30 Years of Passive Infrared Motion Detectors - a Technology Review

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Introduction

The term "Passive Infrared", or "PIR", is commonly assigned to the technology of motion detectors used to detect people by sensing the thermal infrared radiation emitted by the human body. PIR detectors are very popular as automatic light switches, alarm sensors and door openers.

Infrared detection in military applications and pyrometry has a long history. Although some more recent IR applications like fiber optics communication or focal plane arrays for imaging have rapidly evolved in the last decades, PIR motion detection technology went its own way, and has not much in common with other infrared applications at 10 microns wavelength, due to the requirements for low cost and room temperature operation. The PIR market has reached an estimated annual volume of close to 100 million units today, but it is still a small and confined market, and was over most of the years out of the interest of technological investments.

The development of the technology has been dictated by the availability of components and sensors, but has also strongly been influenced by the designs and inventions of some key engineers in the field, and furthermore by fashions and trends. Only a few companies have actively developed the technology, and the larger part of the products, especially those from far east manufacturers, are copies. Development was therefore erratic to some extent, and not free of errors. It may therefore be of great interest to PIR design engineers, to know the background of today's common solutions.

History

At the end of the sixties, there was a growing need for volumetric detection in security installations, and alternatives to microwave and ultrasonic motion detectors were explored. PIR promised lower cost and less false alarms, but it took another 10 years to achieve this goal. The basis of the technology evolved at Optical Coating Lab. in California, a company specialized in non contact temperature measurements (pyrometers) [1] and at Barnes Engineering, active in military infrared applications.

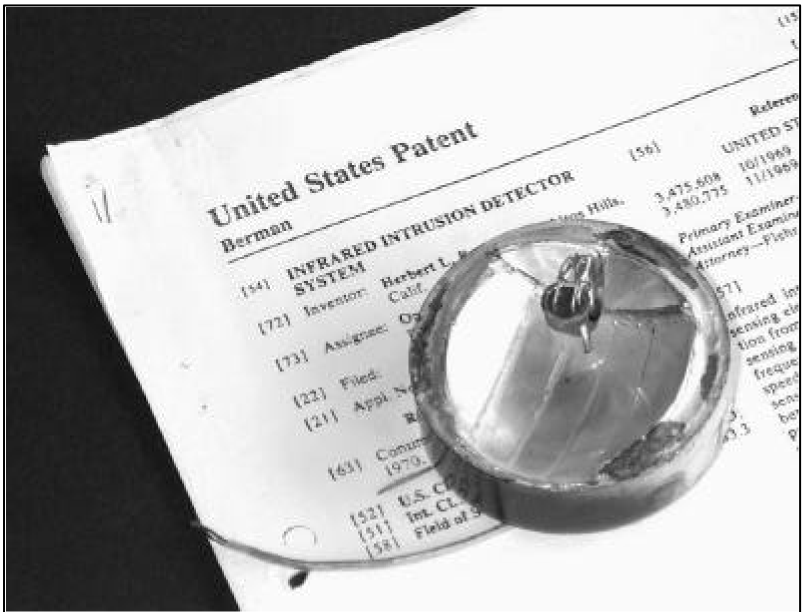


Fig. 1: The very first PIR intruder alarm sensor head made by Berman, introducing the segmented mirror for spacial modulation, around 1970

The credits belong to Herbert Berman [2] who invented in 1970 the segmented mirror made from metallized plastic as an effective system for optical gain and the spacial modulation needed to generate a signal when people move across the field of view. The principle of spacial modulation, or, in other words, the creation of a number of discrete sensitive zones, is one of the basic elements of PIR up to this day.

Frank Schwartz at Barnes [3] pioneered the use of differential sensors, and in Europe, Heimann offered an intruder alarm with a large area TGS pyroelectric cell and a space modulating grid.

PIR motion detectors always use thermal sensors, detecting the small temperature increase when the sensor element is exposed to radiation and absorbs it. Quantum detectors are not practical for PIR due to their need for cooling.

