Techniques for PIR-based motion detection

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PIR operation and limitation
Infrared radiation (IR)
Wien's displacement law

Black-body radiation curve for different temperatures will peak at different wavelengths that are inversely proportional to the temperature

\[ \lambda_{\text{max}} = \frac{b}{T} \quad \text{where} \quad b \approx 2898 \text{ \(\mu\)m K} \]

Mammals with a skin temperature of about \(300^\circ\text{K}\) emit peak radiation at around \(10 \text{ \(\mu\)m}\) in the **far infrared**. This is therefore the range of infrared wavelengths that pit viper snakes and passive IR cameras must sense.
Indoor ($T_A = 72 \, ^\circ F$) vs outdoor ($T_A = 94 \, ^\circ F$)
PIR sensor range is affected by: Environmental conditions including ambient temperature and light sources
Pyroelectric infrared (PIR) sensor

Part: IRA-S210ST01, courtesy Murata.com

<table>
<thead>
<tr>
<th>Operating Temperature Range</th>
<th>-40°C to 70°C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shape</td>
<td>Lead</td>
</tr>
<tr>
<td>Field of View</td>
<td>theta1=theta2=45deg.</td>
</tr>
<tr>
<td>Electrode</td>
<td>(2.0x1.0mm)x2</td>
</tr>
<tr>
<td>Responsivity(typ.)</td>
<td>4.6mV</td>
</tr>
<tr>
<td>Optical Filter</td>
<td>Smicro meter Long Pass</td>
</tr>
<tr>
<td>Supply Voltage Range</td>
<td>2V to 15V</td>
</tr>
<tr>
<td>Storage Temperature Range</td>
<td>-40°C to 85°C</td>
</tr>
</tbody>
</table>

Spectral response of window materials

300°CK (9.3 µm)

Heat source movement

Sensor output voltage

Image source: Murata.com
PIR sensor operation, heat source movement

Pyroelectric Infrared Sensor IRA-S210ST01 (courtesy Murata.com)

~ 3.6 mVpp

Direction
Distance
Speed

<table>
<thead>
<tr>
<th>Distance [inch]</th>
<th>Vpp [v]</th>
</tr>
</thead>
<tbody>
<tr>
<td>30</td>
<td>3.14</td>
</tr>
<tr>
<td>70</td>
<td>1.42</td>
</tr>
<tr>
<td>90</td>
<td>0.92</td>
</tr>
<tr>
<td>130</td>
<td>0.42</td>
</tr>
</tbody>
</table>
Noise reduction techniques
**Advantages**
- Simple, low power

**Disadvantages**
- Gain/bandwidth are fixed in hardware
- Filter capacitors can act as noise sources (see next slide)
Barium titanate (BaTiO₃)
SNR improvement with capacitor free design

Capacitor as noise source:
- Ceramic - Microphonic
- Tantalum - $1/f^3$

Noise Source

Bandpass Filter

Capacitor Free
Single chip ultra-low power PIR solution

Advantages

- Configurable gain and pass band → allows for optimizations for detecting targets at different distances and speeds
- Low noise → Improved SNR in signal chain reduces false detections
- Low average power consumption → long battery life
- Fewer components → lowers BOM cost and simplifies layout
MSP430 analog signal acquisition current

$I_{AV} = 5 \mu A @ 20 \text{ sps}$
Battery life calculation

• Assumptions (based on TIDA-00489)
  – Current in low power mode: 5 \( \mu \text{A} \)
  – Active-mode duration when event occurs: 60 s
  – Additional current during active period: 645 nA
  – Average current during wireless transmission: 1.12 mA
  – Duration of wireless transmission: 104 ms
  – Number of detection events per hour: 10
  – Battery derating factor: 85%

• Battery life
  – CR2032 @ 240 mAh: 4+ years
  – CR2450 @ 600 mAh: 10+ years
Sub-1 GHz communication options

• Option 1: MSP used to run simple Sub-1G protocol and interface to external transceiver
• Option 2: Capacitor-less solution can be migrated to a wireless MCU (less integration of analog generally possible). Example below:
Other topics to consider

• Multiple PIR sensors and to reduce false triggering (e.g., due to pets)
• Dual-mode detection techniques:
  – PIR + optical ToF (improved sensitivity to longitudinal movement)
  – PIR + ultrasonic
  – PIR + discrete doppler
• Tamper/masking resistance
Advanced motion detection

- Multiple PIR
- PIR + camera
- PIR + ToF
- PIR + Ultrasonic
- PIR + uWave
Sensor and Fresnel lens combination

Image source: Murata.com
The solutions consist to use three sensors with different lenses, in order to have different covered zones.

