Bringing intelligent autonomy to fine motion detection and people counting with TI mmWave sensors

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Architects and urban planners of smart buildings, factories and cities need increasingly intelligent sensors to address the challenges of resource conservation, alleviate growing safety concerns with increased security, and provide more seamless human-machine interaction.

Specifically, detecting the position and tracking the movement of people will enable the autonomous operation of systems in tomorrow's smarter world. As shown in **Figure 1**, these systems can include indoor/outdoor security and surveillance; automated doors; factory safety scanners for machinery; and automation equipment for control of lighting, heating, ventilation and air conditioning (HVAC) and elevators.

Millimeter wave (mmWave) is a sensing solution that is set to revolutionize the detection, localization and tracking of people in these systems. TI's mmWave sensors are unique in that they can sense the range, velocity and angle of objects regardless of environment while providing on-chip processing for high-level algorithms. These features serve occupancy and movement sensors in building, factory and city automation by reducing false detection, providing high accuracy for location and direction of travel, and maintaining privacy, all in a single chip for at-the-edge processing.

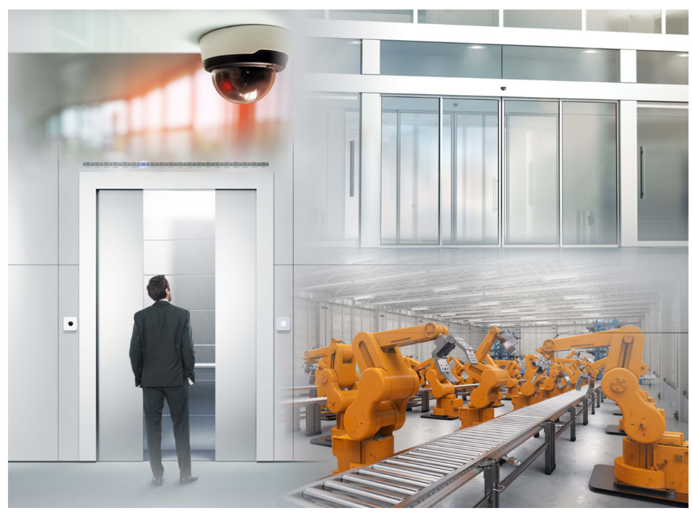


Figure 1*. TI mmWave sensors enable intelligent sensing across a variety of building and factory applications such as indoor/outdoor security, automated doors, factory automation and automated control of lighting and elevators.*

Today's technology

Today's sensors for occupancy and people tracking use technologies such as passive infrared (PIR), optical cameras, active infrared such as LIDAR and 3-D time of flight (ToF), and 10 GHz-to-24 GHz microwave. **Table 1** compares these technologies and lists their pros and cons. However, with rising expectations for security, safety and efficiency, the next generation of sensors must deliver both accurate and reliable sensing while overcoming common sensing challenges. Let's consider the challenges of sensors designed to detect people and measure occupancy.

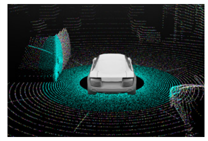
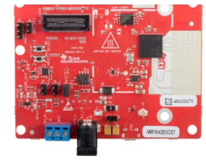
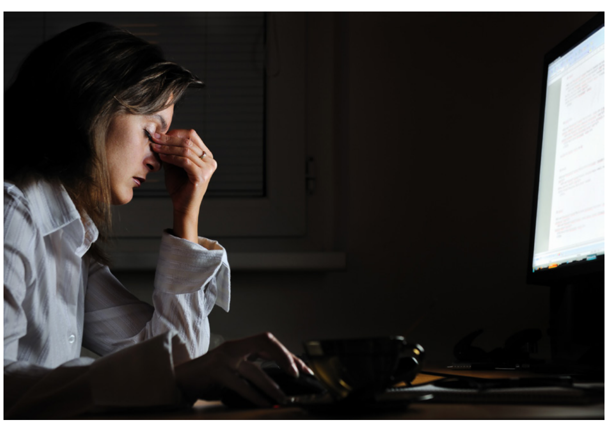
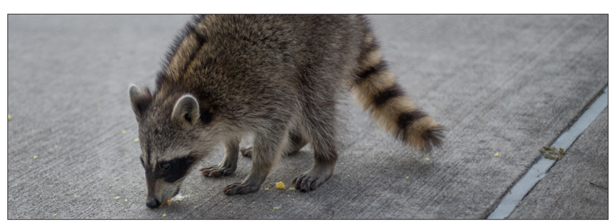
	Passive infrared (PIR)	Optical cameras	Active infrared (LIDAR, ToF)	Microwave (10 GHz or 24 GHz)	TI mmWave
					
