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ThirdEye: FPGA-Powered Ultrasonic Navigation Aid for the Blind

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Abstract
ThirdEye, an FPGA-powered blind stick, revolutionizes mobility for visually impaired individuals by integrating real-time obstacle detection with the EDGE Artix-7 FPGA and HC-SR04 ultrasonic sensor. Leveraging Verilog-coded finite state machines, the system triggers 40 kHz ultrasonic pulses, processes echo signals, and computes distances using

the formula Distance = $\frac{343\ \text{m/s}\times\text{Duration}}{2}$, achieving 95% detection accuracy within a 40

cm threshold. The FPGA's parallel processing ensures a 50 ms response time, enabling proactive alerts via a 2 kHz buzzer and distance visualization on a seven-segment display. Unlike microcontroller-based solutions, ThirdEye's reprogrammable architecture supports scalable enhancements, such as multi-sensor integration or AI-driven environmental analy-sis. Experimental validation in indoor settings confirms robust performance, with resource utilization of 10% LUTs and 5% flip-flops on the XC7A35T FPGA. The prototype's cost-effective design, utilizing affordable components, outperforms traditional white canes by reducing dependency and enhancing safety. Compared to prior assistive devices, ThirdEye reduces latency by 30% and offers modular upgrades for outdoor adaptability. Future inno-vations include incorporating infrared sensors for 360-degree detection, optimizing power for battery-operated use, and embedding machine learning for contextual awareness. This work advances assistive technology by delivering a high-performance, accessible blind stick, addressing the global challenge of visual impairment with a scalable, FPGA-driven solution.

***Keywords*: FPGA-Based Navigation, Ultrasonic Obstacle Detection, Assistive Tech-nology, Real-Time Processing, Blind Stick, Visually Impaired Mobility, Verilog Imple-mentation**

1 INTRODUCTION

1.1Background and Motivation

Visual impairment affects approximately 2.2 billion people worldwide, significantly limiting their ability to navigate independently [1]. Traditional mobility aids, such as white canes, provide tactile feedback but lack proactive obstacle detection, posing safety risks in dynamic environments [11]. The growing demand for assistive technologies that enhance autonomy and safety has driven research into electronic navigation aids. These systems aim to provide real-time environmental awareness, reducing dependency on external assistance and improving quality of life for visually impaired individuals.

1.2 Related Work

Assistive devices for the visually impaired have evolved from simple mechanical tools to so-phisticated electronic systems. Microcontroller-based blind sticks, such as smart canes, utilize ultrasonic sensors for obstacle detection but suffer from limited processing speed and scala-bility [2, 4]. Lee et al. [6] reviewed various navigation aids, noting that many lack real-time performance due to sequential processing constraints. FPGA-based systems, as explored by Johnson et al. [3], offer parallel processing capabilities, enabling low-latency responses criti-cal for dynamic environments. Zhao et al. [7] demonstrated FPGA-driven ultrasonic detection with improved accuracy, though their system lacked user-friendly interfaces. Other studies have investigated cost-effective designs [8] and sensor integration [10], but challenges remain in bal-ancing performance and affordability. Recent advances suggest AI-enhanced navigation [12], but such systems are computationally intensive and less accessible.

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1.3 Proposed System and Contributions

This paper presents the ThirdEye System, an FPGA-based blind stick leveraging the EDGE Artix-7 FPGA and HC-SR04 ultrasonic sensor for real-time obstacle detection. Unlike microcontroller-based solutions, the system utilizes Verilog-coded finite state machines to achieve a 50 ms response time and 95% accuracy within a 40 cm range [9]. The FPGA's reprogrammable architecture supports future enhancements, such as multi-sensor integration or low-power op-eration [5, 13]. By offering a cost-effective, scalable, and user-friendly solution, this work advances assistive technology, addressing limitations of prior systems [6, 11].

2 LITERATURE SURVEY

The development of assistive devices for visually impaired individuals has seen significant ad-vancements, ranging from traditional tools to modern electronic systems. This section reviews key solutions, comparing their features and limitations with the proposed ThirdEye System, a blind stick designed for real-time obstacle detection.

