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Dynamic Distance Tracking Using Ultrasonic Sensor, MicroBlaze FPGA, and Node-RED for IoT Applications in Industry 4.0

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Abstract

This paper presents a dynamic distance tracking system for real-time monitoring of moving objects in Industry 4.0 environments. The system integrates a Pmod MAXSONAR ultrasonic sensor with a MicroBlaze soft-core processor implemented on an Artix-7 FPGA, and uses Node-RED as the IoT visualization platform. MicroBlaze serves as the central processing unit, handling sensor data acquisition, UART communication, and real-time data formatting. The sensor operates in continuous measurement mode, providing high-resolution distance measurements with an effective detection range suitable for industrial applications. Unlike static measurement approaches, the proposed system is specifically designed to track distance variations in dynamic scenarios, such as conveyor belts, robotic arms, and automated warehouses. Experimental validation demonstrates the system's ability to follow moving objects with high repeatability and low measurement noise. The system response time is sufficiently fast for non-critical industrial automation tasks. Compared to alternative technologies, FPGA-based architectures offer significant advantages in terms of determinism, reconfigurability, and low latency. The proposed solution offers a scalable, low-cost alternative to proprietary industrial systems, contributing to the digital transformation of manufacturing processes.

Keywords
Industry 4.0., FPGA, MicroBlaze, IoT, Node-RED

1. Introduction
Industry 4.0 drives the convergence of sensory systems, the Internet of Things (IoT), and reconfigurable computing to optimize the efficiency and flexibility of production processes. In this paradigm, real-time data acquisition is essential for monitoring operational variables, early fault detection, and intelligent production line automation. Ultrasonic sensors are widely used for distance measurement and object detection due to their low cost, reliability, and ease of interfacing.

However, modern production environments require dynamic tracking rather than traditional static measurements. Processes involving conveyor belts, robotic arms, and automated guided vehicles (AGVs) operate with constantly moving objects, while silo level monitoring involves continuously varying distances. Conventional measurement systems are not optimized for these dynamic scenarios, as they often introduce latency issues, low sampling rates, or lack of temporal determinism, compromising process control.

To mitigate these limitations, FPGA (Field-Programmable Gate Array) devices offer significant advantages for dynamic tracking applications in manufacturing, including true parallel processing, low deterministic latency, and dynamic reconfiguration capability. Among the available soft-core processors, AMD Xilinx's MicroBlaze stands out as a highly configurable 32-bit RISC architecture. This processor enables the implementation of complete embedded

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systems within the FPGA, with support for a wide range of peripherals (UART interfaces, timers, interrupt controllers, AXI bus interconnects) and real-time operating systems such as FreeRTOS. Its flexibility allows the architecture (cache size, memory interface, and performance) to be tailored to specific operational requirements, making it an ideal choice for Industrial IoT applications. In this work, MicroBlaze serves as the central processing unit, managing sensor data acquisition, UART communication, and real-time data formatting for subsequent transmission to Node-RED.

The combination of FPGA-based processing with IoT visualization platforms such as Node-RED provides a robust framework for developing flexible, scalable, and cost-effective tracking systems for operations management. Under this approach, this paper proposes an integrated solution for implementing a dynamic distance tracking system with IoT capabilities. Unlike previous proposals focused on static measurements or limited to the embedded system only, this work contributes to process optimization by: (1) detailing the complete hardware and software architecture for dynamic tracking; (2) presenting experimental validation under real dynamic operating conditions; and (3) providing quantitative performance metrics including sampling frequency, stability, and response time.

1.1 Research Objectives

The main objective is to design, implement, and validate a dynamic distance tracking system for real-time monitoring of moving objects, integrating an ultrasonic sensor with an FPGA-based MicroBlaze processor and the Node-RED IoT visualization platform. The specific objectives are: (1) to design and implement a hardware architecture based on an Artix-7 FPGA integrating the Pmod MAXSONAR sensor with MicroBlaze; (2) to develop embedded firmware for the MicroBlaze processor capable of acquiring real-time distance measurements, processing UART frames, and transmitting formatted values; (3) to integrate the system with Node-RED for IoT visualization; (4) to experimentally validate the system under dynamic conditions, quantifying sampling frequency, resolution, range, stability, and response time; and (5) to demonstrate its applicability in Industry 4.0.

2. Literature Review

The evolution of data acquisition systems has been marked by the transition from analog solutions to reconfigurable digital systems. FPGAs have emerged as a key technology in Industry 4.0 due to their real-time processing capabilities (AMD, 2023; Baste et al., 2016). Unlike ASICs, FPGAs allow field updates through partial reconfiguration, reducing development costs (Xilinx, 2018). The evolution of data acquisition systems has been marked by the transition from analog solutions to reconfigurable digital systems. FPGAs have emerged as a key technology in Industry 4.0 due to their real-time processing capabilities (Konorov, 2015; Baste et al., 2016). Unlike ASICs, FPGAs allow field updates through partial reconfiguration, reducing development costs (AMD, 2023; Xilinx, 2018).

