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FPGA DomoSync: An FPGA-Based IoT Home Automation

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ABSTRACT

This paper presents FPGA DomoSync, an FPGA-based IoT home automation system aimed at enhancing living spaces' safety, efficiency, and comfort. The primary objectives include designing an FPGA-based home automation system, enabling remote control of household appliances via smartphones, and augmenting home security. Leveraging Wi-Fi connectivity, Arduino IDE, Altera Quartus II, and Verilog HDL, the system prototype fulfills these objectives. The results showcase a functional prototype integrating FPGA and IoT elements, remote appliance control, and the capability to secure a house.

1. Introduction

The realm of home automation, nestled within the broader landscape of Internet of Things (IoT) technology, continually evolves to offer safer, more comfortable, and efficient living spaces [1]. This technology enables remote management of household devices, leveraging data collected by IoT devices to optimize user experiences through machine learning.

While historical milestones trace back to early appliances and remote controls in the mid-20th century [2], the modern era of home automation evolved with the internet's advent in the 1990s, culminating in advancements like local network integration, wireless protocols such as Z-Wave, and intelligent devices [2]. Presently, the focus extends beyond convenience, emphasizing safety, sustainability, and sensor-based control for various aspects.

This research introduces an intelligent FPGA-based solution to address contemporary home automation challenges. It aims to seamlessly integrate functions, optimize energy use, fortify security, and unify diverse devices and sensors. The study pioneers an innovative blend of convenience, sustainability, and advanced technology.

This paper discusses the FPGA review, literature survey on existing FPGA-based home automation systems, the proposed system's design, components used, operational workflow, experimental setup, results, and their discussion. Finally, concluding remarks summarize the system's significance.

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2. Literature Review

Home automation, a subset of Internet of Things (IoT) technology, aims to improve living conditions by providing secure, comfortable, and efficient living spaces [1]. Advancements in this field have evolved from early inventions like labour-saving appliances to today's sophisticated systems integrating intelligent devices, sensors, and remote control mechanisms [2].

Notably, the application of Field Programmable Gate Arrays (FPGAs) has garnered attention in the development of home automation systems. These programmable integrated circuits offer versatility in implementing digital circuits, enabling efficient deployment of logic blocks, input/output blocks, connection blocks, and specialized components for diverse applications [3]. FPGA technology has been instrumental in various home automation designs, facilitating system control, sensor integration, and remote monitoring capabilities.

Research in the domain of FPGA-based home automation systems has explored diverse methodologies and technologies. Ahmed *et al*., [4] focused on fire safety and anti-theft measures but lacked remote user control. Devachandra Singh *et al*., [5] integrated Bluetooth for remote control within a limited range. Next, Alim *et al*., [6] emphasized security with radio frequency identification (RFID) but incurred complexity and cost. Ooi *et al*., [7] proposed a system integrating wireless sensor networks (WSN) for real-time energy monitoring but faced scalability challenges. Ajao *et al*., [8] established a cyber-physical infrastructure for smart room and window control with a drawback in complexity. Pooja *et al*., [9] employed FPGA as a central controller, emphasizing data transfer via Global System for Mobile Communications (GSM) with potential cost implications. Pawar *et al*., [10] merged FPGA and ESP8266 for remote monitoring, focusing on security and circuit flexibility, yet lacking extensive sensor integration.

3. Proposed Design

FPGA DomoSync represents a paradigm shift in home automation, addressing limitations observed in previous designs. Leveraging the ESP32’s versatile sensor compatibility, including an IR flame sensor alongside the DS18B20 temperature sensor and light-dependent resistor (LDR), enhances safety measures beyond Bluetooth range limitations seen in prior systems. The system’s FPGA-controlled home appliances – fire alarm, fan, light, and door offer comprehensive household management, unifying diverse functionalities. Verilog HDL programming ensures efficient FPGA control, distinguishing it from complex and costly technologies like RFID and GSM-based communication. Relying on Wi-Fi for mobile phone data transfer improves accessibility, overcoming scalability challenges posed by WSNs. This proposed system that is fortified by safety-centric sensors, versatile communication, and comprehensive household control, emerges as a cost-effective and pioneering home automation solution, surpassing previous designs’ capabilities. The block diagram of the suggested design is shown in Figure 1.

