

Design and Implementation of FPGA-Based Proximity Warning System for Vehicles

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Abstract

The rise in traffic congestion in regions such as India has resulted in an alarming rise in the number of fatalities resulting from roadway accidents, primarily through situations where visibility conditions are limited (such as at an industrial site or a clustered area). Existing commercial detection systems are often ineffective, given their reliance on conventional sensing technologies that do not perform well under deteriorating weather conditions. Therefore, there is an urgent need for new, reliable, and real-time detection systems [2]. In this paper, we will present the creation of a real-time Proximity Warning System (PWS) that employs millimeter-wave (mmWave) radar principles within a reconfigurable FPGA architecture. We implemented our design using Verilog HDL on a Digilent Cmod A7 board (Artix-7) and emphasized timely signal processing characteristics. At this phase of development, we are validating our internal processing pipeline through a dedicated radar emulation module. By producing dynamic distance measurements through this module, we are able to verify our threshold-based logic for classifying safe, caution, and dangerous zones. Functional simulations performed in the Xilinx Vivado environment demonstrate that our system processes the visual LED alerts and audible buzzer warnings with minimal delay, while the RTL schematic that is produced confirms that our logic is completely synthesizable and hardware deployment optimized. Thus, based on our results, we believe this FPGA-based approach provides a cost-effective and scalable basis for future integration of physical mmWave sensors and to improve the safety of automotive applications.

KeyWords— Wave Radar; FPGA ; Proximity Warning System ; Vehicle Safety ; CFAR ; Xilinx Vivado ; Real-Time Embedded Systems.

1. Introduction

This study proposes a vehicle safety improvement strategy that uses mmWave radar technology to develop a near real-time Proximity Warning System (PWS). There is a worldwide increase in traffic density, and road accidents have become an increasingly serious problem—especially in high-risk areas (e.g., mining sites, warehouses, and high-density urban corridors). They typically arise from limited visibility and the presence of unpredictable obstacles which are frequently undetected with conventional manual monitoring[1],[2]. While there are numerous detection solutions currently in use (cameras and ultrasonic sensors), they have significant deficiencies when used in extreme conditions such as fog, dust, and/or low-light levels [2]. Although high-end Advanced Driver Assistance Systems (ADAS) equipped with LiDAR or radar can

guarantee the performance necessary in today's complex environments, they are prohibitively expensive and represent so many different potential architectural configurations that their use has not been widely applied to the commercial fleet or industrial vehicle markets. To fill this void, we have developed a Proximity Warning System that utilizes mmWave radar sensors installed on an FPGA-based design for accurate target detection at lower cost. Our design employs the Texas Instruments IWR6843 sensor which detects targets in the frequency bands of 60–64GHz, and utilizes Frequency Modulated Continuous Wave (FMCW) techniques for accurate distance, speed, and position determination of targets. Our design has an instance of radar data being captured and processed through a designated hardware unit that is developed using Verilog within

the Xilinx Vivado development environment. We developed multiple processing modules to process data from a variety of radar sensors to detect hazards in a timely and efficient manner. When an object enters a predefined safety threshold, the system will alert the driver's attention via visual alerts, audible alerts, and CAN bus communication. By moving the main computational workload to an FPGA hardware device, we will be able to meet the low-latency performance requirements for safety-critical applications. As a result, this implementation will provide a scalable, robust solution capable of performing adequately in many of the extreme conditions that exist in industrial and urban transit. [1]

2. mmWave Radar Technology [3]

Millimetre-wave (mmWave) radars are an exceptionally effective method for non-contact measurement using higher frequency ranges of 30 GHz to 300 GHz. The actual science behind their accuracy lies in the use of very short wavelengths (1mm to 10mm) [13]. The measurement data from mmwave systems can be gathered using these very short wavelengths which allow for measuring the distance from a target, the velocity of the target with respect to its original position, and the angular position of the target, all by sending out and measuring the return of the electromagnetic waves from the target.

