# TI Designs: TIDEP-01003
# Zone Occupancy Detection Reference Design Using mmWave Sensor

## Description

The TIDEP-01003 shows how TI's single-chip millimeter-wave (mmWave) technology can be used for zone occupancy detection. Sensing the movement of personnel or objects into a zone of interest can be used for area scanners and parking spot monitoring. The zone occupancy detection system can monitor areas of interest across a field of view of ±60 degrees with a maximum range of 10 m. This reference design uses the IWR1443BOOST evaluation module (EVM), and integrates a complete radar processing chain onto the IW443 device. The processing chain includes the analog radar configuration, analog-to-digital converter (ADC) capture, low-level FFT, and signal processing. This reference design is intended to be built on top of the TI mmWave SDK for a cohesive software experience, including APIs, libraries, and tools for evaluation, development, and data visualization.

## Resources

| | |
|---|---|
| TIDEP-01003 | Design Folder |
| IWR1443 | Product Folder |
| IWR1443BOOST | Tool Folder |
| mmWave SDK | Tool Folder |

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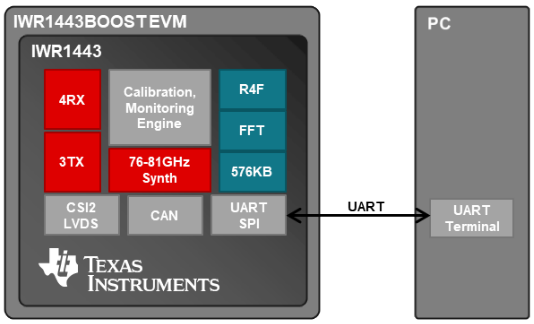
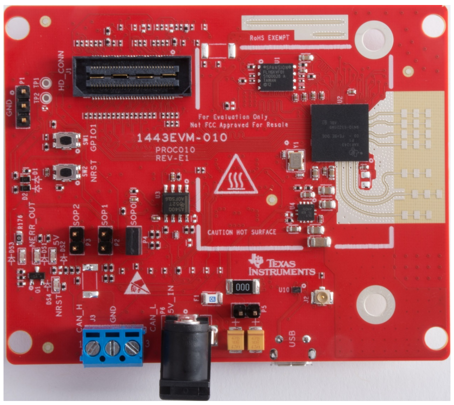
## Features

- Demonstrates environmentally robust zone occupancy detection using TI's single-chip mmWave sensor
- Detects intrusion of an object or person into an area of interest with a field of view up to 120° and range of 0 m to 10 m
- References the processing chain source code provided, based on the mmWave software development kit (SDK)
- Based on proven EVM hardware designs, enabling quick time to market and out-of-the-box demonstrations

## Applications

- Area Scanner Safety Guard
- Proximity Sensor
- Light Curtain Safety Guard
- Radar for Transport



# 1 System Description

The TIDEP-01003 provides a reference for creating a zone occupancy detection application using TI's IWR1443, based on 77-GHz mmWave radio-frequency complementary metal-oxide semiconductor (RF-CMOS) technology. Frequency-modulated continuous-wave (FMCW) radars enable accurate measurement of distances and relative velocities. Thus, radars are useful for detection of occupancy and whether an object or person has entered a space of interest.

In area scanner or light curtain safety-guard applications, where it is important to have precisely defined "keep-out" zones, the ability of radar to accurately localize detected objects can be used to implement multiple detection zones and trigger corresponding responses. A single radar deployed to equipment with a critical "keep-out" perimeter could implement a multi-stage response, so that when an object or person first approaches the perimeter, a moderate warning flag is raised. Then, if the perimeter is breached, a critical response is triggered.

Similarly, in parking spot occupancy applications, a mmWave radar device can monitor multiple parking spots. With each parking spot comprising a zone, the zone occupancy detection system can detect whether or not a spot is occupied by a vehicle.

An important advantage of radars over camera and light-detection-and-ranging (LIDAR)-based systems is that radars are relatively immune to environmental conditions such as rain, dust, and smoke. Because FMCW radars transmit a specific signal (called a chirp) and process the reflections, they can work in both complete darkness and bright daylight (radars are not affected by glare). When compared with ultrasound, radars typically have a much longer range and faster transit time for their signals.