Berman used thermistor sensors. They delivered much more signal than the thermopiles used in pyrometry or military units. At that time, these sensors were home made from tiny thermistor flakes soldered into a transistor housing and fitted with a germanium filter with 8 to 14 microns bandpass coating. By 1975, a small number of such PIR alarms were on the market produced in hundreds or thousands. Although using the same technology, they were built by each manufacturer into existing detector housings available from microwave or ultrasonic devices.

False alarm rates were high due to the instability of the thermistors while detecting a 1/10'000°C temperature change at the sensor element, and also due to humidity and pressure waves getting into the non-hermetic sensors. "Spike noise" from the sensors causing false alarms was the common theme among PIR engineers in those years. Amplifiers added more spikes originating from transistor popcorn noise, chemical effects in electrolytic capacitors and instabilities in resistors. A remedy, (Berman's second patent [5],) was the use of a redundant 2-channel system that only gives an alarm output when both channels produce a signal. This expensive but reliable approach was commonly used till the early 80ties for high reliability alarm detectors.
Electromagnetic interference was recognized as a problem from the beginning, and most PIR alarm detectors had complete shielding of the input section with filters and feed-through capacitors. Later, some manufacturers forgot about this importance. Their low cost detectors were not reliable and had a rather negative effect to the image of PIR.

Pyroelectric sensors

The use of pyroelectric materials for the sensor was very promising and much fundamental work was done in those years [6],[7],[9]. A special challenge was the use of PVF (polyvinylidene fluoride), a plastic film known as „Saran®" wrapping [8]. It was easy to make large area sensors with many sensing elements connected electrically in series or parallel, eliminating the need for a segmented mirror or lens. However, PIR units with PVF sensors finally disappeared from the market due to the difficulty to seal them against humidity and air drafts, to make effective RF shielding and to avoid microphonic effects (PVF is also piezoelectric).
A major breakthrough was achieved in 1979 with the commercial availability of the dual (or differential) pyroelectric sensor. Lithium tantalate sensors were pioneered by Eltec Instruments and PZT ceramics duals were introduced at the same time by Mullard (now Nippon European Works) and Plessey in England.
Pyroelectric sensors with integrated field effect transistor were built into sealed TO5 transistor housings (Fig.2) and were much easier to use than thermistors. The need for the troublesome voltage regulator to supply the thermistor and the input amplifier was eliminated. It became now easier for newcomers to make a PIR, and the market expanded.

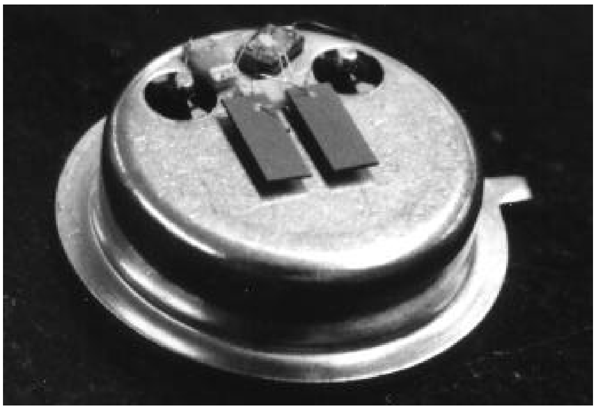


Fig. 2: Inside view of pyroelectric differential sensor with two air-suspended pyroelectric elements

The differential operation of the sensors compensates the influence of wind, warm air, daylight and other stimuli onto the detector, and drastically reduced false alarms. No alarm unit or outdoor light switch would work today without the differential sensor.
The first to use dual sensors was John Grant of Peak in England. He came up with a design dedicated to higher volume production, that included simple assembly, a good quality mirror with „step-focus" design, and effective RF shielding. It was very compact for that time and his concept has been copied over and over (Fig.3). [13]
People less oriented to the past developed straightforward designs with pyroelectric sensors like the alarm from IME in England, with a folded plastic mirror system designed by Burke Ward [17]. The mirror did not infringe the Berman patent and the cigarette-box sized unit marked substantial progress while US products were still large and bulky.