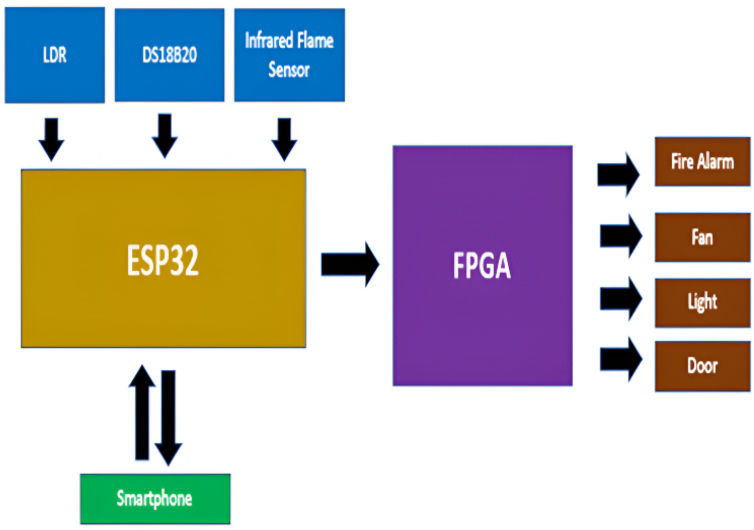


Fig. 1. Block diagram of the suggested design

4. Components Used in the Design

4.1 Altera DE2-115 Development and Education Board

The Altera DE2-115 is a versatile development platform featuring the Cyclone IV EP4CE115 FPGA by Intel. Equipped with a range of programmable logic and signal processing capabilities, the board integrates peripherals like Ethernet, UART, and audio interfaces for seamless device integration. Abundant memory resources, including Synchronous Dynamic Random-Access Memory (SDRAM) and flash memory, further enhance its functionality.

4.2 ESP32 IoT Module

The ESP32 is a robust microcontroller unit (MCU) renowned for its extensive capabilities. With ample general-purpose input/output (GPIO) pins, it interfaces flexibly with devices and sensors, including a transmitter pin for Universal Asynchronous Receiver Transmitter (UART) communication with the FPGA. It functions to build the web application and communicates via Wi-Fi with the smartphone.

4.3 Light Dependent Resistor

The Light Dependent Resistor (LDR), also known as a photoresistor, is a passive electronic component that exhibits a change in resistance based on the intensity of incident light. The LDR is used to measure the luminosity of a room. It has a high resistance in the dark, typically around several megaohms, and its resistance decreases as the light intensity increases.

4.4 DS18B20 Temperature Sensor

The DS18B20 temperature sensor is a digital sensor widely used for accurate temperature measurements in various applications. It is used to measure the temperature of a room. It operates on the principle of the 1-Wire communication protocol, enabling multiple sensors to be connected to a single microcontroller pin.

4.5 Infrared Flame Sensor

The infrared (IR) flame sensor is a specialized component for detecting flames through infrared radiation. It converts emitted light to an electrical signal via an infrared receiver, swiftly identifying flame presence for fire and gas leak detection, industrial safety, and more. By distinguishing flames from other sources, it minimizes false alarms, ensuring reliable fire risk response and enhancing safety.

4.6 Fire Alarm

The fire alarm is used to alert the user when the fire is detected. The red light emitting diodes (LEDs) on the Altera DE2-115 represents the fire alarm.

4.7 Fan

A fan is used to cool down high temperatures. The user can turn it on and off as desired. The seven-segment displays of the Altera DE2-115 represent the fan.

4.8 Light

The light is represented by an LED in this system. It can also be turned on or off as per the user's wish.

4.9 Door

In this home automation system, the door is important to secure a house. An electromagnetic lock is used to serve as the door. Like the fan and light, the door can be unlocked or locked by the user.

4.10 Smartphone

A smartphone is needed to control and monitor sensors and home appliances. It also receives messages from Telegram if the threshold value of the sensors is reached.

5. System Workflow

The system comprises two subsystems: one for monitoring DS18B20, LDR, and IR flame sensors and another for managing home appliances. The ESP32 and smartphone's internet connection initiates both subsystems, linking them through a unique IP address generated by the ESP32. In the first subsystem, the ESP32 checks sensor inputs and conditions like temperature (>32ºC), luminosity (>4000), and flame detection. If met, the user is alerted via Telegram. The second subsystem allows smartphone-controlled appliances through a web application. The application sends integer values to the ESP32, which are converted to characters and sent to the FPGA via UART. Every action that can operate the home appliances has an integer value assigned to them to act as an instruction. FPGA decodes the data, validating and executing appliance commands if valid. This orchestrated workflow impeccably aligns with the established objectives: crafting an IoT-based home automation system, enabling remote control of household appliances, and bolstering home security through a seamless amalgamation of sensor monitoring and appliance management. The flowcharts of both processes are depicted in Figure 2 and Figure 3, while Table 1 provides integer values (commands) and outputs.

