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INFRARED OCCUPANCY DETECTION TECHNOLOGIES IN BUILDING AUTOMATION - A REVIEW

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ABSTRACT

Occupancy sensing, based on the use of single or sometimes on multiple technologies, is used to gather the information about human presence the building automation system requests. Infrared sensing technologies are the most widely used in occupancy detection. This paper issues occupancy detection from a building automation system, like an automatic lighting control point of view, reviews the main concepts and terminologies related to occupancy detection in buildings. Infrared occupancy sensing technologies, passive technologies such as PIR, active IR technologies, such as light barriers/gates based on the transmitter–receiver pair or transmitter-mirror pair, are discussed in detail. The main focus is on PIR sensor as it is the most common infrared technology used in motion and occupancy detection. Author's own contribution to this subject is given in the form of a developed FEM simulation model for a typical PIR sensor. The available IR technologies and the benefits and drawbacks of each of the technologies are presented. A comparison between other occupancy sensing technologies and their combination use is presented. In order to reach higher accuracy in occupancy detection, a network of sensors spreads around a building can be used. This paper reviews some studies of occupancy detection and motion tracking based on IR sensor network technologies and the associated methods in use.

Keywords: occupancy detection, building automation, lighting control, infrared sensors.

1. INTRODUCTION

Energy consumption and indoor environment of buildings are largely influenced by the presence and behavior of occupants. Therefore modern building automation systems request real-time information on occupancy. They gather this information for improving energy efficiency of the building and/or improving environmental quality in the building. This information is used to control lighting, air conditioning, heating, etc. The scope of this work is restricted on fast responsive technologies, which can be used for lighting control in buildings. Among those, the infrared technologies are most often used.

Energy saving is the primary focus when considering an installation of an automatic lighting control. Many studies focusing on lighting control in an office building have been published. The most common, and arguably, the most successful lighting control strategy is occupant sensing, which employs an occupant sensor to switch lights on and off according to detected occupancy. Lighting controls have the potential to reduce lighting energy consumption significantly and to moderate peak demand in commercial buildings [1]. [2] States that typical energy saving when using an automatic lighting control instead of a manual control is between 25% to 33%. Energy savings were the smallest in classrooms (about 20%) and in open offices (20-25 %). In private offices, savings were around 25% to 50%. In conference rooms, rest rooms, warehouses and storage spaces savings were over 50%. [3] Studied energy savings in open-plan offices in a single building. Lighting control based on occupancy detection resulted in 35 % energy savings alone. In combination of improved luminaires, occupancy sensors, light sensors for day light harvesting and individual dimming control, energy saving increased up to 70%. The additional bonus was an increased satisfaction of occupants due to the individual dimming control.

Potential energy savings will be achieved particularly in offices, which are sporadically occupied. For obvious reasons many of these academic studies have investigated the buildings of universities or other educational institutes. It is rather obvious that some energy savings will be achieved by automatic lighting control. What will be the energy saving compared with the investment of occupancy based lighting control and what kind of impact the control system has to the users of the building. [4] Found it their study that in many cases the investment costs would be so high that it would take decades before the savings would compensate them. They also found that with automatic light control the users become less responsible for turning lighting off when exiting the spaces. In generally people seem to be more responsible to control the lighting of their private spaces than spaces, which are in general use. It is clear that automatic lighting control would bring energy savings special in spaces of general use. [2] found out that people were more responsible for manually turn of lights during the after hours or weekends and less responsible during the normal office hours. The authors [4] found that the less responsible behavior of the users after taking in use the automatic lighting control reduced about 30% the potential energy savings that would have been available.

Occupancy detection uses sensors, which cannot result in 100% accuracy. Neither can they indicate presence, but instead a motion. Occupant(s) can stay in the idle position for a long time causing a failure situation in occupancy detection. In this failure, usually named as a positive failure, lights turn off while there is still occupant(s) present. This is an uncomfortable situation and should be avoided. A delay time is introduced to turning lights off after the last motion has been observed.

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Setting a value for the delay time is a compromise between comfort and energy consumption. In some cases taking in use automatic lighting control the energy consumption may even increase [4]. This is possible in buildings where diligent users have previously manually controlled lighting in an efficient way. With an automatic control, lights will be on during the delay time, even there might not be any demand for it. [2] Shows the effect on delay time to energy consumption. Increasing the time delay reduces the energy save which could be achieved.

2. CONCEPTS AND TERMINOLOGY IN OCCUPATION DETECTION

Melfi *et al*. [5] introduced concepts and terminology for occupancy. These have been widely adopted in the papers covering this subject. [5] introduced a concept occupancy resolution, which can be defined using four levels of resolution: occupancy, count, identity and activity. Occupancy in its simplest form means whether someone is present in the given zone or not. The occupancy resolution increases by adding the spatial and temporal information. Spatial resolution means the location information about the occupant(s), like room, floor or building. Temporal resolution covers the information when the occupant(s) is/are present in the defined zone of the building. Time accuracy could be given in a format day, hour, minute and second. The least accurate information about occupancy is the answer to the question is there someone present in the given zone. This information could be enough for just for the decision weather turn light on or off in the given zone of the building. This information might not be enough for some other building automation applications. Occupancy resolution is increased by defining the number and the identity of occupants. Some occupancy detection technologies can find out the number of occupants. Some software based on the use of a pattern recognition algorithm may give the information about occupant(s) identity. For even further increasing the resolution we could define the activity, meaning what the occupants are doing. We may even need historical information about how the occupants have been moving in the building. A tracking history showing occupant(s) moving history across different zones in the building. This information could be available from a sensor network, which covers the main entrances and corridors or the hole building.

2.1 Explicit methods

Occupancy detection is usually accomplished by using dedicated devices like PIR and ultrasonic sensors. These devices have typically fixed installations in optimally set locations in the building. The only function of these devices is occupancy detection, which they can perform optimally. There are also some drawbacks related to the dedicated occupancy detection systems. The purchase and installation may cost much and the maintenance costs follow regularly on a time basis. Changing the layout of spaces in the building may cause a need to relocate occupancy detection sensors, upgrade or update hole the system.

2.2 Implicit methods

Implicit occupancy methods [5-7], sometimes called soft or ambient sensing, extracts occupancy data from systems already present in the building for other primary purposes. The benefit is to avoid the costs of a dedicated sensor system. However, some modifications, an addition of hardware or software may be required. [5] Classify the implicit occupancy sensors into three groups according how much modifications are required. Tier I requires no modifications to existing systems other than needed in data collection and at the processing point. Tier II requires only a software addition without a need to change existing hardware. Tier III requires both hardware and software additions.

[6-7] issue subjects how existing systems like a building security system can give information about the people count and activity in the building. It may also give information about manual door and window openings or closings. A building automation system may be able to inform us about manual light switching. All these indicate the presence of people in the building. Further developed methods may monitor the level of computer data communication or detecting the presence of mobile phones or devices in the building. Use of a webcam or a microphone of a personal computer has been proposed although such a method intrudes privacy in a severe way. The measure of used domestic hot water indicates the number of people in the building. Many of the implicit methods are inherently slow responding and therefore cannot be used for applications like a lighting control.

3. INFRARED TECHNOLOGIES IN OCCUPANCY DETECTION

The great benefit of IR technologies is that no daylight or illumination is needed. Human objects are well visible in infrared light. However, animals are equally well visible in IR wavelengths. This may case a problem if human detection is the target, but in some case home or wild animals can also came in the range of an IR sensor. IR methods preserve privacy quite well. Even when using a high resolution imaging, the IR image does not typically reveal so much details of the object that it would easily be used in person identification.

Occupancy detection technologies can be divided in two groups, active and passive. Active sensors emit energy, in case of IR sensors, radiate IR light. Passive sensors, in case of IR sensors, only receive IR light. Active sensors use more electric power than passive ones. Passive IR sensors are dominating in the field of occupancy and motion detection. This is particularly holds for occupancy detection for lighting control in buildings.