**Table 1. Key System Specifications**

| PARAMETER | SPECIFICATIONS | DETAILS |
|---|---|---|
| Field of view (FOV) | 120° azimuth, 30° elevation | The field of view of the sensor is determined by the antenna design of the IWR1443BOOST EVM. The design used in the IWR1443BOOST enables a wide FOV with elevation information for 3D point cloud information. |
| Frame rate | 5 Hz | This parameter defines the data output and visualizer update rate. |
| Maximum range | 10 m | The maximum range is defined by the radar chirp characteristics, and can be configured to suit application requirements. The maximum range defined for this reference design is with respect to the dimensions of the testing site. |
| Range resolution | 4.7 cm | Range resolution is the ability of a radar system to distinguish between two or more targets on the same bearing but at different ranges. |
| Maximum velocity | 2.05 m/s | This is the native maximum velocity obtained using a two-dimensional FFT on the frame data. |
| Velocity resolution | 0.26 m/s | This parameter represents the capability of the radar sensor to distinguish between two or more objects at the same range that are moving with different velocities. |

# 2 System Overview

## 2.1 Block Diagram

The TIDEP-01003 is implemented on the IWR1443BOOST EVM. The EVM is connected to a host PC through universal asynchronous receiver-transmitter (UART) for visualization.

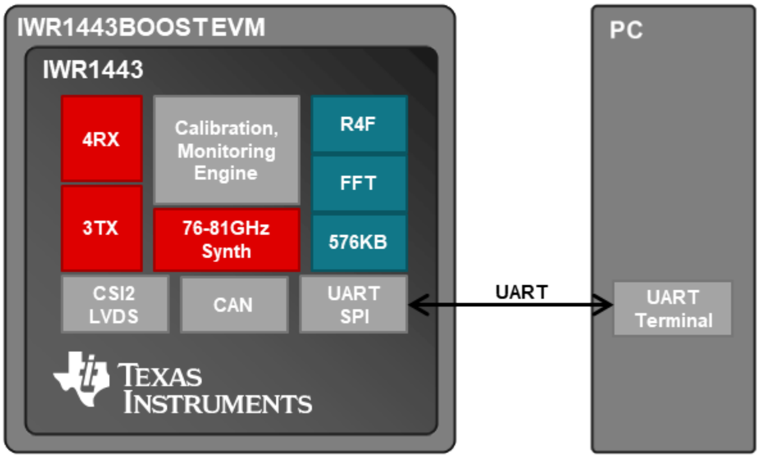



**Figure 1. Zone Occupancy Detection System Block Diagram**

## 2.2 Highlighted Products

### 2.2.1 IWR1443

The IWR1443 is a highly-integrated, single-chip radar device for industrial applications in TI's 45-nm, low-power RFCMOS technology, which is a FCBGA, 0.65-mm pitch package.

The radar subsystem (BSS) is responsible for the RF and analog functionality of the device. The subsystem incorporates a built-in self-test (BIST) processor for the continuous motoring and calibration of the analog and RF modules.

The master subsystem (MSS) contains a user-programmable ARM core, user-accessible memories, and peripherals for the configuration and control of the entire device. The MSS communicates with the BSS through the mmWave link API and the mailbox peripheral.

## 2.3 System Design Theory

### 2.3.1 Operation

The IWR1443 is loaded with a flashed image that, when booted and initialized, receives a chirp configuration specified using the zone occupancy visualizer. In the zone occupancy visualizer, the location and dimension of the zones to monitor are set as well as other visualization properties. Then, using the visualizer, the chirp configuration is loaded and sent to the sensor to start monitoring the area of interest for zone occupancy.

The strongest reflections reported by the radar device are reported as detected objects to the host PC through the UART. The detected objects collectively form a point cloud representation of the scene as seen by the sensor. If an object generates a point cloud of at least 3 points within a zone, the zone is considered occupied and the visualizer updates to highlight the occupied zone.

### 2.3.2 Use Case Considerations

This reference design is intended to demonstrate the detection of people or objects moving into a zone for an indoor environment. Given this use case, the system implements static clutter removal so that other permanent fixtures in the scene, such as walls, do not trigger a zone occupancy detection. The use case drove the design of the chirp configuration in Table 2 with primary considerations being achieving high range resolution and sufficient maximum velocity for human movement, including walking.