- The **first sensor** will cover the whole area. This sensor will trigger the MCU and the rest of the circuit.
- The **second sensor** will cover the bottom and top vertical zone.
- The **third sensor** will cover the medium vertical zone.
Advanced motion detection

- Multiple PIR
- PIR + camera
- PIR + ToF
- PIR + Ultrasonic
- PIR + uWave
**PIR + camera system**

For systems that combine PIR sensors with cameras (for example, home security systems, video doorbells), it is possible to use the PIR to trigger the camera.

Once activated, the camera can determine whether the motion occurs within specific user-defined zones.

This helps to reduce nuisance notifications (e.g., due to pedestrians on sidewalk/street, movement of trees, etc.).
Advanced motion detection

- Multiple PIR
- PIR + camera
- PIR + ToF
- PIR + Ultrasonic
- PIR + discrete Doppler
PIR motion detection: False alerts

Motion is detected because PIR more sensitive to lateral motion compare to longitudinal)
Motion detection using Time of Flight (ToF)

Distance is detected because:
• Time between emitted and reflected wave is measured (ToF)

Motion is detected because:
• There is difference in distance between consecutive measurements.
PIR with ToF motion detector eliminating false alerts

- Passive single of multiple PIR/s
- Low Standby Current of 1.65 μA
- Optimized for low-power battery operations
- Motion sensitivity up to 30 ft
- Generates interrupt
- Great flexibility
- Low cost

- Active ToF with multiple Tx
- Sleep Mode Current 10 - 20 μA
- Interrupt driven low-power battery operations
- Motion sensitivity 1.6 to 12 m
- Registers: phase and amplitude
- Great flexibility
- Low cost
TIDA-010021: Wide-range (120° FoV at 1.6 Meters) proximity sensing with immunity to sunlight

Features

- Three NIR emitters support up to 3 zones of detection with a single OPT3101 device
- Total system Field-of-View (FoV) of 120° is covered by three LED emitters and one photodiode
- Detection range up to 1.6 meters without lens
- Adaptive high dynamic range (HDR) feature enables the detection range of system very wide
- ToF based sensing AFE (OPT3101) makes measurement insensitive to object color and reflectivity and supports operation under high ambient condition (outdoor and Indoor Conditions)
- Proximity sensing and direct distance measurement output with accuracy of ±10%
- Low power mode running at 1 sample per second with a power drain of 30 mW
- Exempt group lamp classification LED as emitter
Advanced motion detection

- Multiple PIR
- PIR + camera
- PIR + ToF
- PIR + Ultrasonic
- PIR + discrete Doppler
ToF measurement using PGA460

<table>
<thead>
<tr>
<th></th>
<th>Standard</th>
<th>Advanced</th>
</tr>
</thead>
<tbody>
<tr>
<td>Drive Mode</td>
<td>Half-bridge (direct)</td>
<td>Transformer</td>
</tr>
<tr>
<td>Recommended Supply Voltage</td>
<td>6V</td>
<td>9V</td>
</tr>
<tr>
<td>Minimum Distance</td>
<td>30cm</td>
<td>15cm</td>
</tr>
<tr>
<td>Maximum Distance</td>
<td>3m (human sized target)</td>
<td>6m (human sized target)</td>
</tr>
<tr>
<td>Power per 1s interval</td>
<td>3.7mW</td>
<td>7.8mW</td>
</tr>
<tr>
<td>Solution Cost (at high volume)</td>
<td>$1.50</td>
<td>$2.00</td>
</tr>
</tbody>
</table>
TIDA-060024: Ultrasonic proximity-sensing module (PSM) reference design
Advanced motion detection

- Multiple PIR
- PIR + camera
- PIR + ToF
- PIR + Ultrasonic
- PIR + discrete Doppler
Doppler effect (Doppler Shift)

Motion is detected because:
- Reflected and emitted wave have different frequencies.
- Ultrasonic, Microwave, mmWave and ToF can be used to measure Doppler shift.
**Doppler effect (Doppler shift)**

The Doppler effect (or the Doppler shift) is the change in frequency or wavelength of a wave in relation to an observer who is moving relative to the wave source.