Description	Measures changes in infrared light in order to detect motion	Analyzes imagery to determine people movement and behavior	Measures infrared light ToF	Discrete components assembled to create a radar for motion detection	TI single-chip radar sensor provides range, velocity and angle information about objects
Pros	✓ Simple, low-power consumption	✓ Algorithms applied for variety of applications ✓ Video for recording and monitoring	✓ High angular resolution provides a rich data set, similar to cameras	✓ High sensitivity to motion (breathing, typing) ✓ Extended range (+50 m) ✓ Insensitive to weather, changing environments	✓ High sensitivity to motion (breathing, typing) ✓ On-chip processing for single-chip tracking, classification ✓ Extended range (+50 m) ✓ Insensitive to weather, changing environments
Cons	✗ Low sensitivity to fine motion ✗ False detection outdoors from sunlight, temperature ✗ Limited range, no position or distance information	✗ False detection from shadows, occlusion, day/night, environment ✗ Complex software and processing requirements ✗ No position/range information ✗ Privacy considerations	✗ Limited range in the presence of sunlight (5-10m) ✗ Complex software and processing requirements	✗ Hardware and software design and integration complexity ✗ No position information ✗ Large form factor	✗ Lower angular resolution than cameras or active infrared

***Table 1**. Existing technologies in building automation, including their pros and cons.*



(a)

(b)



(c)

***Figure 2**. False detection examples: PIR sensors used in typical commercial office spaces are prone to false negative detection (a); false detection on direction of motion causes automatic doors to open unnecessarily and waste resources (b); animals can cause false detection when sensors are only sensitive to motion (c).*

False detection

One of the largest challenges facing sensors today is false detection, seen in **Figure 2**. This is the response or failure to respond – whether though an alarm, system trigger, etc. – upon the occurrence of a sensing event. False detection can take two distinct forms, either a false positive or a false negative, and occurs because of particular sensing failures or sensitivities of a technology.

False negatives are the failure of a sensing system to respond to an event that would be considered important. False positives occur when a sensing system responds to an event that would not be considered important. Depending on the greater system to which it's tied, a sensor false positive can have a result that's as harmless as a light turning on, or perhaps more seriously, a result that requires a security guard to investigate.

False negatives – sensitivity to motion

Have you ever been working late night at your desk in an office, only to have the lights shut off on you because you were not moving enough for the lighting sensors to register your presence? This example of a false negative is common with PIR sensors because of their poor sensitivity to fine motion. People are generally stationary indoors except for their finer motions, such as typing on a computer, adjusting their position on a couch or just breathing. For accurate occupancy sensing, being sensitive to these types of very fine motions is mandatory.

False positives – environment

One common cause of false positives is the environment, where ambient conditions such as lighting, precipitation, temperature, humidity or airflow can cause the inadvertent trigger of a sensor. An example of this is a camera or PIR sensor placed outdoors, where direct sunlight or precipitation can "blind" the sensor and cause it to register a motion event that isn't there.

False positives – direction of motion

Another example of a false positive comes from not being able to accurately detect the direction of a person in motion. Consider an automatic door. How many times have you just walked past an automatic door at a convenience store or warehouse only to have it open? This wastes energy by running the motor of the door and letting air-conditioned air out. Being able to infer the direction a person is intending to go, rather than responding based just on their proximity will be critical to improving the efficiency of tomorrow's sensing systems.

False positives – accurate location

Detection based on location can also be a false positive. Consider an optical camera system used for surveillance and motion detection inside a secure perimeter. An example of a false positive would be the camera alerting a security guard to movement outside the secure perimeter, not just inside it. Being able to accurately determine the position of a moving object can be critical to understanding if the moving object is inside or outside an area of concern.

False positives – detection of non-humans

For most intelligent automation systems, the principal concern is the detection and localization of people, not other objects. Unfortunately, moving objects such as swaying trees, scurrying animals or passing vehicles can trick motion detection systems into believing there is a person present. In order to overcome this problem, a sensor should be able to filter or classify objects based on their size and movement characteristics.

Privacy

With automation systems increasingly moving toward high levels of connectivity and intelligence, implementing sensors in public and private spaces will alert the public to the potential recognition of personal identity. Having a sensor that can provide meaningful data while still maintaining anonymity will be an important advantage.

