comparison with hole-unaware deployment. Results demonstrate clear improvements in terms of accuracy in detection when using hole-aware placement, which helps rationalizing energy management. For example, in scenarios requiring high levels of user comfort, a hole-unaware deployment can result in a 9.61% of waste of energy usage, while hole-aware placement reduced this wastage to 1.3%.

The preliminary study presented in this paper is the first step in our ongoing project. The next one is to use these results in the design of a wireless sensor network for efficient energy control in smart buildings. We think such an optimal deployment will help to make the whole system effective, and to rationalize the settings of actuation parameters in a way that balances user's comfort and energy saving.

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