Technical White Paper

mmWave Radar for Safe Sensing in Industrial Stationary and Mobile Applications

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ABSTRACT

Industrial automation has revolutionized manufacturing, logistics, and other sectors by increasing efficiency, reducing human error, and enhancing productivity. However, the integration of complex machinery and autonomous systems has also introduced new safety challenges. Ensuring the safety of operators, maintenance personnel, and even the machinery itself has become a critical concern as automated systems become more sophisticated. The new IEC TS 61496-5 provides guidelines for the design of electrosensitive protective equipment (ESPE) and this document highlights technical options for designing such ESPE with TI's mmWave radar technology.

Among the various types of ESPE, radar safety sensors are gaining prominence due to their robustness, accuracy, and ability to function effectively in challenging environments where optical or infrared sensors may fail. The Texas Instruments IWR6843 radar sensor and LP87745 power management integrated circuit (PMIC) are key components in developing radar-based safety systems that comply with IEC TS 61496-5. This technical paper explores the application of these components in both stationary and mobile industrial applications, focusing also on ISO 13849.

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1 Introduction

This document discusses potential subsystem concept options for a Radar Protective Device Type 3 according to IEC TS 61496-5 using the IWR6843 mmWave sensor and LP87745 PMIC devices. All other components and interconnects are assumed to be compliant with the desired safety target. The safety function should also be capable of PL d as per ISO 13849 for use cases in mobile applications.

An electro-sensitive protective equipment (ESPE) is applied to machinery presenting a risk of personal injury. It provides protection by causing the machine to revert to a safe condition before a person can be placed in a hazardous situation.

IEC 61496 establishes requirements for ESPEs, which are designed to protect individuals from hazardous machinery operations. These systems detect the presence of persons or objects within a defined area and initiate protective actions, such as stopping machine motion or disabling power, to prevent injury. The standard applies to various ESPE technologies, including LiDAR, cameras and radar sensors.

1.1 Regulatory Needs for Electro-Sensitive Protective Equipment (ESPE)

In the European Union (EU) Machinery Directive mandates a number of type C standards for machines so that these machines can be sold in the EU. See the example of 2 machinery type C standards that call for ESPE protections: the robots and the doors and gates. Both offer different ways to specify safety, either safeguarding, safety sensors or torque limiting. Focusing on the first option and especially how those standards (ISO 13855 and EN 12978, respectively) point to IEC 61496 (see Figure 1-1). Since August 2023, ESPE standards have a new extension covering “Radar Protective Devices” (IEC TS 61496-5).

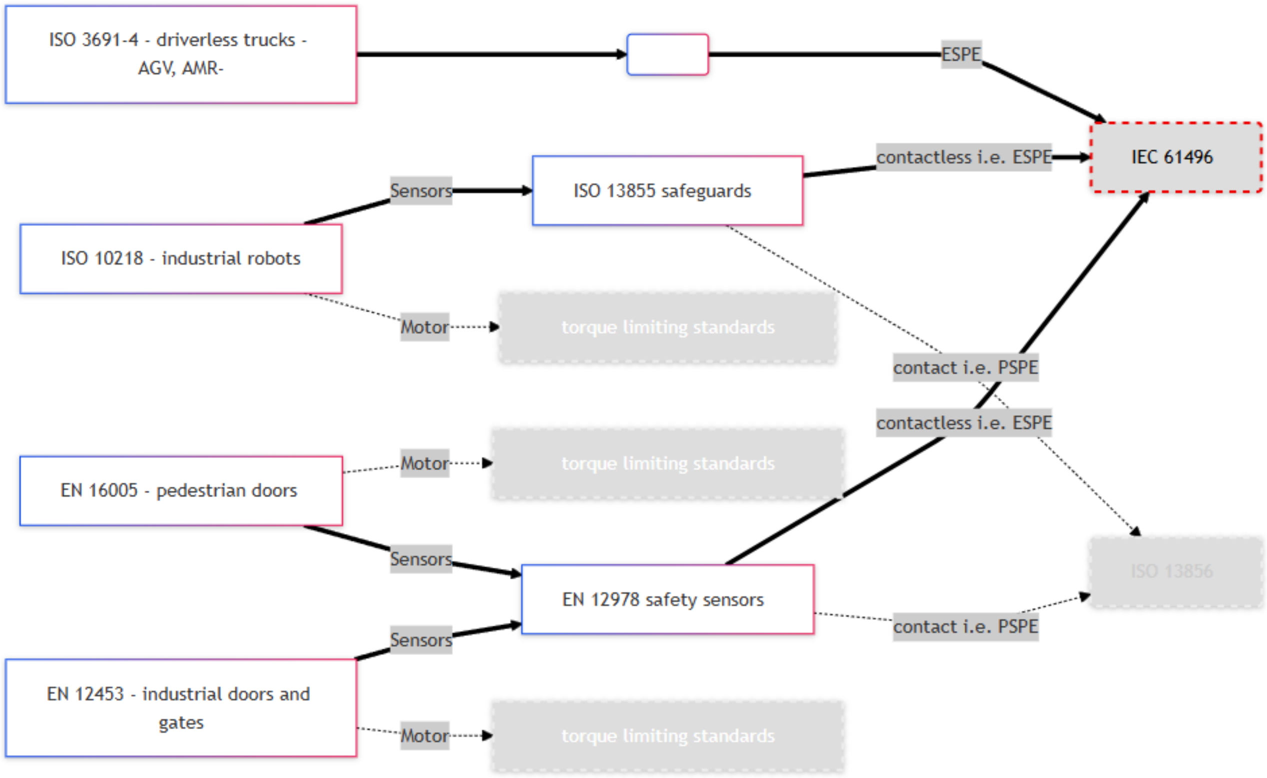


Figure 1-1. Safety Standards Interactions

1.2 Different Types of Electro-Sensitive Protective Equipment (ESPE)

IEC 61496 defines the standards for electro-sensitive protective equipment (ESPE), outlining both general requirements and specific sensing technologies to ensure safe operation in industrial environments.

Structure of IEC 61496:

- IEC 61496-1: This part provides the generic principles and performance requirements applicable to all types of ESPE. It serves as the foundational framework for safety equipment design and functionality.
- IEC 61496-2 to 5: These parts focus on the specific technologies used in ESPE systems, categorized as follows:
  - IEC 61496-2: Active Opto-Electronic Protective Device (AOPD) – Utilizes light beams for detection.
  - IEC 61496-3: Active Opto-Electronic Protective Device Responsive to Diffuse Reflection (AOPDDR) – Relies on light reflections for object detection.
  - IEC TS 61496-4: Vision-Based Protective Device (VBPD) – Employs cameras or image-processing technologies for area monitoring.

  - IEC TS 61496-5: Radar Protective Device (RPD) – Uses radar waves for detecting presence and motion, offering a robust alternative to optical systems

2 Advantages of Radar Sensors in Industrial Applications

Radar sensors offer several advantages over other types of ESPEs, making them ideal for both stationary and mobile industrial applications:

- Environmental Robustness: Radar sensors can operate reliably in environments with dust, moisture, and extreme temperatures.
- Material Penetration: Radar can detect objects behind non-metallic obstacles, such as plastic or wood, enhancing detection reliability.
- Long Range and High Accuracy: Radar sensors are effective at detecting objects at various distances with high precision.
- Resistance to Environmental Interference: Radar technology is less affected by environmental factors like sunlight, fog, or reflective surfaces, which can impair other sensor types.
- Versatility: Radar sensors can be deployed in a wide range of applications, from guarding stationary machinery to ensuring the safe operation of mobile equipment like AGVs or AMRs. 3D and high sensitivity to motion allows restart prevention safety features.