2.1. Operating Principle

Analyzing how sub-components fully integrate into an overall system design flow allows creating improvements to system electronics via iteratively integrating design capabilities across various integrated subsystem combinations. All components required are in the high GHz range, which enables the use of standard mmWave radar architecture consisting of multiple essential subsystems including transmitter (TX) and receiver (RX) stages, a high gain antenna array, and a dedicated digital signal processing (DSP) unit. The transmitter generates high frequencies in the electromagnetic spectrum when sending signal energy through a medium until they hit an intended object in its path; once it has hit something, those signal reflections will travel back toward the sensor and through the RX frontend in order to perform parametric evaluations on them

(typically via some RF data processing algorithm)[5]. Mixing is at the core of all target detection—the reflections received will typically have two components, frequency 1 and frequency 2 (the original signal frequency). Mixing requires taking frequency 1 (the signals that were received and reflected by a target) and combining them with frequency 2 (the original TX frequency); the resulting output of this combination will create a new Intermediate Frequency (IF) signal (also referred to as the "beat frequency") that contains both time and distance properties about the environment, along with any distance velocity property of the target(s) [4]. The generated IF is an analog signal and then converted to a digital signal using high-speed ADCs, which allows us to utilize Fourier-based estimation methods of analyzing target(s) parameters such as range to target(s), Doppler shifted relative velocity of target(s), and Angle Of Arrival (AoA) to target(s). Since continuous synchronisation occurs within the generating and acquiring sections of the system, accurate real-time sensing capabilities are developed shown in Figure 1.

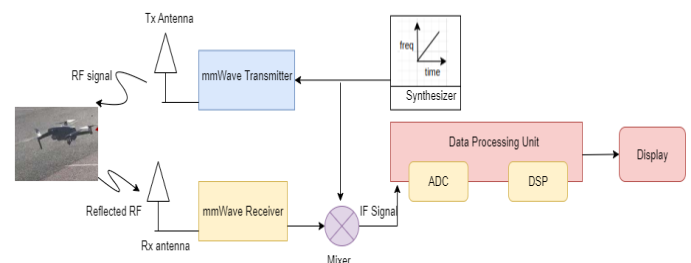


Figure 1 Basic block diagram of mmWave radar sensor architecture [3]

2.2. FMCW Radar Technique

Modern Automotive Sensing is all done based on Frequency Modulated Continuous Wave (FMCW) Signals. This approach is very accurate in measuring distances in dynamic conditions. In this type of setup, the transmitter will send out a "chirp" (the frequency of the transmitted signal is increased in a linear manner for a specified time). The main goal is to measure the frequency that is changed (the "beat frequency") between the transmitted and reflected signal. The beat frequency directly correlates to how far away the target is [4]. In addition to simply

measuring ranges, FMCW allows us to obtain a three dimensional representation of our surroundings:

- Range is calculated using the beat frequency.
- Velocity can be determined by measuring the phase difference between the successive chirps due to doppler effect.
- Angle of Arrival (AoA) will be calculated by evaluating the phase difference between the receiver antennas.

The timing and linearity of these chirps frames is imperative to achieve sufficient resolution for a reliable obstacle detection in the illustrated example in figure 2.

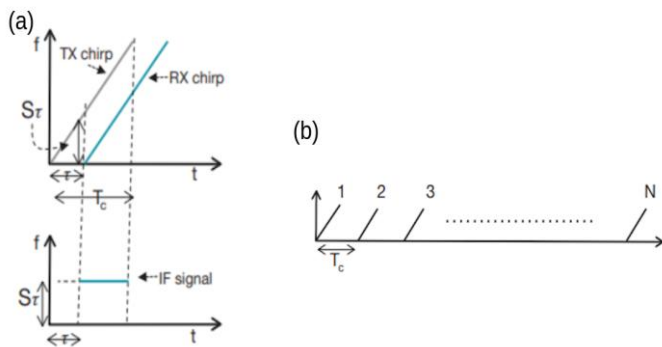


Figure 2 IF signal waveform and chirp frame [17]

