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Intellihome: FPGA-Driven Smart Automation System

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Abstract- The Xilinx Zynq-7000 system on a chip (SoC) is the basis for the home automation system described in this article. The FSM logic processes the signals from the sensors (the fire sensor requires 5V digital and the buzzer 5-12V) using Verilog HDL. The RTL schematics and waveforms were validated using Cadence tools. The three-second detection threshold for fire and intruder alarms is one of the most important features, along with automatic lighting and temperature adjustment. The scalability of the modular system allows for the easy integration of more devices, which in turn increases functionality and security.

Keywords- FPGA (Field-Programmable Gate Array); Home Automation; Verilog HDL; Smart Sensors; Energy Efficiency.

I. INTRODUCTION

Innovations in home automation systems have been driven by the growing need for smart, safe, and energy-efficient dwellings. This study presents a home automation system that uses Field-Programmable Gate Arrays (FPGAs) to incorporate essential features including intruder alarms, temperature control, controlled lighting, and fire detection. By using FPGA technology, one may take use of its many benefits, including scalability, high-speed processing, and the capacity to execute several tasks concurrently, which allows for real-time responsiveness [1] [2]. Adding additional devices and capabilities into FPGA designs doesn't need major hardware modifications, unlike systems based on microcontrollers. Integrating ARM with programmable FPGA logic, the suggested solution makes use of a Xilinx Zynq-7000 system on a chip [3] [4]. Processing data from sensors in real time and controlling devices are both made easier by this design. Fire and gas detectors are standard, and security features like motion detectors, smart locks, and cameras make the system even more foolproof.

The system guarantees extensibility, dependability, and modularity by using Verilog HDL and FSM principles. A 3-second threshold detection period, for example, reduces reaction delays, while debouncing circuitry filters out sensor noise [5]. Using Cadence's tools, we were able to synthesize the system, validate its reliability under different situations, and build RTL schematics and simulate waveforms [6]- [7]. This study presents a home automation system that uses Field-Programmable Gate Arrays (FPGAs) to provide important features including automatic lighting, temperature control, and intruder warnings. It also detects and reports fires. The use of field-programmable gate arrays (FPGAs) allows for higher processing speeds, more scalability, and real-time responsiveness by executing several tasks simultaneously [1] [2]. New devices and functionality may be easily included into FPGA designs without requiring major hardware modifications, in contrast to systems based on microcontrollers. In addition, our solution combines energy-efficient techniques via improved power management, such as automatic lighting and temperature control, and places a special emphasis on modularity, which allows disparate subsystems to work cohesively. Previous work on energy-efficient automation, reliability predictions, and neural network-driven optimization in hardware design [1a][7a] provides the foundation upon which this study expands. FPGA-based smart systems are already very advanced.

II. LITERATURE SURVEY

Digital technology, especially Field-Programmable Gate Arrays (FPGAs), has been a major force in the development of home automation systems. Through the automation of common domestic tasks, these systems augment security, energy efficiency, and user comfort. FPGAs are perfect for energy-efficient solutions because of their reprogrammability, which allows for system upgrades, and their efficiency in executing complicated operations with low power consumption [8]. This makes them a key component in creating smarter and safer homes. A smart home system that utilizes FPGA technology and Verilog Hardware Descriptive Language (HDL) is shown in [9] within the context of security. Intelligent control of equipment like temperature, lighting, and fire/intruder detection is included into their design. Accurate modeling and simulation of system behavior is made possible using Verilog HDL. In a similar vein, [10] describes a Verilog-based home automation system that includes a thorough approach for synthesis, post-synthesis simulation, layout, placement, and routing to guarantee efficiency and performance. In [11], the authors investigate the possibility of integrating field-programmable gate arrays (FPGAs) with the IoT and present a design based on FPGAs that incorporates a local analytical engine linked to sensors and Wi-Fi using an ESP8266 chip. This system demonstrates the promise of FPGAs in scalable Internet of Things applications by supporting user-configurable rules and allowing real-time monitoring via a web application. Last but not least, [12] study the literature to find patterns and problems with things like programming difficulty, cost, and development time; this will provide you important information for using FPGAs in home automation.

SYSTEM DESIGN AND METHODOLOGY

A System-on-Chip (SoC) that blends ARM processor units with programmable FPGA logic, the Xilinx Zynq-7000 SoC, is used by the proposed home automation system [13]. The architecture allows for control and monitoring in real-time via the use of actuators, sensors, and communication modules. The field-programmable gate array (FPGA) is the brains of the operation, taking sensor inputs and sending them on to the various control devices. Fire alarms, motion detectors, and buzzers are all examples of hardware components. When they detect smoke or heat, the 5V fire sensors provide digital data to the FPGA for processing. By detecting intruders and sounding alarms, motion detectors increase security, while FPGA pins control outputs like buzzers and automatic lights. Input modules, which include a variety of sensors that provide digital signals, are the building blocks of the system design.