Fig. 3: John Grant's innovative PIR design, 1979

Fresnel lenses and other progress of the 80ties:

Whereas most progress in the 70ties happened in England, fresnel lenses were introduced first in the USA, driven by the search for simple alternatives to get around Berman's patent. The Arrowhead model 8700 of 1981 device offered a novel, compact design with exchangeable lenses and was the forerunner of most of today's alarm devices. Early fresnel lenses had the fine grooves of those used for illumination purposes of visible light. Later, the so called „progressive" fresnel lenses were introduced, made with grooves of equal thickness, and characterized by wide grooves in the center and aspheric overall curvature. There is still a dispute among manufacturers who invented it first, but credits may well belong to Augustine Fresnel (born 1788).

Fig. 4: "Standard" design PIR intruder alarm around 1986 with fresnel lens

The later 80ties were marked by substantial improvement of electronic components, mainly due to improved purity of materials: In a 1983 presentation [4] on the same subject, the major concern in PIR alarm detectors were false alarms due to alpha particles emanating from contaminants, and noise from various sources, the never ending spike-noise problem. Although the progress in the computer industry was of little direct use in PIR detectors, the high purity of silicon wafers made amplifiers free of popcorn noise and epoxy package materials for chips substantially free of radioactive contaminants, because these criteria are crucial in large memory chips.

The availability of reliable components including single chip solutions at low cost led to more widespread application of PIR technology, but also far east manufacturers entering the market with lowest cost products.

Electromagnetic interference remains an important issue. Improvements that became possible with compact SMD technology and multilayer boards are outweighed by the growing need to withstand high RF fields at high frequencies from today‘s mobile communication.

Light- and „Energy“ switches

In 1981, Marcel Züblin picked up the idea of switching light with a PIR. The idea was not new, but he postulated 180° field of view, 2-wire operation and an affordable price as the imperative ingredients for the product to replace the manual wall switch, and he was determined to make it work. A quick marketing analysis showed that the potential market was enormous, and 400'000 units were planned for the first year, a figure that was far beyond of what alarm manufacturers were producing in those years. Although simple and obvious in its application, the light switch was not successful in the beginning and needed over five more years to become successful as Busch Jäger’s "Wächter" in Germany [14].

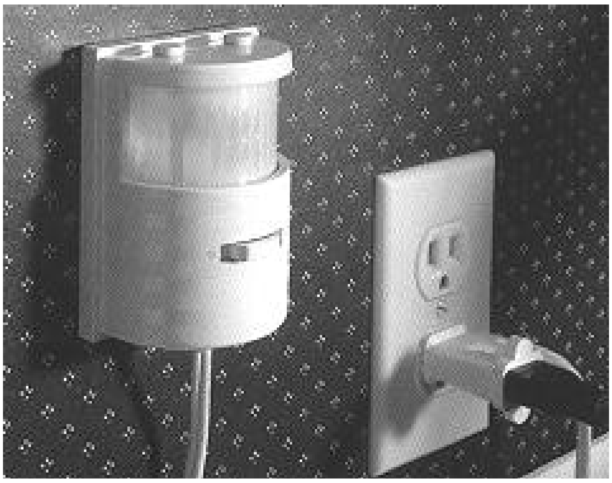


Fig. 5: Züblin‘s first PIR light switch introduced by RCA in 1985

This phenomenon was observed again and again. Many PIR products disappeared because the potential market was heavily overestimated. Marketing people may argue that this is true for any new and unknown product, but PIR products seem to suffer even more because people do not understand how passive infrared works.

More recently, in 1992, PIR motion detectors were not only considered to switch light for comfort and safety, but to control energy in buildings, mainly to switch heating, ventilation, air-conditioning and light according to need. Such "presence" or "occupancy" detectors required another set of specifications, and PIR detectors were adapted accordingly. Presence detectors are generally ceiling mounted and require a zone pattern to catch any sitting person in the room. Sensitivity is very high compared to alarm systems and has often an adaptive mode to increase it to the utmost possible. While a false alarm is annoying for an alarm system, it is of less importance for the presence detector. However, the presence detector should never miss someone and leave him in the dark.

Although the presence or occupancy detector for energy control is still in the beginning, some people consider this field as the largest potential for PIR applications, especially when such detectors are linked to building automation communication buses and perform an integral function for energy, security and comfort.