These characteristics make radar safety sensors an attractive solution for industries seeking to enhance safety while maintaining operational efficiency.

The first three sensing technologies (AOPD, AOPDDR, and VBPD) rely on optical principles and, as such, are susceptible to environmental factors that can compromise their performance. These include:

- Solar Glare: Intense sunlight can saturate sensors, reducing their effectiveness.
- Welding Arcs: Bright, rapid flashes can confuse or temporarily blind optical systems.
- Obscurants: Smoke, dust particles (for example, wood flakes, fabric fibers), and other airborne materials scatter or block light, impacting detection accuracy.

Any environmental condition that adversely affects one type of optical sensor impacts all optical-based technologies due to their reliance on light. In such situations, radar-based protective devices (RPD), as defined in IEC TS 61496-5, offer a reliable alternative. Radar systems operate independently of visual conditions, making them ideal for challenging environments where optical sensors may fail.

Beyond those aspects, generic to radar, TI mmWave radar sensor combine Frequency Modulate Continuous Wave modulation (FMCW) combined with Multiple Inputs Multiple Outputs (MIMO) antenna patterns offers a unique ability to sense presence in a volume. This combination allows radar sensors to not only detect when a human enters the danger zone but also if they remain present in the danger zone which other optical sensors may struggle to provide as a sensor output.

3 Safety Concept Evaluation/Analysis

For this specific safety concept evaluation and analysis, the focus is on the Radar sensing part. However, in order to fulfill the requirements for an electro-sensitive protective equipment (ESPE), assumptions have to be made for the rest of the modules.

The IWR6843 device that is used in this concept analysis includes the entire millimeter wave blocks and analog baseband signal chain for three transmitters and four receivers, as well as a customer-programmable MCU and DSP (see Figure 3-1). The IWR6843 is a Functional Safety-Compliant device, developed for functional safety applications. Safety documentation is available to aid IEC 61508 for functional safety system design up to SIL 3.

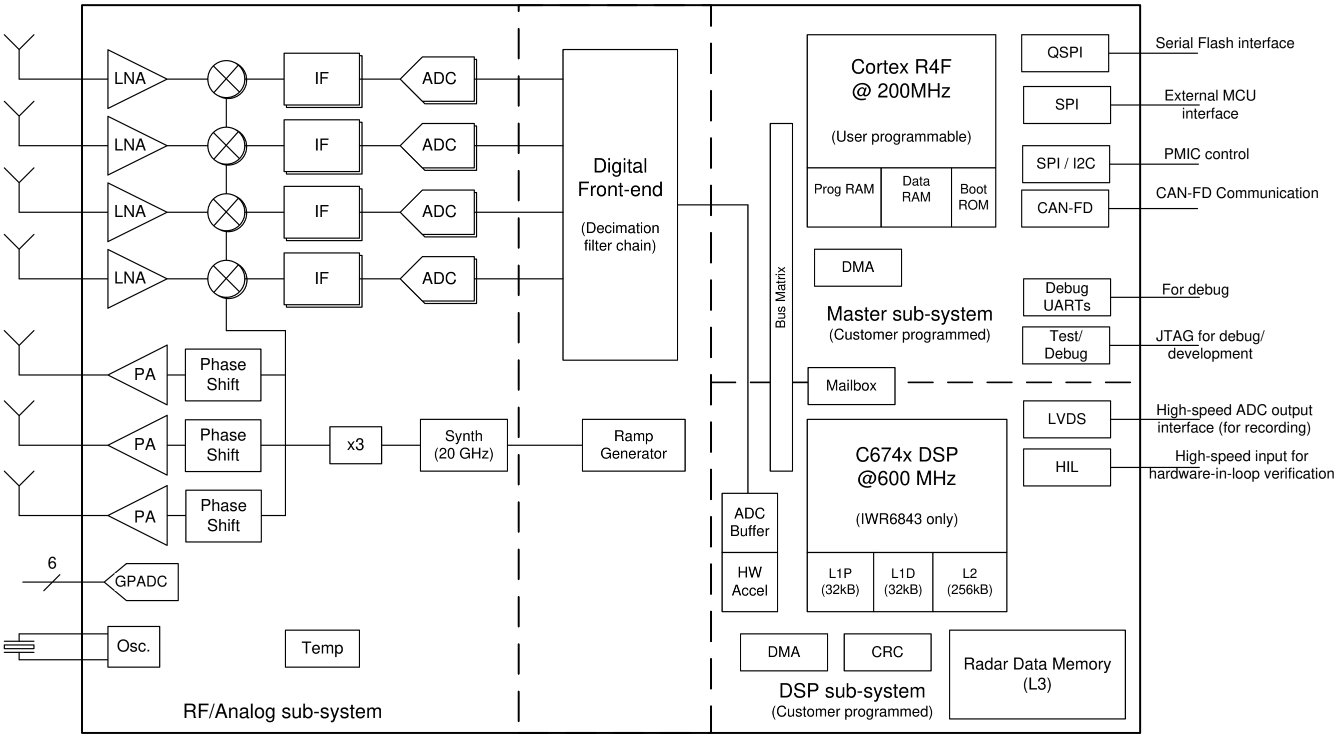
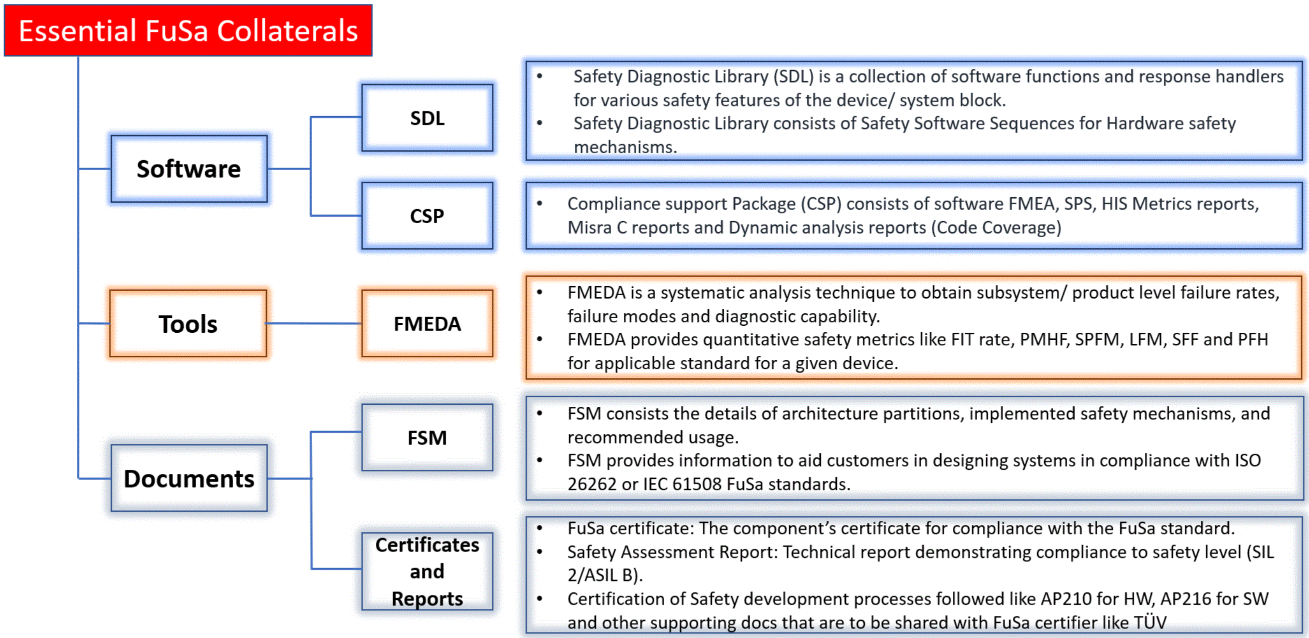


Figure 3-1. IWR6843 Block Diagram

TI provides essential collaterals as shown in Figure 3-2, which are required for the successful FuSa certification of the system. The essential Fusa collaterals are only disclosed to the customers on request through Secure Resources.