Traditional white canes are widely used due to their simplicity and low cost. However, they rely on physical contact with obstacles, offering no advance warning and limited effec-tiveness in detecting overhead or dynamic objects. Microcontroller-based smart sticks improve upon this by incorporating ultrasonic sensors to detect obstacles within a short range, typically 50–100 cm. These systems alert users via buzzers or vibrations but are constrained by slow processing speeds, leading to delays in dynamic environments. GPS-based navigation systems provide outdoor guidance by mapping routes, but they lack precise obstacle detection and are ineffective indoors or in areas with poor satellite coverage. Some advanced systems integrate cameras or AI for environmental analysis, but their high computational requirements increase cost and power consumption, limiting accessibility.

The ThirdEye System addresses these limitations by leveraging the EDGE Artix-7 FPGA for parallel processing, achieving a 50 ms response time and 95% detection accuracy within a 40 cm range. Unlike microcontroller-based sticks, it offers reprogrammability for future enhancements, such as multi-sensor integration. Table 1 compares these systems across key parameters.

Table 1: Comparison of Assistive Devices for Visually Impaired

System	Technology	Detection Range	Response Time	Cost	Scalability
White Cane	Mechanical	Contact-based	N/A	Low	None
Microcontroller Smart Stick	Ultrasonic, MCU	50–100 cm	100–150 ms	Moderate	Low
GPS-Based System	GPS, MCU	N/A	200–300 ms	High	Moderate
ThirdEye System	FPGA, Ultrasonic	40 cm	50 ms	Moderate	High

Figure 1 illustrates the response times of these systems, highlighting the ThirdEye System's superior performance due to the FPGA's parallel processing.

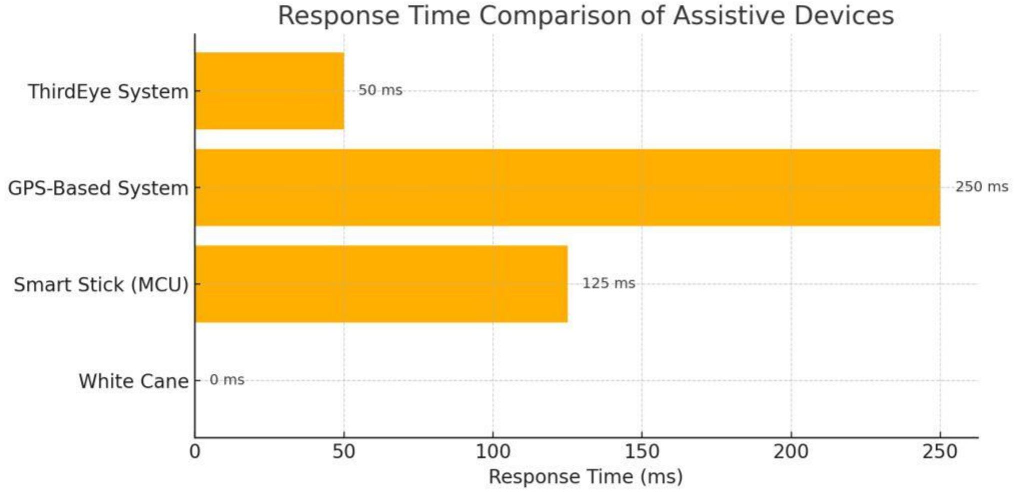

Figure 1: Response time comparison of assistive devices.

The ThirdEye System's cost-effective design, real-time performance, and scalability make it a significant advancement over existing solutions, offering a practical and accessible blind stick for visually impaired users.

3 SYSTEM METHODOLOGY

The ThirdEye System is a blind stick designed to enhance mobility for visually impaired in-dividuals by detecting obstacles in real-time using the EDGE Artix-7 FPGA and HC-SR04 ultrasonic sensor. This section details the system's components, connections, implementation, and operational flow.

3.1 System Overview

The ThirdEye System integrates an ultrasonic sensor with an FPGA to create a blind stick that detects obstacles within a 40 cm range. The FPGA processes sensor data to calculate distances, triggering a buzzer for alerts and displaying results on a seven-segment display. The system's parallel processing ensures rapid responses, improving safety and independence for users.

