

mmWave Radar Sensing and Sensor Fusion in Humanoid Robots



Overview

This application brief explores mmWave sensing, safety, and sensor fusion for precise object and movement detection in humanoid robots. mmWave radar excels in low-visibility conditions compared to vision-based sensors, while also offering low-cost, low-power operation in adverse weather conditions.

What's covered in this application brief:

- **Importance of sensing in humanoid robots:** Compares sensor types, specifications and system integration considerations for humanoid robot designs.
- **Introduction to mmWave radar sensors:** Explains radar IC capabilities and the evolution toward 60GHz and 77GHz solutions.
- **Benefits of mmWave sensors:** Details radar advantages in cost, weather resilience, range, and functional safety certification.
- **Sensor fusion:** Demonstrates how multi-sensor integration overcomes single-sensor limitations for improved environmental awareness.
- **Radar and camera sensor fusion:** Presents practical implementations using TI's development tools and Robotics SDK.

Introduction

Humanoid robots (as shown in [Figure 1](#)) are rapidly transitioning from research platforms to production systems across manufacturing, logistics and service industries. For system integrators and OEMs, the core engineering challenges center on achieving reliable autonomous navigation in unstructured environments, implementing robust perception systems that function across varying operational conditions, and meeting functional safety requirements for human-robot collaboration.



Figure 1. Modern Humanoid Robot

Critical design considerations include sensor selection for 360-degree environmental awareness, real-time processing of multi-modal sensor data, power budget constraints in mobile platforms and system-level safety certification pathways. As humanoid form factors become standardized, the differentiation increasingly lies in the sophistication of the sensing architecture. In particular, the ability to maintain operational reliability when individual sensor modalities are compromised by environmental factors such as lighting variations, airborne particulates or surface reflectivity changes.

Importance of Sensing in Humanoids

Like how humans rely on their senses to navigate and interact with the world, humanoid robots also require sophisticated sensing systems to perform tasks autonomously and effectively. Table one shows common sensors used in humanoid robots.

Table 1. Common Types of Sensors Used in Humanoid Robots

Sensor Type	Description	System Application	Design Considerations
Cameras (Visual Systems)	RGB, depth, or infrared cameras capture visual information for object recognition and scene understanding.	Navigation, perception, object manipulation, human-robot interaction	Lighting dependency, computational requirements for image processing, frame rate vs. resolution trade-offs
mmWave Radar	Millimeter-wave radar detects range, velocity, and angle of objects using RF signals in 60-77 GHz bands.	Navigation, collision avoidance, presence detection, gesture recognition	Weather/lighting independent, power consumption, angular resolution limitations, interference management in multi-radar environments
LiDAR	Laser-based ranging creates high-resolution 3D point clouds of the environment.	Navigation, mapping, obstacle detection, localization	Cost, mechanical reliability (rotating vs. solid-state), performance degradation with vibration, sensitivity to reflective/absorptive surfaces
Tactile Sensors	Force, pressure, and contact sensors provide touch feedback for manipulation tasks.	Gripper systems, contact detection, force control, surface texture identification	Sensor density vs. cost, signal conditioning complexity, durability under repeated contact, integration with control loops
Auditory Systems (Microphones)	Microphone arrays capture sound for voice commands, environmental awareness, and localization.	Human-robot interaction, sound source localization, anomaly detection	Noise cancellation requirements, beamforming complexity, acoustic echo challenges, speech recognition processing demands

Introduction to mmWave Radar Sensors

Designers often use radar-based sensor ICs for position and proximity sensing because of their long-range capabilities, high-motion sensitivity and privacy features compared to vision-based sensing. With their high accuracy, radar sensors are also popular in the automotive and industrial markets for applications such as blind-spot detection, collision detection, people presence and motion detection.

In recent years, 60GHz and 77GHz radar sensors have replaced 24GHz radar sensors, delivering higher resolution, improved accuracy and smaller form factors. The 60GHz and 77GHz radar bands have also enabled new applications such as object presence detection in industrial robotics and mobile robotics applications found in factories or homes.