- Safety Diagnostic Library (SDL) is a collection of software functions and response handlers for various safety features of the device/ system block.
- Safety Diagnostic Library consists of Safety Software Sequences for Hardware safety mechanisms.

- Compliance support Package (CSP) consists of software FMEA, SPS, HIS Metrics reports, Misra C reports and Dynamic analysis reports (Code Coverage)

- FMEDA is a systematic analysis technique to obtain subsystem/ product level failure rates, failure modes and diagnostic capability.
- FMEDA provides quantitative safety metrics like FIT rate, PMHF, SPFM, LFM, SFF and PFH for applicable standard for a given device.

- FSM consists the details of architecture partitions, implemented safety mechanisms, and recommended usage.
- FSM provides information to aid customers in designing systems in compliance with ISO 26262 or IEC 61508 FuSa standards.

- FuSa certificate: The component's certificate for compliance with the FuSa standard.
- Safety Assessment Report: Technical report demonstrating compliance to safety level (SIL 2/ASIL B).
- Certification of Safety development processes followed like AP210 for HW, AP216 for SW and other supporting docs that are to be shared with FuSa certifier like TÜV

Figure 3-2. Essential FuSa Collaterals

The mmWave Software Diagnostic Library (SDL) is a collection of functions for access to safety functions and response handlers for various safety mechanisms for TI mmWave sensors. These functions assist in the development of software applications involving functional safety. The mmwave SDL release package contains a Compliance Support Package (CSP). The Compliance Support Package (CSP) is evidence that TI provides to customers for software components that have been developed using the rigorous development process for functional safety software. The CSP is intended to assist you in your certification efforts for the integrated system.

The used LP87745-Q1 PMIC device (see Figure 3-3) is designed to meet the power management requirements of the IWR mmWave devices in various industrial radar applications. The LP87745-Q1 is a functional safety-compliant device, developed for functional safety applications. Safety documentation is available to aid IEC 61508 and ISO 26262.

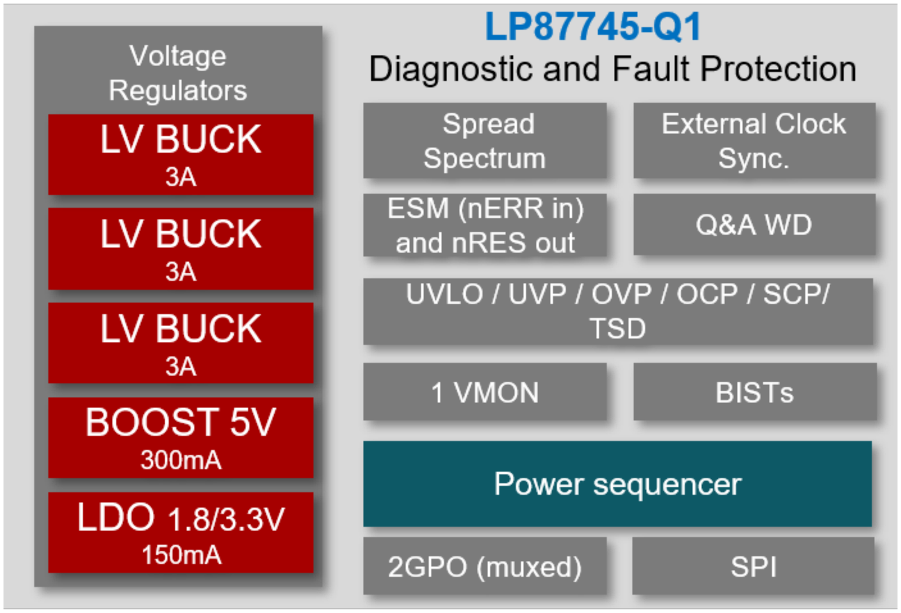


Figure 3-3. LP87745-Q1 Block Diagram

3.1 System Requirements

The EU Machinery Directive sets the foundation for machinery safety, making it the starting point for any organization aiming to ensure safe machine positioning and operation in Europe. It represents a proactive approach to preventing accidents and promoting workplace safety.