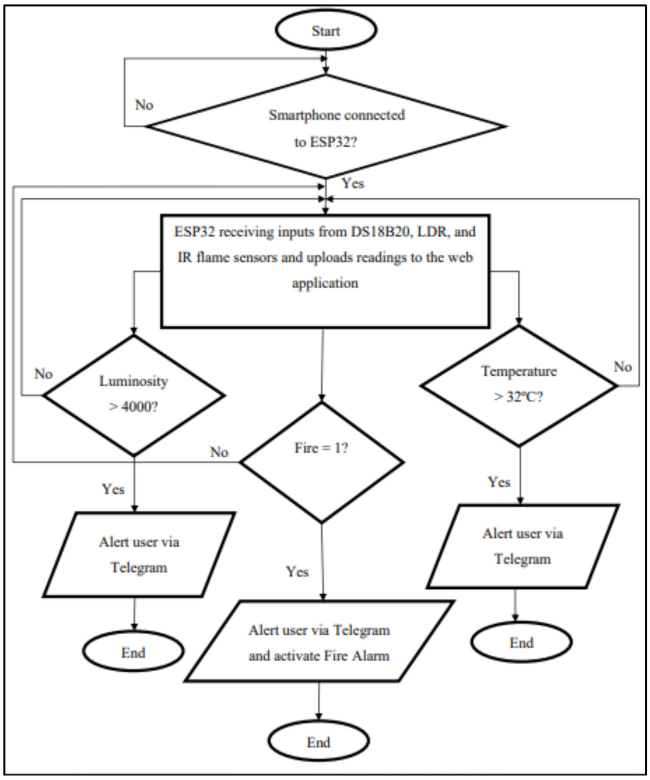


Fig. 2. Flowchart of the first subsytem

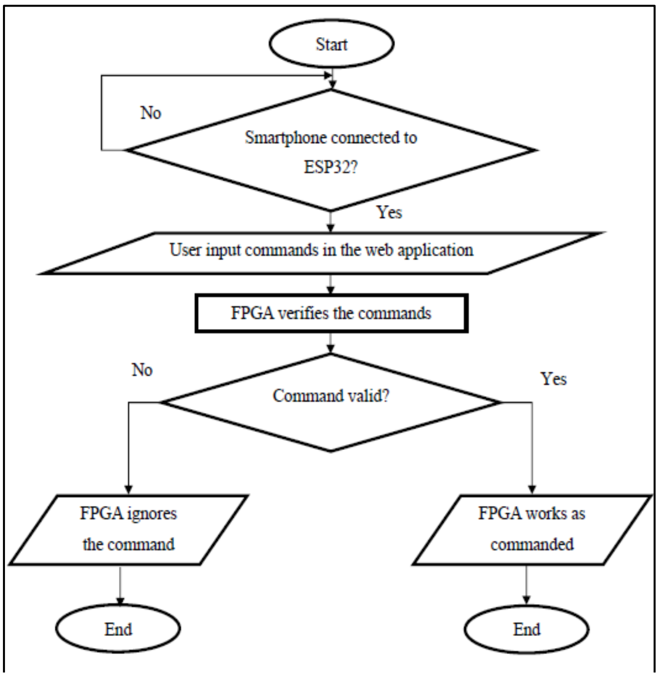


Fig. 3. Flowchart of the second subsystem

Table 1
Commands and their outputs

Commands	Output (Home Appliances)
97 (ASCII character: "a")	fan0 = 7'b1111111 (blank) fan1 = 7'b1000000 (O) fan2 = 7'b1001000 (N) fan3 = 7'b0001110 (F) fan4 = 7'b0001000 (A) fan5 = 7'b1001000 (N)
98 (ASCII character: "b")	fan0 = 7'b1000000 (O) fan1 = 7'b0001110 (F) fan2 = 7'b0001110 (F) fan3 = 7'b0001110 (F) fan4 = 7'b0001000 (A) fan5 = 7'b1001000 (N)
99 (ASCII character: "c")	light = 1 (ON)
100 (ASCII character: "d")	light = 0 (OFF)
101 (ASCII character: "e")	door = 0 (LOCKED)
102 (ASCII character: "f")	door = 1 (UNLOCKED)
103 (ASCII character: "g")	firealert = 18'b111111111111111111 (Fire Alarm activated)
104 (ASCII character: "h")	firealert = 18'b000000000000000000 (Fire Alarm disabled)