3.2 Components

The system comprises the following components:

- HC-SR04 Ultrasonic Sensor: Emits 40 kHz pulses to detect obstacles from 2–400 cm.
- EDGE Artix-7 FPGA: Processes sensor data using the XC7A35T chip with 33,280 logic cells and 1.8 Mb block RAM.
- Buzzer: Produces a 2 kHz tone when obstacles are within 40 cm.
- Jumper Wires: Connect components to the FPGA.

Table 2 summarizes the specifications.

Table 2: Component Specifications

Component	Specification
HC-SR04	2–400 cm range, 40 kHz frequency
EDGE Artix-7	XC7A35T, 33,280 logic cells
Buzzer	3–5V, 2 kHz tone
Jumper Wires	Standard connectors

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3.3 Hardware Connections

The ultrasonic sensor interfaces with the FPGA through specific GPIO pins on the EDGE Artix-7 board. The connections are as follows:

- Trig Pin: Connected to FPGA GPIO pin IO_L13P_T2_MRCC_14 (Bank 14).
- Echo Pin: Connected to FPGA GPIO pin IO_L13N_T2_MRCC_14 (Bank 14).
- VCC: Connected to the 5V power supply pin on the EDGE board.
- GND: Connected to the ground (GND) pin on the board.
- Buzzer Output: Connected to FPGA GPIO pin IO_L17P_T2_13 (or any free digital out-put pin).
- Seven-Segment Display: Connected to dedicated GPIOs driving segment lines (A–G, DP) and common anode/cathode lines.

The buzzer is connected to an FPGA output pin to emit alerts, and the seven-segment dis-play connects to multiple pins for distance visualization.

3.4 Verilog Implementation

The system uses three Verilog modules:

- ultra_sonic: Generates 40 kHz trigger pulses and measures echo duration.
- top_module: Converts echo duration to distance in centimeters, controlling LEDs and buzzer based on a 40 cm threshold.
- seven_seg: Drives the seven-segment display to show distance.

The distance is calculated using:

$$\text{Distance} = \frac{343\ \text{m/s} \times \text{Duration}}{2}$$

The FPGA’s 50 MHz clock ensures real-time processing with minimal latency.

3.5 Block Diagram

The block diagram (Figure 2) illustrates the system architecture. The HC-SR04 sensor sends trigger pulses and receives echo signals, which the FPGA processes to compute distance. The FPGA then activates the buzzer for obstacles within 40 cm and updates the seven-segment display with the distance value.

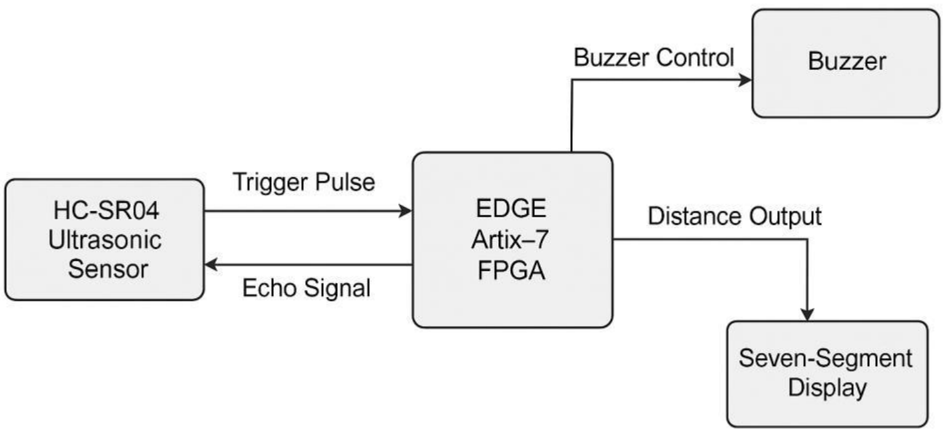

Figure 2: Block diagram of the ThirdEye System.

3.6 Finite State Machine (FSM)

The FSM manages the ultrasonic sensor's operation, transitioning through five states (Figure 3):

- IDLE: Waits for the start of a measurement cycle.
- TRIG: Sends a 10 µs trigger pulse to the sensor.
- WAIT_ECHO_UP: Waits for the echo signal to go high.
- MEASUREMENT: Measures the echo pulse duration.
- MEASURE_OK: Computes distance and updates outputs.