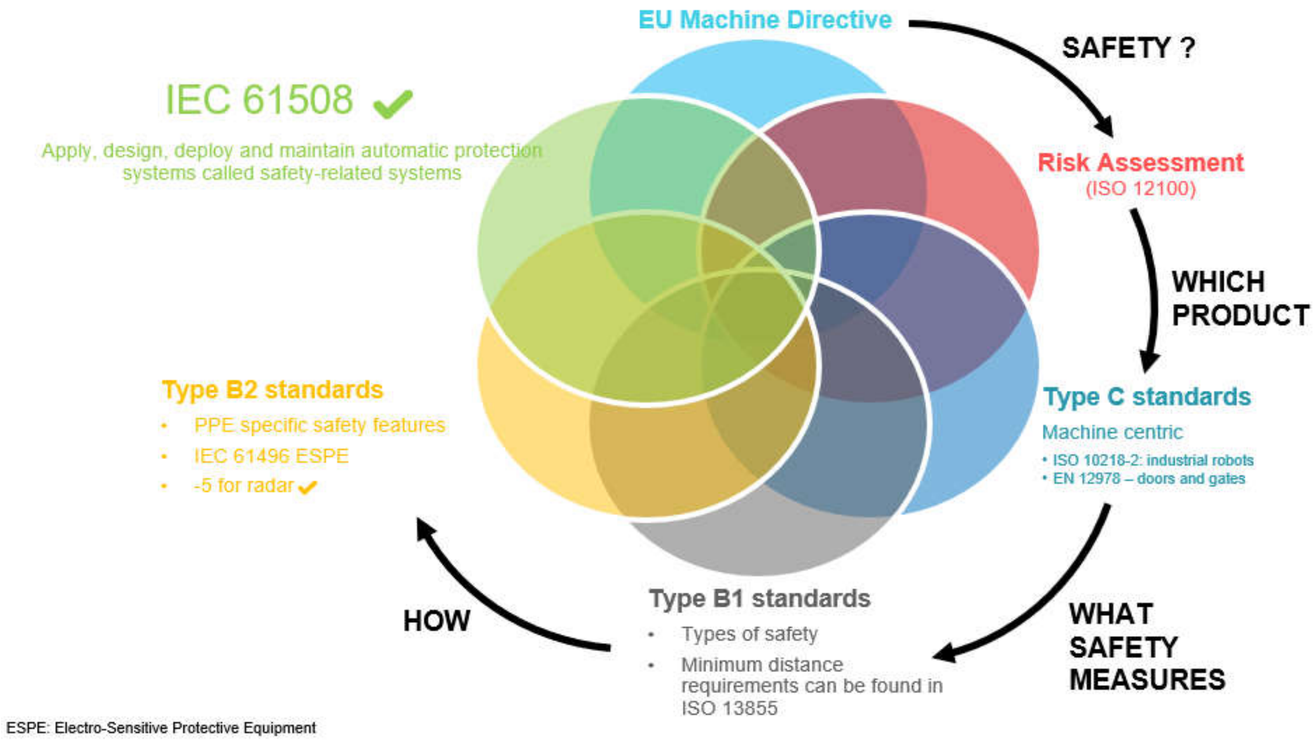


Figure 3-4. Positioning Safety in Europe: Starts With EU Machine Directive

3.1.1 Stationary Use Case

The operation of industrial robots often involves risks due to high speeds, heavy loads, and sharp tools. Ensuring the safety of human operators in proximity to these robots is paramount. IEC 61496, the international standard governing the design and application of electro-sensitive protective equipment (ESPE), provides a framework for implementing safety measures using devices such as safety sensors.

A radar sensor is ideal for detecting entry into a hazardous area, offering adjustable protection zones. The radar sensor would be positioned in a way to cover the robot's operating area, ensuring all potential entry points are monitored. Different zones could be defined as seen in Figure 3-5.

If a person enters the yellow warning zone, the system reduces the robot's speed, allowing for continued operation while signaling caution. If a person breaches the red hazard zone, the system initiates an emergency stop of the robot to prevent harm within a specified safety time.

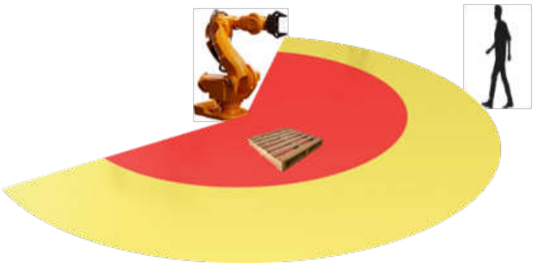


Figure 3-5. Industrial Robot (Safer Human Presence Detection)

Safety assessments are a critical step in designing industrial robot applications, particularly in fenceless setups where human workers share close proximity with robots. A very simplified example of safety assessment and calculation follows. For this specific example, consider the case of an industrial robot and carry a risk assessment based on a typical robot arm, speed, stopping time in relation to typical human worker speed to provide background for the considered safety time.

Key Definitions

- **Stop Zone:**

  The area where the robot could strike a human if its arm reaches the furthest extent of its motion.

  UR10 Robot Arm Reach: 1.0m

  -> Stop Zone: 1.0m
- **Slow Down Zone:**

  The area where the robot must slow down to prevent a human, moving at maximum speed, from entering the stop zone during the robot's stopping time.

  Maximum Human Speed: 3.6m/s (13 km/h)

  Worst-Case Stopping Time: 1250 ms (1.25 seconds)

  Slow down zone has to be bigger than 3.6m/s * 1250ms + 1m = 5.5m

  -> Target Slow Down Zone: 6.0 m (rounded up for margin).
- **Safety Time Calculation**

  The safety time is the margin required to account for system reaction delays.

  Safety time ~(target slow down zone- min slow down zone)/max human speed

  0.5m/3.6m/s =138.9ms

  To provide additional safety margins, the safety time is rounded to **100ms** which seems to be a realistic value.

  This simplified safety assessment highlights the importance of understanding both robot capabilities and human factors in defining critical safety parameters. In this example, the key outcomes are:
- **Stop Zone:** 1.0m
- **Target Slow Down Zone:**

  6.0m
- **Safety Time:**

  100ms

3.1.2 Mobile Use Case

For a mobile use case, consider an example for an autonomous mobile robot (AMR) that is used to transport goods in a warehouse. The environment is dynamic, with workers frequently moving around. The goal is to prevent collisions and ensure worker safety without compromising the robot's operational efficiency. The radar sensor can be configured to create multiple detection zones. As shown in Figure 3-6, within the yellow “Slow down zone” it detects objects or people at a moderate distance, prompting the AMR to slow down and issue visual or audible alerts. Within the red “Stop zone” it detects closer proximity, triggering an immediate stop to avoid collisions.

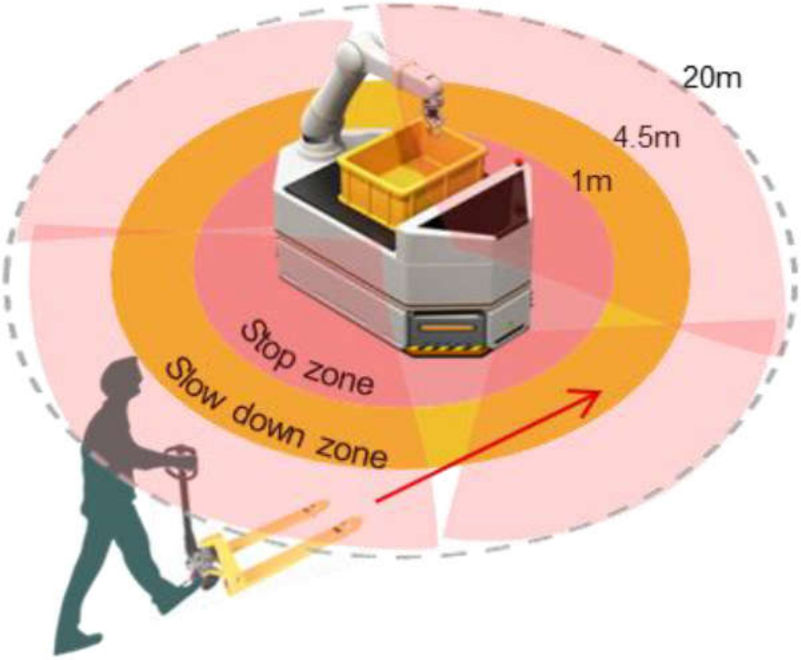


Figure 3-6. Mobile robot (Safe Human Presence Detection)

ISO 3691-4 standard defines the safety requirements and verifications for driverless industrial trucks, including AMRs.

According to ISO 3691-4 the safety-related parts of the detection of persons in the intended path of an autonomous mobile robot shall comply also with IEC 61496.

The mobile robots shall be fitted with ESPE for the detection of persons and the minimum required PL according to ISO 13849-1 is PL d.

3.2 Considerations for Sensing Architectures

This section explores the pros and cons of various sensing architectures, providing a foundation for understanding the system-level design of radar-based safety sensors. The architectures are categorized based on their configurations and design approaches.

3.2.1 System Level Architecture

3.2.1.1 Bi-Static With Spatial Diversity

In this setup, two different sensors are physically separated and the sensing zone is defined by the overlap of their respective fields of view. The main benefit is minimization of dependent fault injectors (DFI), while the main drawback is the highest cost and installation complexity.

