mmWave radar sensors in robotics applications

Dennis Barrett
Product marketing manager

Adrian Alvarez
Application engineer co-op

Texas Instruments

Introduction

When you conjure up an image of robots, you might envision massive machine arms with visible coils and wire harnesses along a factory floor, with welding sparks flying. These machines are very different than robots portrayed in popular culture and science fiction, which present a future where robots are ubiquitous assistants in everyday living.

Today, breakthroughs in artificial intelligence technology are driving the advancement of robotics for service robots, unmanned aerial vehicles and autonomous vehicles, with growth rates from $31 billion in 2016 to $237 billion by 2020[1].

As robotic technologies advance, so do complementary sensor technologies. Much like the five senses of a human being, combining different sensing technologies offers the best results when deploying robotic systems into changing and uncontrolled environments. One relatively new technology in robotic sensing is complementary metal-oxide semiconductor (CMOS) millimeter-wave (mmWave) radar sensors.

Sensor technologies in robotics

Sensor technologies in robots include force and torque sensors, touch sensors, 1-D/2-D infrared (IR) range finders, 3-D time-of-flight LIDAR sensors, cameras, inertial measurement units (IMUs), GPS and others. CMOS mmWave radar sensors enable the accurate measurement of not only the distance of objects in their field of view but also the relative velocities of any obstacles. These sensing technologies all have advantages and drawbacks, as shown in **Table 1**.

Sensors	Detection range	Detection angle	Range resolution	Detectable information	Bad weather	Night operation	Detection performance
mmWave 	Long	Narrow and wide	Good	Velocity, range, angle	Good	Yes	Robust and stable
Camera 	Medium	Medium	Medium	Target classification	Poor	No	Complexity to calculate object coordinates
LIDAR 	Long	Narrow and wide	Good	Velocity, range, angle	Poor	No	Poor in bad weather
Ultrasonic 	Short	Wide	Good	Range	Poor	No	Short-range applications

***Table 1**. Sensor technology comparison.*

One important advantage that mmWave sensors have over vision- and LIDAR-based sensors is their immunity to environmental conditions such as rain, dust, smoke, fog or frost. Additionally, mmWave sensors can work in complete darkness or in the glare of direct sunlight. Mounted directly behind enclosure plastics without external lenses, apertures or sensor surfaces, the sensors are extremely rugged and can meet Ingress Protection (IP)69K standards. TI's mmWave sensors are also small, lightweight and produce designs that are three times smaller and half the weight of miniature LIDAR range finders[2].

Detecting glass walls

Figure 1 illustrates the use of glass walls and partitions in modern architecture and service robots that vacuum or mop floors, for example, need to sense these surfaces to prevent collisions. These elements have proved difficult to detect using camera- or IR-based sensors. But mmWave sensors can detect the presence of glass walls as well as materials behind them.

Figure 1. Modern architecture makes extensive use of glass surfaces.

To demonstrate this capability, we set up a simple experiment using the Texas Instruments (TI) IWR1443BOOST mmWave sensor evaluation module (EVM) with a pane of glass positioned 80 cm away. We then placed a wall panel behind the glass at a distance of 140 cm, as shown in **Figure 2**.

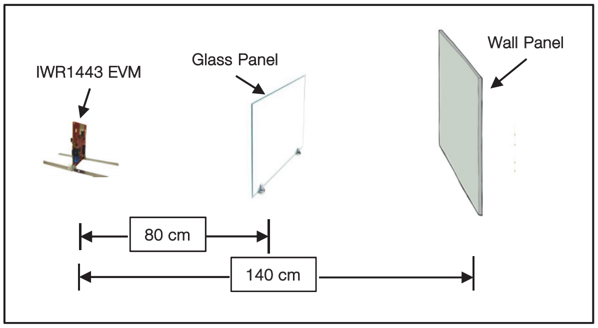

Figure 2. Test setup for detecting glass walls.

Using the demo software and visualization tools included with the EVM in the mmWave Demo Visualizer, the results shown in **Figure 3** clearly demonstrate the mmWave sensor detecting the glass wall surface, as well as the wall behind the glass.