**Table 2. Chirp Configuration**

| KEY INPUT PARAMETERS | |
|---|---|
| PERFORMANCE PARAMETERS | |
| Antenna pattern | Two Tx, four Rx in azimuth plane |
| Maximum range | 10.125 m |
| Range resolution | 4.7 cm |
| Maximum velocity | 2.05 m/s |
| Velocity resolution | 0.26 m/s |
| Frame duration | 200 ms |
| ADC sampling rate | 7.5 MSPS |
| DERIVED CHIRP DESIGN PARAMETERS | |
| Chirp valid sweep bandwidth | 3.2 GHz |
| Chirp repetition time | 129.7 µs |
| Number of samples per chirp | 240 |
| Nfft_range | 256 |
| Number of chirps per frame | 48 |
| Nfft_doppler | 16 |

# 3 Hardware, Software, Testing Requirements, and Test Results

## 3.1 Required Hardware and Software

### 3.1.1 Hardware

The following hardware is required to get the demonstration running:

- IWR1443 EVM
- A 5-V, 2.5-A power supply for the IWR1443 EVM
- A PC for Code Composer Studio™ (CCS) and the demonstration UART terminal

### 3.1.2 Software

For this reference design, software is provided for the IWR1443 device and the host PC.

The software required for the target IWR1443:

- Latest mmWave SDK. The SDK automatically installs the required component versions. These components are listed in the SDK's release notes in the /docs folder of the software package. Install the SDK and all required components before installing and building the demonstration source.
- Code Composer Studio (CCS). See the SDK release notes for the required version.
- Latest mmWave Industrial Toolbox. Using CCS, access and install the mmWave Industrial Toolbox through the Resource Explorer. The Industrial Toolbox contains a quick start guide with precompiled binaries for the device, the source code, and a detailed user's guide to run the demo as presented in this reference design. When installed, the material specific to the zone occupancy detection system is located at [mmWave Industrial Toolbox install directory]/labs/lab0016_zone_occ_14xx.

The software required for the host PC:

- Latest mmWave Industrial Toolbox. The zone occupancy detection visualizer is packaged in the Industrial Toolbox. The /gui folder includes the compiled executable and source code for the visualizer.

The application software used in this reference design is from the mmWave SDK version 1.02.00.05 and mmWave Industrial Toolbox version 2.5.0. TI recommends getting the latest version of the demo software from the mmWave Industrial Toolbox.

## 3.2 Testing and Results

### 3.2.1 Test Setup

To characterize and demonstrate the capabilities of the zone occupancy detection system, the IWR1443Boost EVM was set up in a conference room as depicted in Figure 2.

The setup conditions were as follows:

- EVM positioning: The EVM was mounted at a height of 1.5 m above the ground. The EVM was oriented vertically with the antenna facing straight ahead to survey the area of interest.
- Ground truth reference: Marker cones were placed on the ground to define a ground truth reference grid. The grid was defined by range and angle from 0 m to 11 m and 0 to 180 degrees (where possible and not limited by room dimensions). Each grid of zone sectors had a height of 1 m and spanned a 30 degree angle.

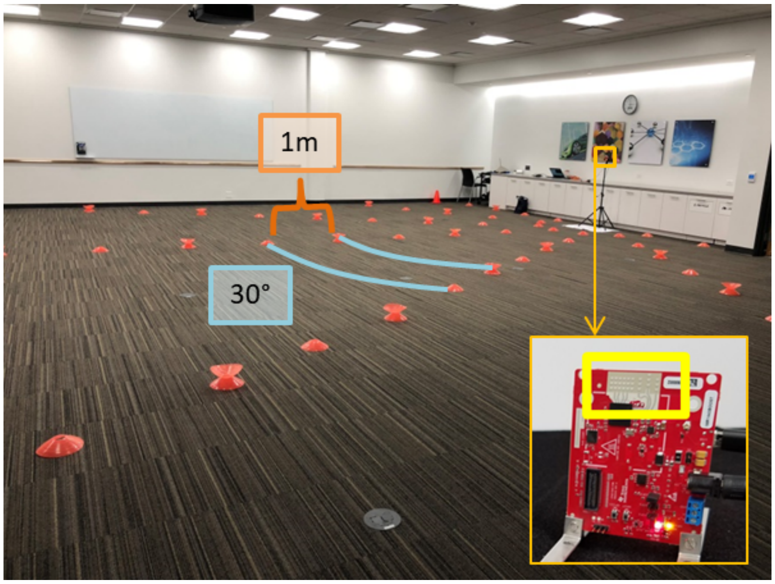



**Figure 2. Zone Occupancy Detection Testing Environment and Configuration**

The areas of zone detection were characterized for two test cases:

- Human walking in an arc from 0 to 180 degrees at a constant range.
- Human walking in a straight line at a constant angle

Figure 3 and Figure 4 illustrate the paths the person walked for the arc test and straight line tests. For each path indicated by a red line, the person walked the path once and then back, effectively traversing the path twice. The black dotted lines indicate the walls of the room that limited the range of the testing. For each path walked, the output of the zone occupancy system was recorded and the cumulative point cloud results were saved.

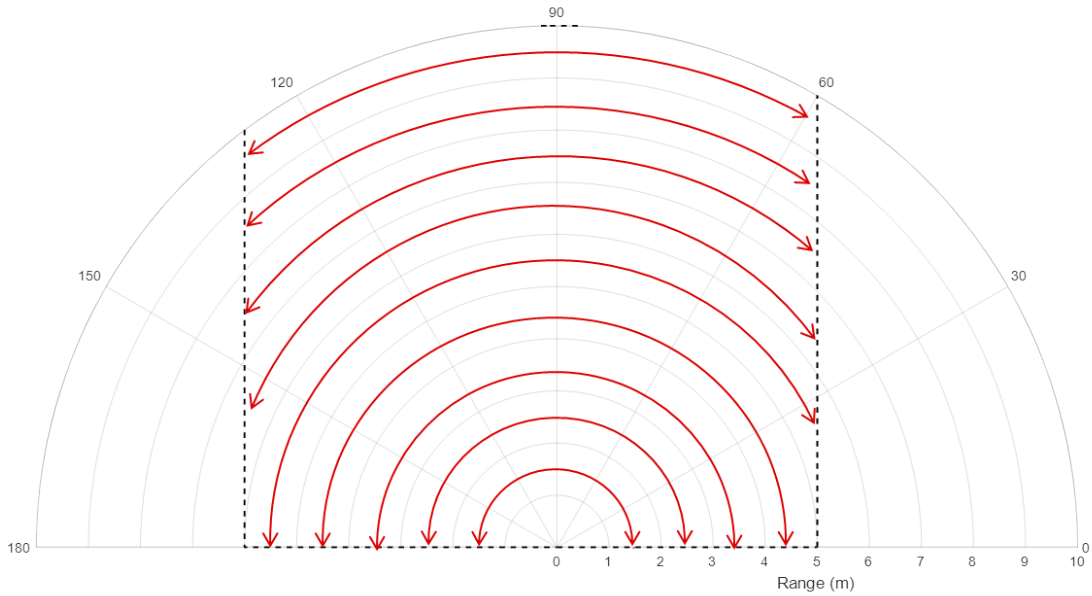



**Figure 3. Human Walking Paths in an Arc Test Case**

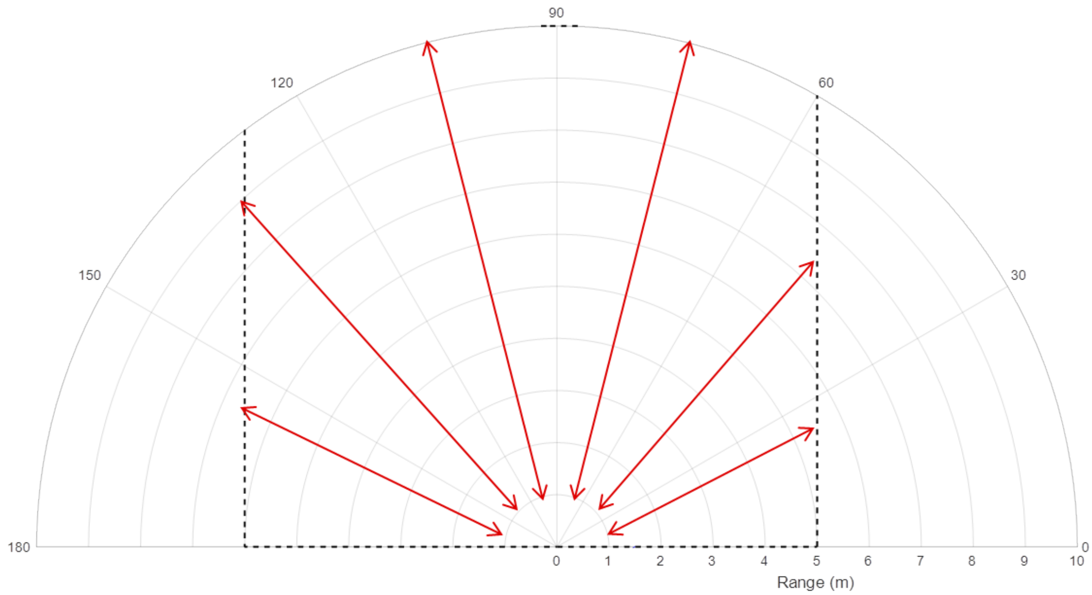



**Figure 4. Human Walking Paths in a Straight Line Test Case**

### 3.2.2 Test Results

#### *3.2.2.1 Test Case: Human Walking in an Arc From 0 to 180 Degrees at a Constant Range*

The zone occupancy detection system implements an occupancy detection rule that requires at least 3 simultaneously detected points for a zone sector to be considered occupied. As described above, the arc walking test case had 9 test paths; for each one, the output of the zone occupancy detection system was captured during each path walk.