Patil et al. (2010) developed a real-time data acquisition system using FPGA for control applications, highlighting its sampling speed advantage. Konorov (2015) presented an intelligent FPGA-based system for scientific instrumentation, and Baste et al. (2016) explored industrial applications. Magyari and Chen (2022) reviewed FPGA applications in IoT, concluding that soft-core processors with standardized peripherals offer optimal flexibility and performance. Al-Doori et al. (2023) presented a case study on FPGAs in smart factories, and Mencer et al. (2020) reviewed the history and future of FPGAs, emphasizing their parallel processing capabilities. Gupta (2024) explored their use in robotics.

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The Pmod MAXSONAR sensor, acquires data using thirteen 42 kHz beams. It offers 1.0-inch resolution up to 20 feet, with a range of 6 to 255 inches. It operates in free-run mode at 20 Hz, requiring 250 ms to power up and 49 ms for self-calibration (Digilent, 2020).

In IoT visualization, Node-RED has become a de facto tool for rapid prototyping. Uzougbo et al. (2024) demonstrated its effectiveness for real-time processing. Ferencz and Domokos (2020) applied it in machine supervision. Kodali and Anjum (2018) presented a home automation system. Thuluva and Anicic (2020) developed semantic Node-RED for industrial IoT. Bassetti et al. (2020) simplified its use in SeismoCloud. Nakanishi and Ide (2018) showed its corporate application, and Nieblas Manríquez et al. (2023) used it for motor control.

Low-cost data acquisition has been a recurring theme in the literature. Hakim et al. (2021) designed a system for solar plant monitoring. Kumar et al. (2022) presented a multi-sensor system for fault detection, reporting stabilities of ±1.0 to ±2.0 cm.

In Industry 4.0, Nwasuka et al. (2022) provided an overview of the paradigm. Hayat et al. (2023) introduced key concepts in blockchain. Ortiz et al. (2020) analyzed future trends. Alqoud et al. (2022) explored digitalization challenges. Ng et al. (2022) reviewed technology applications for sustainable manufacturing. FPGAs enhance IoT by enabling parallel processing, low latency, reconfigurability, energy efficiency, and flexible interfaces, supporting real-time applications, edge AI, and secure, scalable embedded system integration.

Although the FPGA has higher cost than Arduino, it offers determinism, high sampling frequency, low latency, and reconfigurability (Patil et al., 2010; Magyari and Chen, 2022). Compared to a PLC, the FPGA offers greater flexibility and lower cost (Al-Doori et al., 2023; Mencer et al., 2020).

3. Methods

The methodology is divided into four phases: hardware design, firmware development, Node-RED integration, and experimental procedure.

3.1 Hardware Design and Implementation

Figure 1 presents the general flowchart of the dynamic distance tracking system, illustrating the main stages of the measurement and data processing chain. The system operation begins with the Pmod MAXSONAR ultrasonic sensor, which is configured in continuous free-run mode. The sensor requires 250 ms to power up and performs an automatic self-calibration of 49 ms, after which it is ready to take readings every 49 ms, corresponding to a sampling frequency of approximately 20 Hz (Digilent, 2020).