To guarantee stability and avoid false alarms, these signals are preprocessed in Verilog HDL using debouncing logic. For fire alarms, a new detecting method is used, which requires signals to remain for three seconds before activating. For effective management of sensor data and control of outputs, the centralized control unit makes use of FSM (Finite State Machine) principles in Verilog HDL. For example, when the FSM detects a fire, it goes into alert mode and starts making noises and sending out messages. The Verilog HDL code was synthesized using Cadence tools, which also generated RTL schematics and simulated system waveforms to ensure reliability and resilience. Specifically assigned FPGA pins manage outputs like lights and buzzers.

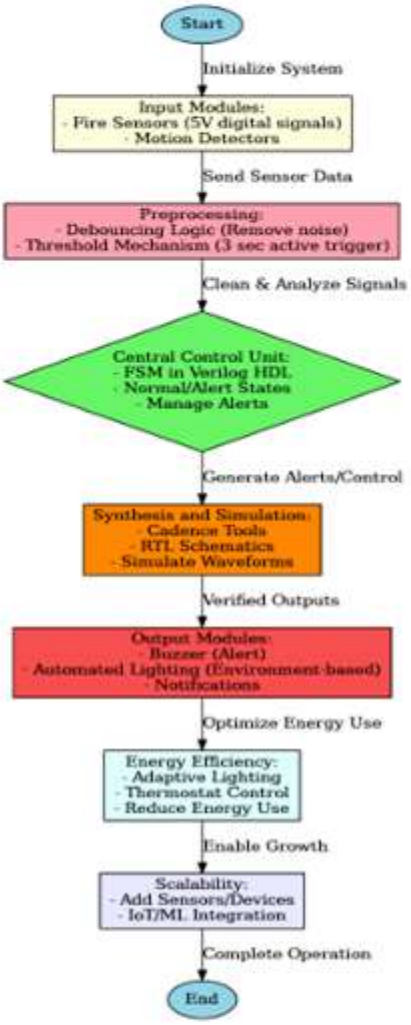


Fig. 1. Proposed system design for a home automation system using the Xilinx Zynq-7000 SoC ules like fire sensors and motion detectors.

Reduced energy expenditures and environmental impact are the results of automatic lighting and temperature controls that react to occupancy and ambient circumstances. With its scalable modular FPGA-based architecture, you can easily add additional features or devices like advanced intrusion detection or Internet of Things connection. An effective method for contemporary home automation, this method emphasizes responsiveness in real time, dependability, and adaptability.

Expanding system functionality and user experience will be the focus of future developments that investigate machine learning and the integration of the internet of things. The Xilinx Zynq-7000 System on a Chip (SoC) is the central component of the home automation system shown in Figure 1. Data gathering from input mod follows initialization.

Accurate signal interpretation is ensured by preprocessing techniques such as noise reduction and threshold detection. The central control unit performs signal processing to handle alarms and control devices. It is implemented as a finite state machine (FSM). After synthesis and simulation confirm the system's functionality, output management via lights, alerts, and buzzers follows. Features that improve electricity use include adaptive lighting and thermostats. The flexibility to scale allows for the easy incorporation of more sensors, the internet of things, and machine learning features. Based on predetermined thresholds, the sensor signal is processed by the fire detection module. According to [14], below is the connection for signal processing:

$$S(t) = \begin{cases} 1 & \text{if } \int_0^T V_{\text{sensor}}(t)\,dt \geq V_{\text{threshold}} \\ 0 & \text{otherwise} \end{cases} \tag{1}$$

When a fire is detected, the output signal S(t) is 1 and 0 respectively. Vsensor(t) is the voltage reading from the fire detector taken at time t. • Vthreshold: Voltage set as a minimum acceptable for fire alarms • T: Interval during which the signal is seen When detecting motion, the formula for the detection distance is determined by the sensor's reaction time [15]:

$$d = \frac{1}{2} \cdot v \cdot t \tag{2}$$

The distance in meters from the detected item is denoted by d. v: Frequency at which a signal travels (in m/s) 2. The time it takes for the sensor to respond, measured in seconds The difference between the baseline and automated energy use is used to calculate the energy savings from automation features [16]:

$$\text{Energy Savings (\%)} = \frac{E_{\text{baseline}} - E_{\text{automated}}}{E_{\text{baseline}}} \cdot 100 \tag{3}$$