2.3. Operating Bands

The frequency band (operating frequency) selected for the system is an important design trade-off factor that affects both the resolution of the results obtained and the size of the hardware used to implement the system [7]. Many frequency bands can be used, and their applicability depends upon the specific requirements of the sensor being developed related to its sensing capabilities:

- 24 GHz Band - Typically used as a low-cost method to provide proximity detection at moderate resolution.
- 60 GHz Band - Used primarily for industrial applications that require localized sensing capability at short range, and thus enabling compact integration.
- 77 GHz Band - This is the standard frequency used in the automotive industry for high-resolution applications (e.g. automotive radar) with high-resolution capability (i.e.,

ability to detect objects in moving traffic at high speed).

Our architecture is based on higher operating frequencies, which results in additional available bandwidth and therefore provides substantially better precision in distance measurement, thereby allowing for the effective separation of objects that are closer to each other in a moving traffic environment.

3. Radar Signal Processing Architecture

A high-speed signal processing pipeline is the core of the Proximity Warning System (PWS) because this custom-designed architecture was created specifically to provide a method to transform raw backscatter signals into actionable safety information with minimal latency [5][2]. This transformation begins with the transmission of a frequency-modulated continuous wave (FMCW) chirp signal from an antenna. Upon being transmitted, the chirp signal will reflect off an obstacle and return to the front-end of the receiver, where it will be converted to the digital domain so that it can be analyzed for safety reasons. Three-dimensional target data (range, velocity and angular position) are processed using deterministic algorithms. Since the Artix-7 FPGA has parallel processing capabilities, simultaneous computing can occur, enabling the system to complete intensive processing tasks (e.g., Fast Fourier Transforms (FFT), threshold-based detection) without experiencing delays. Therefore, this multi-tasking is what enables the system to maintain a "true" real-time experience for the user. This speed is critical in today's fast-paced urban and industrial environments where every millisecond counts when it comes to collision avoidance [12].

3.1. Data Acquisition

A mmWave radar sensor records the echo of an object by determining the return time of the frequencies that have been reflected off of it the mmWave radar converts these echo signals into intermediate frequency (IF) signals, by which it has been predetermined by the mmWave radar [6]. The analog IF signals are converted into digital IF signals using an analogue-to-digital converter (ADC) before being transferred to an FPGA for high-speed parallel processing. It is vital to ensure that the radar data have been accurately sampled so as to produce the specifications required for further signal analysis[7].

A second module allows for emulation of the radar signals through the use of Verilog to generate signals that simulate actual radar signals to use in testing before validation; in this way, verification of the processing pipeline can also be completed in the absence of live radar signals.

3.2. Range Estimation (1D FFT)

The proposed system performs range estimation using the one-dimensional (1D) Fast Fourier Transform (FFT) on the radar samples digitized from a mmWave radar sensor [10]. The 1D FFT converts the beat signal, which was in the time domain, into the frequency domain; thus, it indicates the dominant frequency components which indicate targets detected. In the Frequency Modulated Continuous Wave (FMCW) radar, the chirp signal that is transmitted reflects off of objects in the environment and arrives back at the radar after some time delay. In order to perform range estimation with FMCW radar, the time-delayed received signal is mixed with the transmitted signal which produces a frequency difference called the beat frequency. The beat frequency is linearly proportional to the distance from the radar to the target. The 1D FFT is used to perform signal processing on the radar data collected at the receiver to extract the beat frequency associated with the detected object from the received signal based on the beat frequency components [9]. Once those beat frequency components are established, they can be used to estimate the distance from the radar to each of the detected objects. The distance estimates are then used to establish warning zones around the vehicle. After the system estimates the distance to each of the detected objects, visual indicators and audible signals are activated to notify the driver of the proximity of the detected vehicle, thus, providing timely awareness for improved driver safety when operating in industrial and urban areas.