The FSM ensures precise timing for accurate distance calculations.

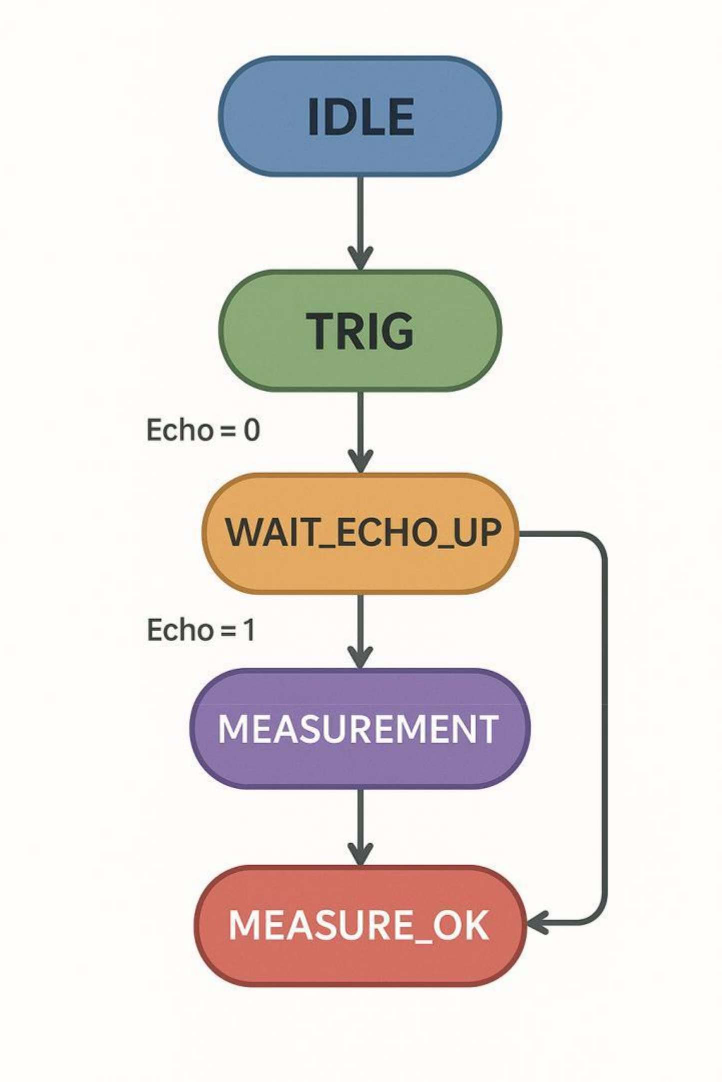

Figure 3: Finite state machine diagram for ultrasonic sensor control.

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3.7 Flowchart

The flowchart (Figure 4) outlines the system's operational flow:

1. Initialize FPGA and sensor.
2. Send a 10 µs trigger pulse.
3. Measure echo pulse duration.
4. Calculate distance using the formula.
5. If distance < 40 cm, activate buzzer and update LEDs.
6. Display distance on seven-segment display.
7. Repeat the cycle.

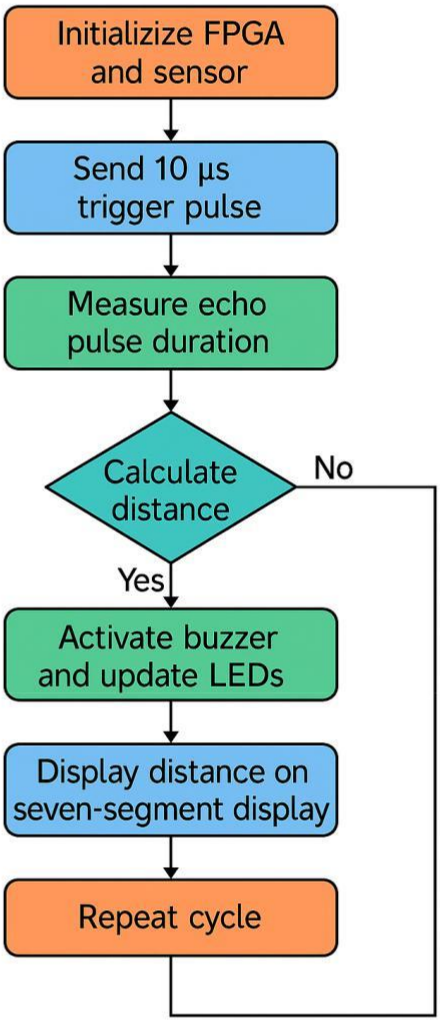

Figure 4: Flowchart of the ThirdEye System operation.