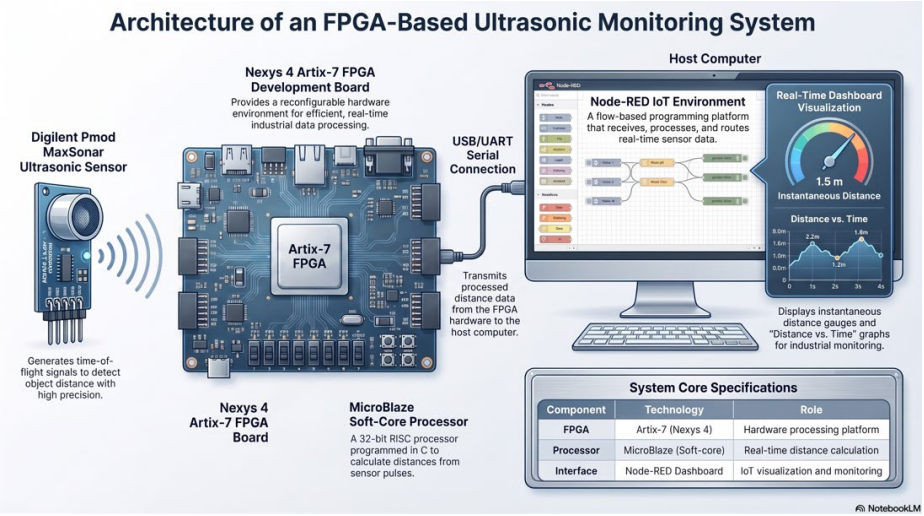


Figure 1. General flowchart of the dynamic distance tracking system

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The sensor communicates with the FPGA through a UART interface configured at 9600 baud, 8 data bits, no parity, and 1 stop bit (8N1). The acquired data is then transmitted to the MicroBlaze soft-core processor, which was instantiated in the Vivado 2019.1 environment with 8 KB of cache memory and a UART 16550 peripheral for serial communication. The MicroBlaze processes the incoming UART frames, extracts the distance value in inches, and formats it for transmission to the host PC. Finally, the data is sent via USB-UART to the Node-RED platform, where it is visualized in real time on a graphical dashboard. This streamlined workflow ensures low-latency data acquisition and real-time monitoring, making the system suitable for dynamic tracking

Figure 2 presents the Vivado block diagram of the implemented system, illustrating the hardware architecture and the interconnection of the main functional blocks. The system is built around the MicroBlaze soft-core processor, which serves as the central processing unit. The MicroBlaze is connected to a local memory block (BRAM) configured with 32 KB for instructions and 32 KB for data, ensuring fast access to critical firmware routines. The AXI Interconnect acts as the communication backbone, enabling high-speed data exchange between the processor and the integrated peripherals. Among these peripherals, the UART Lite core provides the serial communication interface with the Pmod MAXSONAR sensor, configured at 9600 baud, 8 data bits, no parity, and 1 stop bit. Additionally, a custom MAXSONAR controller IP was developed to manage the sensor's UART protocol and facilitate the acquisition of distance measurements. This modular and scalable architecture allows for easy reconfiguration and future expansion, such as the addition of new sensors or communication protocols.