3.1 Infrared emission of a human object

Using Planck's law and assuming the conditions of a black body, the spectral density of radiation can be calculated corresponding to the temperature of an object. With a human object, this temperature is about 37 °C, setting the peak of emission around 9.4 um. The IR-radiation will be spread over the IR-range from 0.7 um to

1000 um, but around 50 % of total radiation will be between wavelengths from 5 um to 14 um. The Stefan-Boltzmann law describes the total power radiated from a black body surface at certain temperature. The law specifies the radiated power per unit surface area. A graphical presentation to this law (1) will be found in the paper of [8] or [9] and in many text books of physics and therefore it is not reproduced here.

$$u(\lambda) = \frac{8\pi hc}{\lambda^5} \frac{1}{(e^{hc/\lambda kT} - 1)} \quad (1)$$

u(λ) is energy density of electromagnetic energy versus wavelength or in other words spectral radiance of a body.

$$P = A\varepsilon\sigma T^4, \text{ where } \sigma = \frac{2\pi^5 k^4}{15c^2h^3} \quad (2)$$

A is area of the surface, ε is the emissivity of the surface and σ is the Stefan-Boltzmann coefficient (5.670367×10^{-8} W·m^{-2}·K^{-4}, k is Boltzmann's constant, c is the speed of light in vacuum and h is Planck's constant ($6.62607004 \times 10^{-34}$ m^2·kg·s^{-1}).

The third law which is usually mentioned in this context is Wien's displacement law which states that the maximum spectral radiance of a black body takes place at the wavelength λ_{max} according the equation (3), where constant b is called Wien's displacement constant (2.8977729×10^{-3} m·K).

$$\lambda_{max} = \frac{b}{T} \quad (3)$$

A human body radiates infrared in all directions. Total amount of radiation and its power depends on the size of a human object. Considering an average surface area of a human object, a rough estimate for the total power will be around 100 W. The IR detector will observe only part of the total radiation. The amount of radiation the sensor observes depends on the distance and the clothing of the human object. Hands and a face are the major source areas as they are usually non-covered. Thick thermally well insulating winter clothing minimizes thermal emissions. The amount of radiation the detector observes depends on the heat source and the distance between the source and detector.

3.2 Atmospheric attenuation

Air between the IR source and detector causes some attenuation in IR transmission. Atmospheric attenuation is caused by absorption and scattering. Absorption is related to the concentration of water and various gases like carbon dioxide, oxygen, methane and ozone. Scattering is caused by various air impurities. Scattering is significant below 2 um wavelengths and quite negligibly above it. Absorption and scattering depend on the wavelength of IR radiation. In generally there are two main windows for a good IR transmission, 2-5 um and 8-13 um. The gap between these windows is caused by absorption with water molecules. Considering the human detection, the use of long wavelength 6-15 um (LWIR) is the most promising choice. This choice is based on the facts that human object infrared emission is largely on this range and air visibility is high, not much affected by humidity or air gases and pollutants. Visibility through smoke or mist is the best on this bandwidth. In building automation and in generally indoor applications air quality is normally good allowing high IR visibility and stable conditions. In exceptional situations like in a fire, usually large amount of smoke and particles in the air reduces the IR visibility. However, in such situation high accuracy occupancy detection is vitally important.

3.3 Infrared sensors

Infrared sensors can be classified to belong either of two fundamental classes, the photon detectors and the thermal detectors [8]. In a photon detector IR radiation generates free electrons and holes which produce electrical currents. The photon detectors can further be divided into groups like intrinsic, extrinsic, photo emissive and quantum well detectors. In a thermal detector, sometimes called also an energy detector, IR radiation causes heating of the detection element, leading to changes in its physical properties. These changes can be monitored externally by using electric circuitry. Thermal detectors are divided in to classes: thermocouples, pyroelectric detectors, bolometers and micro bolometers. Heat transfer is inherently a slow phenomenon compared with the photoemissions in photon detectors and this causes slow responding time. Thermal detectors are also less sensitive than photon detectors, but they are still well suitable for occupancy and motion detection. Benefits of thermal detectors are inexpensive price and room temperature operation.

4. PIR SENSOR

PIR (Pyroelectric IR) sensors are widely used in presence and motion detection. They are the most common choices for occupancy detection in the applications of surveillance and automatic lighting control. Reasons for the wide usage are relative inexpensive and robust technology. It is a passive method, which does not require as much power as the comparable active methods. PIR sensor's current consumption can be just 1 uA [10] while operating in stand-by. Another benefit of PIR technology is that it is unobtrusive and privacy-preserving.

PIR sensor is a thermal IR detector, which outputs a voltage change depending on the temperature change of the sensor element. The sensor element is made of a material having a high pyroelectric constant. The element is also sensible to the background thermal radiation. PIR sensor typically has two detector elements connected in series with opposite polarities. This arrangement prevents triggering to an event caused by the change of background IR. Relatively high electrical noise at the output is typical for all pyroelectric elements. Analog signal shaping is used to reduce the noise created in the detector itself or the noise coming from the environment. At the final stage, there is a comparator, which produces a binary output indicating an observed human motion or presence. Normally, an adjustable dead time is introduced in the sensor to prevent multiple triggers from the same target.

4.1 Signal generation in a pyroelectric detector

Pyroelectricity is a physical phenomenon, which has been known since ancient times. However, the full understanding about it has been revealed much later. Use of the phenomena in motion and occupancy detection has been started quite recently, in the last few decades.

Materials having a significant high pyroelectric effect have a crystal structure, which in normal steady state condition is already polarized. This means that positive and negative charges will be gathered on the opposite ends of the crystal. In the detector element, the crystals are oriented in such a way that there is a voltage difference over the detector element. Radiation, which will be absorbed on the detector surface, creates heating of the detector element. The generated heat reduces the level of polarization, which is measured as a voltage change over the detector element. The measured voltage has a bipolar waveform based on the polarization changes. The first positive slope is due to the steady state polarization. The following negative slope follows the reduction of the polarization. The final positive slope is explained by return to the original steady state condition.

The pyroelectric effect is observed in a material, which has a significantly high pyroelectric constant p. The most often used materials used in PIR detectors are leadtitanate $PbTiO_3$ and lithiumtantalate $LiTaO_3$.The thermodynamic equation for the crystal will be

$$C_Q \frac{d(\Delta T)}{dt} + G\Delta T = \varepsilon W_0 \tag{4}$$

ΔT is the temperature change, C_Q is the heat capacity, G is the thermal conductance and ε is the emissivity of the crystal. The time dependent solution for ΔT is

$$\Delta T = \frac{\varepsilon W_0}{G}\left(1 - e^{-t/t_0}\right) \tag{5}$$

t_0 is C_Q/G.

The current of crystal is proportional to the pyroelectric coefficient p, the active area A_s, which absorbs the radiation and temperature change speed versus time d(ΔT)/dt.

$$I_p = pA_s \, {d(\Delta T)}/{dt} \tag{6}$$

As the equation (1) shows, detector current is proportional to the temperature change, not the absolute temperature. The temperature change is directly proportional to the absorption of infrared radiation. Solving d(ΔT)/dt in equation (6) and writing it to equation (4) results in the equation (7).

$$I_p(t) = pA_s \frac{\varepsilon W_0}{G} e^{-\frac{t}{t_0}} \tag{7}$$

Equation (7) shows only parameters related the pyroelectric element itself. An electric circuit is used for amplifying and shaping the signal.

4.2 Analog signal processing of PIR sensor

After the detector, an amplifier with a bandpass filter follows. This combination amplifies the signal reduces noise from the signal. Considering a moving human target, typical distance between the detector and the target is between 0.5-10 meters and moving speed is from 0.5 m/s (walking) to 3 m/s (running). The thermal time constant related to the detector sets the lower limit for the bandpass filtering of the signal. This sets the PIR sensor's response time typically around 0.5 seconds. The upper corner of the bandpass filter can be 2 Hz [9].