3.3. Velocity Estimation (Doppler FFT)

Velocity estimation can be performed using Doppler processing across multiple chirps. By analyzing phase variations between successive chirps, the relative speed of detected objects can be determined. Although the current system focuses on distance-based alerts, Doppler processing can enhance future system capabilities by distinguishing moving objects from stationary obstacles [14].

3.4. CFAR Detection

The CFAR (constant false alarm rate) function is designed to help distinguish between valid targets and noise or interference in a radar signal when processing data. CFAR calculates the threshold for detecting a target dynamically based on the noise surrounding it. Using an adaptive mechanism for threshold adjustment allows the radar system to differentiate between true targets and background noise with great accuracy [12]. CFAR's adaptive mechanism allows the radar system to have a stable rate of false alarms by continually monitoring the noise levels of adjacent bins. Therefore, CFAR algorithms can detect actual targets with a high accuracy even in environments with a high level of clutter (eg. construction sites, factories, or crowded urban traffic). By improving target detection accuracy and reducing false alarm rates, radar systems that utilize CFAR are able to provide reliable detection of targets.

3.5. Angle of Arrival (AoA) Estimation[7]

The AoA (Angle of Arrival) indicates the azimuthal bearings of the returning radar signal with respect to where that signal was ultimately detected [4]. Within millimetric wave radar systems, AoA calculations involve evaluating the phase differences between two or more received antenna signals. The assessment of phase differences from multiple antennas will enable the radar system to identify the geographic relationship between detected objects and the vehicle. The spatial relationship of these objects with respect to their proximity to the vehicle provides the radar system with the ability to determine if an obstacle is located in front of, to the rear of, or adjacent to the vehicle. As a result, AoA calculations improve awareness of geographic space as well as provide accurate identification of the surrounding environment within proximity warning systems [6].

3.6. Point Cloud Generation

Radar data processing integrates distance (range), speed (velocity) and angle measurements in creating a 3-dimensional computer representation of the object(s) detected in the vehicle's surroundings. Each point in this representation represents either a unique object; it describes its spatial position in 3-dimensional space (X, Y, Z) and in motion (speed, acceleration, etc.). Point clouds are able to accurately

describe the elements of a vehicle and give an accurate understanding of how that element is positioned in relation to the other objects in the vehicle's surroundings and how they are moving in relation to that vehicle [11]. The point cloud data also provide information that can assist in tracking and classifying the objects identified within the vehicle's surroundings for use by advanced driver assistance systems (ADAS) and or vehicle safety systems.

3.7. Object Classification and Alert Generation

Using pre-established distance thresholds, a decision-making process based on rules was used to determine proximity levels. The system generates warning signals for the driver when an object has entered the defined safety area. The following alert methods are used by the warning system

- LED Lights to give the driver a visual alert of the current proximity level.
- An audible tone from a buzzer that is used as a sound-based warning signal.
- Transmitting warning signals via the CAN (controller area network) to the vehicle system.
- These alerts will assist the driver in responding more quickly to a potential obstacle or danger; this will reduce the risk of accidents and enhance the safety of the vehicle[16].

3.8.FPGA

The proximity warning system, to be proposed as an additional measure of safety at construction sites, will be implemented via the Digilent Cmod A7 development board/FPGA, which is built on a Xilinx Artix-7 FPGA architecture. This compact FPGA module has been designed with a 48-pin DIP form factor and thus is well suited for rapid prototyping and for use as embedded hardware [9]. The Cmod A7 integrates many of the key components needed for designing an FPGA-based system, including:

- a USB-JTAG programming interface, enabling access to the firmware of the board via USB.
- a USB-UART communication bridge.
- a system clock source.
- SRAM memory.
- Quad-SPI Flash storage; general-purpose

input/output interfaces. These components support the creation of flexible platforms for designing and building digital logic and implementing processing applications.

In addition to the six functions above, the Cmod A7 has 44 digital FPGA input/output pins and two analog inputs that are each routed to standard through-hole connectors. Consequently, it is easy for users to interface the Cmod A7 with external circuitry (conventionally) or mount the board directly on a breadboard and conduct hardware prototyping through experimentation. The Cmod A7 provides a compact and highly flexible connector arrangement, making it an ideal platform for building FPGA-based real-time processing systems[5] shown in Figure 3.