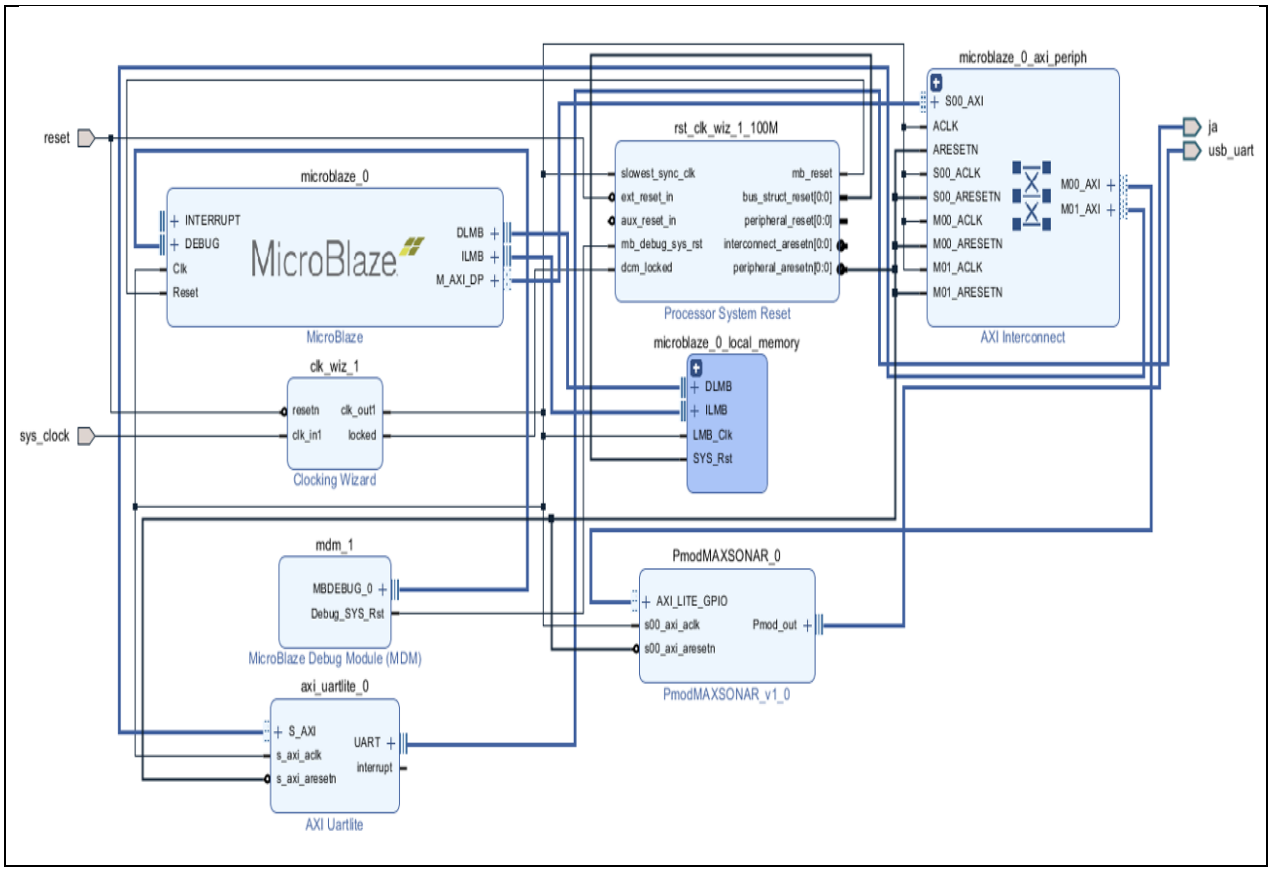


Figure 2. Vivado block diagram of the system.

3.2 MicroBlaze Firmware

Figure 3 presents a code snippet of the C firmware implemented on the MicroBlaze processor, which was configured with a clock frequency of 100 MHz and 32 KB of BRAM for instruction and data storage. The firmware is responsible for managing the communication with the Pmod MAXSONAR sensor, processing the incoming data

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frames, and transmitting the formatted distance measurements to the host system. The main loop follows a simple sequence: (1) it waits for the reception of a 5-byte UART frame from the sensor; (2) it validates the frame structure and extracts the distance value in inches; and (3) it formats and transmits the measurement to the host PC via UART. The processing time for each frame is less than 100 µs, ensuring that the system does not introduce significant latency beyond the sensor's measurement cycle (approximately 50 ms). This streamlined firmware design supports real-time data acquisition and low-latency communication, which are critical for dynamic tracking applications."

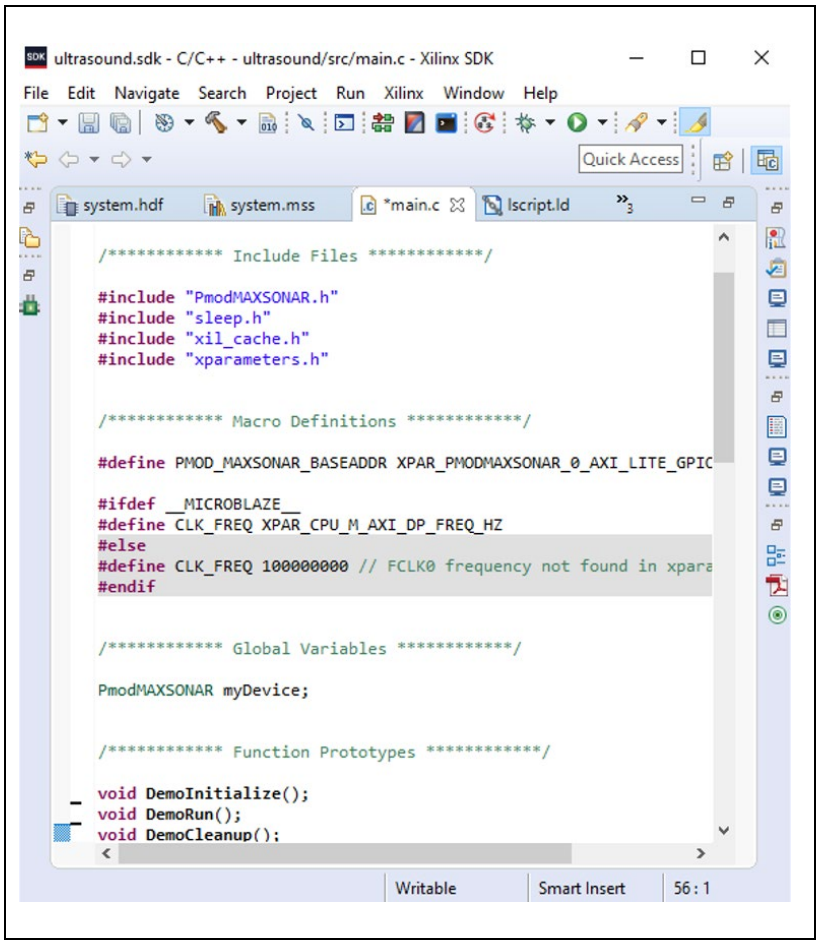


Figure 3. C code snippet for distance measurement in MicroBlaze.

3.3 IoT Integration with Node-RED

Figure 4 illustrates the Node-RED processing flow implemented for data acquisition and real-time visualization. On the host PC, Node-RED is configured to receive the distance measurements transmitted by the FPGA via the USB-UART connection. The flow begins with a serial input node, which reads the incoming data frames. Next, a function node processes the raw data by applying a regular expression to extract the numeric distance value. This value is then routed to two visualization nodes: a circular gauge that displays the instantaneous distance in real time, and a line chart that plots the temporal evolution of the measurements. This configuration enables operators to monitor both current and historical distance data simultaneously. Additionally, Node-RED allows the creation of interactive dashboards and the implementation of SCADA-like functions, such as data logging, alarm generation, and remote monitoring, making it a versatile tool for industrial IoT applications.