4.3 Optics of PIR sensor

Focusing IR-radiation to the surface of a PIR sensor requires some kind of a spherical lens or lenses are used. Typically multiple lenses are mounted on a sphere. They can be plano-convex lenses, which planar surfaces are facing outwards. Size of a single lens will be an optimized for the given size of the sphere and the size and distance of the IR source. Lens material should have a high IR transmission coefficient. A slim lens would be an ideal one. Often PIR optics is composed of numerous Fresnel lenses made of high-density polyethylene (DPE) plastics having the refraction index of 1.54 [11]. Such optics can be manufactured fast and inexpensively in large volumes. It results in a small material thickness featuring sufficiently good IR transmission characteristics.

Use of multiple lenses means that the field of view is not uniform, but segmented. Each lens creates a cone of visibility. You can also say that a cone has two beams as there are two detectors inside a PIR sensor. This is desirable characteristics of a motion detector. The polarity and the amplitude of the signal depend on which one of the detectors is absorbing the larger part of the radiation and what is relative division between the detectors. There is a small gap in the field of view just in the middle of each segment while at that point both of the sensors are absorbing equal amount of radiation. The width of the gap gets larger when an object moves further from the sensor. This also means the time delay in the detection of a moving object is longer in case of a more distant object. Fresnel lens with grooves has even more gaps in its field of view. The way the grooves have been realized has an impact on the optical characteristics. If constant groove width is used, the grooves have variable groove depth. The lens becomes smoother in the middle and deeper near the sides. In that case, optical transmission is higher in the middle of the lens [11].

PIR optics can de optimized for various targets like for wide range, long range, vertical barrier, animal detection or animal immunity. This will be done by reducing the lens diameter in such sectors which point in less interesting directions. In case animal immunity for example, downwards looking sectors will be depreciated. A sensor mounted on ceiling should have a wide field of view, a sensor mounted on corridor wall, just a narrow field of view.

4.4 Detection range

The signal amplitude follows the law of $1/r^2$, where r is the distance between the target and the detector. This indicates the detection range cannot be extended easily. The maximum sensing distance is determined by the noise equivalent power NEP. NEP indicates the power level at which SNR is equal to one. Improving SNR is possible either by using lower noise analog electronics or increasing the size of detection surface. Costs set the limits for both of these parameters. The visibility of air at IR wavelengths is good. The maximum detection distance can be over 100 meters. In practice the maximum sensing distance is much less than that, maybe around 10 meters. In occupancy detection accuracy can be improved by using an aperture sizing in multiplexed sensing optics, but this reduces the radiation collection area and therefore the detection range.

4.5 Long range PIR detection

The detection range of a passive PIR sensor can be extended over 100 meters. Such distances are possible with a sensor having multiple detection element pairs, a detector pair for each segmented observing area, improved optical concentrators (lenses, mirrors, filters) and improved low-noise front-end electronics and offset compensation circuitry. For IR used optic is better be made of germanium or GASIR (chalcogenide glass). Signal amplitude is directly dependent on the velocity of an object. This means that an object moving with a low speed is difficult to detect. IR change emitted by a slow moving object cannot be separated from the slowly changing background IR. To detect slow velocity objects, the low-frequency corner of the electronics must also be set at low frequency. This increases total electronics noise as the 1/f noise increases rapidly at very low frequencies.

[12] Have designed and constructed a long range PIR sensor able to detect crawling people at the distance of 140 m and walking or running people at the distance of more than 200 m. They used seven detector pairs and equally many segmented areas, adjustable offset voltage compensation and an adaptive detection threshold for the minimizing of false alarms. The potential applications of such a device are intruder detection or military use.

4.6 Limitations and potential failures

PIR technology requires line-of-sight (LOS) conditions. If the object is behind a wall or another obstacle, detection is not possible. Although the detection range can be long, noise sets the limits for practical detection range. Used optics also affects in the detection range. PIR sensors are almost always used for outputting only the binary information about motion or presence. In such an operation it is unable to provide the count of occupants. The dead time introduced in PIR detectors causes a significant limitation in accuracy. PIR sensors are prone to false-positive errors, meaning the case when there is someone present, but the sensor indicates the opposite. This error is particularly troublesome in lighting control. On the other hand, PIR technology is less sensitive to false-negative errors than ultrasonic or microwave technologies. The combination use of these technologies reduces errors, in other words, improves accuracy. The recent studies of PIR technology in occupancy detection are focusing on the use of PIR networks, the use of multiple PIR sensors together.

4.7 Numerical simulation model for a PIR sensor

As part of this study, FEM simulation model for a PIR sensor was developed. The model includes the optics and the front end electronics of a PIR sensor. The optics could also be Fresnel lenses, but for the sake of simplicity, it is composed of numerous plano-duplex lenses. The model visualizes the diffraction of rays, light focusing on the detector surface and signal waveform generation and shaping.

Comsol Muliphysics (ver. 5.3a), its Ray Optics- and AC/DC-module were used. The ray optics module is a computational tool for modelling the propagation of light showing ray tracing through the geometry, reflections, refractions and absorption in boundaries. These characteristics are available from the geometrical optics interface. Several quantitative measures like light intensity, power, energy etc. can be calculated. The ray heating interface could solve the heating in a domain caused by light absorption. With the heat transfer module, it could fully handle all thermal issues in a PIR sensor. In that case, it would be necessary to include the required material information and the accurate geometry of the PIR detector element as well as the thermal interface to surroundings. As this information is difficult to obtain, the full thermal analysis has been omitted. A major limitation is related to the ray heating interface. It can be included in a time dependent simulation, but its solution is always for the case time is indefinite. The reason behind this limitation is related to the different time scales of light propagation and heat transfer. Heat transfer is a very slow process compared with light propagation. Instead of thermal effects, one could use absorbed intensity on the detector surface (W/m^2) and the mathematical relationship between the intensity and the output electrical signal. By including AC/DC-module and its electrical circuit interface, it is possible to simulate the signal shaping the external electric circuit performs. Time scale transforming for the component values of the circuit is needed. By this way, the circuit is transformed to a nanosecond scale, typical for light propagation.

In this simulation, the heat source traverses perpendicularly over the detector’s field of view. Only the rays which direct towards the detector are included in the simulation. This keeps simulation time in reasonable limits. In this approach, the changing distance between the source and the detector must be included in the simulation.

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In the figure below the model geometry and some of the simulation results are presented. Figure-1 shows the CAD model. The transparent figure shows the hexagon lenses and the detector element behind it. Figure-2 shows some of the rays refracting in the lens and reaching the detector element. Depending on the angle of arrival some of rays hit the first some the second detector element. Figure-3 shows the solid angle Ω_i , angle α and distance L_i while the source moves further from the detector. The intensity observed at the detector can be expressed using Equ. 8.

$$\frac{I_i}{I_0} = \cos(\alpha) \cdot \left(\frac{L_0}{L_i}\right)^2 \tag{8}$$

A typical electric circuit of PIR sensor is shown in the Figure-4. Figure-5shows the subtraction of the absorbed power integrals. According to the equation (6) this has to be differentiated. Figure-6 shows the differentiated and filtered output signal of PIR sensor. Figures 5-6 are presented using normalized values.