Solution complexity

Solution complexity can be an incredible barrier to entry for a sensing technology in building automation. Ensuring that a solution is simple in terms of hardware and software design can greatly reduce the investment that users must make to bring the technology to market and cover all corner cases that a sensing system must handle.

Having processing and decision-making at the edge also simplifies hardware and software design for building automation systems. With decisions at the sensor edge, users can realize simpler system designs and cost savings by minimizing data transfer, data storage and the need for a centralized system or person to make decisions.

Environmental occlusion

A significant challenge to sensors is that objects in the environment can often occlude line-of-sight vision to objects of interest. Walls, foliage, optically opaque glass and other objects block sensors based on optical technologies and ultimately limit the installation, placement and use of these sensors. Sensors that use radio frequency (RF) and other penetrating technologies have an advantage in that they can see through certain materials, opening up new ways to implement these sensors.

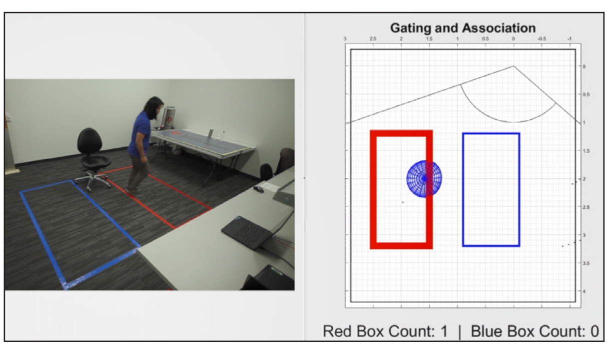


Figure 3. *mmWave range and angle information provides high-accuracy position information. As a person walks into the red "keep-out" zone, the red box is highlighted. This information can be used to trigger building automation systems.*

Introducing mmWave technology

TI's mmWave technology and IWR family of sensing devices have a number of key features that translate into tangible benefits for building automation applications, including the reduction of false detection.

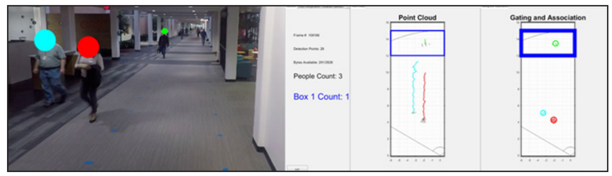


Figure 4. *Velocity information and onboard tracking enables TI mmWave sensors to determine the direction of travel. Note the tracking tail of the blue and red dots, indicating a person's direction down the hallway. This capability can infer where a person is going and if they are moving toward specific areas of interest.*

mmWave is the only sensing technology that can provide three unique sets of data: range, velocity and angle. It is with this data combination that mmWave sensors can accurately determine the location of people as well as their direction of travel. **Figure 3** shows how these data sets could be used to trigger the activation of a system when a person enters a specific region. The velocity data enables mmWave sensors to ignore objects that are not moving in the environment. Since people are always moving – even if just a small amount when they fidget or breathe – mmWave can pick them up.

Figure 4 shows how to use velocity data to infer a person's direction of travel and speed. TI's mmWave sensors are unique in that they embed processing cores onboard the sensor in order to process the range, velocity and angle data in real time. The sensors also implement advanced algorithms to enable capabilities such as tracking the history of a person's movement, triggering systems based on location or direction of travel, or classifying objects based on their size and motion.

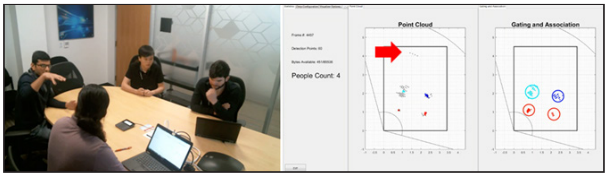


Figure 5. A conference room contains many static objects that can be sources of false detection for conventional sensors. Static clutter removal algorithms onboard TI mmWave sensors ignore static objects like chairs and tables, as well as reflections from the wall (as shown at the red arrow).

Conducting embedded processing onboard the sensor means that TI mmWave sensors can perform all operations on a single chip, with no external processor necessary.

The unique data set and on-chip processing of TI mmWave sensors enables building automation systems to reduce false detection. mmWave sensors can detect very fine motions such as those from when a person is typing, talking or breathing in order to prevent false negatives on occupancy, while ignoring objects that are static. Static objects can also be a source of false detection depending on size and shape; **Figure 5** shows an example of how mmWave can ignore these static objects using an algorithm known as static clutter removal. Moving objects such as fans, curtains, or swaying trees can also be ignored by using methods of classification or filtering as shown in **Figure 6** and **Figure 7**.

mmWave sensors transmit and receive RF signals and are by nature very resilient to environmental effects that can be common sources of false detection. They can sense accurately regardless of ambient lighting, temperature, humidity and airflow and can even continue sensing in the presence of precipitation. This makes them especially strong for indoor or outdoor applications where sensing must be constant across a variety of environmental conditions. In addition, this resilience means that mmWave sensors do not require any complex software to cover environmental corner cases such as shadows or weather.