Relationship between observed frequency $f$ and emitted frequency $f_0$ is given by:

$$f = \left( \frac{c \pm v_r}{c \pm v_s} \right) f_0$$

where
- $c$ is the velocity of waves in the medium
- $v_r$ is the velocity of the receiver relative to the medium
- $v_s$ is the velocity of the source relative to the medium

If the speeds $v_s$ and $v_r$ are small compared to the speed of the wave, the relationship between observed frequency $f$ and emitted frequency $f_0$ is approximately

$$f = \left( 1 + \frac{\Delta v}{c} \right) f_0$$

$$\Delta f = \frac{\Delta v}{c} f_0$$
**Intermediate frequency (IF)**

*Intermediate frequency (IF)* is a frequency to which a carrier wave is shifted as an intermediate step in transmission or reception. The intermediate frequency is created by mixing the carrier signal with a local oscillator signal in a process called **heterodyning**, resulting in a signal at the difference or beat frequency.

**Heterodyning** is a signal processing technique that creates new frequencies by combining or mixing two frequencies. Heterodyning is used to shift one frequency range into another, new one, and is also involved in the processes of modulation and demodulation. The two frequencies are combined in a nonlinear signal-processing device. In the most common application, two signals at frequencies \( f_1 \) and \( f_2 \) are mixed, creating two new signals, one at the sum \( f_1 + f_2 \) of the two frequencies, and the other at the difference \( f_1 - f_2 \). These frequencies are called heterodynes. Typically only one of the new frequencies is desired, and the other signal is filtered out of the output of the mixer. Heterodyne frequencies are related to the phenomenon of "beats" in acoustics.
Intermediate frequency (IF) cont.

\[ \cos(2\pi f_1 t) + \cos(2\pi f_2 t) = 2 \cos\left(2\pi \frac{f_1 + f_2}{2} t\right) \cos\left(2\pi \frac{f_1 - f_2}{2} t\right) \]

Doppler frequency \( f_d \) is proportional to the object speed \( v \):

\[ f_d = v \frac{44 \text{ Hz}}{\text{km/h}} \cos \alpha \quad \text{or} \quad f_d = v \frac{158 \text{ Hz}}{\text{m/s}} \cos \alpha \]
Motion detector using Doppler Effect
Motion detector using Doppler Effect cont.

For detecting Persons, BW is around 4Hz to 400Hz.
Comparing different motion detector technologies
## Motion sensor technology comparison