Referring to Table 1, the integer values are codes of specific American Standard Code for Information Interchange (ASCII) characters which is significant as the FPGA decodes characters of the integers coming from the ESP32. The names "fan0", "fan1", "fan2", "fan3", "fan4", and "fan5" are assigned to the seven-segment displays that represent the fan. The LED and electromagnetic lock connected to the FPGA are called "light" and "door". Lastly, "firealert" is the name of the 18 red LEDs on the Altera DE2-115, thus, its data has 18 bits.

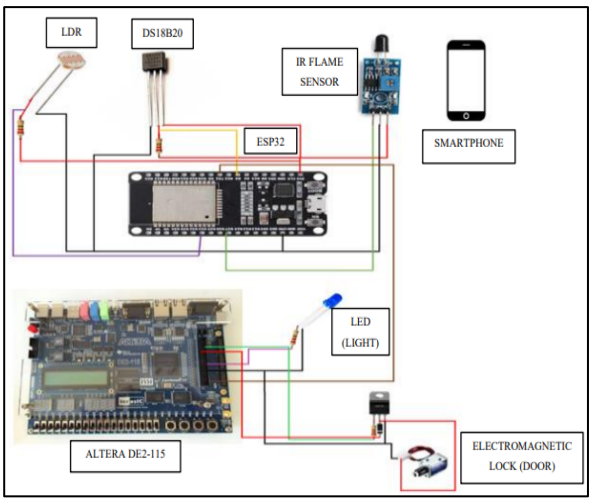


Fig. 4. Experimental setup of the design

The design was constructed according to Figure 4. The design establishes the smartphone's wireless connection to the ESP32 as the sensor interface. The ESP32 interfaces with the LDR and DS18B20 with a 10kΩ resistor at their data pins. The LDR's resistor sets luminosity thresholds via resistance adjustments, and the DS18B20's resistor maintains voltage levels for precise temperature readings, preventing errors. The ESP32's transmitter (TX) pin also links to FPGA GPIO pin AG26, enabling UART communication.

Regarding home appliances, they directly connect to the FPGA's GPIO pins on the Altera DE2-115 board. An LED, representing an electric light, attaches to the FPGA with a protective 10kΩ resistor in series to manage the LED current flow. A high FPGA signal illuminates the LED. The electromagnetic lock, emulating a door lock, connects to the FPGA via a 1N4007 diode, TIP120 transistor, and 10kΩ resistor. The TIP120's base resistor regulates the current, activating the transistor, while the diode ensures one-way current flow. With a high FPGA signal, the TIP120's base triggers the lock, permitting current to flow and activating the electromagnetic lock. The fan and fire alarm use FPGA outputs. A seven-segment display signifies the fan, showing patterns for status (ON/OFF). Red LEDs act as the fire alarm, reacting to FPGA signals for illumination or deactivation.

6. Results and Discussion

The web application interface displays sensor readings and enables remote appliance control. Telegram alerts prompt users based on sensor inputs (luminosity, temperature, and fire). Tables 2-5 depict successful appliance operations, demonstrating achievement of all three objectives. Additionally, ModelSim simulation validates the system's functionality, confirming successful interaction between the ESP32 and FPGA.

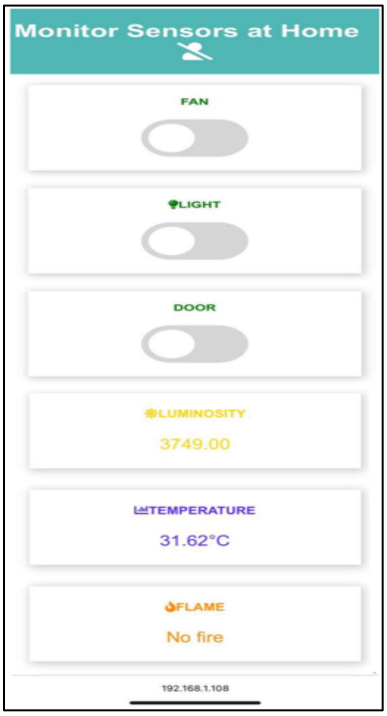


Fig. 5. The graphical user interface of the web application

In Figure 5, the graphical user interface of the web application is shown. The web application has a unique IP address that the ESP32 generates. This IP address changes daily. The user can only access the web application after entering the correct username and password that protects the web application. In the web application, the user can observe the sensor readings, updated every 2 seconds, and there are three toggle buttons to manage the home appliances. Besides that, a user slash icon is on top of the web application to log the user out.