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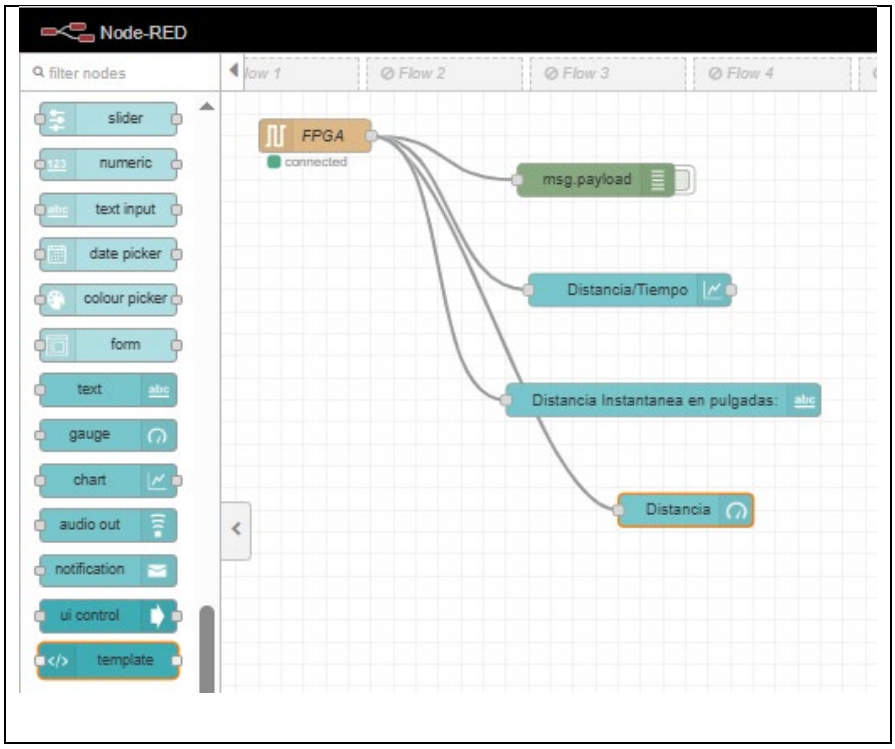


Figure 4 shows the Node-RED processing flow.

3.4 Experimental Procedure

The experimental procedure was designed to validate the system's dynamic tracking capability under realistic operating conditions. In this setup, the Pmod MAXSONAR sensor was fixed in position, while a target object was manually moved toward and away from the sensor, covering an approximate distance range of 25 to 100 inches. This range was selected to represent typical industrial scenarios, such as object presence detection on conveyor belts or fill-level monitoring in containers. During the experiment, the sensor operated in continuous free-run mode, generating one measurement every 49–50 ms, which corresponds to an effective sampling frequency of approximately 20 Hz. A total of 4,800 distance measurements were recorded and automatically logged by the Node-RED platform. The experiment was conducted at a controlled ambient temperature of approximately 25°C to minimize the influence of temperature variations on the speed of sound. To evaluate the repeatability and stability of the system, a segment of the measurement where the object remained stationary (approximately 73 inches) was isolated for statistical analysis. This segment was used to calculate the standard deviation and assess the measurement noise under static conditions.

4. Data Collection

Data were collected using the dynamic distance tracking system described in Section 3. The Pmod MAXSONAR sensor operated in continuous free-run mode. During the experiment, the object was manually moved toward and away from sensor, covering a distance range of approximately 25 to 100 inches. All measurements were captured in real time by the MicroBlaze processor, which processed the incoming UART frames, extracted the distance value in inches, formatted the data, and transmitted it to the host PC via the USB-UART connection at 9600 baud. On the PC side, Node-RED was configured to receive the serial data, parse the incoming frames, and display those values on screens. Throughout the entire data collection process, no data loss or transmission errors were observed, confirming the robustness and reliability of the communication link between the FPGA and the host system.