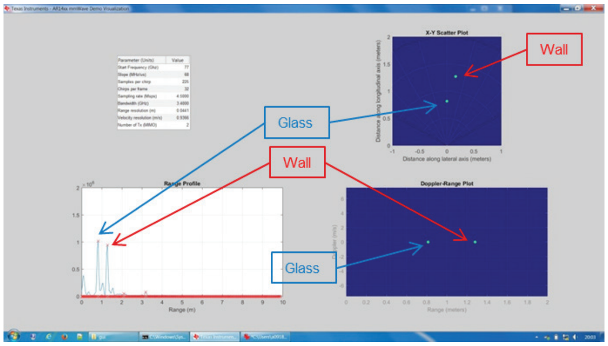

Figure 3. Test results showing detection of glass and wall panel.

Using mmWave sensors to measure ground speed

Accurate odometry information is essential for the autonomous movement of a robot platform. It's possible to derive this information simply by measuring the rotation of wheels or belts on the robot platform. This low-cost approach is easily defeated, however, if the wheels slip on surfaces such as loose gravel, dirt or wet areas.

More advanced systems can assure very accurate odometry through the addition of an IMU that's sometimes augmented with GPS. mmWave sensors can supply additional odometer information for robots that traverse over uneven terrain or have a lot of chassis pitch and yaw by sending chirp signals toward the ground and measuring the Doppler shift of the return signal. **Figure 4** shows the potential configuration of a ground-speed mmWave radar sensor on a robotics platform. Whether to point the radar in front of platform (as shown) or behind the platform (as is standard practice in agriculture vehicles) is an example trade-off. If pointed in front, then you can use the same mmWave sensor to also sense surface edges and avoid an unrecoverable platform loss, such as going off the shipping dock in a warehouse. If pointed behind the platform, you can mount the sensor at the platform's center of gravity in order to minimize the pitch and yaw effect on the measurement, which is a large concern in agriculture applications.

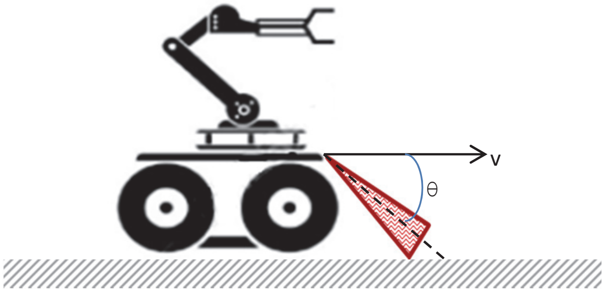

Figure 4. *Ground-speed radar configuration on a robotics platform.*

Equation 1 calculates velocity under uniform ideal conditions:

$$f_d = (2V/\lambda) * \cos\theta \qquad (1)$$

where V is the velocity of the vehicle, λ is the wavelength of the transmitted signal, θ is the antenna depression angle and f_d is the Doppler frequency in hertz.

Expanding Equation 1 enables you to compensate for velocity-measurement errors for variables such as uneven terrain that result in sensor pitch, yaw and roll and introduce a rotational velocity component. These calculations are beyond the scope of this paper, but you can generally find them in literature.[3]

Safety guards around robotic arms

As robots interact more with humans—either in service capacities or in flexible, low-quantity batch-processing automation tasks—it is critical that they do not cause harm to the people with whom they interact, as shown in **Figure 5**.

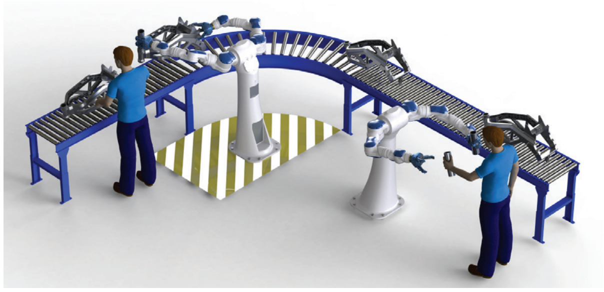

Figure 5. *Robots of the future will be more interactive with humans.*

Historically, the common method is to create a safety curtain or keep-out zone around the robot's field of operation to ensure physical separation, as shown in **Figure 6**.