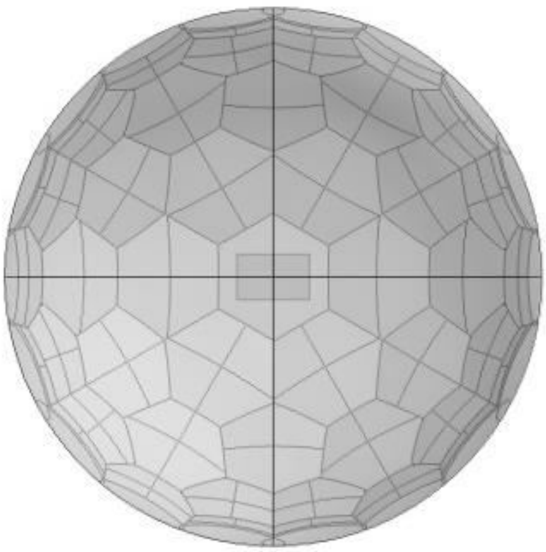


Figure-1. The CAD model of the PIR sensor optics and the detector.

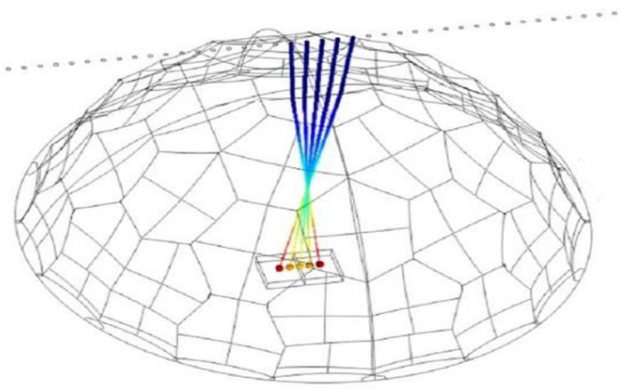


Figure-2. Some of the raysin the simulation.

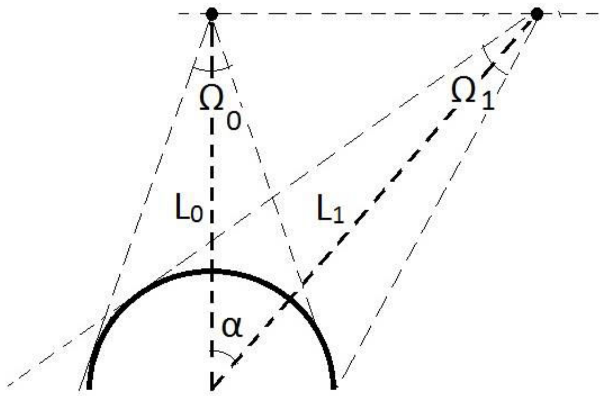


Figure-3. Solid angles Ω_i, angle α and distances between the source and the detector.

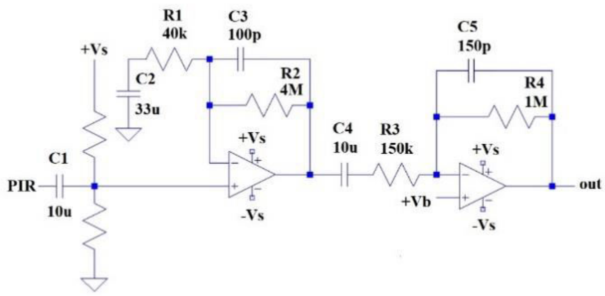


Figure-4. The amplifier & shaping circuitry.

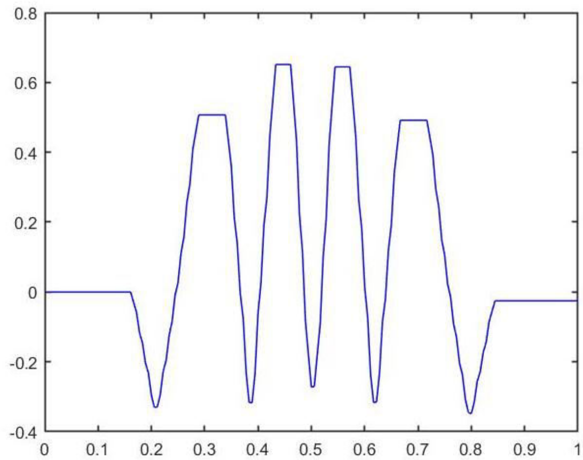


Figure-5. Subtraction of the absorbed IR-powers P_2-P_1 (y-axis) versus time (x-axis).

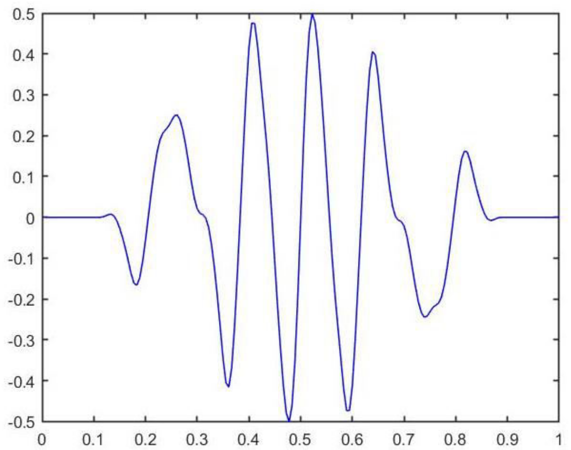


Figure-6. Output voltage (y-axis) versus time (x-axis).

4.8 Advanced use of PIR signal

The comparator of a PIR sensor creates a binary output, indicating only occupancy or motion. Some papers [13-16] issues a more elaborate use of PIR signal. A PIR sensor is typically constructed using PIR elements followed by a two-stage amplifier and a comparator. The comparator features pulse discrimination and produces the binary output. The analog signal of the second amplifier output is used for further analysis.

The amplitude, shape and polarity contain information about the size, distance, speed and gait of the target [15]. The polarity indicates the moving direction of the target. With machine learning methods, more information about the target can be achieved.

[15] presents some figures of PIR signal for cases two people are walking in the opposite directions at the front of a PIR sensor in the same or in the opposite directions and for the case two people are moving at different distances from the sensor. Changing the moving direction changes the polarity of the signal. Changing the moving speed affects on the signal time duration. A more distant object seems to create a signal of smaller amplitude. Using multiple PIR sensors improves accuracy. [15] Assembled 2 x 2 PIR sensors on ceiling and on both sides of a corridor. They implemented machine learning algorithms for human detection. The achieved accuracy was 92-94 %. According to them, accuracy over 90 % requires the use of multiple PIR sensors on opposite walls. The signal amplitude depends on the distance, but also on time duration object stays within a cone. Time increases when the distance increases. This makes it very difficult to measure distance with a single PIR sensor. As the amplitude is dependent on time, it is also dependent on the walking speed of a person [14]. In their experiment [14] they used two PIR sensors on the opposite sides of a corridor. A detected person could be located in one of the three areas between the sensors.

[17] presents an evaluation board of PIR sensors added with the temperature, humidity and lighting sensors. The board also has 16-bit, 860 smps ADCs for PIR signal acquisition. Sensors will be used to reject false positive triggering. A sudden increase in temperature or lighting conditions might cause a false trigger, but it can be rejected by using simultaneous temperature and lighting level information. A/D-converted PIR signal data can be Fourier and wavelet (CWT, continuous wavelet transform) transformed. The Fourier transformed signal shows the frequency components of the signal. Wavelet transformed data can be presented in a time-frequency domain. With a classification algorithm, the object can be classified according to its specific moving style to be a walking human adult, a walking human child, a moving pet, a falling person, a moving or rolling person on the floor, a background fire or just an external sunlight change. For achieving reasonable accuracy in the classification, machine learning methods need to be implemented.

[18] uses just one PIR sensor with advanced pattern recognition methods in order to separate human and non-human origin PIR signals. They use Wavelet Packet Entropy (WPE) for feature extraction and the least square support vector machine (LS-SVM) as a classifier. They found that WPE is an effective method in extracting the tiny difference of human and non-human PIR signal. Improvement was 1.3 % in detection accuracy and 4 % reduction in false alarm rate compared with the traditional methods. The method could also be used in separating cases of one human and several human beings.