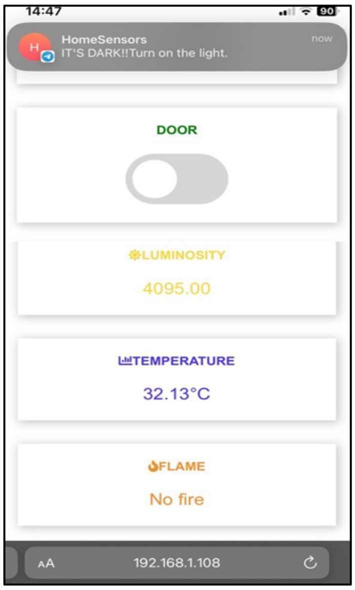


Fig. 6. Telegram message alerting the user that it is dark (luminosity > 4000) and prompting the user to turn on the light

Alluding to Figure 6, a Telegram notification prompts the user to activate the lights when luminosity surpasses 4000. Programmed within the ESP32, this notification triggers when the specified condition is met.

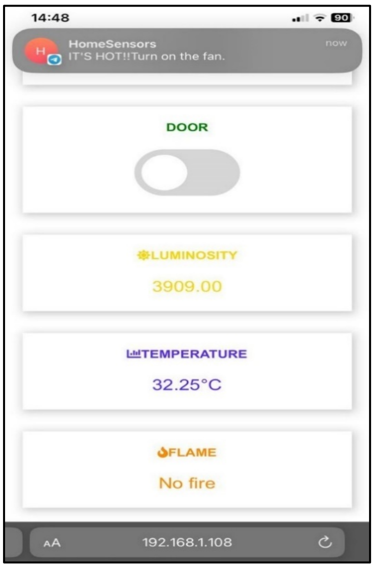


Fig. 7. Telegram message alerting the user that it is hot (temperature > 32ºC) and prompting the user to turn on the fan

In Figure 7, it is shown that Telegram notifies the user about the high temperatures in the house. The message also prompts the user to turn on the fan to lower the temperature so that it can be below 32ºC, as this temperature is considered high.

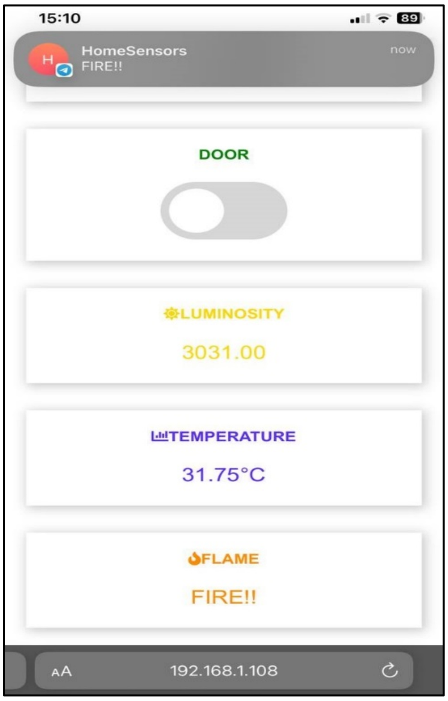


Fig. 8. Telegram is sending a warning that there is a fire

Based on Figure 8, when the IR flame sensor senses fire, the ESP32 instructs Telegram to send a message informing the user of fire in the house. Aside from that, the web application also notifies the user about a fire.