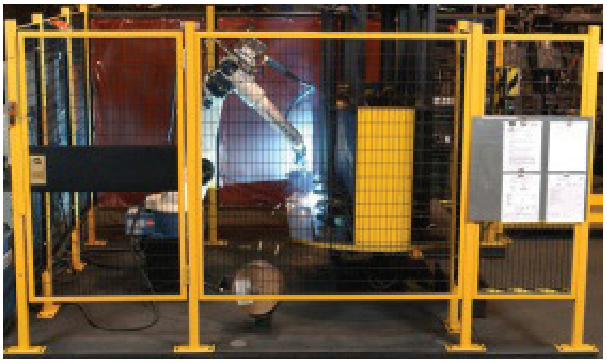

Figure 6. *Robotic arm with a physical safety cage.*

Sensors make it possible for a virtual safety curtain or bubble to separate robotic operation from unplanned human interaction, and also to avoid robot-to-robot collision as density and operation programmability increase. Vision-based safety systems require controlled lighting which increase energy consumption, generate heat and require maintenance. In dusty manufacturing environments

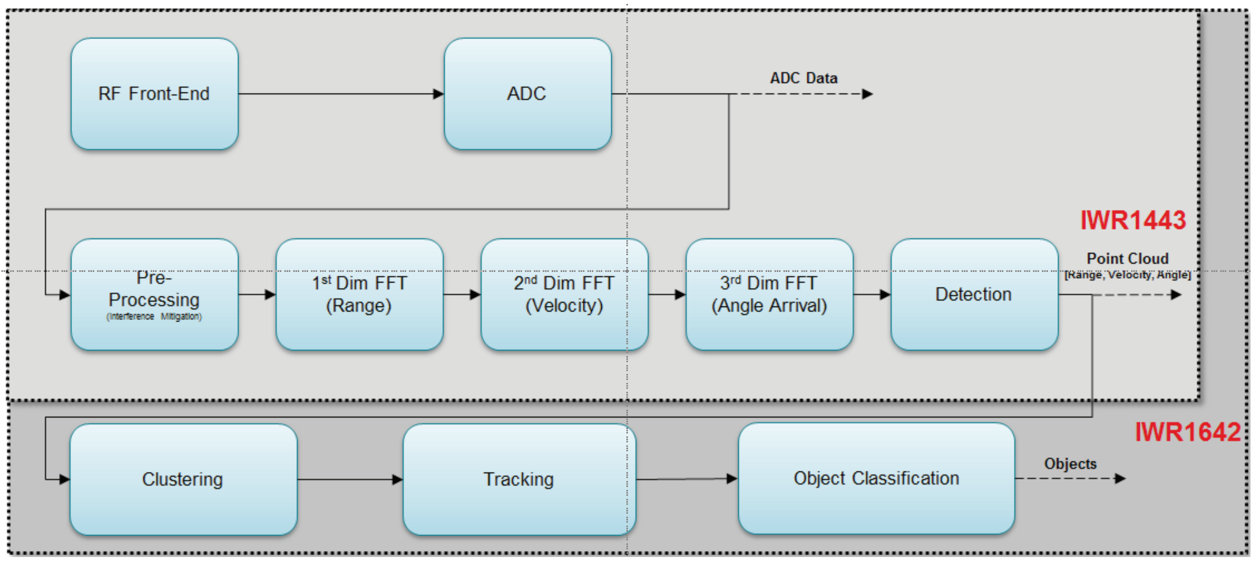

Figure 7*. TI IWR mmWave sensors processing chain.*

such as textile or carpeting, lenses need frequent cleaning and attention.