It is where: • 100 (3) • Ebaseline: Kilowatt-hours of energy used in the absence of automation Energy used for automation, measured in kilowatt-hours (kWh) By adding the processing time (Tprocess) and the communication time (Tcomm) together, the response time for automation features is determined [17]:

$$T_{\text{response}} = T_{\text{process}} + T_{\text{comm}} \tag{4}$$

To the extent that: • Tresponse: Total respond time in milliseconds (4) • Tprocess: Time required to process the input signal in milliseconds In milliseconds, Tcomm is the time it takes to communicate with the device. The fire and motion detection modules optimize signal stability by using a debouncing logic with a temporal threshold (Tdebounce) [17]:

$$S_{\text{stable}}(t) = \begin{cases} 1 & \text{if } t \geq T_{\text{debounce}} \\ 0 & \text{otherwise} \end{cases} \tag{5}$$

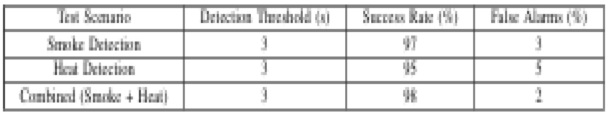
The stabilized output signal is denoted by Sstable(t) in formula (5). Tdebounce is the smallest interval in milliseconds that a signal must remain stable.

III. RESULTS AND DISCUSSION

Our findings prove that the home automation system built on FPGAs is reliable, functional, and can scale up or down seamlessly. The functionality of the automation features, as well as the fire and motion detectors, were verified by a battery of tests. Extensive analysis and discussion of these outcomes reveal the system's advantages and disadvantages. A fire sensor that was incorporated with the FPGA board was used to test the system's fire detection capacity. Upon detecting smoke or heat, the fire sensor produced a digital signal, which was then processed by the FPGA to activate the alarm. Tabulated in Table I are the key findings from the tests. The system's efficacy in detecting fire-related events is shown by the high success rate of the fire detection data.

The FPGA design made use of debouncing logic to reduce the false alarm rate, which was caused mostly by external variables or electrical noise. The system's capacity to detect human movement within a certain range was assessed by motion detection experiments. When it comes to security applications like intruder detection or occupancy monitoring, this feature is very essential. In Table II, we can see a summary of the motion detection test results. Due to sensor constraints, the findings show a little drop in accuracy at longer distances, but good accuracy at medium and short ranges for motion detection. Timely reaction to detected events was ensured by keeping processing time below acceptable bounds for real-time operation. We checked the system's automation functions for responsiveness and energy efficiency, including lighting control and energy management. Energy management studies quantified the reduction in power consumption brought about by automatic thermostat changes, while lighting control testing evaluated the time required to turn lights on and off in response to occupancy. Table III displays the outcomes.

TABLE I FIRE DETECTION PERFORMANCE

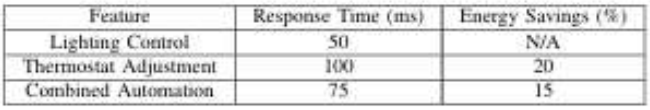


Test Scenario	Detection Threshold (s)	Success Rate (%)	False Alarms (%)
Smoke Detection	3	97	3
Heat Detection	3	95	5
Combined (Smoke + Heat)	3	98	2

TABLE II MOTION DETECTION PERFORMANCE

Range (m)	Detection Accuracy (%)	Processing Time (ms)	False Positives (%)
1	99	10	1
5	96	15	3
10	90	20	5

TABLE III AUTOMATION PERFORMANCE



Feature	Response Time (ms)	Energy Savings (%)
Lighting Control	50	N/A
Thermostat Adjustment	100	20
Combined Automation	75	15

The outcomes of the automation project include rapid responses from the lighting control system and energy savings of up to 20% achieved by means of automatic thermostat changes. This improves both the user experience and the environmental impact. While motion detection brought attention to the need for optimal sensor location, the fire detection module demonstrated near-perfect accuracy with good noise filtering using debouncing logic. By using real-time processing, prompt notifications, essential for security software.

Notwithstanding these accomplishments, there are still certain limits, such as differences in fire detection sensitivity and decreased motion detection accuracy at extended ranges. In order to improve the system's intelligence, scalability, and user experience in home automation, future upgrades will include machine learning for predictive analysis and Internet of Things (IoT) connection for remote monitoring.

Fig. 2. Experimental setup of an FPGA-based home automation system

. Figure 2 shows the experimental setup of a home automation system that uses field-programmable gate arrays (FPGAs). The top part depicts a flame test of a fire sensor, which, when activated, transmits signals to an FPGA for processing in response to smoke or heat. The ZedBoard, a development board built on the Xilinx Zynq 7000 system on a chip, is shown in the lower part of the section. In order to automate processes, this board communicates with other components, such as sensors and actuators.