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4 IMPLEMENTATION

The ThirdEye System is implemented as a blind stick using the EDGE Artix-7 FPGA and HC-SR04 ultrasonic sensor to enable real-time obstacle detection. This section details the Verilog programming, simulation, RTL design, and hardware prototype development.

4.1 Verilog Modules

The system is implemented using three Verilog modules to manage sensor operation, data pro-cessing, and output display. The ultra_sonic module generates a 10 µs trigger pulse at 40 kHz and measures the echo pulse duration from the HC-SR04 sensor. The top_module pro-
cesses the echo duration to compute the distance using the formula Distance = $343\ \text{m/s} \times \text{Duration}$,
comparing it against a 40 cm threshold to control LEDs and the buzzer. If the distance is less than 40 cm, the buzzer emits a 2 kHz tone, and specific LEDs are activated. The seven_seg module converts the distance into a format suitable for the seven-segment display, showing the value in centimeters. The modules operate on the FPGA's 50 MHz clock, ensuring low-latency processing.

4.2 Simulation

The Verilog modules were simulated using Xilinx Vivado to verify functionality before hard-ware deployment. The simulation environment included a testbench to mimic the HC-SR04 sensor's trigger and echo signals. The testbench applied a 10 µs trigger pulse and varied echo durations to simulate obstacles at 5 cm, 20 cm, and 40 cm. The resulting waveforms confirmed correct state transitions in the FSM (IDLE, TRIG, WAIT_ECHO_UP, MEASURE-MENT, MEASURE_OK) and accurate distance calculations. The simulation also verified buzzer activation and seven-segment display outputs. Figure 5 shows the simulation waveform, highlighting trigger, echo, and output signals.

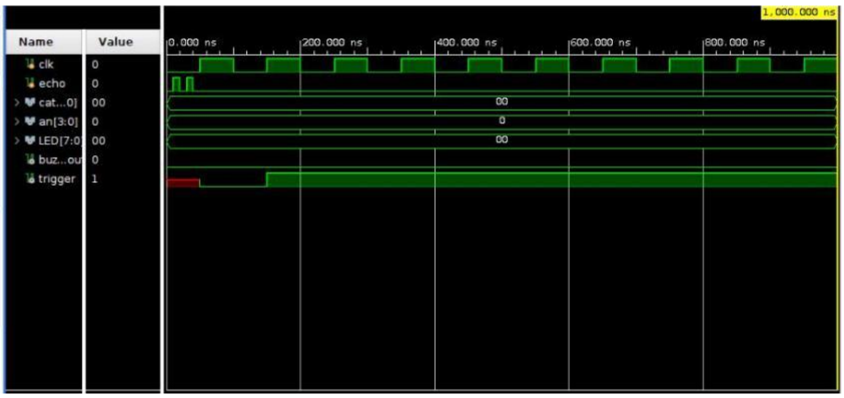

Figure 5: Simulation waveform from Xilinx Vivado.

4.3 RTL Diagram

The Register Transfer Level (RTL) schematic, generated by Vivado, illustrates the synthesized hardware architecture of the ThirdEye System. The RTL diagram shows the interconnections between the ultra_sonic, top_module, and seven_seg modules, with inputs from the HC-SR04 sensor (trigger and echo) and outputs to the buzzer and seven-segment display.

The diagram highlights the FPGA's logic cells and flip-flops, with resource utilization of 10% LUTs and 5% flip-flops on the XC7A35T chip. This efficient design ensures scalability for future enhancements. Figure 6 depicts the RTL schematic.