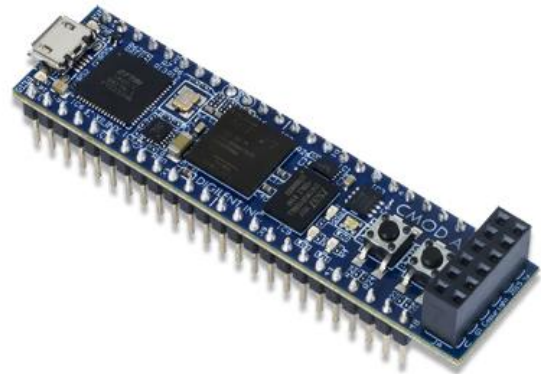


Figure 3 DigilentCMOD A7 [5]

4. System Features[9]

Key hardware features of the DigilentCmod A7 FPGA board include;

Memory

- 512 KB SRAM memory with an 8-bit data interface and approximately 8 ns access time
- 4 MB Quad-SPI Flash memory for FPGA configuration storage
- Programming and Communication
- Integrated USB-JTAG interface for FPGA programming and debugging
- USB-UART bridge for serial communication
- Power and Connectivity
- Can be powered through USB or an external 3.3 V – 5.5 V supply connected to DIP pins
- User Interaction Components

- Two user LEDs
- One RGB LED
- Two push buttons
- Expansion Interfaces
- 48-pin DIP connector providing 44 digital I/O pins and two analog inputs.

One Pmod connector for additional peripheral modules

4.1. Vivado

FPGA circuit development, synthesis & simulation are accomplished using Vivado Design Suite technology. Within this suite of tools you can build your digital circuits using Hardware Description Languages such as Verilog or VHDL then convert them into hardware forms that can be utilized on FPGA devices [11] shown in Figure 4.

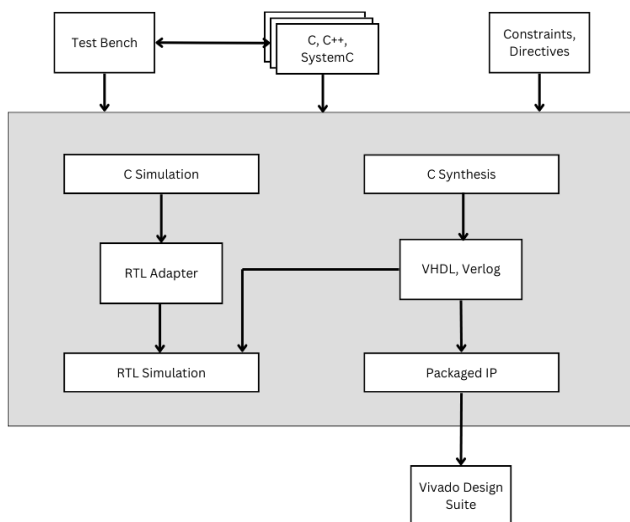


Figure 4 Vivado Design Workflow[10]

With the toolbox of Vivado, designers will have the ability to perform functional simulations, synthesize and implement designs, and verify hardware all from one platform. Using this single supply of functions will allow you to simulate & test your newly developed Verilog modules prior to deploying them onto FPGA hardware. This design environment will provide a means to ensure that the systems work properly and to achieve an overall increase in the speed of the process of developing hardware [10].

5. Radar Signal Emulation

In the prototyping and validation of the Proximity Warning System, we used a Radar Signal Emulation

method instead of a hardware integration method. This method is important in keeping external sensor noise from affecting the internal logic of the FPGA in the early development of the product. The radar emulation module was developed using Verilog HDL and simulated the flow of real data from an mmWave radar. By creating fake distance and speed data in the Xilinx Vivado Design Suite, we were able to thoroughly stress test the processing pipeline of the system. This allowed us to verify that our threshold-based alert logic—such as the transition from "Caution" to "Danger" zones—functions correctly under various simulated scenarios. Using this modular verification method ensures that the hardware architecture is robust and stable before we proceed with physical integration with the TI IWR6843 radar sensor.