Other PIR applications

PIR seems to be the most effective "people detector". PIR detectors are small, simple, cheap, very low power and do not emit anything. Unlike radar, ultrasonic or active (reflective beam type) infrared, PIR senses the body temperature as an additional criterion beyond the size and motion of the person. PIR detectors are especially useful in combination with a radio transmitter for wireless alarm systems, because the "passive" nature of PIR allows continuous operation for 10 years from a lithium battery. Hundreds of other applications have already been considered, from computers to coffee machines and toys. Few of them have been realized. So why is PIR so rarely used ? Engineers are scared to use an electro-optical system they do not understand.

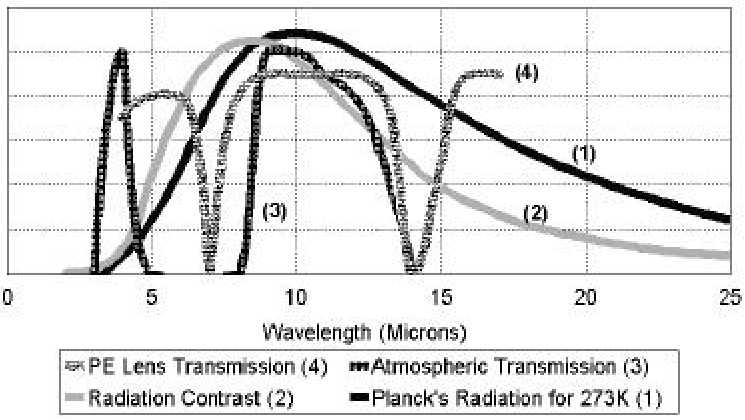
Intelligent signal discrimination

The signals generated by the PIR sensors are very low frequency (0.2...4 Hz) due to the thermal inertia of the sensors, and a single pulse, or some very few pulses indicate the motion of a person. There is in most cases no time to integrate signals over a certain period. An immediate output is given upon a single signal pulse, no matter whether it originates from a moving person, from noise or interference. It has been tried to analyze the waveform of such a signal, but unfortunately, all attempts to filter the signal or discriminate its shape brought little success. Amplitude and duration of the signal are determined by the temperature of the moving person, the speed of walking, and the distance from the

sensor, and all these parameters can vary from case to case without being indicative to what actually happens. Counting a sequence of pulses at the expense of slow and less sensitive detection is the only approach used in alarms.
It has been discussed over years that the problem could be solved with a small sensor array, giving at least some image resolution. Such parts are readily available for thermal imaging, integrating either pyroelectric layers or thermopiles to silicon wafers. However, the required sensitivity for PIR applications has not been reached yet. An alternative could be the combination of a PIR with a low resolution camera in the visible range. A very low number of pixels could be adequate to sense typical patterns of moving people. Such systems could replace today‘s combinations of PIR with microwave or ultrasonic sensors.

The infrared spectrum of PIR detectors

According to Planck’s law, the spectrum of infrared radiation from a body at ambient temperature (293K) peaks at 10 microns wavelength (curve 1). Satellite surveillance, for example, struggles with the transparency of the atmosphere. Humidity, dust and molecular absorption cause substantial absorption. One of the so called "atmospheric windows" between 8 and 14 microns is the best suitable wavelength to sense thermal radiation over kilometers (curve 3) [15]. Traditionally, this wavelength band has been chosen for PIR sensors [11],[12].



Few people considered that the PIR device senses the contrast between a human body and the background. The contrast however, the first deviation of Planck's equation, peaks at 8.3 microns and extends rather to 5 microns (curve 2). Almost any PIR has either a lens or a front window made from polyethylene (PE). This material has characteristic absorption bands at 7 and 14 microns. The atmospheric window is of no importance to PIR. Absorption is exponential with distance, and the effects from the atmosphere to PIR motion detectors with 10 or 20 meters of range can be totally neglected. From all these considerations, a 5 micron long wavelength pass filter (open at the long wavelengths) will give a better signal than a 8 to 14 micron bandpass.