Figure 5 shows a series of snapshots from one of the arc test paths and illustrates how the zone occupancy detection system responded. In the top left and bottom right panels, the human has walked outside the sensor's field of view (0-30° and 150-180°), resulting in no detections. From the 2nd to 5th panel, the person is walking through the angles 30-60°, 60-90°, 90-120°, and then 120-150°. In these zones within the sensor field of view, the person walking generated a detectable point cloud, which triggered the zone occupancy system to highlight the grid sector to illustrate occupancy.

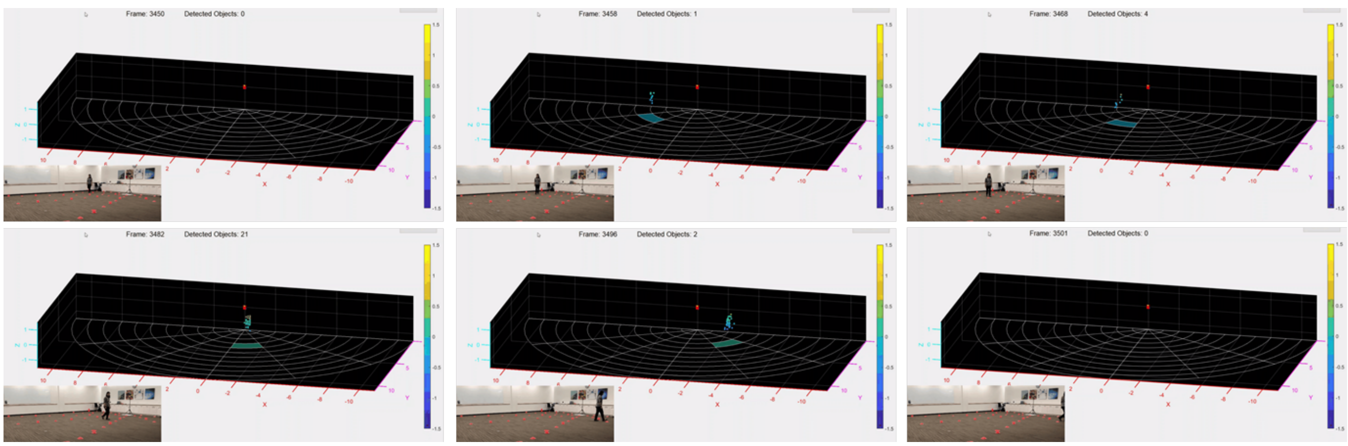


**Figure 5. Snapshots of Arc Test: Walking From 0-180° at 3 to 4m Range**

The results of the arc walking test case are compiled and represented in Figure 6. The figure was generated by plotting the saved point cloud data from each test path together onto the single plot. Each color represents a different test path. Each circle is a point in the cumulative point cloud for the path walked. For example, the dark purple circles represent the total recording of the point cloud as the person walked in an arc from 180 degrees to 0 degrees and then back to 180 degrees at a distance of 1 to 2 m from the radar.