Since mmWave sensors are robust, detecting objects regardless of lighting, humidity, smoke and dust on the factory floor, they are well suited to replace vision systems, and can provide this detection with very low processing latency—typically under 2 ms. With a wide field of view and long detection range, mounting these sensors above the area of operation simplifies installation. The ability to detect multiple objects or humans with only one mmWave sensor reduces the number of sensors required and reduces cost.

Point-cloud information generated by mmWave sensors

mmWave radar sensors convert radio frequency (RF) front-end analog data to a digital representation through an analog-to-digital converter. This digitally converted data requires high-speed external data buses to bring the data stream to the processing chain, where a series of mathematical operations generate the range, velocity and angular information for points detected in the sensor's field of view. Because these systems are traditionally large and expensive, TI sought to integrate all of this functionality onto a single monolithic piece of CMOS silicon, thus reducing size, cost and power consumption. The additional digital processing resources now handle data post-processing for such tasks as clustering, tracking and classification, as shown in **Figure 7**.

A person walking in front of an mmWave sensor generates multiple reflection points. Each of these detected points can be mapped in a 3-D field relative to the sensor (as shown in **Figure 8** on the following page) within the popular robot operating system visualization (RVIZ) visualization tool. This mapping collects all points over a quarter-of-a-second time period. The density of the point information collected provides a good amount of fidelity with leg and arm movement visible, enabling object classification as a moving person. The clarity of the open spaces in the 3-D field is also very important data for mobile robots so that they can operate autonomously.

Mapping and navigation using mmWave sensors

Using the point information for objects detected by the IWR1443BOOST EVM, it is then possible to demonstrate the use on mmWave radar as

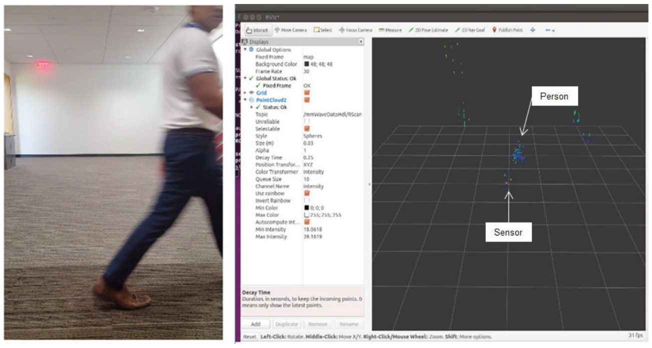

Figure 8. *Point cloud of a person shown in RVIZ, captured with the IWR1443BOOST EVM.*

the only sensor to accurately map obstacles in a room, and to use the free space identified for autonomous operation. There are several robotic open-source communities, including [Robot OS (ROS)]() and [Arduino](). In order to quickly demonstrate the use of a single mmWave radar in mapping and navigation applications, we chose Robot OS and mounted the IWR1443BOOST EVM on the ROS community's Turtlebot 2 development platform, as shown in **Figure 9.**

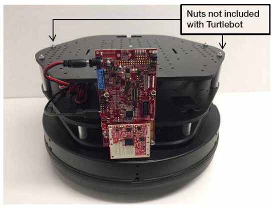

Figure 9. *IWR1443BOOST EVM mounted on a Turtlebot 2.*

Implementing a basic driver for the EVM (ti_mmwave_rospkg), we integrated the point-cloud information into the navigation stack using the OctoMap and move_base libraries, as shown in **Figure 10.**

We placed obstacles in an interior office environment and drove the Turtlebot 2 through the area to build a 3-D occupancy grid map using the OctoMap library. **Figure 11** on the following page is a screen shot of the occupancy grid using RVIZ.

We used the map generated from OctoMap with move_base, inputting a final destination and pose position as shown by the green arrow in the screen capture of **Figure 12** on the following page. The Turtlebot 2 successfully and efficiently navigated to the selected spot and then rotated to the appropriate pose, avoiding obstacles both staticly and dynamically in its path. This demonstrated the efficacy of using a single forward-facing mmWave sensor for basic autonomous robotic navigation quickly in the ROS enviroment.