Table 2
Results of fan operation

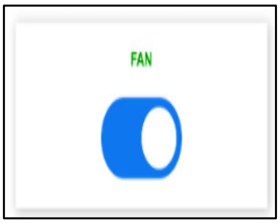
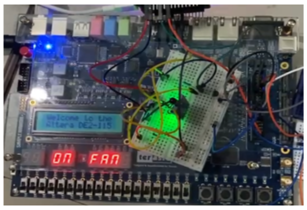
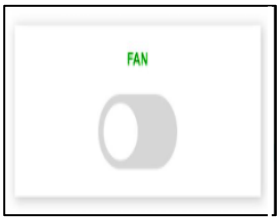
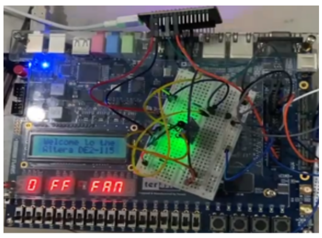
Web application	Output
 "FAN" is toggled.	 Seven-segment display showing "ON FAN", which symbolizes the fan has been turned on
 "FAN" is untoggled.	 Seven-segment display showing "OFF FAN", which symbolizes the fan has been turned off.

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Table 3
Results of light operation

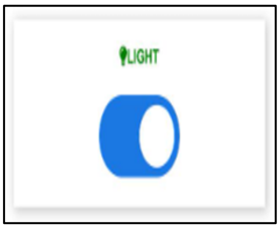
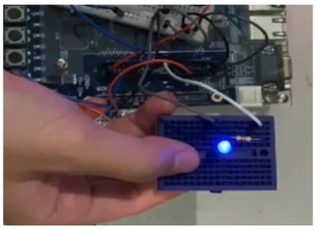
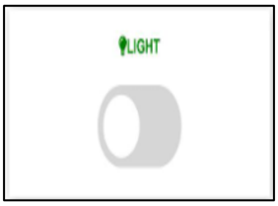
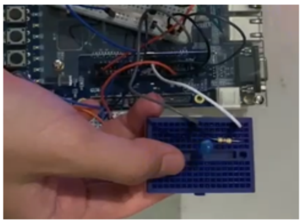
Web Application	Output
 “LIGHT” is toggled	 LED lights up which symbolize the light has been turned on
 “LIGHT” is untoggled	 LED turns off, which symbolizes the light has been turned off

Table 4
Results of door operation

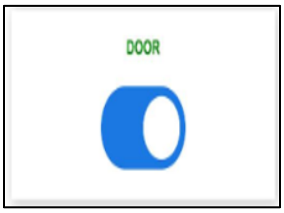
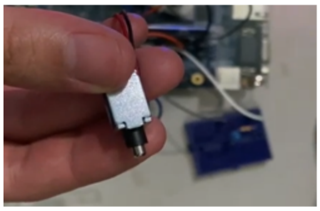
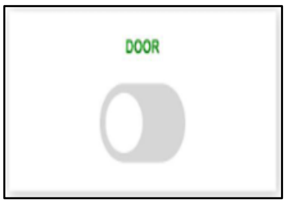
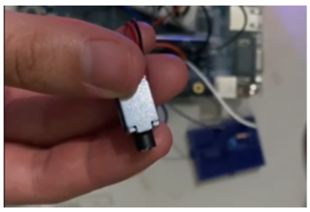
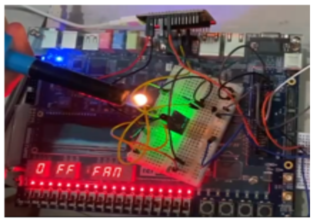
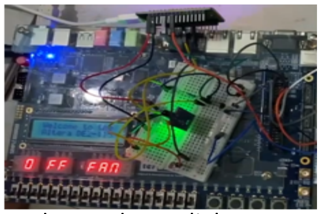
Web application	Output
 “DOOR” is toggled.	 The electromagnetic lock’s tongue extends, which symbolizes the door has been locked.
 “DOOR” is untoggled.	 Electromagnetic lock’s tongue retracts, which symbolizes the door has been unlocked.

Table 5
Results of fire alarm operation

Web Application	Output
 Web application detects fire.	 Red LEDs light up, which symbolizes the fire alarm being activated.
 The web application does not detect fire	 Red LEDs do not light up, which symbolizes the fire alarm being disabled

Based on Table 2 to Table 4, the respective toggle buttons of every card on the web application dedicated to each home appliance enable the appliances' control. Furthermore, the web application can automatically activate and disable the fire alarm according to whether it detects fire or not as shown in Table 5. Thus, the three objectives have been achieved as the home automation system has FPGA and IoT elements that allow the remote monitoring and operating of home appliances to prevent the wastage of electricity and time, and it can lock the door remotely, enhancing the home's security.