4.9 PIR sensor networks for motion tracking and people counting

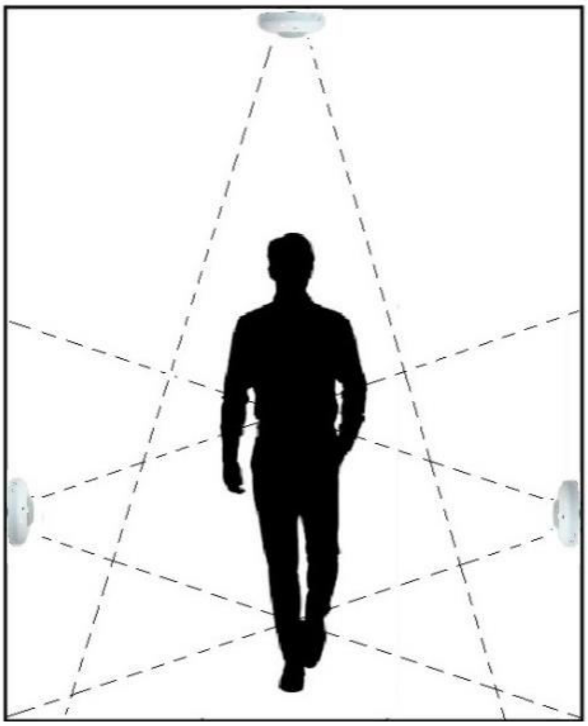
A typical application in buildings is detecting and counting the number of people walking in a hallway. By locating several PIR sensors in a way they will have a different FOV over the target area, a more accurate information about the number of the people and their moving direction can be achieved. In such an application the FOV of each PIR sensor will be reduced by hiding part of its lens. In this way, the sensor will become more focused in the selected direction and its signal will have less peaks. A large number of studies have shown how just a few PIR sensors can be used to accurately count the number of people and their moving direction.

[19] used three PIR sensors in a hallway, one sensor mounted on the ceilings and two sensors on the opposite sides of walls. The sensor network was able to detect and count people walking in a line or walking side by side. In their experiment, the maximum number of people was three. The case where people are walking in a line is rather simple to resolve. The number of peaks in the signal waveform is related to the number of people passing the FOV. The polarity of the first peak indicates the walking direction. The case where people are walking side by side is more complex. As the sensors are observing the target area from different directions, they detect the approaching person at different moment of time. In case several people are passing over the FOV, the duration of a peak is typically longer than in case of just one person. Analyzing the signal waveform, different cases can be solved. [19] found in the experiments that three sensor network featured 100 % accuracy in solving

the moving direction. 89% accuracy in solving the number of people walking in a line, 85 % accuracy when two and 65% accuracy when three people walking side by side.

[20-21] used sparse wireless pairs of unidirectional PIR sensors in a way the sensors are mounted facing each other on the corridors or hallways. People are entering in the field of view of the sensor at bit different moment of times. This time difference gives an understanding the motion speed and the direction. This information can further be extended by using an algorithm based on the direction or probabilistic distance of an occupant. Using an algorithm with a simulated building model, an accurate people occupancy counter can be build up. Use of multiple PIR sensors partly compensates the limitation of PIR sensor masking time and minimizes other sources of errors. [20-21] demonstrated also that solar and artificial lighting harvesting is capable to power a PIR sensor based system.

Larger PIR networks are used in indoor positioning of occupants. [22-23] has build a network of 9 wireless sensors with one route and data collecting nodes. Each sensor node has 6 PIR elements covering 360 deg. field of view. The sensor can be mounted on the ceiling or on the floor. Using Kalman filtering the noise of the PIR sensors can be reduced. Various machine learning methods were used. Coarse location was solved using probabilistic neural network classifier or a simple Naive Bayes classifier. The fine location was obtained by the bearing-crossing method. Positioning accuracy of two people moving in a 10 m x 10 space was 0.5 m.



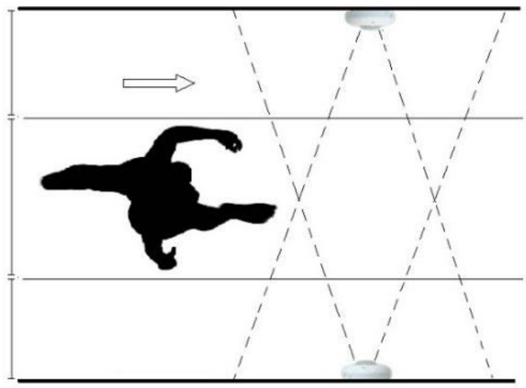


Figure-7. Three PIR sensors mounted on the ceiling and on the walls in a hallway seen at front a) and above b).

4.10 Low-resolution thermal array sensors

High-resolution imaging rises serious concerns about privacy intrude. For avoiding these concerns low-resolution imaging provides a solution. Low-resolution thermal arrays, which typically have a resolution of 8x8, 4x16 or 16x16 pixels are available for various applications in building automation including occupancy detection and counting, temperature monitoring, fire detection, fall detection and the detection of unusual activity (elderly persons), etc. Despite the increasing market size and the number of applications, just a few manufacturers control the market of these products. These components will gain market share from both the traditional PIR sensors and the high resolution imaging products (cameras).

Low-resolution IR arrays are based on thermopile technology, which is sensitive to far infrared range, typically in wavelengths between 8 and 13 um. The sensor is capable to accurate measure temperature seen in the detection area of each pixel. The accuracy in the measurement can be better than 0.1 °C. The difference from PIR sensor elements is that a thermopile element is sensitive also to a motionless object. By this mean, a thermopile is a real presence sensor. Other benefits compared with other technologies are the real-time or the near real-time response, high immunity to optical issues like lighting level and background changes. Compared with high-resolution imagers the low-resolution imager is naturally less expensive. A single low-resolution IR array sensor is able to provide information about object's movement and its coarse-grained tracking information. By this way, it can replace a network of PIR-sensors. A low number of pixels cannot reveal enough information for the identification of a human person. Privacy of the detected person is well preserved.

A low-resolution imaging processing uses similar procedures as a high-resolution image processing. [24] describes the procedure they used with their 16x16 pixels IR-imager: first resizing and resampling. This increases the size and quality of the image (reducing the effects of aliasing). Then background subtraction, rescaling and blob detection. Finally a morphological area adjustment, which is a specific procedure the authors used.

[25] used a single 8x8 pixels thermal array sensor [26] and developed indoor human detection and positioning algorithms. The algorithms showed improvement in positioning accuracy and improved separation between human and non-human objects. The temperature variation of the environment is still a major problem. Adaptive background estimation and noise reduction based on Kalman filtering were utilized. K-Nearest Neighbors classifier was used to estimating the number of people. A significant improvement in accuracy in human detection was obtained. The main difficulty is still the separation of human beings from other moving heat sources.

[27] used 4x16 pixels thermal array (Melexis MLX90620) [28]. According to the authors, this pixel arrangement suits better for rectangular spaces and corridors than an array of 8x8. Authors compared various machine learning classifiers (K-Nearest Neighbors, Linear Regression and Multilayer Perceptron) and found that the nominal classification algorithms performed better than the numerical ones. Entropy based classifiers were used the first time in this kind of application and they showed the best performance.

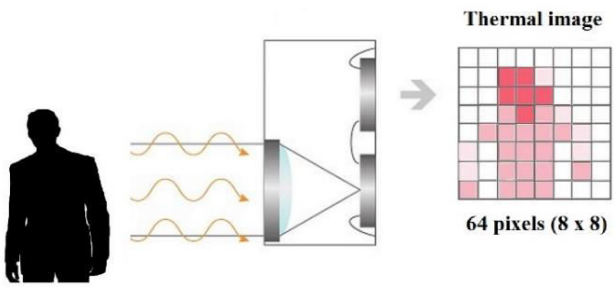


Figure-8. Low-resolution thermal imaging.