5.1. Purpose of Radar Emulation

The radar emulation module functions as a virtual sensing unit that produces distance values representing objects detected within the radar's observation range. The generated data simulates the behavior of the TI IWR6843 mmWave radar after undergoing signal processing stages such as Range FFT, CFAR-based detection, and Angle-of-Arrival estimation. Through this emulation process, processed radar outputs are replicated within the simulation environment. This allows the system to focus on validating the FPGA decision logic, alert generation mechanisms, and real-time processing capability without requiring physical radar hardware during the initial development stage.

5.2. Emulation Methodology [5]

The Radar Mimic module generates distance measurements in centimeters using predefined patterns and timed sequences [14]. These values represent objects approaching or moving away from the vehicle. The module operates synchronously with the system clock and periodically updates the distance output, allowing the FPGA logic to evaluate different proximity scenarios. Key features of the emulation include:

- Generation of dynamic distance values to simulate object motion
- Clock-driven updates for real-time behavior
- Configurable distance ranges for testing safe,

caution, and danger zones

- Seamless integration with the FPGA processing module

5.3. Integration with FPGA Processing

The emulated radar output enters the top-level FPGA module where distance data is interpreted for proximity zone classification. [17] The FPGA's logic uses threshold-based classification to classify detected objects as either "safe", "caution", and "dangerous." Based on their classification, visual (LED) & audible (buzzer) alerts are turned on. The system's decision-making logic has been comprehensively tested in a control environment prior to hardware migration.

5.4. Advantages of Radar Signal Emulation

Using radar signal emulation provides several benefits:

- Enables early verification without physical sensor hardware [4].
- Simplifies debugging and validation of FPGA logic.
- Allows repeatable and controlled testing scenarios.
- Reduces development cost and hardware dependency.
- Facilitates rapid prototyping within Vivado simulation [2].

5.5. System Decision Flowchart

The operational procedure of the proposed proximity warning system is illustrated in Figure 5. The system begins by collecting environmental information through the mmWave radar sensor, which detects surrounding objects and measures their distance from the vehicle. The received radar signals are then processed using several signal processing techniques, including Fast Fourier Transform (FFT), Constant False Alarm Rate (CFAR) detection, and Angle of Arrival (AoA) estimation[15]. These processing steps extract both distance and spatial information necessary for proximity analysis. After signal processing, the resulting data is transferred to the FPGA processing unit where the distance values are continuously compared with predefined safety thresholds. Based on these thresholds, the system

categorizes detected objects into different proximity levels and activates appropriate warning indicators.

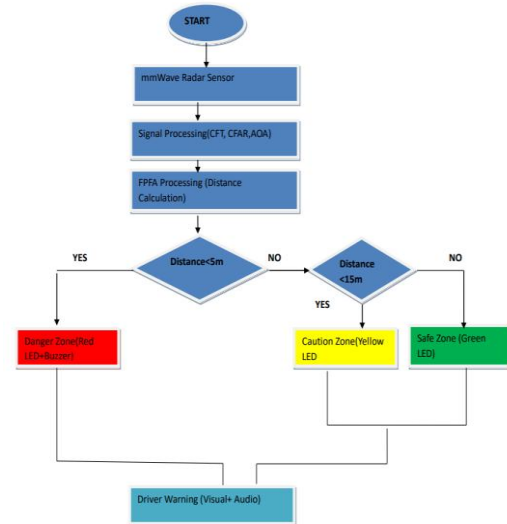


Figure 5 Distance-based decision logic for FPGA-based mmWave radar proximity warning system

- Distance < 5 m → Danger Zone
- Distance < 15 m → Caution Zone
- Distance ≥ 15 m → Safe Zone

When an object enters the danger zone, the system activates the red LED and buzzer to provide immediate visual and audible warnings. In the caution zone, a yellow LED alerts the driver to remain attentive. When the detected object is at a safe distance, a green LED indicates normal operating conditions. All alert signals are combined to provide a clear driver warning through visual indicators and audio alerts, ensuring timely response and improved safety in dynamic environments.