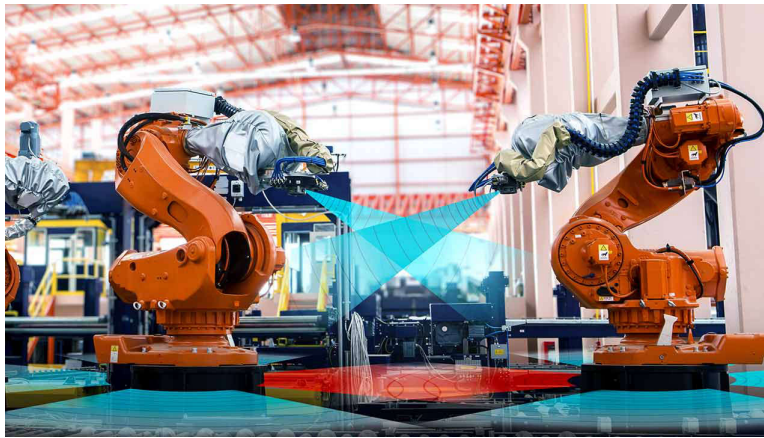


Figure 2. mmWave Sensor Embedded in Industrial Robots

Benefits of mmWave Sensors Over LiDAR and Cameras

mmWave Radar technology is often used instead of lidar, cameras and other optical sensors because of cost savings and ability to work well in adverse weather conditions while cameras can be affected by poor lighting and weather. Radar also has a broad range and coverage that allows sensors to detect objects more than one hundred meters away. Designers often use radar in mobile robot applications to reduce power consumption since radar can consume as little as 1.5mW for presence detection. However, pairing radar with lidar, cameras, or other optical sensors provides complementary failure modes—when one sensor is degraded by environmental conditions (fog affecting cameras, reflective surfaces confusing lidar), the other maintains detection capability, improving overall system availability.

From a functional safety standpoint, TI's non-contact radar sensors such as the [IWR6843](#) were designed through an extensive hardware and software development process, and feature device certification from TÜV SÜD. All TI radar sensors feature built-in functional safety mechanisms that provide the necessary diagnostic coverage required by IEC 61508 to meet hardware capabilities as high as Safety Integrity Level (SIL) 2 at the component level.

TI provides functional safety collateral through a diagnostic software library, compiler qualification kits, third-party operating systems, development tools and additional documents to help engineers streamline their safety design process and the system-level certification.

Sensor Fusion

Using only one type of sensor in humanoid robots can result in limitations, such as incomplete or inaccurate data collection. For example, cameras may struggle with depth perception in poor lighting and when detecting transparent objects. Similarly, lidar sensors typically can't detect transparent objects like water or glass. Lidar is also prone to experiencing ghost objects from reflective surfaces as well as missed detections from dark matte materials. These constraints can lead to errors in navigation, object manipulation and environmental interaction.

Sensor fusion addresses these issues by integrating data from multiple sensors to create a more accurate, reliable, and comprehensive understanding of the robot's environment. By combining inputs from various sensing modalities, humanoid robots can make more informed decisions, enhancing their ability to perform complex tasks like navigating uneven terrain, grasping objects of different shapes and sizes, and interacting in dynamic, real-world environments.

Advantages of sensor fusion include:

- Increased accuracy by merging data from different sensors
- Redundancy to ensure functionality if one sensor fails
- Improved environmental awareness with a fuller view of surroundings
- Better adaptability to dynamic environments

Radar and Camera Sensor Fusion

Radar is often used in robotic systems due to its durability in harsh conditions as well as its reliability when detecting objects during various movements. TI sensor ICs were developed to help engineers maximize the accuracy and awareness of the robots they're developing systems for. These devices can help mitigate the shortcomings of a single-sensor system.

For example, the camera and radar sensor module in [Figure 3](#) uses an IMX219 camera and an [IWR6843ISK EVM mmWave radar sensor](#). This module uses an object-level fusion approach that applies to both camera vision processing and radar processing chains that focus on object clustering and tracking; allowing engineers to track and detect objects in a three-dimensional environment.



Figure 3. Camera and Radar Sensor Module Built With IMX219 and IWR6843ISK

Summary

As humanoid robots transition from controlled environments to real-world deployment, mmWave radar technology will become increasingly crucial to achieving the reliability and safety standards required for human-robot collaboration.

The combination of weather-independent operation, functional safety certification, and seamless sensor fusion capabilities positions radar as a useful component in next-generation humanoid platforms. Engineers who develop sensing systems around radar-optical fusion today are building the foundation for truly autonomous humanoid robots capable of operating safely alongside humans in complex environments.

Additional resources

- TI's [Humanoid robot overview landing page](#)
- On-demand webinar: [Sensing in Robotics](#)
- Development tools: [Radar Toolbox for mmWave Sensors](#)
- Demo overview: [Camera and Radar Fusion Demonstration](#)
- Product folder: [IWR6843AOP evaluation module for single-chip 60GHz antenna-on-package \(AoP\) mmWave sensor](#)
- Evaluation module: [D3 Engineering DesignCore® radar evaluation modules](#)
- White paper: [Optimizing functional safety for industrial robots](#)
- Functional safety manual: [Streamlining Functional Safety Certification in Automotive and Industrial functional safety manual](#)

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