5. IR LIGHT BARRIER SENSORS

5.1 Retro-reflective light barrier

A light barrier is an active IR technology. It uses combination an IR light emitter diode and a receiver. The light barrier can be a single transmitter and receiver unit with a reflector or two separate units, a transmitter and a receiver. This kind of light barrier is a retro-reflective type. Retro-reflective type light barriers using a reflector can have the measurement range of max 2-10 meters. With a separate transmitter and a receiver, the range can be extended to over 100 meters. This type of a light barrier is called a through-beam type.

In the most typical application, a light beam is formed over an entrance to detect object passing in or out from a room. An object passing through the entrance interrupts the beam causing detection. Typically, the beam is infrared light though visible light can also be used. Applications of light barriers are versatile. They can be used for security applications in human machine interfaces. In building automation, the applications for example include burglar alarming or occupant counting. By using two horizontally separated light barriers, the moving direction of an occupant can be defined. This information can also be defined by a combination use of a light barrier and a PIR sensor(s). A light barrier provides more accurate spatial resolution compared a PIR sensor. The drawback is higher power consumption. Although they are accurate, light barriers are seldom used in building automation [29].

5.2 Diffuse reflective light barrier

A diffuse reflective light barrier sensor is an active IR technology. Instead using a reflector, the sensor measures reflection from the object. It uses an integrated combination of light emitter IR diode, a position sensitive detector and a signal processing unit. Lambert’s cosine law says that reflected energy from a small surface depends on the cosine of the angle between the arriving light beam and the surface normal. Part of the measured light of the detector is reflected light from the object and part is reflected or direct ambient light. Ambient lighting conditions and air visibility affects on the measured light. Surface emissivity, size and roughness affects on the amount of reflected light. These set the limit for detection range, but applying the triangulation method the distance can be measured without a significant impact of object surface emissivity variation. Output is typically a voltage signal which amplitude corresponding to the detection distance.

Commercial diffuse reflective sensors exist and are usually called an infrared distance or a proximity sensor. They are able to measure the distance to the object with a resolution of typically few centimeters. Detection ranges can be 20-150 cm (Sharp GP2Y0A02) or 100-550 cm (Sharp GP2Y0A710). Output can be an analog voltage or a digital serial bus. [30] States that these components have a too slow response considering an application of human occupancy detection.

[30] made an on-site study on occupancy counting in a university building. They used different sensors, among them sidewall mounted diffuse-reflective sensors, which could measure the distance and speed of an object. They managed to reach the detection range of 0.3-2 m with target speed of max 5 m/s. Occupancy detection accuracy was 95% over a measurement period of one hour.

According to [31-32] a low-cost IR diode array working on a reflection light scanner principle is an efficient people counter when installed at a doorway. They constructed an array including three highly directional IR-diode emitters and receiver pairs on a vertical line. Phototransistors are used as receivers. Two such lines were set on the opposite sides of a doorway. As the operating principle is diffuse reflective, a relatively high light power must be used. The emitter receiver pairs are successively activated and read. The highest signal comes from the pair which is closest the object. The time varying outputs of each pair are recorded. After processing the data, the number of people and their walking speeds can be resolved. Authors conclude that performance of the IR diode array as a people counter is far more reliable than that of an ordinary light barrier. A simple light barrier is unable to count people. A light barrier can easily make an erroneous detection of moving hands and other false detections. A diode IR emitter receiver array is a more accurate and robust people counter.

6. COMPARISON BETWEEN INFRARED AND OTHER PRESENCE/MOTION DETECTION TECHNOLOGIES

[33] lists comparable methods passive methods like infra-red (PIR) sensors, ultrasonic range sensors, microwave sensors, smart cameras, break beam sensors and laser range-finders. [34] made a comparison between three unobtrusive methods, PIR, carbon dioxide (CO2) and Device-free Localization. As human beings are the major sources of CO_2 it can be used to indicate the number people in a space. However, CO_2 concentration is affected by sensor location, ventilation efficiency and room layout. The CO_2 method has an extremely long response time and cannot be used for occupancy based lighting control. Device-free Localization (DfL) method uses received radio signal strength (RSS) values to estimate room population. Human body which contains much water efficiently absorbs radio waves. Radio frequencies used by IEEE 802.15.4 and particularly 2.4 GHz are better suitable for this purpose than WLAN IEEE 802.11 bands. The method works well when occupants locate in the line-of-sight. [35] has made a large survey on occupancy detection technologies. Pros and cons of them have been presented. Depth sensors like Kinect camera, which has been available together with XBOX 360 play station (Microsoft), uses time-of-flight (TOF) principle. The image shows distance related information about the target. Depending on how the camera is used, it can be more or less privacy invasive. Detailed information, biometric data about the target can be achieved. As an occupancy detector it can solve some of the problems of a conventional camera, like problems related to shadows or frequent illumination changes [36].

6.1 Ultrasonic sensors

Contrary to PIR sensing ultrasound sensing technique is an active method consuming much more electricity than PIR sensing. Ultrasound sensor is like a beacon which transmits short bursts of non-audible sound and measures the reverberation. This resembles much the widely used ultrasonic ranging principle. The received signal is then Fourier transformed in order to detect moving objects (Doppler shift). In case multiple moving objects are present in the space they can be detected from the spectra and even the directions and speeds relatively the sensor can be resolved. The acoustic properties of the space affect on the measurements. Walls, ceilings, corners, furniture and in generally everything inside the space have an impact on the acoustic properties. The noticeable difference from infrared sensing is that no line-of-sight conditions between the sensor and the objects are required. While operating in non line-of-sights (NLOS) conditions an ultrasound wave reflects from surfaces before reaching the target and on the way back to the sensor. Compared with PIR, an ultrasonic sensor can detect slight motions nearly twice the distance. A typical ultrasonic sensor detects hand motion at distance of 15 feet, arm and upper torso motion at distance of 25 feet and full body motion at distance of 35 feet [37].The ultrasound burst can be formed to a chirp to minimize artifacts [33]. This principle is widely used also in radar systems to improve the SNR. A chirp is formed by linearly increasing amplitude versus frequency. A typical length of a chirp is over 200 ms. Typical ultrasonic systems operate at 40 kHz, but some research have been done on systems operating near audio frequencies (20-22 kHz) [38]. Such a system can be build using cheap commodity speakers and microphones, which still operates at these frequencies.

Some ultrasonic methods do not use Doppler shift principle. [33] uses a system, which consists of an omni-directional ultrasonic tweeter with a co-located microphone that first transmits an ultrasonic chirp into a room and then measures the response over time as the signal decays. A chirp is a waveform which amplitude linearly increases in frequency. This technique in general is a method of improving SNR. When there are more people in a space, the signal decays more rapidly and hence the reverberation time can be used as a feature for estimating occupancy. Authors claim that at near audio frequencies (20-24 kHz) the signal transmission seems to be more omnidirectional and that is a benefit in this application.

Ultrasonic sensors are prone to false-positive errors. This is caused by the high sensitivity. In generally ultrasound detection suits better for a larger room than infrared detection. Air flow which is moving curtains, flowers or other objects may cause false alarms. With machine learning methods, a large number of false alarms can be eliminated. Depending on the amount of learning cycles and room calibration, ultrasound occupancy detection shows a typical error rate of 1-10 %.

6.2 Microwave sensors

Microwave sensors are the most often used motion/presence detector after PIR sensors. Its operation principle equal to that of ultrasonic sensor's. The differences between these technologies are that the field of view of a microwave sensor is wider. It is difficult to make the beam narrower. This is mentioned as a problem in an occupancy sensing application. Typically commercially available microwave sensors operate at 5.8 GHz. Other frequency bands, lower and higher, have been used in research. Especially the lower frequencies can penetrate through light build walls making the sensor sensitive to occupancy behind the walls. This is one of the main limitations of microwave sensors. In building automation microwave sensors are used in large spaces, like sport halls, corridors, garages or outdoor locations. Like ultrasonic sensors, microwave sensors are very sensitive to false-on-errors.