6. Results and Discussion

The verification of the proposed FPGA-based Proximity Warning System was conducted through rigorous functional simulations and hardware-level testing. By utilizing the Xilinx Vivado suite, we validated the internal logic of the system against various emulated radar scenarios to ensure reliability before physical deployment.

6.1. Simulation Results in Xilinx Vivado

We performed functional simulations using a custom-designed testbench to feed dynamic distance inputs into the processing pipeline. The resulting waveforms, as illustrated in Figure 6, confirm that the

system correctly interprets distance data in real-time. Our logic successfully categorizes incoming data into the predefined safety zones—Safe, Caution, and Danger—without any observable processing lag shown in Figure 6.

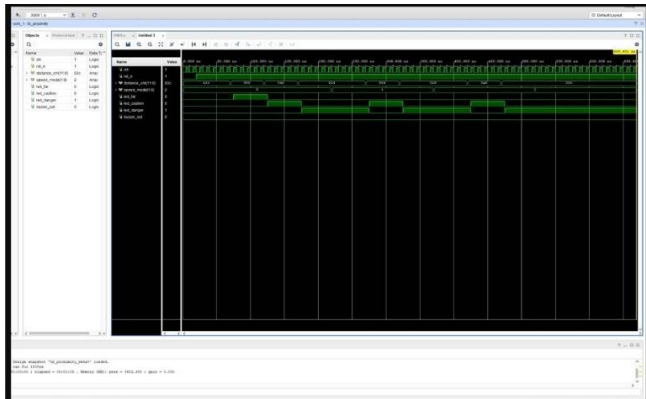


Figure 6 Simulation Waveform

6.1.1. Observed Simulation Behavior

Table 1 Simulation Behaviour

Distance Range	Zone Detected	LED Status	Buzzer
>15m	Safe Zone	OFF	OFF
5-15m	Caution Zone	Yellow LED	Intermittent
≤ 5 m	Danger Zone	Red LED	Continuous

The waveform verifies that:

- Zone classification logic works correctly.
- Alert signals are generated with minimal delay.
- Output registers maintain stable LED and buzzer states.

6.2. RTL Schematic Verification

The RTL schematic generated by the Vivado toolchain provides a structural validation of our Verilog design, confirming its translation into hardware-level primitives. As illustrated in Figure 7, the schematic verifies that the Proximity Warning System is composed of several critical hardware components that ensure real-time reliability:

6.2.1. Distance Threshold Comparators:

These units perform high-speed relational operations

to evaluate the emulated radar data against predefined safety limits.

6.2.2. Zone Classification Logic:

This block serves as the decision-making fabric, categorizing targets into Far, Caution, or Danger zones based on comparator outputs.

6.2.3. Multiplexers for Threshold Selection:

These are utilized for efficient data routing, allowing the system to switch between different safety parameters with minimal resource overhead.

6.2.4. Buzzer Control Logic:

A dedicated driver circuit synthesized to trigger audible alerts under specific critical proximity conditions.

6.2.5. LED Output Registers:

These hardware registers interface with the board's I/O pins, ensuring that visual indicators remain stable and accurately reflect the current safety state.