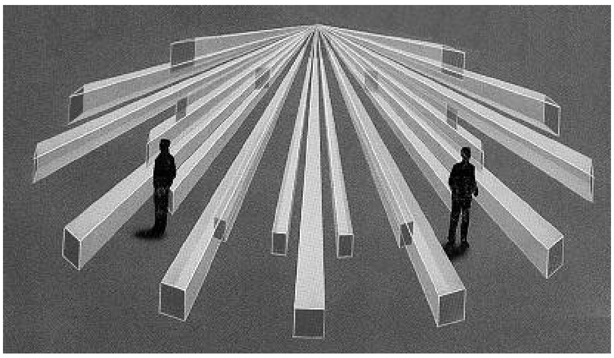
Mirror or lens ?

Most segmented mirrors disappeared in favor of fresnel lenses, due to obvious reasons such as cost, availability of standard products, easier design and tooling of lenses. Lenses are also more flexible to arrange the zones.
The advantage of most mirror systems is that the zones intersect at the front window. This means that the front window can be made much smaller than a lens, in the size of one single element of the lens array. The fact that the zones intersect means also that disturbances onto the front window, such as sunlight, wind or warm air from a heater fully compensate due to the differential operation of the sensor. Consequently, mirror systems are very useful for outdoor operation and applications exposed to the public. Fig. 7 shows a room thermostat with integrated PIR presence detector, having a very small, unobtrusive and vandal proof window. This unit will reduce ventilation, air conditioning and heating when nobody is in the room.

Fig. 7: Hotel room thermostat with integrated presence detector. The mirror system needs only a small front opening (oval window at bottom left)

How many zones ?

An ongoing controversy among PIR manufacturers concerns optics or lenses, and their respective number of zones or lens segments. At first, it seems to be good to have as many zones as possible, distributed over a wide angle. Sales and marketing people will certainly agree with this.



A more detailed analysis includes the consideration of the size of the human body versus the size (angle) of the zones, the sensors size, the focal length, the fact that the sensor is slow and cannot follow fast transitions through zones. Generally, the zones are designed to have a cross section equal to the human body at half the maximum detection distance. The surface per lens segment determines the energy received from the target. The ratio of this lens area to the sensor area is the optical gain and will determine the maximum signal output available. Small 2 mm size lenses will therefore not give any signal gain and the PIR may not work at all.

Practical considerations include also the thickness of the strongly absorbing lens, and the deformations occurring when molding thin lenses. The designer wants the fresnel grooves inside, although optically, they are preferrably on the outside. He overlooks the losses from oblique rays (zones that are not perpendicular to the lens). To make a powerful lens, it is recommended to use the minimum number of zones possible for the application, and make the lens as large as possible within the limits of a design. Electronics will become simpler with strong signals, reliability and electromagnetic compatibility better and overall system cost lower.

How to make the best lens

Today‘s PIR alarms and light switches show a large variety of lens designs. Most obviously, it is easiest to make flat lenses (fresnel lens arrays). Surprisingly, they do not lose their focussing power when they are bent to a cylindrical shape, what allows detection up to large horizontal angles such as 270°.