Conclusion

mmWave sensors were initially expensive and large in size, and required multiple discrete components. Now, however, driven by TI's integration of RF, processing and memory resources onto a single monolithic CMOS die, it is now realistic to say that mmWave sensors will complement or displace established sensing technologies in robotics.

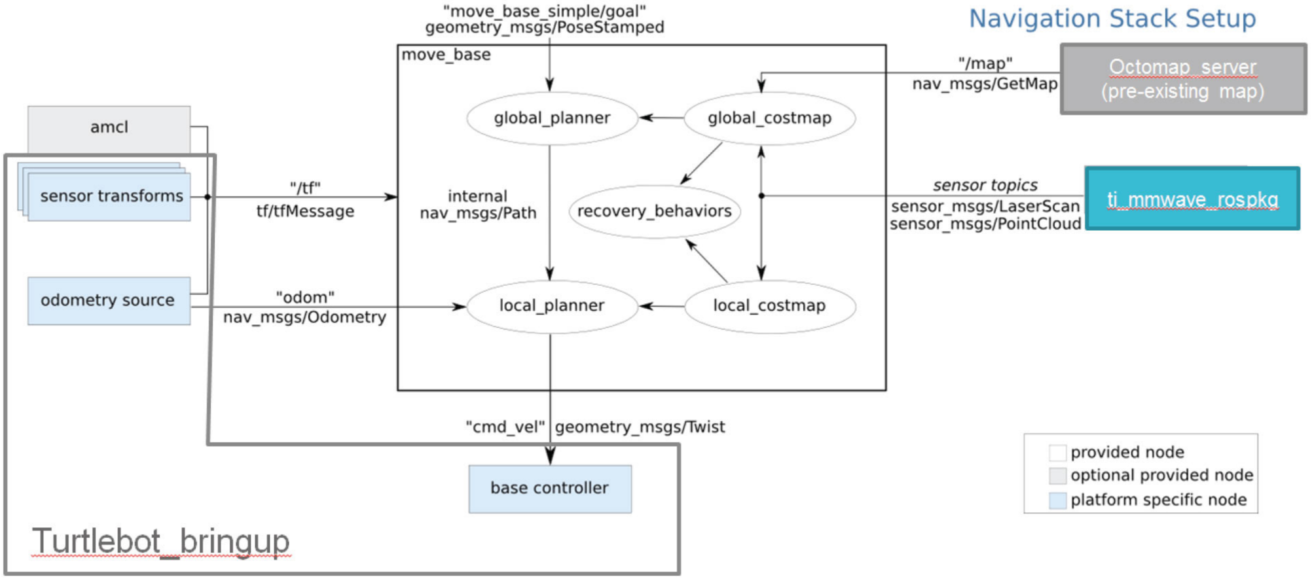

Figure 10. *ROS library navigation stack used with the IWR1443BOOST-equipped Turtlebot 2.*

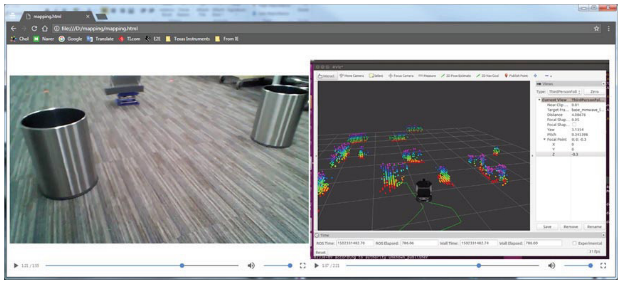

Table 11. Generating an occupancy map using the OctoMap library in ROS.