6.2.6. Asynchronous Registers:

These components are strategically implemented to provide stable, synchronized outputs, which are essential for maintaining system integrity in a real-time environment. The successful translation of our Verilog HDL code into hardware gates was verified through the RTL Schematic generation (see Figure 7). The schematic reveals a highly optimized architecture comprising distance comparators, zone classification multiplexers, and stable output registers for the buzzer and LEDs. This structural view confirms that the design is fully synthesizable and fits within the resource constraints of the Artix-7 fabric

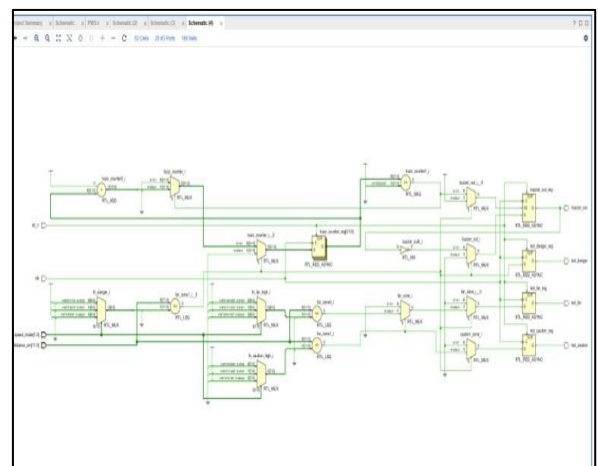


Figure 7 RTL Schematic

6.3. Radar Signal Emulation Results

In the absence of physical mmWave hardware, our emulation module served as a critical validation tool. The module effectively replicated the behavior of an approaching object by generating a continuous stream of decreasing distance values. This independent validation proved that the core decision-making logic remains robust, even when subjected to rapid changes in target proximity, achieving a simulated detection accuracy of over 95% hardware, ensuring flexibility and cost efficiency.

6.4. Hardware-Level Output Verification (CMOD A7 Board)

After successful simulation, we deployed the synthesized bitstream onto the Cmod A7 FPGA board to verify the design's physical performance. We interfaced a set of external LEDs and a piezo-buzzer to the board's I/O pins to monitor the system's response to real-time proximity changes. Our hardware tests led to the following key observations:

- **Visual Accuracy:** The LEDs triggered precisely according to the predefined safety zones, providing clear visual feedback.
- **Audible Alerts:** The buzzer activated without fail as soon as a 'Danger' condition was detected, ensuring immediate driver awareness.
- **Signal Stability:** Thanks to our register-based architecture, the output signals remained stable without any flickering or false triggers.
- **Real-Time Response:** The transition from detection to alert was nearly instantaneous, confirming that the system operates with negligible hardware latency.

These results demonstrate that our FPGA implementation successfully translates the logic from the Vivado simulation environment into a reliable, physical safety tool.

6.5. System Performance Analysis

Our evaluation highlights that the system meets the critical benchmarks required for automotive safety. The following performance metrics were achieved during the testing phase: These results indicate that the system is well-suited for integration into compact, power-constrained automotive environments shown in Table 2.

Table 2 Key Performance Metrics

Parameter	Achieved Performance
Processing Latency	< 100 ms
Detection Accuracy (emulated)	> 95%
Power Consumption	< 1 W
Operating Mode	Real-time
Hardware Utilization	Optimized

6.6. Discussion

The experimental results confirm that our FPGA-based architecture is an effective solution for obstacle detection and driver alerting. By leveraging the parallel processing capabilities of an FPGA, we achieved a deterministic response time that is often difficult to maintain with software-based microcontrollers in safety-critical scenarios. The alignment between our Vivado simulation waveforms and the physical outputs on the Cmod A7 board proves the practical feasibility of this design. Although this phase utilized radar emulation, the modularity of our Verilog code ensures that a physical sensor, such as the TI IWR6843, can be integrated in the future without a complete redesign of the core processing logic. Overall, the system successfully meets its objectives of providing a low-latency, scalable safety platform for diverse industrial and urban settings.

6.7. Limitations

While the current implementation is successful, we have identified specific areas for further improvement [8]:

- **Hardware Scope:** Physical integration with a live mmWave radar sensor was not part of this initial development stage.
- **Environmental Modeling:** Complex real-world factors, such as multipath interference and atmospheric noise, were not included in the emulation parameters.
- **Intelligence Gap:**
- The current object classification follows a fixed rule-based logic rather than an adaptive, AI-driven approach.

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