The common occupancy detection technologies are based on motion detection. They are sensitive to motion, but fail to detect a stationary object. To overcome this limitation, human heart and respiratory signals are considered for indications of the presence of a stationary human object. Microwave radar is able to wirelessly sense human respiratory signals, ECG and breathing. Typical vertical chest displacement caused by breathing is between 5 and 20 mm. This movement can be detected by using 24 GHz radar [39]. The output low frequency signal indicates the presence of a living human being. Authors [39] claim false-positive-errors can be eliminated leading to an error rate less than 0.01 %. [40] presents a similar system operating at 2.4 GHz ISM band. The detection distance is between 1-1.5 m. obviously, the short detection distance is the main limitation of this technology.

6.3 Combination use of occupancy detection technologies

Occupancy information based on a single detector is often coarse-grained and inaccurate. Using multiple sensors improve accuracy by overcoming drawbacks of an individual detector. A proper fusion of the sensors reduces the errors that are typical for one type of sensors. Typically, PIR based system is enhanced by using some other technologies like microwave or ultrasound [41]. PIR sensors are prone false-off errors therefore a combination of a sensor which gives less false-off errors, results in better performance. According to [33] combination use of several technologies like a PIR, a pressure sensor, an audible sensor, an additional light sensor or a CO_2 sensor can rise the detection accuracy over 90 %, even to 97 %.

The review paper of [29] discusses dual sensor technology use. The most common combinations are: PIR + ultrasonic, PIR + microwave. Sometimes also PIR + audible sound. These are common solutions for classrooms and private offices. By using dual technology false-on and false-off rates are reduced. However, a dual technology use is more expensive than a single technology solution. Basically similar kind of image processing as with a high resolution imaging can be used. [24] uses 16x16 pixels IR module. They implement first background subtraction and blob detection. Then they implement blob classification using iterative morphology to adjust area.

[42] used a combination of PIR, ultrasonic and CO_2 sensors. The target was to detect weather a seat is occupied or not. A PIR sensor detects an approaching person, an ultrasonic sensor detects from the distance of 2 meters whether there seems to be anything on the chair. A CO_2 sensor adds its information with a delay indicating whether the number of persons in the room has changed. The combination is a reinforced information on the seat occupancy.

[43] addressed also the problem weather a seat in open-plan office environment is occupied or not. The target is HVAC and lighting control of the office. Multiple technologies, like PIR, vibration, strain and mechanical sensors have been used. Sensors, except the PIR, have been mounted in the chair. A vibration sensor (a tri-axis acceleration sensor) was highly susceptible to nearby vibrations, but a strain and a mechanical (switch) sensors had high accuracy. The strain sensor between 91 - 97 %, the mechanical switch 99%. Possible errors were: with the vibration and strain sensors false negative and false positive, with the mechanical sensor false negative. Although the mechanical switch is accurate its durability causes concern.

7. CONCLUSIONS

This paper presented a review on infrared occupancy detection technologies. A detailed presentation about PIR sensors, its physics, functions and the different ways it can be implemented into a building automation system was given. The use of PIR sensors in a network featuring detection and indoor tracking of an occupant was discussed. A numerical model for a PIR sensor was developed. Some results of ray optics FEM-simulations were shown. Other infrared technologies like light barriers, diffuse reflection sensors and low resolution IR-imaging were presented. An introduction to the most common other occupancy detection technologies, like the microwave and the ultrasound, was given. A comparison between technologies was made and a summary was shown in a table. Finally, a discussion about the benefits of combination use of several technologies was presented. In building automation PIR sensors will certainly be used in future, but also new technologies like low-resolution IR-arrays will be adopted to occupancy detection and counting. In modern building automation, for example lighting and heating control will be based on real-time information about presence or the demands of occupants.

Table-1. A comparison between motion detection technologies.

Technology	Device/Sensor	Method	Line of	Resolution							Error (typ.)	Privacy	Price
			sight	Presence	Count	Spatial	Temporal	Identity	Activity	Track	false-		
IR light	PIR (single)	passive	yes	yes	no	yes/low	yes/low	no	no	no	off	preserving	low
	PIR(network)	passive	yes	yes	yes	yes	yes/low	no	no	yes/low	off	preserving	medium
	low res. imaging	passive	yes	yes	no	yes	yes	no	yes/low	yes/low		preserving	medium
	high res. Imaging	passive	yes	yes	yes	yes	yes	no	yes	yes		invasive	high
IR/light barrier	retro-reflective	active	yes	yes	no	yes	yes	no	no	no		preserving	low
	diffusive-reflective	active	yes	yes	no	yes	yes	no	no	no		preserving	medium
visible light	camera	passive	yes	yes	yes	yes	yes	yes	yes	yes		invasive	high
IR/visible	depth camera	active	yes	yes	yes	yes	yes	yes	yes	yes		invasive	high
Ultrasound	sonar	active	no	yes	no	yes/low	yes	no	no	no	on	preserving	low
Microwave	radar, UWB	active	no	yes	no	yes/low	yes	no	no	no	on	preserving	low
Acoustic	microphone	passive	no	yes	no	no	yes	no	no	no	on/off	invasive	low
Force/pressure /vibration	piezoelectric	passive	yes	yes	no	yes	yes	no	no	no	on/off	preserving	low

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REFERENCES

[1] Judith D. Jennings, Francis M. Rubinstein, Dennis Di Bartolomeo, Steven L. Blanc. 2013. Comparison of Control Options in Private Offices in an Advanced Lighting Controls Testbed. Journal of the Illuminating Engineering Society, 29:2, 19 Sep, pp. 39-60, DOI:10.1080/00994480.2000.10748316.

[2] Bill Von Neida, Dorene Manicria, Allan Tweed. 2001. An Analysis of the Energy and Cost Savings Potential of Occupancy Sensors for Commercial Lighting Systems. Journal of the Illuminating Engineering Society, 30:2, pp.111-125, DOI:10.1080/00994480.2001.10748357.

[3] Anca D. Galasiu, Guy R. Newsham, Cristian Suvagau and Daniel M. Sander. 2007. Energy Saving Lighting Control Systems for Open-Plan Offices: A Field Study. LEUKOS, 4:1, pp. 7-29,https://doi.org/10.1582/LEUKOS.2007.04.01.001.

[4] Scott Pigg, Mark Eilers, John Reed. 1996. Behavioral Aspects of Lighting and Occupancy Sensors in Private Offices a case Study of a University Office Building. Proceedings of the 1996 ACEEE Summer Study on Energy Efficiency in Buildings, Vol. 8, 161-170.

[5] Ryan Melfi, Ben Rosenblum, Bruce Nordman, Ken Christensen. 2011. Measuring Building Occupancy Using Existing Network Infrastructure, Proceedings of the International Green Computing Conference, Orlando, FL, USA. pp.1-8.

[6] Weiming Shen, Guy Newsham. 2016. Implicit Occupancy Detection for Energy Conservation in Commercial Buildings: A Review, Proceedings of the 2016, IEEE 20th. International Conference on Computer Supported Cooperative Work in Design. pp. 625-631.

[7] Weiming Shen, Guy Newsham, Burak Gunay. 2017. Leveraging existing occupancy-related data for optimal control of commercial office buildings: A review, article in press, 13 pages, Advanced Engineering Informatics.

[8] U.C. Sharma. Infrared detectors. M. Tech Credit Seminar Report, Electronic Systems Group, EE Dept, IIT/Bombay,https://www.ee.iitb.ac.in/~esgroup/es_mtech04_sem/es_sem04_paper_04307417.pdf.