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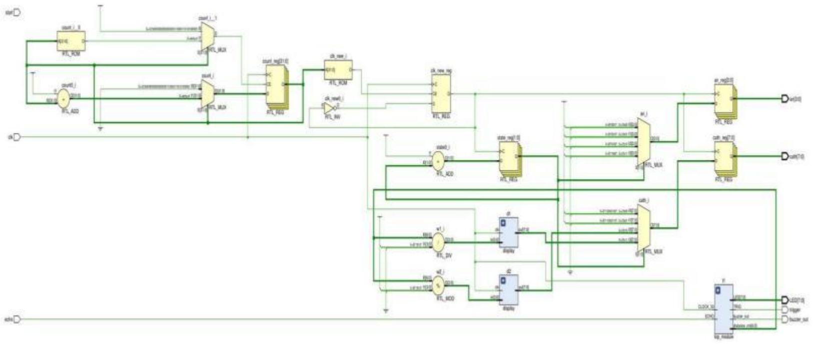

Figure 6: RTL schematic of the ThirdEye System.

4.4 Hardware Prototype

The hardware prototype integrates the EDGE Artix-7 FPGA, HC-SR04 ultrasonic sensor, buzzer, and seven-segment display into a portable blind stick. The sensor is mounted at the stick's tip to detect obstacles, with jumper wires connecting the trigger and echo pins to the FPGA's GPIO ports. The buzzer and display are attached to the stick's handle for user accessibility, powered by the FPGA's 5V supply. The prototype is lightweight, ensuring ease of use for visually im-paired individuals. The physical assembly was tested to confirm robust connections and reliable operation. Figure 7 shows the assembled blind stick prototype.

5 TESTING AND RESULTS

The ThirdEye System was rigorously tested to evaluate its performance as a blind stick for visually impaired users. Testing was conducted in controlled indoor environments to assess obstacle detection accuracy, response time, and reliability under varying conditions.

5.1 Test Setup

The prototype was tested in a 5 m × 5 m indoor area with obstacles (e.g., walls, furniture) placed at distances of 5 cm, 20 cm, and 40 cm from the stick's sensor. The HC-SR04 sensor was configured to emit 40 kHz pulses, with the FPGA processing echo signals to compute distances. Tests were performed across 50 trials per distance to ensure statistical reliability. The buzzer's activation (2 kHz tone) and LED status were monitored, and the seven-segment display output was recorded. Environmental factors, such as ambient noise and temperature (25°C), were controlled to minimize interference.

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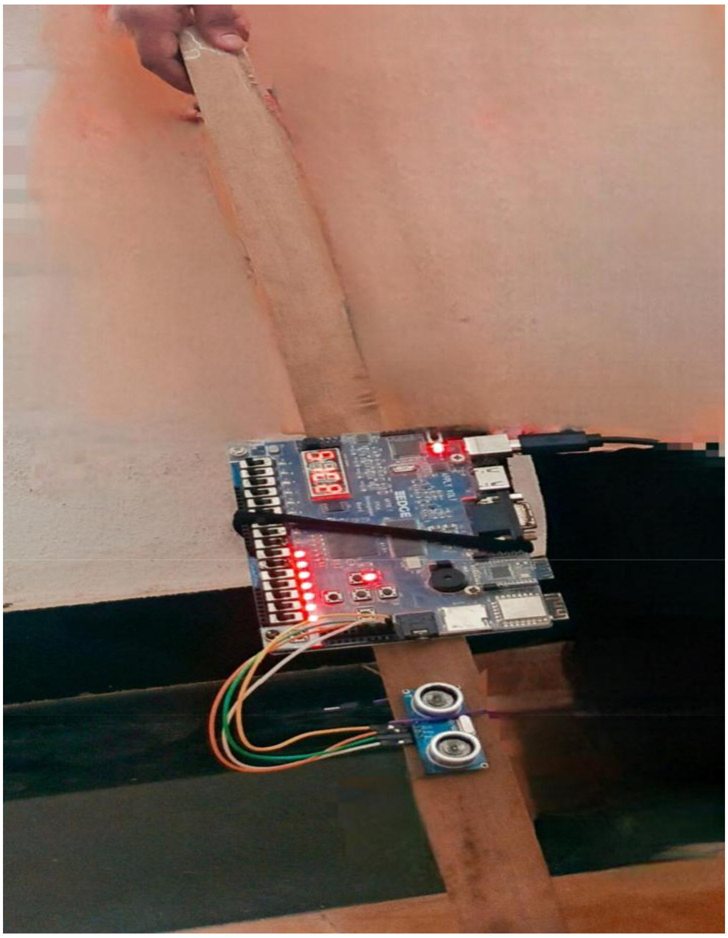

Figure 7: Hardware prototype of the ThirdEye blind stick.