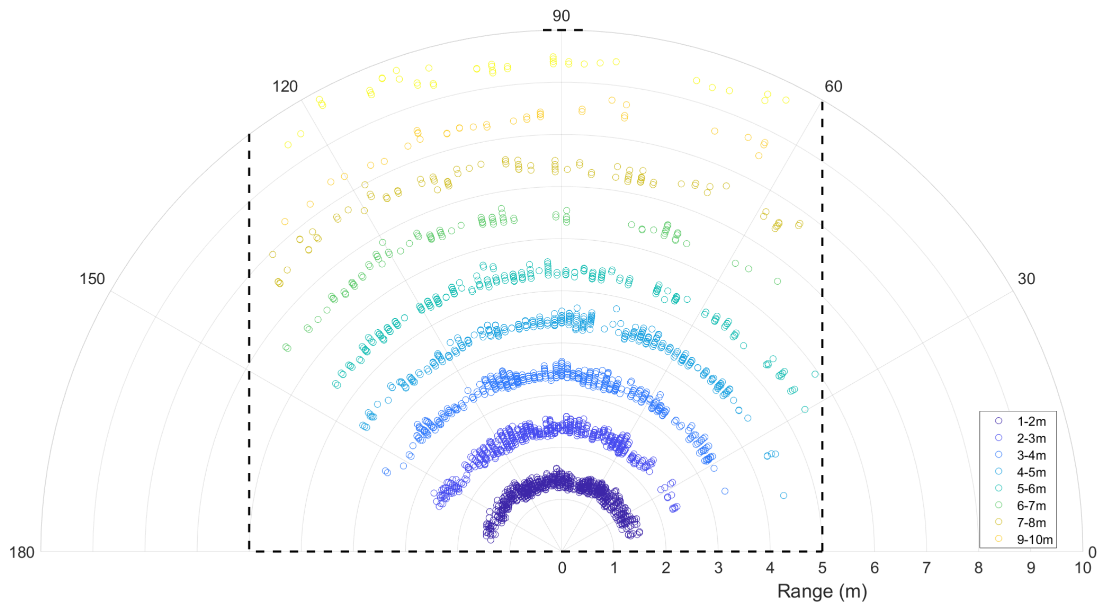



**Figure 6. Cumulative Point Cloud Results From Human Walking in an Arc Test Case**

Table 3 summarizes the ability of the zone occupancy detection system to detect a person walking the arc paths described in Figure 3. In some cases, such as 0-30 degrees at 3 to 4 m, the cumulative point cloud plot shows detections in that sector but the table denotes that the zone occupancy detection system was not triggered. At these angle and range combinations, the person did not generate at least 3 points in a single frame as the person walked across the zone sector.

**Table 3. Zone Occupancy Detection Summary for Arc Test**

| | | Angle (°) | | | | | |
|---|---|---|---|---|---|---|---|
| | | 0-30 | 30-60 | 60-90 | 90-120 | 120-150 | 150-180 |
| Range (m)(1) | 1-2 | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| | 2-3 | X | ✓ | ✓ | ✓ | ✓ | ✓ |
| | 3-4 | X | ✓ | ✓ | ✓ | ✓ | X |
| | 5-6 | X | ✓ | ✓ | ✓ | ✓ | X |
| | 6-7 | - | ✓ | ✓ | ✓ | ✓ | X |
| | 7-8 | - | ✓ | ✓ | ✓ | ✓ | - |
| | 8-9 | - | X | ✓ | ✓ | X | - |
| | 9-10 | - | X | ✓ | ✓ | X | - |

(1) Legend: ✓ = Zone occupancy detection triggered, X = No detection triggered, - = Wall obstruction, not testable

#### *3.2.2.2 Test Case: Human Walking in a Straight Line at a Constant Angle*

Figure 7 shows a series of snapshots from one of the straight line test paths, and illustrates how the zone occupancy detection system responded. In the top left, the human starts walking at 1 to 2 m, and as the snapshots progress, ends at 9 to 10 m. In these zones, the person walking generated a detectable point cloud, which triggered the zone occupancy system and highlighted the zone sector to illustrate occupancy.