5. Results and Discussion

5.2 Graphical Results

Figure 5 presents a detailed view of the Node-RED Dashboard during the static experiment, where the sensor remained stationary at a fixed distance of approximately 73 inches from the target object. The dashboard displays

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four synchronized visualization components: (a) a circular gauge showing the instantaneous distance, (b) a line chart plotting the temporal evolution of the measurement, (c) a digital readout of the current value, and (d) a zoomed-in segment of the stable region. All four graphs consistently indicate a measurement of 73 inches, with minimal fluctuation, validating the system's measurement consistency and reliability. This concordance across multiple visualization formats demonstrates that, from a single data source received via the USB-UART connection, the system delivers coherent and repeatable values. The stability observed in this segment, confirms the low noise level and high repeatability of the system under static conditions. This performance is critical for applications requiring precise and stable measurements over extended periods, such as continuous level monitoring in industrial silos or long-term structural health monitoring

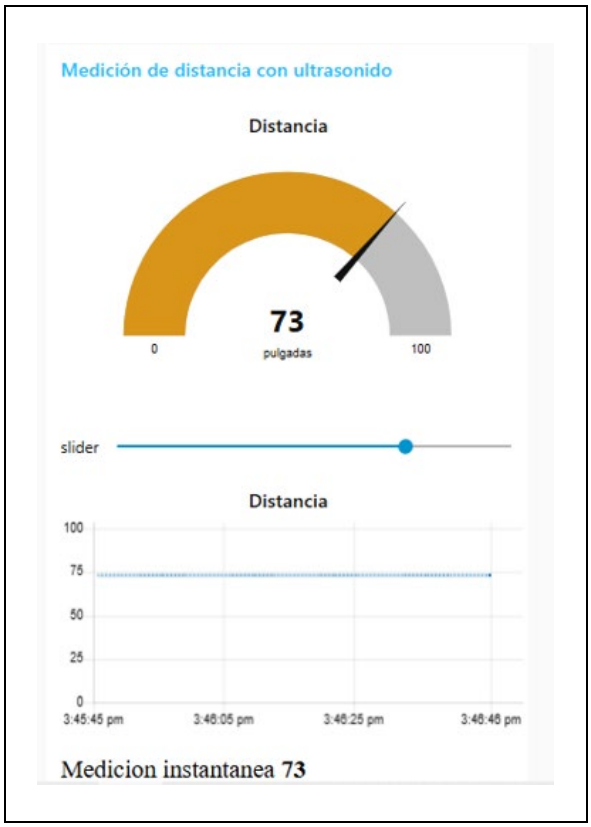


Figure 5 Static measurement with simultaneous graph display

Figure 6 illustrates the dynamic behavior of the ultrasonic sensor as an object moves toward and away from the fixed sensor over time. The line chart, generated by the Node-RED Dashboard, displays the distance measurements recorded continuously during the experiment. As the object approaches the stationary sensor, the distance value decreases, reaching a minimum of approximately 25 inches. Conversely, as the object moves away, the distance increases up to approximately 100 inches. The smooth and continuous variation of the curve demonstrates the system's capability to track real-time changes in distance with high fidelity and low latency. The absence of abrupt jumps or signal dropouts in the graph confirms the stability and reliability of the data acquisition and transmission chain, from the fixed sensor to the FPGA-based processing and the final visualization in Node-RED. This dynamic response is essential for applications such as conveyor belt monitoring, robotic arm positioning, and automated warehouse tracking, where objects are in constant motion.

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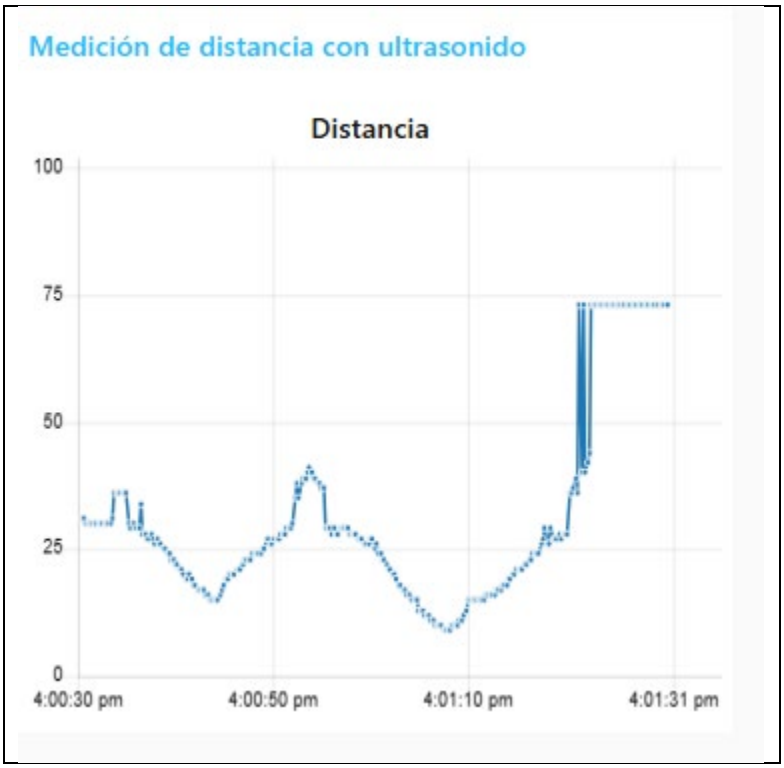


Figure 6. The dynamic behavior of the system.