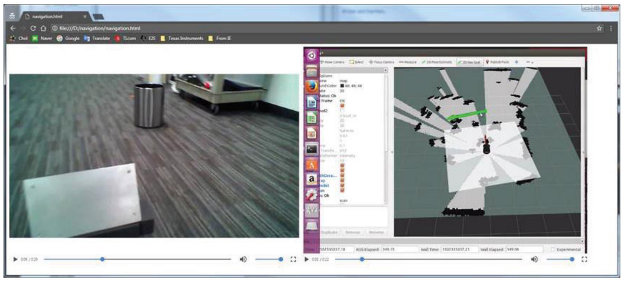

Table 12. Using the IWR1443BOOST EVM occupancy map for autonomous navigation of a Turtlebot 2 with the ROS move_base library

To summarize, here are the advantages of mmWave sensors vs. other technologies:

- mmWave sensors are not sensitive to environmental conditions such as direct sunlight, shadows or light reflections off of water.
- mmWave can detect glass walls, partitions and furnishings where light-based sensing solutions could fail.
- mmWave provides Doppler velocity information on objects, and as such can help augment robot odometry in case of wheel slippage on wet surfaces.
- mmWave-based sensors are less mechanically complex, and thus reduce manufacturing alignment and error-calibration processes. Without apertures or lenses, they are mountable directly behind enclosure plastics. Integrated calibration means less in-line manufacturing complexity. Wide field-of-view possibilities eliminate the need for mechanical rotating sensor mechanisms.
- TI's highly integrated single monolithic CMOS mmWave sensors enable all processing to occur within the sensor. This lowers bill of materials costs, makes for a small sensor and reduces the million instructions per second needed from the central controller processor vs. vision-based systems.

mmWave sensor technology enhances the intelligent operation of robotics while increasing robustness in real-world environments. The application of this technology will further accelerate the rapid adoption of robotic systems.

Additional Resources

- Safety Area Scanner Lab using IWR6843
- Autonomous Robot Sense and Avoid Lab with IWR6843/IWR1843
- Intelligence at the edge powers autonomous factories
- Safety Guards Overview
- mmWave for Mobile Robots Overview

References

1. Tractica. "Robotics Market Forecasts." 2Q17.
2. Barrett, D., D. Wang, A. Ahmad and V. Mahimkar. "Using mmWave sensors to enhance drone safety and productivity." Texas Instruments white paper SPYY001, 2017.
3. Fleming, W.J., and A.K. Hundiwal. "Radar Ground Speed Sensors." 35th IEEE Vehicular Technology Conference, 1985, pp. 262–272.

IMPORTANT NOTICE AND DISCLAIMER

TI PROVIDES TECHNICAL AND RELIABILITY DATA (INCLUDING DATASHEETS), DESIGN RESOURCES (INCLUDING REFERENCE DESIGNS), APPLICATION OR OTHER DESIGN ADVICE, WEB TOOLS, SAFETY INFORMATION, AND OTHER RESOURCES “AS IS” AND WITH ALL FAULTS, AND DISCLAIMS ALL WARRANTIES, EXPRESS AND IMPLIED, INCLUDING WITHOUT LIMITATION ANY IMPLIED WARRANTIES OF MERCHANTABILITY, FITNESS FOR A PARTICULAR PURPOSE OR NON-INFRINGEMENT OF THIRD PARTY INTELLECTUAL PROPERTY RIGHTS.

These resources are intended for skilled developers designing with TI products. You are solely responsible for (1) selecting the appropriate TI products for your application, (2) designing, validating and testing your application, and (3) ensuring your application meets applicable standards, and any other safety, security, or other requirements. These resources are subject to change without notice. TI grants you permission to use these resources only for development of an application that uses the TI products described in the resource. Other reproduction and display of these resources is prohibited. No license is granted to any other TI intellectual property right or to any third party intellectual property right. TI disclaims responsibility for, and you will fully indemnify TI and its representatives against, any claims, damages, costs, losses, and liabilities arising out of your use of these resources.

TI’s products are provided subject to TI’s Terms of Sale (www.ti.com/legal/termsofsale.html) or other applicable terms available either on ti.com or provided in conjunction with such TI products. TI’s provision of these resources does not expand or otherwise alter TI’s applicable warranties or warranty disclaimers for TI products.

Mailing Address: Texas Instruments, Post Office Box 655303, Dallas, Texas 75265
Copyright © 2020, Texas Instruments Incorporated