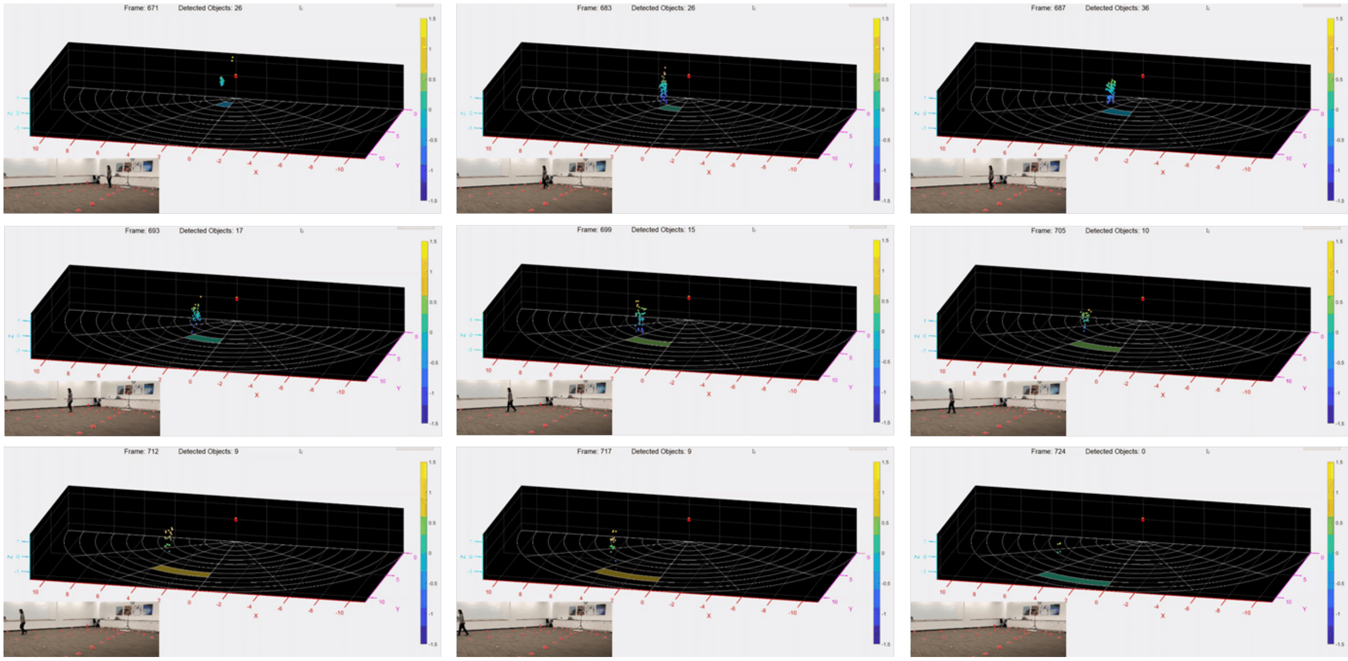


**Figure 7. Snapshots of Straight Line Test: Walking From 1 to 10 m at 60 to 90° Angle**

The compiled results of the straight line walking test case are depicted in Figure 8. Each color represents a different test path, and each circle is a point in the cumulative point cloud for the path walked. For example, the green circles represent the total recording of the point cloud as the person walked a line from 1 m to 10 m and back to 1 m at a constant angle within 90 to 120 degrees.