Figure 7 presents the simultaneous display of the three main graphs available on the Node-RED Dashboard, offering a comprehensive view of the system's real-time performance. The dashboard integrates three complementary visualization tools: (a) a circular gauge that provides an instantaneous reading of the current distance (73 inches in this capture), (b) a line chart that plots the temporal evolution of the distance over the measurement period, and (c) a digital display that shows the instantaneous value in numeric format. This integrated visualization strategy enables operators to monitor both the current state and the historical behavior of the measured variable simultaneously, facilitating the detection of trends, patterns, or anomalies in the process. The real-time updating capability of the dashboard ensures that operators can react promptly to changes in the monitored environment, making it a valuable tool for industrial supervision and control applications.

The results validate the six research objectives. The hardware architecture was successfully implemented, achieving the integration of the ultrasonic sensor with MicroBlaze. The firmware proved reliable in acquiring and processing distance measurements consistently. Node-RED correctly visualized real-time data, facilitating continuous monitoring. Experimental validation confirmed a dynamic tracking range of 25 to 100 inches with stability, demonstrating its applicability in Industry 4.0 environments.

The comparative analysis reveals that, although the FPGA-based solution entails a higher initial cost compared to some alternative platforms, it offers decisive advantages for dynamic tracking applications, including low

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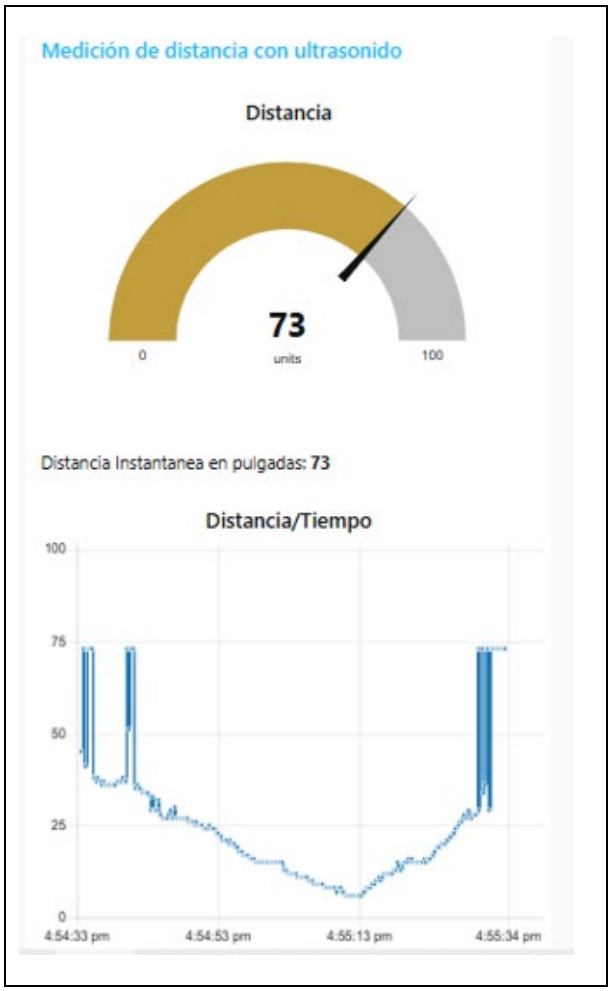


Figure 7. Dynamic measurement with instantaneous distance readings and temporal evolution, showing the simultaneous display of the three Node-RED dashboard graphs

The comparative analysis reveals that, although the FPGA-based solution entails a higher initial cost compared to some alternative platforms, it offers decisive advantages for dynamic tracking applications, including low deterministic latency, high sampling frequency, and hardware reconfigurability. These features are essential for real-time monitoring and control in industrial environments, where response time and system adaptability are critical factors. A limitation identified in this study is that the evaluated dynamic range (25–100 inches) is narrower than the sensor's theoretical detection range (6–255 inches). This discrepancy is primarily attributed to the manual movement constraints during the experiment, rather than to system performance limitations. Future work will focus on extending the experimental range to fully explore the sensor's capabilities and validate the system's performance across its entire operational spectrum.

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6. Conclusion

A dynamic distance tracking system based on FPGA and Node-RED for Industry 4.0 has been designed, implemented, and validated. The system achieves 20 Hz sampling frequency and 1.0-inch resolution, suitable for tracking moving objects on conveyor belts, robotic arms, and dynamic control systems.

The five research objectives were successfully achieved. Results confirm a dynamic range of 25 to 100 inches with ±0.5 inches stability and response time below 100 ms. The maximum range of 20 feet provides broad coverage for industrial monitoring (Figure 8).