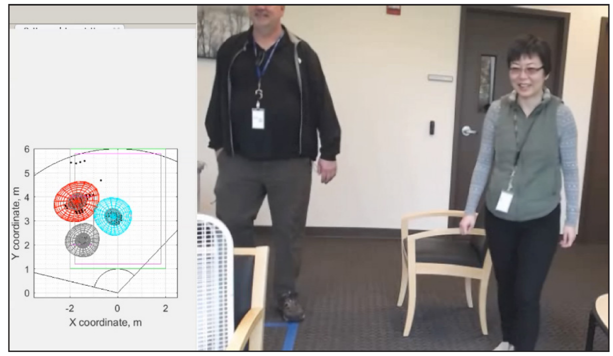


***Figure 6**. An indoor scene with a moving fan and two people. The moving fan would normally be identified as motion by other technologies and cause false detection, but the mmWave sensor recognizes and classifies the motion of the fan as not belonging to a person, and indicates this as a grey track. A person is identified as a colored track for a person.*

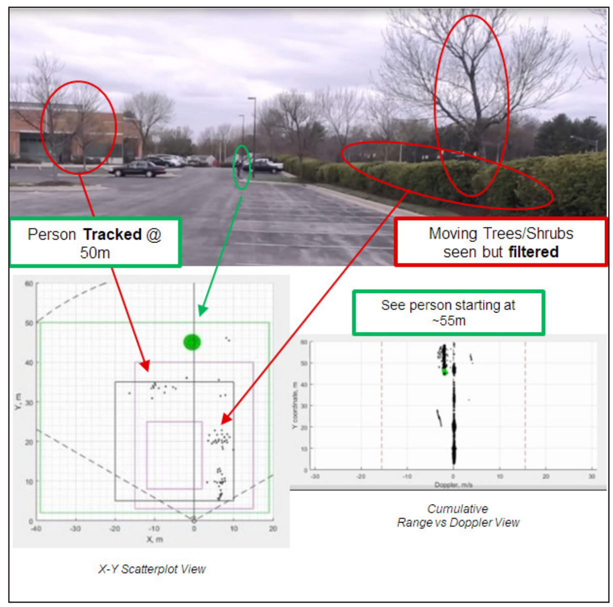


***Figure 7**. An outdoor scene on a windy day with moving clutter such as trees and shrubs. The moving trees would normally be identified as motion by other technologies and cause false detection, but the mmWave sensor recognizes and filters the motion of the clutter as not belonging to a person. The person is indicated by a colored track while the moving trees/shrubs show black points but no colored track.*

In applications where privacy is important – such as in bathrooms, locker rooms or gymnasiums – there may be sensitivities over the use of cameras and other optical-based solutions. In contrast, an mmWave sensor's use of RF signals means that the sensors do not provide any personally-identifiable information.

The sensor signals can transmit through different types of materials such as drywall, plywood and plastic, enabling unique installation options that can be hidden behind walls and other objects to avert system damage or maintain a clean industrial design.

mmWave for motion detection and people counting

The People Counting and Tracking Reference Design Using mmWave Radar Sensor shows the use of TI's mmWave sensors for indoor and outdoor people-counting applications. This reference design uses the IWR6843 device, which includes both RF/analog and digital processing cores to run onboard algorithms enabling a single-chip people-counting system that can detect and track people up to 14 m away.

The reference design includes both hardware and software components; **Table 2** summarizes its features. The hardware component leverages the IWR6843 evaluation module (EVM) in order to achieve an antenna-dependent field of view of 120 degrees horizontally and 30 degrees vertically.

From a software perspective, the reference design includes two base configurations that support operation at 6 m and 14 m, as well as dedicated algorithms that can remove the effect of static objects and track the movement history of multiple people. The capability of the IWR6843 to run onboard algorithms is an important means by which mmWave sensors bring tangible benefit to building automation applications. The reference design implements two key algorithms:

- The static clutter removal algorithm is used to ignore objects that are not moving in a scene. This algorithm analyzes velocity (Doppler) information from the mmWave sensor to filter out objects that are considered part of the static background, such as walls and furniture. Since humans are moving objects, this algorithm allows higher-level applications and algorithms to easily ignore non-human static objects in order to help reduce false detection.