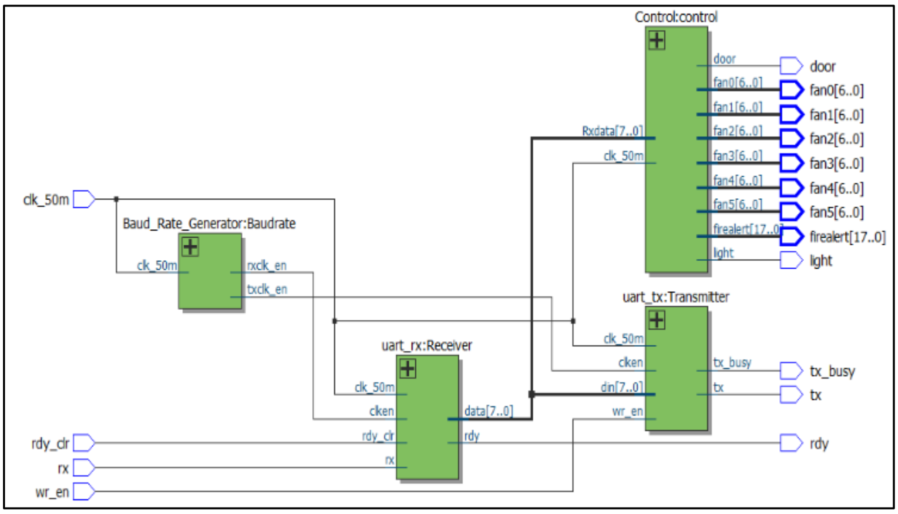


Fig. 9. RTL view of the FPGA design

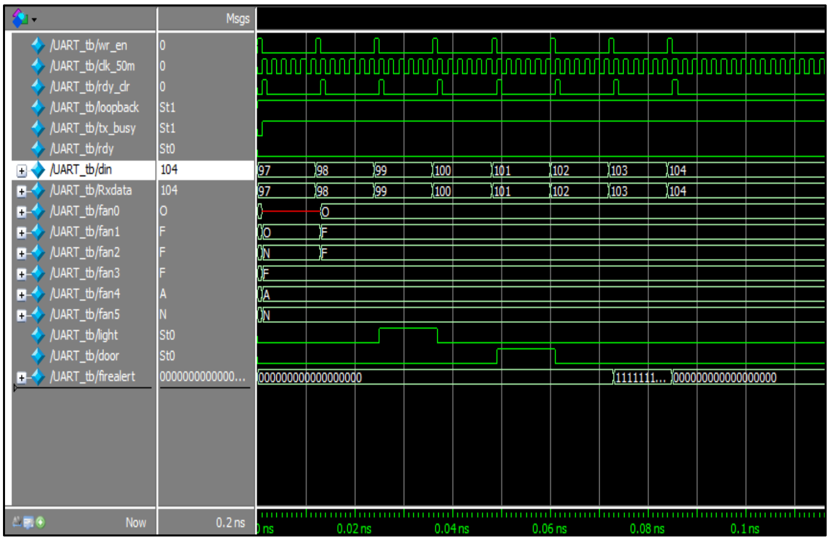


Fig. 10. RTL simulation waveforms of the FPGA design

The simulation result in Figure 10 shows that the input to the FPGA is “din”, which is the name of the integer values from the ESP32. This input is obtained from the FPGA’s UART receiving line. It operates the home appliances corresponding to each value of din it receives.

4. Conclusions

In conclusion, the FPGA DomoSync system marks a significant step in home automation, leveraging FPGA and IoT technologies to realize remote monitoring and control of home appliances while ensuring enhanced security through the integration of sensors. The system’s successful development on the Altera DE-115, combined with Arduino IDE, Verilog HDL, and Altera Quartus II, underscores its viability and functionality. However, upon critical reflection, several potential avenues for improvement have surfaced. Primarily, the reliance on Wi-Fi connectivity could be optimized further, considering scenarios with unstable networks or in environments lacking connectivity. Exploring alternative communication protocols or implementing failover mechanisms may increase system robustness. Moreover, the system’s sensor suite, while comprehensive, could benefit from expansion for broader environmental monitoring. Additionally, refining the web application’s user interface to offer improved intuitiveness and user experience represents another promising area for future iterations of the FPGA DomoSync system. These potential developments stand as directions for further refinement and innovation, aiming to fortify the system’s versatility and user-friendliness.

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