[9] Mohan Shankar, John B. Burchett, Qi Hao, Bob D. Guenther, David J. Brady. 2006. Human-tracking systems using pyroelectric infrared detectors. Optical Engineering. 45(10), 106401, 10 pages.

[10] Panasonic Motion Sensors PaPIRs. Panasonic Industrial Devices. 1, pp. 1-16.

[11] Fernando Erismann. 1997. Design of a plastic aspheric Fresnel lens with a spherical shape. Optical Engineering. 36(4): 998-991.

[12] Mariusz Kastek, Tomasz Sosnowski, Henryk Polakowski, Mirosław Dąbrowski, Tomasz Orżanowski. 2008. Long-range PIR detector used for detection of crawling people. Proceedings of SPIE, the International Society for Optical Engineering.

[13] Piero Zappi, Elisabetta Farella, Luca Benini. 2008. Pyroelectric Infrared Sensors Based Distance Estimation. pp. 716-719, 2008 IEEE Sensors Conference.

[14] Piero Zappi, Elisabetta Farella, Luca Benini. 2010. Tracking Motion Direction and Distance with Pyroelectric IR Sensors. IEEE Sensors Journal. 10(9): 1486-1494, DOI 10.1109/JSEN.2009.2039792.

[15] Jaeseok Yun, Sang-Shin Lee. 2014. Human Movement Detection and Identification Using Pyroelectric Infrared Sensors, 14, Sensors, pp. 8057-8081, DOI 10.3390/s140508057.

[16] Fatih Erden, Ali Ziya Alkar, Ahmet Enis Cetin. 2015. A robust system for counting people using an infrared sensor and a camera. Infrared Physics &Technology, 72, pp. 127-134,http://dx.doi.org/10.1016/j.infrared.2015.07.019.

[17] IDA-01069 Advanced Motion Detector Using PIR Sensors Reference Design for False Trigger Avoidance, 2017, Application note TIDUCV3B, February 201, Revised October 2017, Texas Instruments. p. 36.

[18] Linhong Wang. 2011. Human infrared signal recognition using single PIR detector. 2011 4th International Congress on Image and Signal Processing. pp. 2664-2668.

[19] P. Zappi, E. Farella, L. Benini. 2007. Enhancing the spatial resolution of presence detection in a PIR based wireless surveillance network, IEEE. pp. 295-300.

[20] F. Wahl, M. Milenkovic, O. Amft. 2012. A distributed PIR-based approach for estimating people count in office environments, IEEE 15th International Conference on Computational Science and Engineering 2012. pp. 640-647.

[21] F. Wahl, M. Milenkovic, O. Amft. 2012. A green autonomous self-sustaining sensor node for counting people in office environments, pp. 203-207, the 5th European DSP Education and Research Conference 2012.

[22] Bo Yang, Jing Luo, Qi Liu. 2014. A novel low-cost and small-size human tracking system with pyroelectric infrared sensor mesh network. Infrared Physics & Technology, 63, pp. 147-156.

[23] Bo Yang, Qifan Wei, Meng Zhang. 2017. Multiple human locations in a distributed binary pyroelectric infrared sensor network. Infrared Physics & Technology, 85, pp. 216-224.

[24] Martin Bergert, Alistair Armitage. 2010. Room Occupancy Measurement Using Low-Resolution Infrared Cameras. p. 6, ISCC.

[25] Anna A. Trofimova, Andrea Masciadri, Fabio Veronese, Fabio Salice. 2017. Indoor Human Detection Based on Thermal Array Sensor Data and Adaptive Background Estimation. pp. 16-28, Journal of Computer and Communications, 5,https://doi.org/10.4236/jcc.2017.54002.

[26] Infrared Array Sensor Grid-EYE (AMG88), Panasonic Industrial Devices, 6 pages, 02 Apr. 2017,https://industrial.panasonic.com/cdbs/www-data/pdf/ADI8000/ADI8000C53.pdf

[27] Ash Tyndall, Rachel Cardell-Oliver, Adrian Keating. 2016. Occupancy Estimation using a Low-Pixel Count Thermal Imager, 8 pages, IEEE Sensors Journal. 16(10).

[28] MLX90621 16x4 IR Array Datasheet, rev. 3.0, Melexis Inc, 2016, 44 pages, 15 September.

[29] X Guo, DK Tiller, GP Henze and CE Waters. 2010. The performance of occupancy-based lighting control systems: A review. Lighting Res. Technol. 42, pp. 415-431.

[30] Jussi Kuutti, Petri Saarikko and Raimo E. Sepponen. 2014. Real Time Building Zone Occupancy Detection and Activity Visualization Utilizing a Visitor Counting Sensor Network. 11th. International Conference on Remote Engineering and Virtual Instrumentation REV 2014, Porto, Portugal, 26-28 February, pp. 219-224.

[31] Heinrich Ruser. 2005. Object recognition with a smart low-cost active infrared sensor array. 1st. International Conference on Sensing Technology November 21-23 2005, Palmerston North, New Zealand, pp. 494-499.

[32] V. Pavlov, H. Ruser, M. Horn. 2007. Reliable person counter based on object characterization using an infrared light array, Sensor’07 Conf., Paper B7.3, Nuremberg, May 22-24.

[33] Oliver Shih Anthony Rowe. 2015. Occupancy Estimation using Ultrasonic Chirps, pp.149-158, ICCPS ’15, April 14 - 16, Seattle, WA, USA.

[34] Eldar Naghiyev, Mark Gillott, Robin Wilson. 2014. Three unobtrusive domestic occupancy measurement technologies under qualitative review. pp. 507-514, Energy and Buildings. No. 69.

[35] Sirajum Munir, Ripudaman Singh Arora, Craig Hesling, Juncheng Li, Jonathan Francis, Charles Shelton, Christopher Martin, Anthony Rowe, and Mario Berges, 2017. Real-Time Fine Grained Occupancy Estimation using Depth Sensors on ARM Embedded Platforms. IEEE 2017.

[36] Huang-Chia Shih. 2014. A robust occupancy detection and tracking algorithm for the automatic monitoring and commissioning of a building. pp. 270-280, Energy and Buildings, 77, http://dx.doi.org/10.1016/j.enbuild.2014.03.069.

[37] Leslie Hodges. Ultrasonic and Passive Infrared Sensor Integration for Dual Technology User Detection Sensor. Application note, ECE 480 - Design team 5, 8 pages.

[38] Abbass Hammoud, Michel Deriaz, Dimitri Konstantas. 2017. UltraSense: A Self-Calibrating Ultra sound-Based Room Occupancy Sensing System. pp. 75-83, the 8th International Conference on Ambient Systems, Networks and Technologies 2017.

[39] Fabian Lurz, Sebastian Mann, Sarah Linz, Stefan Lindner, Francesco Barbon, Robert Weigel, and Alexander Koelpin. 2015. A Low Power 24 GHz Radar System for Occupancy Monitoring. 3 pages, IEEE conference 2015.

[40] Ehsan Yavari, Hsun Jou, Victor Lubecke, and Olga Boric-Lubecke. 2013. Doppler Radar Sensor for Occupancy Monitoring. pp. 139-141, BioWireless Conference 2013.

[41] Timilehin Labeodan, Wim Zeiler, Gert Boxem, Yang Zhao. 2015. Occupancy measurement in commercial office buildings for demand-driven control applications-A survey and detection system evaluation. pp. 303-314, Energy and Buildings, No. 93.

[42] Christopher Luppe, Amir Shabani. 2017. Towards Reliable Intelligent Occupancy Detection for Smart Building Applications. IEEE 30th Canadian Conference on Electrical and Computer Engineering (CCECE) 2017.

[43] Timilehin Labeodan, Kennedy Aduda, Wim Zeiler, Frank Hoving. 2016. Experimental evaluation of the performance of chair sensors in an office space for occupancy detection and ocupancy-driven control. pp. 195-206, Energy and Buildings, No. 111.