	Short-range configuration		Medium-range configuration
Hardware/EVM	IWR6843 ISK EVM		
Field of view (antenna-dependent)	120 degrees horizontal, 30 degrees vertical		
Maximum range	6 m		14 m
Range resolution	4.8 cm		12 cm
Maximum velocity	5.17 mps		5.25 mps
Velocity resolution	0.082 mps		0.082 mps
Algorithms used	Static clutter removal, group tracking		
System power	~2 W		
Performance metrics			
Location accuracy	Person location within <16 cm		
Counting density	3 persons per square meter		
Demonstrated accuracy (% frames with accurate person count)	**± 0 persons**	**± 1 persons**	**± 2 persons**
3 people in scene	>95% of frames	100% of frames	100% of frames
5 people in scene	>51% of frames	>85% of frames	100% of frames
7 people in scene	>59% of frames	>85% of frames	>98% of frames
9 people in scene	>14% of frames	>43% of frames	>84% of frames

***Table 2**. Performance specifications of the people-counting reference design (TIDEP-01000).*

- The group tracking algorithm is used to separate and track multiple objects simultaneously. This algorithm monitors the history of the point cloud over time in order to measure the size of moving objects in the scene, pinpoint the location of these objects, and track the movement and location history of the object over time. This enables higher-level applications to determine the exact location and direction of travel of a person moving in the environment.

These algorithms are implemented in an example processing chain running in software on the IWR6843. **Figure 8** illustrates this processing chain, which is implemented in both digital signal processing (DSP) code running on the onboard C674x DSP as well as on the Arm® Cortex-R4F microcontroller. This processing chain implementation and aforementioned algorithms include tunable parameters that enable the software to be adjusted to accommodate different applications and parameters. Users can tweak multiple settings in order to get closer to the desired level of performance in different environments.

TI tested the reference design in different environments, including a conference room, hallway, open office area and elevator to show that performance could be maintained with different tunings. These tunings are provided as examples in the chirp database, located on the mmWave industrial toolbox in TI Resource Explorer.

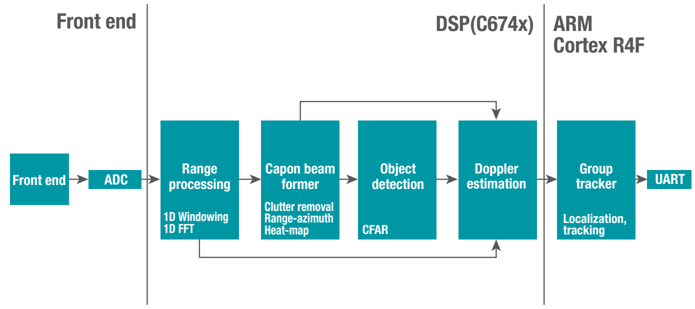


***Figure 8**. Block diagram showing the processing chain implemented in software on the IWR6843, as provided in the people-counting reference design.*

TI Resource Explorer also provides examples that extend the people counting reference design to demonstrate different false detection mitigation techniques using the IWR6843. One example uses classification to recognize moving indoor clutter like fans, blinds, and curtains and is shown in **Figure 6**.

Another example extends the reference design to 50m for outdoor intrusion detection and uses the filtering properties of the group tracking algorithm to remove the signatures of moving trees and bushes and is shown in **Figure 7**. TI Resource Explorer also documents experiments that show the reference design performing under more unusual environmental constraints. We verified performance in a foggy environment, which showed that mmWave sensors could detect and locate people even in a scenario where fog or smoke may be present. We also verified performance when the sensor was hidden behind different materials such as Plexiglas, plywood and layers of drywall, showing that mmWave works in system installations where the sensor may need to be hidden behind objects out of concern for vandalism, environmental protection or privacy.

Conclusion

TI's mmWave sensors are innovating building automation applications by providing a robust, high-accuracy, RF-based sensing medium with an unprecedented data set of range, velocity and angle and powerful on-chip processing. mmWave sensors bring additional value by seeing in challenging environments, such as bright sunlight, darkness, through walls and in rain. These features make mmWave the obvious choice for sensing and help to combat today's challenges of false detection, privacy and solution complexity in order to enable the next generation of building automation sensors with intelligence and at-the-edge decision-making.

The people-counting reference design includes open hardware design files and full software provided as source. TI tested this reference design in a number of different environments to show its ability to be scaled and adjusted for different performance conditions and needs.