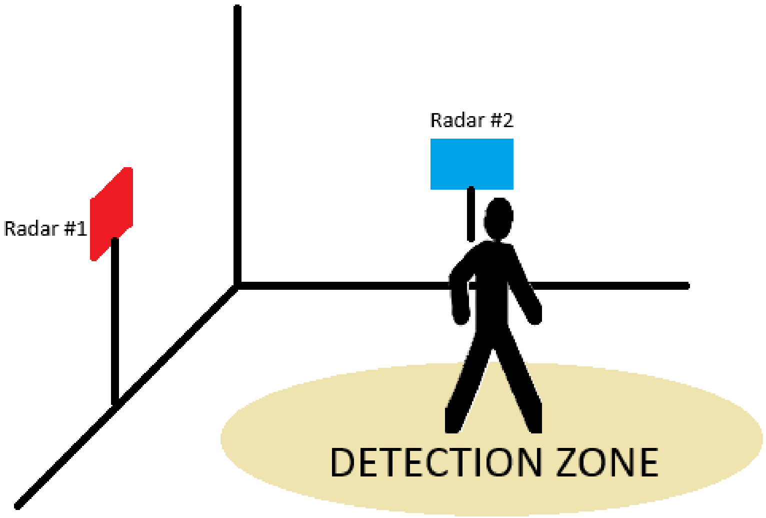


Figure 3-7. Bi-Static With Spatial Diversity Setup

3.2.1.2 Co-Located Bi-Static (Two Sensor Products)

Two radar sensors are placed in the same physical location, creating overlapping fields of view. It reduces the installation cost since both sensors are mounted together. But the hardware costs are still higher compared to mono-static configurations.

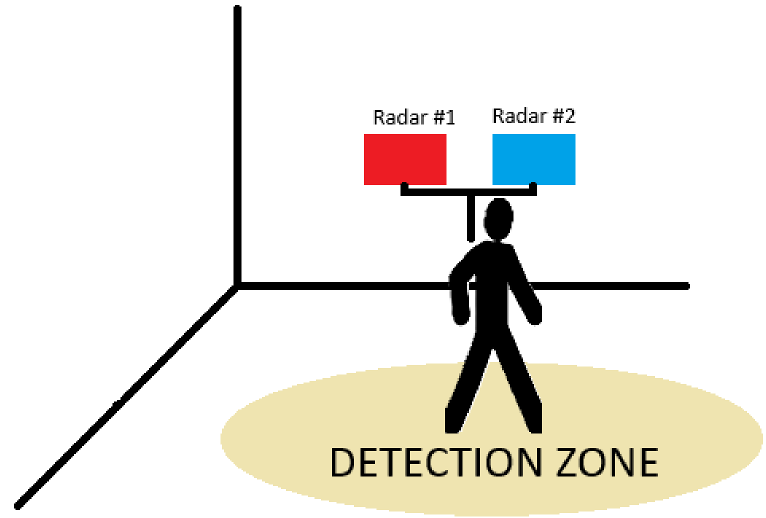


Figure 3-8. Co-Located Bi-Static Setup (Two Sensor Products)

Environmental factors with a coupling effect, such as mechanical vibrations in the supporting structure add new dependent fault injectors (DFI). A mitigation strategy could be to use signal-to-noise ratio (SNR) measurements or onboard vibration sensors to detect and manage faults caused by vibrations.

3.2.1.3 Co-Located Bi-Static (Single Sensor Product, Dual IWR6843)

A single radar sensor contains two integrated IWR6843 radar chips.

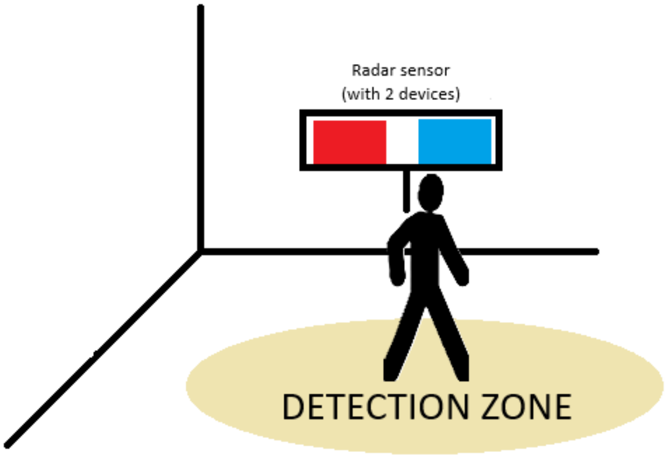


Figure 3-9. Co-Located Bi-Static Setup

The benefit is that it simplifies purchasing and deployment as it is a single product. But it has a higher bill of materials (BoM) costs due to the dual-chip configuration.

New Dependent Fault Injectors (DFI) could be the shared power resource failures (for example, power supply issues affecting both chips). One mitigation strategy could be to ensure the radar sensor enters a safe state when power is lost.

3.2.1.4 Mono-Static (Single Sensor Product, Single IWR6843)

A single radar sensor utilizing one IWR6843 chip operates as a mono-static radar system. It is the most cost-effective solution with minimal hardware requirements.

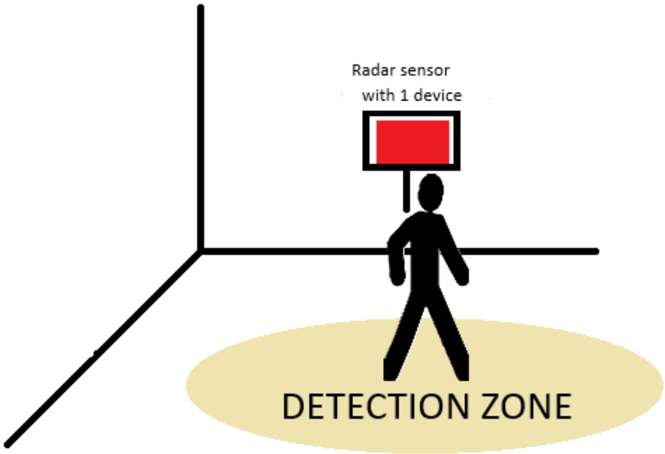


Figure 3-10. Mono-Static Setup

But the Drawbacks are the limited field of view coverage due to the single sensor design. And it has increased complexity in managing the interaction between safety diagnostics and functional code when using a single device.

3.2.1.5 Summary

Each sensing architecture has unique strengths and weaknesses. The choice of configuration depends on the specific application requirements, balancing factors like cost, complexity, field of view coverage, and fault tolerance. Understanding these trade-offs is essential for designing robust and effective radar-based safety systems.

In the next chapters we will focus on the mono-static architecture (Single sensor product, Single IWR6843) as it documents the most complete sets of measures at the radar level.

3.2.2 Latent Fault Monitoring

From a safety architecture, one key consideration is to consider the IEC 61496 requirements. While IEC TS 61496-5 mandates a type 3 ESPE, IEC 61496-1 defines a type 3 with the following wording:

“In cases where a single fault which does not cause a failure to danger of the RPD is not detected, the occurrence of a further fault internal to the RPD shall not cause a failure to danger.”

There are multiple ways to architect a sensor that fulfills this, some of which include:

- SIL 2, HFT=1 (as per 61508): For HFT=1, IEC 61508 states that “no account shall be taken of other measures […] such as diagnostics”
- CAT 3 (as per ISO 13849) which states “not all parts are necessarily physically redundant”
- CAT 2 (as per ISO 13849) with diagnostics of the diagnostics functions

Since the first option with physical redundancy of the sensing element is equivalent to the previously called “co-located bistatic” option, it is not covered in this paper.