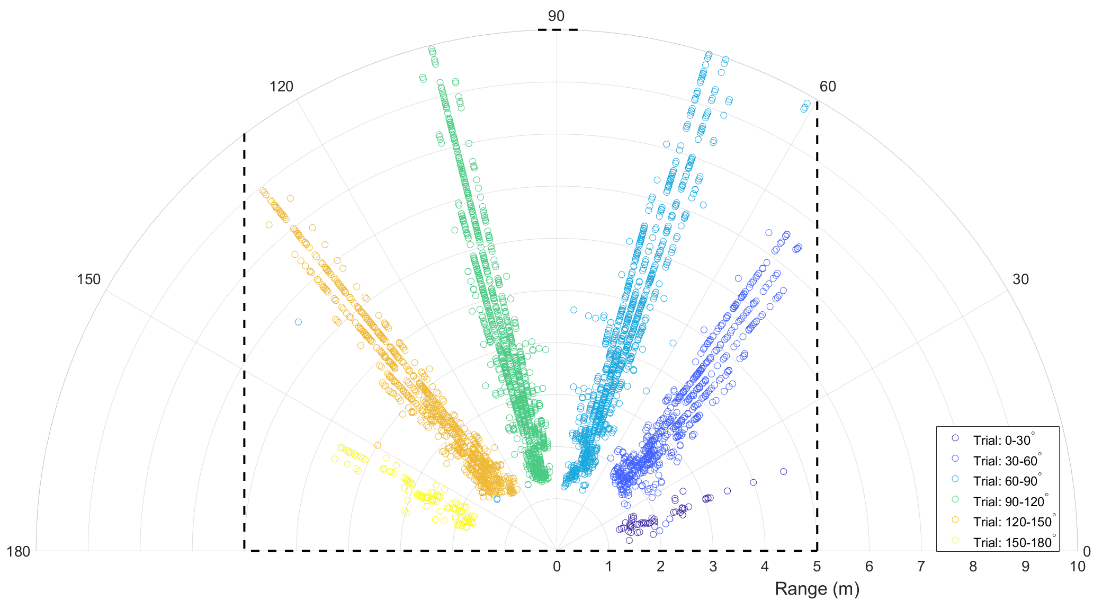



**Figure 8. Cumulative Point Cloud Results From Human Walking in a Straight Line Test Case**

Table 4 summarizes the zone occupancy detection system capabilities for detecting a person walking the straight line paths described by Figure 4.

**Table 4. Zone Occupancy Detection Summary for Straight Line Test**

| | | Range (m) | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | 1-2 | 2-3 | 3-4 | 4-5 | 5-6 | 6-7 | 7-8 | 8-9 | 9-10 |
| Angle (°)[1] | 0-30 | ✓ | ✓ | X | X | X | - | - | - | - |
| | 30-60 | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | X | - |
| | 60-90 | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| | 90-120 | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| | 120-150 | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | X |
| | 150-180 | ✓ | ✓ | X | X | X | X | - | - | - |

(1) Legend: ✓ = Zone occupancy detection triggered, X = No detection triggered, - = Wall obstruction, not testable

### 3.2.3 Observations and Conclusions From Test Results

The results of the arc and straight line walking test cases demonstrate the capabilities of the zone occupancy detection system. Using the IWR1443Boost EVM, the system demonstrated the ability to detect the zone a human was walking in for a range up to 10 m and over a 120° field of view. Furthermore, with three transmitters on the IWR1443, elevation information is enabled and 3D point clouds are generated. As shown in Figure 7 when the person is closer to the sensor, a rich and dense point cloud with elevation information representative of the sensed object's height is generated.

The zone occupancy detection system supports the configuration and customization for specific use cases. The size of the grids that define each zone are fully configurable by range and angle bin size. The detection range can be extended or reduced by designing and loading a different chirp configuration. The mmWave Sensing Estimator tool can be used to design a chirp configuration based on an application's sensing requirements.

# 4 Design Files

## 4.1 Schematics

To download the schematics, see the design files at http://www.ti.com/tool/TIDEP-01003.

## 4.2 Bill of Materials

To download the bill of materials (BOM), see the design files at http://www.ti.com/tool/TIDEP-01003.

## 4.3 Altium Project

To download the Altium Designer® project files, see the design files at http://www.ti.com/tool/TIDEP-01003.

## 4.4 Gerber Files

To download the Gerber files, see the design files at http://www.ti.com/tool/TIDEP-01003.

## 4.5 Assembly Drawings

To download the assembly drawings, see the design files at http://www.ti.com/tool/TIDEP-01003.

# 5 Software Files

To download the software files, see the design files at http://www.ti.com/tool/TIDEP-01003.

# 6 Related Documentation

1. Texas Instruments, *IWR1443 Data Sheet*
2. Texas Instruments, *IWR1443 Evaluation Module (IWR1443BOOST) Singe-Chip mmWave Sensing Solution*, user's guide
3. Texas Instruments, *IWR16xx/14xx Industrial Radar Family*, technical reference manual
4. Texas Instruments, *mmWave SDK*, tools folder

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