<table>
<thead>
<tr>
<th>Motion Detection</th>
<th>PIR</th>
<th>Microphonics</th>
<th>Ultrasonic</th>
<th>Microwave</th>
<th>mmWave</th>
<th>Camera</th>
<th>TOF</th>
</tr>
</thead>
<tbody>
<tr>
<td>Operating Principle</td>
<td>Difference between heat of object and background</td>
<td>Detect audible sound levels compared background</td>
<td>Measure frequency shifts in the reflected ultrasonic sound waves (Doppler Sonar). TOF measurements also used.</td>
<td>Measure frequency shifts in the reflected microwaves (Doppler Radar). TOF measurements also used.</td>
<td>Measure phase and frequency shifts in the reflected millimeter waves as well as TOF measurements (Doppler Radar)</td>
<td>Compares consecutive image frames through image processing to determine motion. Depending on sophistication of algorithm, can filter for human motion.</td>
<td>Modulated IR transmission and reflection. Time of flight for reflections measured to calculate distance. Processing required for background calibration and analysis to detect presence and motion</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Cost</th>
<th>$</th>
<th>$-$**$</th>
<th>$</th>
<th>$-$**$</th>
<th>$**$</th>
<th>$-$**$ (application dependent)</th>
<th>$-$**$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Range</td>
<td>10-12m</td>
<td>10-20m</td>
<td>10-12m</td>
<td>10-30m</td>
<td>~10m (fine motion)</td>
<td>50m+ (broad motion)</td>
<td>30m+</td>
</tr>
<tr>
<td>Requires clear line of sight between object and sensor</td>
<td>Yes</td>
<td>No</td>
<td>No (Can be directive thru use of horn or transducer design)</td>
<td>No</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Power Consumption</td>
<td>Lowest</td>
<td>Low</td>
<td>Medium</td>
<td>High</td>
<td>High</td>
<td>Medium - High</td>
<td>Med</td>
</tr>
<tr>
<td>Fine Motion Detection</td>
<td>No</td>
<td>Maybe (depends on sound level of fine motion relative to background noise)</td>
<td>No</td>
<td>Maybe (depends on field of view)</td>
<td>Yes</td>
<td>Maybe (depends on space, zoom capabilities, and camera resolution)</td>
<td>Maybe (depends on space and field of view)</td>
</tr>
<tr>
<td></td>
<td>PIR</td>
<td>Microphonics</td>
<td>Ultrasonic</td>
<td>Microwave</td>
<td>mmWave</td>
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<td>TOF</td>
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<td>------------------------</td>
<td>----------------------</td>
<td>---------------------------------------------</td>
<td>------------------------------------------</td>
</tr>
<tr>
<td>Major Performance Advantages</td>
<td>Lowest Cost</td>
<td>Passive sensing of sound waves</td>
<td>Capable of measuring the speed of object's motion</td>
<td>Capable of measuring the speed of object's motion</td>
<td>Capable of measuring the speed of object's motion</td>
<td>Capable of detecting stationary objects, Can &quot;see&quot; through walls</td>
<td>Capable of precise distance measurements, Capable of detecting stationary objects</td>
</tr>
<tr>
<td></td>
<td>Lowest Power</td>
<td>With signal processing, capable of masking non-human sounds</td>
<td>Capable of detecting stationary objects</td>
<td>Capable of detecting stationary objects</td>
<td>Capable of detecting stationary objects</td>
<td>No additional sensors are required for motion sensing, Motion events can be recorded and replayed</td>
<td>Capable of detecting stationary objects</td>
</tr>
<tr>
<td></td>
<td>passive sensing)</td>
<td>reasonable range</td>
<td>Can &quot;see&quot; around corners</td>
<td>Can &quot;see&quot; around corners</td>
<td>Can &quot;see&quot; around corners</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Major Performance Disadvantages</td>
<td>Sensitive to false triggering for anything creating changes in temperature or white light</td>
<td>Loss of sensitivity (SNR) in environments with high ambient noise</td>
<td>Can detect motion of objects outside of the desired field of detection by reflection around corners, Will detect motion of inanimate objects, Can be harmful to pets</td>
<td>Can detect motion of objects outside of the desired field of detection (capable of penetrating walls), Will detect motion of inanimate objects, Can be sensitive to certain fluorescent lighting</td>
<td>Can detect motion of objects outside of the desired field of detection (capable of penetrating walls), Will detect motion of inanimate objects, Can &quot;see&quot; in dark environments unless coupled with illumination and filtering for night vision, Dust, dirt, moisture effect on image quality</td>
<td>Cannot &quot;see&quot; in dark environments</td>
<td>Cannot &quot;see&quot; through fog, dust, or smoke, Will detect motion of inanimate objects, Measurement errors for reflective or IR absorbing materials</td>
</tr>
</tbody>
</table>
## Motion sensor technology comparison (cont.)

<table>
<thead>
<tr>
<th></th>
<th>PIR</th>
<th>Microphonics</th>
<th>Ultrasonic</th>
<th>Microwave</th>
<th>mmWave</th>
<th>Camera</th>
<th>TOF</th>
</tr>
</thead>
</table>
| Enclosure influence  | Requires Fresnel lens which directly impacts shape and appearance of enclosure | • Needs hole(s) for microphone input in enclosure  
  • No protrusions required | Vents needed in the enclosure to avoid attenuation of the transducer signals | • Enclosure only needs to be large enough to house transducer  
  • Transducer can be concealed as long as material is transparent to carrier frequency | • Enclosure only needs to be large enough to house transducer  
  • Transducer can be concealed as long as material is transparent to carrier frequency | Enclosure designed around camera lens | Enclosure needs to include IR transparent material to accommodate IR transmission and reception of reflected IR. |
| Direction of motion with highest sensitivity | Lateral                  | Omni         | Longitudinal | Longitudinal | Longitudinal | Uniform in FOV of Camera Lens | Longitudinal |
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