The other 2 options that highlight and leverage redundancy and multi-channel at the sensor level and take advantage of monitoring and fault injection are discussed in the upcoming sections.

Note that certain aspects of the device-level safety mechanisms that are described in the safety manual – which as of time of writing of this white paper is under NDA – are not explicated here either.

3.3 Sensor Level Architecture

The required performance level for both stationary and mobile use case is Pld. PLd can be achieved by either using Category 2 (Cat 2) or Category 3 (Cat 3) architecture (see Figure 3-9) as defined per ISO 13849-1.

With "Category" the ISO 13849-1 standard specifies the resistance to faults. For a Cat 2 this would be a Single channel plus diagnostics as seen in Figure 3-11. For a Cat 3, this would be a dual channel plus diagnostics architecture and no accumulation of faults.

The designated architectures cannot be considered only as circuit diagrams but also as logical diagrams. For category 3, this means that not all parts are necessarily physically redundant but that there are redundant means of assuring that a fault cannot lead to the loss of the safety function. Main relevant understanding of a Cat 3 architecture is that every single failure does not lead in a loss of the safety function. A change into a safe state in case of a fault is okay. Therefore, for a fail-safe application the requirement for single-fault tolerance does not necessarily mean that a two-channel system must be implemented. Also, a single channel system with a high standard of monitoring that responds to a fault with a dedicated deactivation path sufficiently quickly for a dangerous state to be avoided can be fulfill Cat 3.

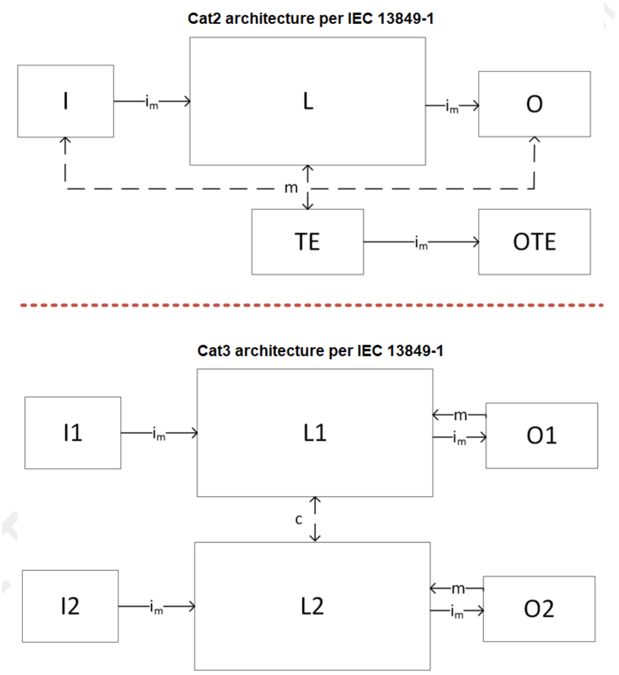


Figure 3-11. Designated Architectures for Categories 2 and 3 per IEC 13849-1

At the sensor level, there are two main possible architectures for PLd:

- A logical dual-channel approach, leveraging IWR6843 unique hardware architecture in combination with the safety PMIC LP87745, which would allow a CAT 3
- A SW diversity approach and higher diagnostics in combination with the safety PMIC LP87745, which would allow at least CAT 2

3.3.1 Sensor Level Architecture for CAT 2

Diagnostics is an important aspect to consider in the context of safety. TI mmWave device include hardware and firmware elements to enable diagnostics of its analog and digital sections. These built-in features are exposed to users through firmware APIs. It helps users to build their software to program and use these APIs to achieve their end-product's safety goals. A Safety Diagnostic Library (SDL) is provided to access these inbuilt Diagnostic and Monitoring features.

In functional mode, the ESPE shall respond by giving appropriate output signal(s) when part of a person greater than or equal to the detection capability (as specified in the relevant part of IEC 61496) enters or is in the detection zone.

In diagnostics mode the IWR6843 is using the diagnostics functions for testing the signal chains. The OSSDs stay in the same state as in previous sensing mode during diagnostics mode. Figure 3-12 shows two options for the scheduling of the diagnostics activity.

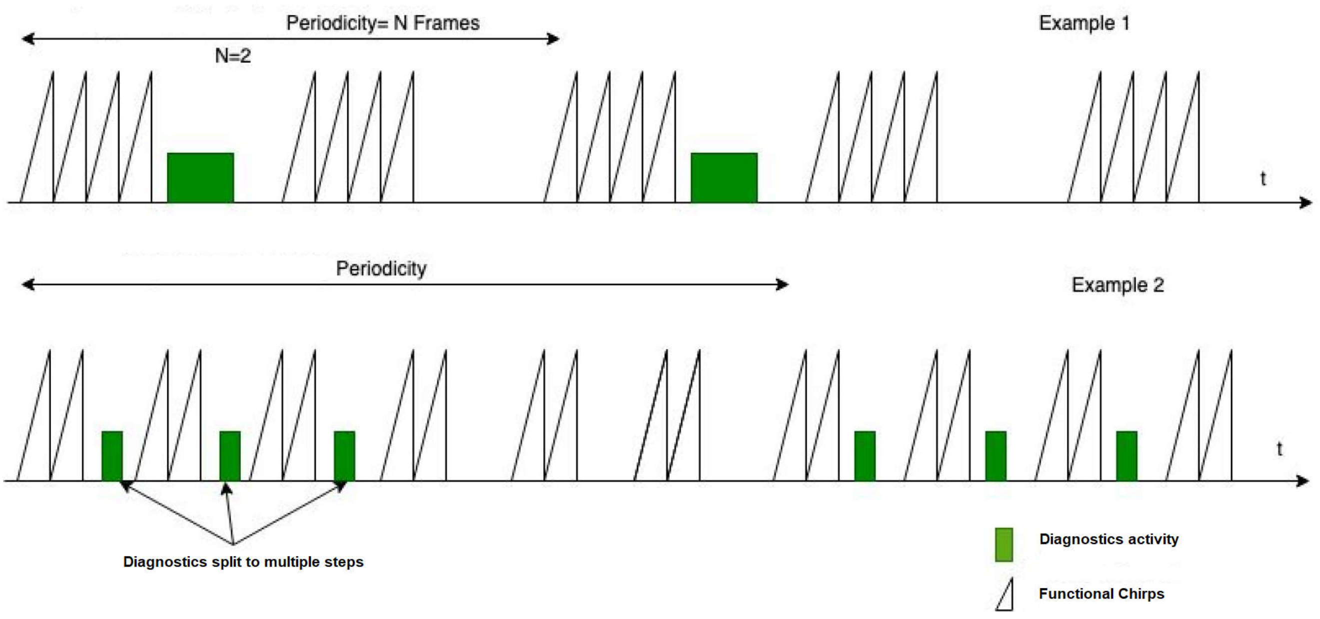
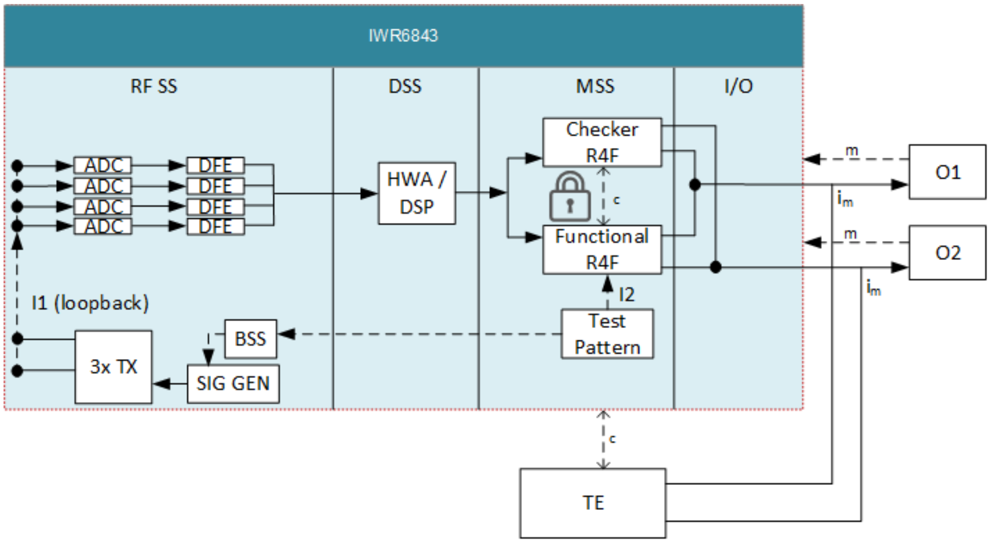