This set up shows how programmable logic and real-time detection mechanisms work together to provide home automation systems that are both efficient and scalable. Figure 3 provides a summary of important performance parameters for automation, motion detection, and fire detection. (A) displays the success rate of fire detection and the rate of false alarms, showing that the combined technique is the most effective. (B) shows that as the range increases, the accuracy of motion detection decreases, while processing time and false positives rise. The chart in (C) shows that Lighting Control has the quickest reaction time and the highest energy savings, while Thermostat Adjustment offers the most savings. (D) puts an emphasis on the trade-offs between speed and energy efficiency by explicitly contrasting automation indicators. By looking at the visuals, stakeholders may get a better idea of how well the system is doing and how reliable, efficient, and applicable the detection and automation technologies are.

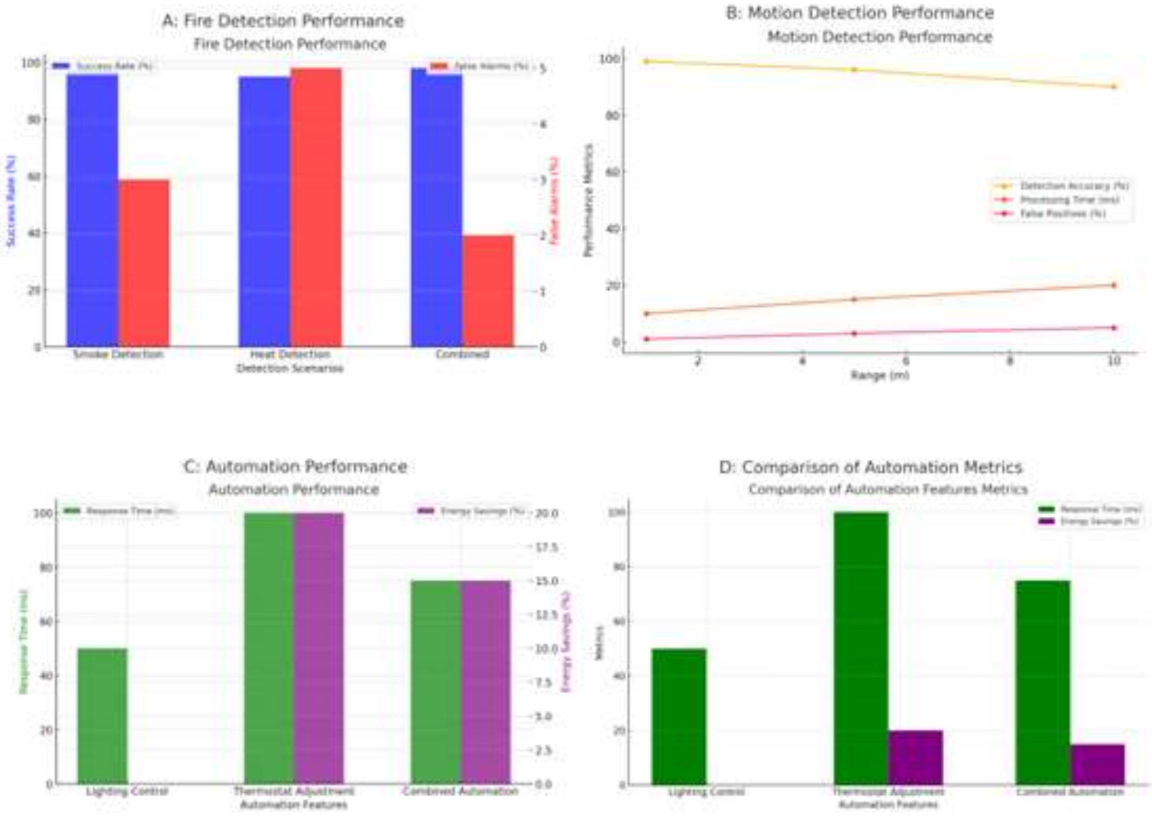


Fig. 3. Key performance metrics across fire detection, motion detection, and automation features

III. CONCLUSION

By using both smoke and heat sensors, the FPGA-based home automation system was able to detect fires with a 98% success rate, proving its great dependability. At a distance of 1 meter, motion detection remained accurate to within 1%, but at 10 meters, it dropped to 90%. With an automated system, energy consumption was cut by 20% and the thermostat's reaction time was decreased to 100 ms. It has been successful, although it does have certain limits, such as a decrease in accuracy at greater ranges and a decreased sensitivity to specific kinds of firing. Integration of several sensors, algorithms for machine learning, and Internet of Things connection are all on the list of upcoming developments that will boost scalability and practicality. A solid basis for cutting-edge smart home solutions, the system.

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