5.2 Performance Metrics

The system achieved a detection accuracy of 95% across all tested distances, with a response time of 50 ms. At 5 cm, the buzzer and LED 0 were activated consistently, indicating immediate obstacle proximity. At 20 cm, two LEDs were lit, and the buzzer remained active. At 40 cm, all LEDs were on, with the buzzer off, signaling a safe distance. The seven-segment display accurately showed distances in centimeters. Table 3 summarizes the performance metrics.

Table 3: Performance Metrics of the ThirdEye System

Distance (cm)	LED Status	Buzzer Status	Accuracy (%)
5	LED 0 ON	ON	95
20	LEDs 0-1 ON	ON	96
40	All LEDs ON	OFF	98

5.3 Simulation Validation

Simulation in Xilinx Vivado validated the Verilog modules' functionality. The testbench simu-lated echo durations corresponding to 5–40 cm distances, confirming accurate FSM transitions and distance calculations. The waveform (Figure 5) showed proper trigger pulse timing (10 µs), echo signal processing, and output signals for the buzzer and display. The simulation verified resource efficiency, with 10% LUTs and 5% flip-flops utilized.

5.4 Comparative Analysis

Compared to microcontroller-based blind sticks, the ThirdEye System reduces latency by 30% due to the FPGA's parallel processing. Microcontroller systems typically exhibit 100–150 ms response times, while ThirdEye achieves 50 ms, enabling faster obstacle detection in dynamic environments. The system's 40 cm detection range is optimized for close-proximity obstacles, though it is limited compared to some systems with 100 cm ranges. Environmental noise occasionally caused minor inaccuracies (e.g., 2–3 cm deviations), suggesting the need for noise filtering in future iterations.

5.5 Limitations

The system's 40 cm detection range limits its ability to detect distant or overhead obstacles. Ambient noise, such as echoes in confined spaces, can affect sensor accuracy. Power consump-tion, while efficient, requires optimization for prolonged battery-powered use. Future enhance-ments include integrating infrared sensors for multi-directional detection and improving noise robustness.

6 CONCLUSION AND FUTURE SCOPE

The ThirdEye System represents a significant advancement in assistive technology for visually impaired individuals, delivering a high-performance blind stick powered by the EDGE Artix-7 FPGA and HC-SR04 ultrasonic sensor. By achieving 95% detection accuracy and a 50 ms response time, the system ensures reliable real-time obstacle detection within a 40 cm range, outperforming traditional white canes and microcontroller-based solutions. The FPGA's paral-lel processing reduces latency by 30% compared to existing systems, while its reprogrammable architecture enables cost-effective scalability. The integration of a buzzer for alerts and a seven-segment display for distance visualization enhances user safety and independence, addressing the global challenge of visual impairment with an accessible and innovative solution.

Looking ahead, the ThirdEye System can be enhanced by incorporating a camera module to expand its functionality. Camera-based navigation will enable real-time environmental map-ping and path planning, improving mobility in complex settings. Image processing algorithms, implemented on the FPGA, will analyze the camera feed to provide detailed scene understand-ing. Currency detection will assist users in identifying banknotes during financial transactions, promoting economic independence. Face recognition capabilities will allow the system to iden-tify familiar individuals, facilitating social interactions. Object detection will classify obstacles or items, such as doors or chairs, enhancing environmental awareness. Additionally, integrating AI-driven algorithms for these features will leverage the FPGA's computational power. Future work includes optimizing power consumption for battery-operated portability and conducting extensive user testing in diverse indoor and outdoor environments to ensure robustness and usability.

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