Figure 3-12. Diagnostics Scheduling

In addition to the diagnostics and monitoring functions the IWR6843 can also be put into loopback mode. When no functional chirps are ongoing, the BSS can schedule loopback test data (I1) collection. Processed input data I1 is then compared against input I2 (lookup table in memory) from the R4F lockstep Core (see Figure 3-13).



Key

i_m	interconnecting means	L1, L2	logic
c	cross monitoring	m	monitoring
I1, I2	input device, e.g. sensor	O1, O2	output device, e.g. main contactor or drive system

The dashed lines represent reasonably practicable fault detection.

TE	Test Equipment
DFE	Digital Front End
HWA	Hardware Accelerator
DSP	Digital Signal Processor

Figure 3-13. Conceptual Block Diagram for Cat 2 Architecture

To ensure that the power supply output power rails are within the desired voltage range, voltage supervision of the power is needed, the Figure 3-14 shows how this is implemented using external voltage supervisors and a Q&A watchdog which is integrated in the PMIC. This Q&A watchdog is needed to monitor the function of the IWR6843. The 1.0V rail can be measured and monitored with the internal ADC as this rail is independent and used only for the Power Amplifier, Low Noise Amplifier and Mixers.

For this concept the selected PMIC is the LP87745 and the optional voltage supervisors are the TPS3703. It is worth mentioning that all of those devices have a safety manual and additional safety documentation.

The MSS processor communicates through messages with the DSS (see Figure 3-14). The MSS running the main software application updates the Q&A watchdog timer via SPI to the LP87745.

The nERROR signal is also checked from the PMIC. If the software cycle is too long or if an nERROR signal occurs, the LP87745 triggers the PMIC_nINT signal that puts the outputs into a safe state.

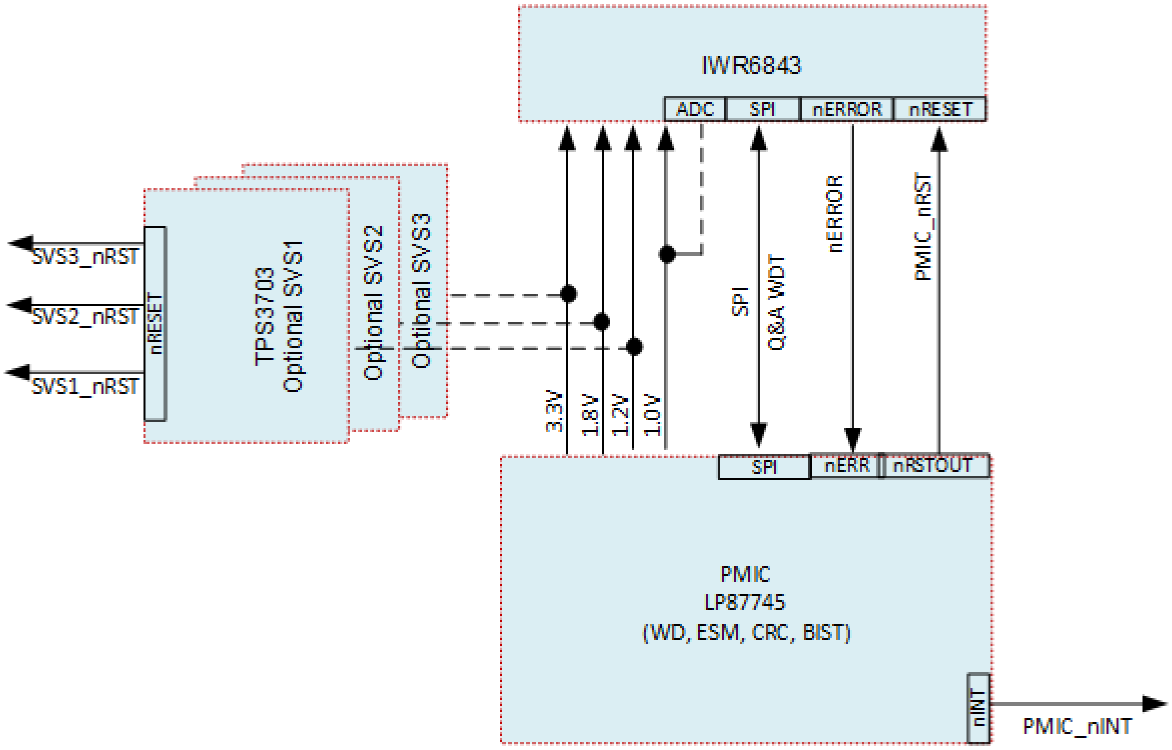
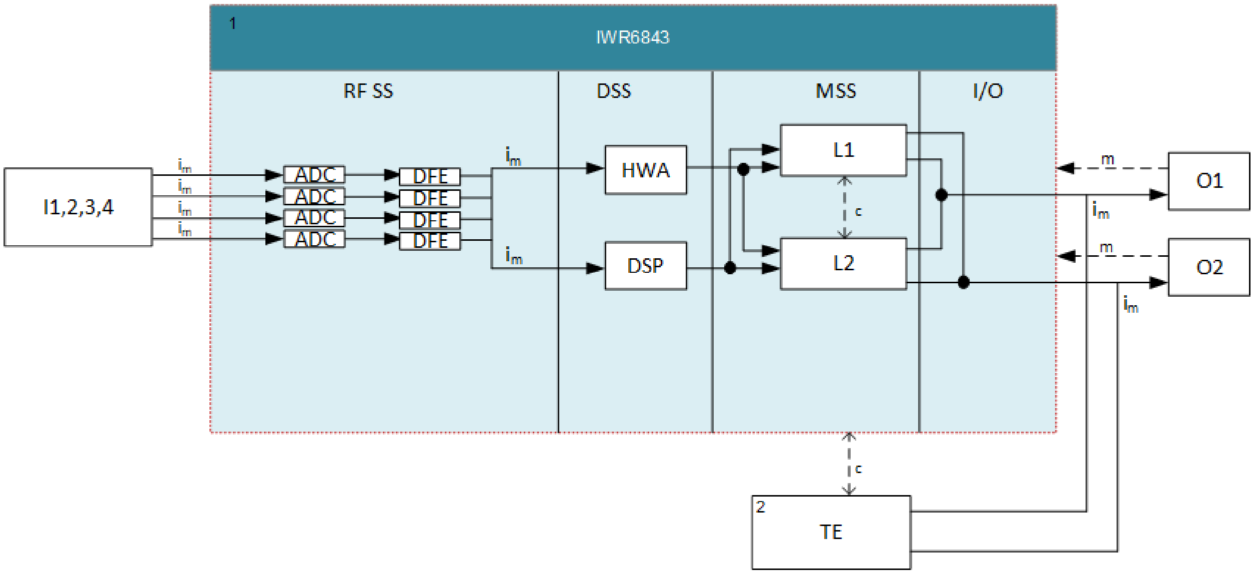