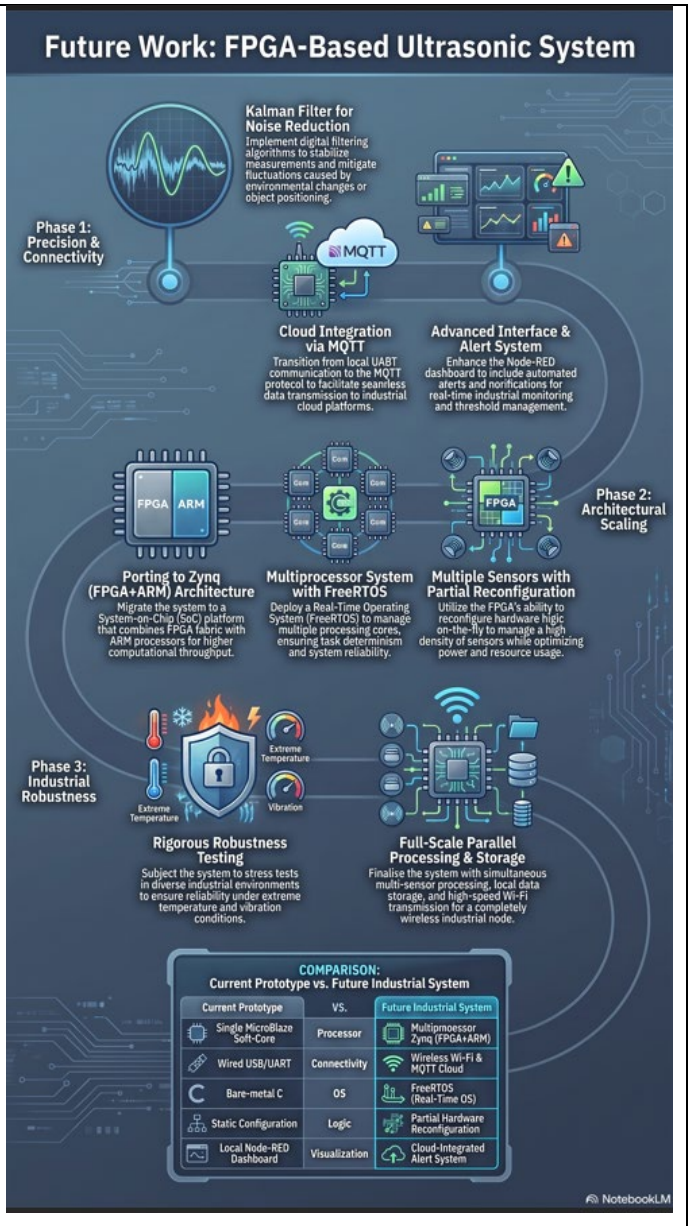


Figure 8. Future work flowchart, showing the eight proposed improvement lines.

The proposed system, specifically validated for dynamic tracking applications, offers significant advantages over conventional static measurement systems. These advantages include deterministic behavior, which ensures predictable and reliable response times; high sampling frequency (20 Hz), enabling the tracking of moving objects

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with adequate temporal resolution; low latency (< 100 ms), suitable for real-time monitoring in non-critical industrial applications; and hardware reconfigurability, which allows the system to be updated or adapted to new requirements without replacing the hardware. The detailed documentation of the complete architecture hardware, firmware, and software along with the experimental validation under dynamic conditions, provides a replicable framework that can be adopted by researchers and practitioners interested in implementing low-cost, FPGA-based tracking solutions for Industry 4.0 applications.

Future work will focus on further enhancing the system's capabilities and expanding its application scope. The following improvement lines are proposed: (1) implement a Kalman filter on the MicroBlaze processor to reduce measurement noise and improve tracking precision; (2) integrate the system with cloud platforms using the MQTT protocol to enable remote monitoring and historical data storage; (3) incorporate multiple ultrasonic sensors through partial FPGA reconfiguration to enable 3D measurement and multi-point tracking; (4) port the system to a Zynq platform (FPGA+ARM) to improve energy efficiency and support more complex processing tasks; (5) conduct robustness tests with objects of different materials, shapes, and colors, as well as under varying environmental conditions (temperature, humidity, and lighting); (6) develop an advanced user interface with an intelligent alert system for industrial applications; (7) implement a multiprocessor system for parallel processing using the FreeRTOS real-time operating system; and (8) develop a multi-sensor ultrasonic system with parallel processing, enabling real-time visual monitoring of multiple variables, with data storage and Wi-Fi transmission capabilities. These enhancements will extend the system's applicability to a wider range of industrial scenarios, including predictive maintenance, autonomous navigation, and smart logistics. Figure 8 presents a flowchart summarizing these eight proposed improvement lines

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Biographies

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