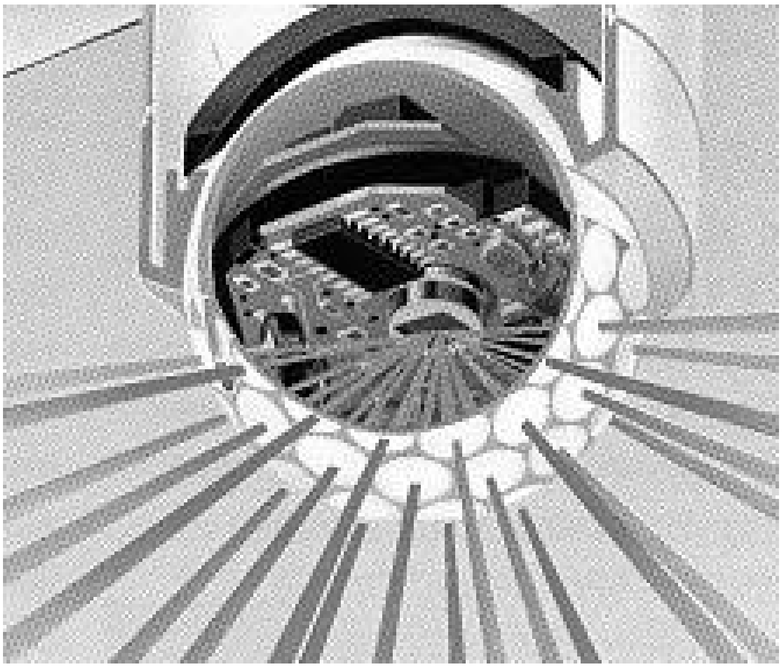


Fig. 9: Sectional view of a typical PIR light switch with “golf ball” lens, made from a large number of small lenses on a hemispherical dome.

More recently, available tooling skills allow the injection molding of 3-dimensional lenses, and there are endless possibilities for the arrangement and combination of fresnel lenses, diffraction lenses, standard spherical or aspherical lenses, cylindrical lenses and prisms in 3-dimensional structures, and in combination with deflection mirrors or prisms. We will definitely see more such creative designs in the coming years. On the other hand, simple designs like the „golf ball lens“ (Fig. 9) offer esthetically pleasing designs and low production cost [16].

Most alarm systems are still mounted in the corner of the room to be protected and a 90° field of view is adequate to cover the room completely. The number of zones is limited to keep signals strong and false alarms low. It is acceptable that an intruder needs to walk a certain distance before being detected. The design of light switches is more creative in terms of mounting position and viewing angle: 180° field of view is common to allow mounting anywhere on a wall, but 270° to "see around the corner" or 360° is in the trend (with the disadvantage that the user must painstakingly cover on the lens all directions he does not want). Presence detectors for office light switching, however, need a large number of zones to cover the room completely. A person has to be detected anywhere. As such presence detectors also need high sensitivity to detect the motion of a hand or a shaking head, it is often required to use several sensors with parallel detection channels. In contrast to Berman‘s redundant system, the channel outputs are logic OR wired.

Step-focus optics

For an ideal detection, short range zones should have a wider opening angle than long range zones, to meet the criterion of having a cross section equal to the size of the human body at half the nominal range. The Peak mirror (Fig.3) was first to accomplish this by placing the short range mirror segments closer to the sensor. This recipe has been used repeatedly, but unfortunately, the steps make mirrors of exotic shape that are difficult and expensive to mold. The principle is also difficult to apply to fresnel lenses. It is discussed today if diffraction lenses (fresnel lenses with a groove periodicity corresponding to a zone plate interference pattern) can solve the problem.

A more recent trend are „pet alley“ or "pet immune“ alarm detectors. The idea is to leave cats and dogs in the house while the alarm system is active. Some products pretend they can solve the problem by extending the zones vertically, what is done either with small mirrors extending the apparent sensor size, or by using cylindrical fresnel lens segments, so that pets create less signal. It is questioned if this problem can ever be solved to distinguish a burglar from a Dalmatian without the aid of an additional camera with image recognition.

No detection at 37°C ?

A persistent question is what happens with a PIR at 37°C, when there seems to be no difference to the body temperature: First, when the air temperature is 37°, this does not mean that the background is also at 37° (the walls of a room, a landscape or the sky). The background is generally very variable. And second, body temperature is not the temperature of the skin or the surface of the clothes. A person may have 28° in the face and 24° on the surface of the jacket at an ambient of 20°. As we are no thermal chameleons, there are always differences to be detected by the PIR. Signals may be somewhat smaller at 30°C ambient than at freezing temperatures. Sophisticated PIR detectors compensate that. In general, it is better to talk about a "detection probability" because the actual conditions of detection (target temperature, background temperature, but also emission coefficients and reflections) vary from situation to situation.

Infrared pollution ?

Finally, I have met many people over all these years suffering from PIR rays, said to be emitted from their alarm units. Some people can feel the red zones shown in the users manual, or see them glow in the dark. They are said to cause headache, inhibit plant growth and do harm to the dog. While our heads are agonized today by our handy's RF output, it is good to remember what a marketing guy said one day: "Passive infrared, its all there, 100% natural and harmless".

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