Figure 3-14. Power Supply and External Test Equipment (TE)

3.3.2 Sensor Level Architecture for Cat 3

In addition to the built-in monitoring and diagnostics features and the external test equipment monitoring as described above for the Cat 2 architecture, there is the option to implement logical redundant processing chains in the IWR6843 for a Cat 3 architecture as shown in Figure 3-15.



Key

i_m	interconnecting means	L1, L2	logic
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The dashed lines represent reasonably practicable fault detection.

TE	Test Equipment
DFE	Digital Front End
HWA	Hardware Accelerator
DSP	Digital Signal Processor

Figure 3-15. Conceptual Block Diagram for Cat 3 Architecture

The IWR6843 device offers different processing nodes to realize the radar processing. The IWR6843 has two processing nodes, a hardware accelerator (HWA) and a digital signal processor (DSP). Up to four different input signals can be processed from the HWA and the DSP. For Cat 3, the mmWave detection processing chain could use both and performs a crosscheck of the calculated results. The crosscheck would be performed from the R4F Core, which can run in lockstep mode. Two different tasks should process the data from the HWA and from the DSP. The results from task 1 and task 2 would then be compared against each other. In case of a mismatch, an error should be signaled to the PMIC and the outputs should be put into a safe state.

This redundant processing for Cat 3 is currently not implemented and supported in any SW deliverables: neither the mmWave software development kit (SDK) nor the radar toolbox. Thus such a software architecture would have to be implemented by the customer.

4 IEC TS 61496-5 Functional Test Results

The IEC TS 61496-5:2023 is a new safety standard created for safety-related systems that employ a Radar Protective Device (RPD) in order to detect people using a frequency-modulated continuous-wave (FMCW) transmission. A list of functional tests are defined by the standard to ensure proper sensor function and detection integrity under specified conditions. Tests listed in the standard include and are not limited to:

- Detection capability
- Response time
- Position accuracy
- Coexistence of other RPDs
- Interference by objects inside detection zone
- Interference by objects outside detection zone
- Manual interference

- Interference from other radio sources

Detailed information on the executed tests and the results can be found in the Radar Toolbox.

5 Other Considerations

5.1 Vibrations

One key point to consider which is considered out of scope for this document is the impact of vibration on the detection capabilities. Vibration of the sensor – if left not compensated - will add a Doppler offset to all the targets equivalent to the vibration vector radial component. This could lead to a target appearing static or a static target appearing to move. The safety assessment should address this case specifically.

Possible ways to address this are either:

- Accelerometer on the PCB to provide an estimation of the vibration
- Background scene analysis for vibration estimation

Some relevant literature references for those topics are:

- F. Hau, F. Baumgärtner and M. Vossiek, "Influence of vibrations on the signals of automotive integrated radar sensors," *2017 IEEE MTT-S International Conference on Microwaves for Intelligent Mobility (ICMIM)*, Nagoya, Japan, 2017, pp. 159-162, doi: 10.1109/ICMIM.2017.7918881
- (Poole et al., 2022, p. 183) Fig 2. Diagram of the frame-level correction/deconvolution algorithm at the core of the proposed real-time vibration compensation scheme

5.2 Clock

The device-specific data sheet of the IWR6843 specifies that the crystal frequency tolerance should be ±50ppm and that those tolerances include initial frequency tolerance, drift over temperature aging and frequency pulling due to incorrect load capacitance.

In the case where a realistic failure of any of the above could lead to a drift of the crystal beyond the ±50ppm it should be noted that the only independent clock monitor in the IWR6843 is the RCOSC that only provides a few % of accuracy diagnostics. For more information, see the *Monitoring and Diagnostic Mechanisms* section in the *IWR6843, IWR6443 Single-Chip 60- to 64-GHz mmWave Sensor Data Sheet*. So an external monitor should be considered of which an option would be to output on pin N7 (MCU_CLK_OUT) with an output clock higher than 20MHz clock to avoid spurs in IF band (rather than OSC_CLKOUT on A14, as OSC_CLK_OUT only monitors the slicer output rather than the full clock tree. A simple MCU with a carefully selected additional crystal implementing a dual counter could help achieve this.

6 Conclusion

Safety mmWave radar sensors from Texas Instruments provide an advanced solution for protecting people and ensuring the safe operation of industrial and mobile robots in dynamic environments. Their ability to adapt to changing conditions and reliably detect potential hazards makes them indispensable in modern industrial settings. Guided by the IEC 61496 standard, these systems deliver both safety and efficiency, fostering harmonious human-robot collaboration.

7 References

Texas Instruments safety collateral cover a wide range of topics ranging from:

1. Radar Functional Safety Enablers
2. Texas Instruments: TUEV certificate showing that those can be used in safety applications: *IWRxx43 TUV SUD Functional Safety Certificate*
3. Safety documentation (for example, FMEDA, Safety manual). For access to those, please contact your TI sales representative.
4. Software diagnostic library (SDL):
    - The mmWave Software Diagnostic Library is available through contact to your local TI sales representative
    - Diagnostics and Monitoring lab illustrates how to include the mmWave Software Diagnostic Library (SDL): https://dev.ti.com/tirex/explore/node?node=A__ANWVDLRvEqRU8HDYJZ-Q8w__radar_toolbox__1AslXXD__LATEST
5. Compiler, linker and other tools as part of the compiler qualification kit (cq_kit)
6. Third party offering for faster time to market:
    a. Safe RTOS such as from WHIS
        i. WITTENSTEIN High Integrity Systems
    b. Free RTOS is available under NDA to provide an easier transition to safety certified RTOS such as safe RTOS.
7. Application support with safety relevant examples usages of the above:
    a. Diagnostics Monitoring Ref which offers a wrapper example above the SDL for all examples
    b. 61496-5 functional safety testing
        i. https://dev.ti.com/tirex/explore/node?node=A__AAORdOaF-chtRs1PKEV2xQ__radar_toolbox__1AslXXD__LATEST&search=61496
    c. Webinars:
        i. Functional Safety Fundamentals Webinar
        ii. Safety software strategies for Compliance and Reliability
        iii. Texas Instruments: *Enabling Functional Safety for mmWave Sensors*
8. Other resources:
    a. Functional Safety for mmWave Sensors
    b. Texas Instruments: *Design Guide for Functional Safety Compliant Systems using mmWave Radar Sensors*
    c. Texas Instruments: *TI mmWave and IEC 61496-5 Functional Tests*
    d. Texas Instruments: *mmWave Diagnostic and Monitoring Reference Design Guide*

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