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Hardware Design and Implementation of Automated Rotary Car Parking System on FPGA

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ABSTRACT

This paper presents the design and implementation of an advanced hardware system for a fully automated rotary car parking solution deployed on a programmable chip. Developed in collaboration with the Department of Mechanical Engineering at the University of Tripoli, this system utilizes a field-programmable gate array (FPGA) to manage and automate the mechanical operations of a rotary parking structure, including vehicle entry, exit, and movement control. The research presents an advanced FPGA-based rotary car parking system that automates vehicle management through real-time control and safety protocols. This system stands out due to its comprehensive integration of mechanical operations, safety features, and adaptability to various configurations, making it a significant advancement over traditional microcontroller and PLC systems. The main contributions of this research compared to other FPGA designs: Utilizes FPGA for immediate control of vehicle entry, exit, and movement, enhancing operational efficiency. And implements safety measures, including weight compliance monitoring and password protection for vehicle retrieval, which are not universally present in other designs. Also, it incorporates temperature sensors for fire safety, activating suppression systems in case of high temperatures, a feature not commonly found in similar systems. Directional sensors provide precise vehicle location tracking, improving overall safety and efficiency during parking operations. The system's design allows for scalability in urban environments, accommodating various parking configurations, unlike many existing systems that are limited in flexibility. Experimental evaluations demonstrate superior performance in managing parking operations compared to traditional systems, emphasizing its practical application in dense urban settings. While the proposed system excels in automation and safety, some alternative designs focus more on user interaction and IoT integration, which may appeal to different user needs and preferences.

Keywords: Rotary Parking System, Smart Park System, FPGA, System-on- Programmable-Chip, Verilog Hardwar Description Language

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تصميم وتنفيذ العتاد لنظام مواقف السيارات الدوّار الآلي باستخدام مصفوفة البوابات المنطقية القابلة للبرمجة

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ملخـــــــص البحـــــــث

تقدم هذه الورقة تصميم وتنفيذ نظام أجهزة متقدم لحل مواقف السيارات الدوارة المؤتمتة بالكامل والمثبت على شريحة قابلة للبرمجة. تم تطوير هذا النظام بالتعاون مع قسم الهندسة الميكانيكية بجامعة طرابلس، حيث يستخدم هذا النظام مصفوفة البوابات القابلة للبرمجة (**FPGA**) لإدارة وأتمتة العمليات الميكانيكية لهيكل مواقف السيارات الدوارة، بما في ذلك التحكم في دخول وخروج المركبات وحركتها. يعرض البحث نظام مواقف سيارات دوارة متقدم قائم على تقنية **FPGA** يتيح إدارة المركبات من خلال التحكم في الوقت الحقيقي وبروتوكولات الأمان. يتميز هذا النظام بدمجه الشامل للعمليات الميكانيكية وميزات الأمان وقابليته للتكيف مع تكوينات مختلفة، مما يجعله تقدمًا كبيرًا مقارنة بأنظمة المتحكمات الدقيقة والـ **PLC** التقليدية. تتمثل الإسهامات الرئيسية لهذا البحث مقارنة بتصاميم **FPGA** الأخرى في استخدام تقنية **FPGA** للتحكم الفوري في دخول وخروج المركبات وحركتها، مما يحسن الكفاءة التشغيلية. كما يتضمن تدابير أمان مثل مراقبة التوافق مع الوزن وحماية بكلمة مرور لاسترجاع المركبات، وهي ميزات ليست شائعة في التصاميم الأخرى. بالإضافة إلى ذلك، يحتوي النظام على أجهزة استشعار لدرجات الحرارة لأمان الحرائق، حيث تقوم بتفعيل أنظمة الإخماد في حالة ارتفاع درجات الحرارة، وهي ميزة غير موجودة بشكل عام في الأنظمة المماثلة. كما تتيح أجهزة الاستشعار الاتجاهية تتبعًا دقيقًا لموقع المركبات، مما يعزز من الأمان والكفاءة الإجمالية أثناء عمليات الوقوف. يتميز تصميم النظام بإمكانية التوسع في البيئات الحضرية، مما يسمح بتكييفه مع تكوينات مواقف مختلفة، على عكس العديد من الأنظمة الحالية التي تفتقر إلى المرونة. وأظهرت التقييمات التجريبية أداءً فائقًا في إدارة عمليات الوقوف مقارنة بالأنظمة التقليدية، مما يؤكد جدواه العملية في البيئات الحضرية الكثيفة. وبينما يتفوق النظام المقترح في الأتمتة والأمان، تركز بعض التصاميم البديلة بشكل أكبر على تفاعل المستخدم ودمج تقنيات إنترنت الأشياء، مما قد يلبي احتياجات وتفضيلات مستخدمين مختلفين.

الكلمات المفتاحية: نظام مواقف السيارات الدوّار، نظام المواقف الذكي، مصفوفة البوابات المنطقية القابلة للبرمجة، نظام على رقاقة قابلة للبرمجة، لغة توصيف العتاد.

1. Introduction

In densely populated urban areas, the rapid increase in vehicle numbers has intensified the issue of limited parking space. Automated parking systems offer a promising solution to this challenge. The concept dates back to early systems in the United States, with designs such as the Bowser, Pigeon Hole, and Roto Park in the 1940s and 1950s [1]. Although these systems gained some traction initially, mechanical issues and long wait times eventually led to decreased interest. However, from the 1990s onward, renewed interest spurred numerous projects, with 25 projects underway by 2012, providing around 6,000 parking spaces [2]. The development of automated parking has been particularly notable in Japan, where over 40,000 spaces have been created since the 1990s using the paternoster-style automatic parking system. By 2012, Japan had reached approximately 1.6 million automated parking spaces [3], showcasing the technology's significant growth and adoption in high-density areas.

Automated parking systems increase parking capacity by using mechanical devices, often powered by electric motors or hydraulic pumps, to transport vehicles to storage locations. Automated systems are often more cost-effective than conventional parking facilities, requiring less space and reducing pollution by minimizing the time vehicles circling for parking. The origins of automated parking trace back to Paris in 1905, with a pioneering system that utilized elevators to transport vehicles across different levels [4]. Another early innovation, the Paternoster system, emerged around the mid-20th century, offering a compact, Ferris wheel-inspired design that optimized space use. This approach led to widespread adoption due to its simplicity and efficiency [3]. The mechanical part of this project has been designed and built in the Department of Mechanical Engineering, University of Tripoli [5].

In this study, a rotary car parking system is implemented using a Field Programmable Gate Array (FPGA) platform. Unlike traditional microcontrollers, FPGA boards offer significant advantages, including high-speed processing, customization, reduced power consumption, and flexibility. In recent years, there has been an increasing preference for rotary parking systems due to their effective space utilization. The literature on Automated rotary car parking systems highlights significant advancements in technology, particularly through the integration of FPGA and IoT (Internet of Things). These systems address urban parking challenges by automating the parking and retrieval processes, thereby enhancing efficiency and user experience. FPGA technology allows for real-time processing and control of parking systems, enabling the selection of optimal parking modes and improving response times [6].

The incorporation of IoT facilitates remote control and monitoring through mobile applications, streamlining user interaction with the parking system [7]. Automated processes significantly reduce the need for physical user interaction, allowing for a more efficient parking experience. Systems can manage multiple vehicles and parking slots simultaneously [6]. Studies indicate that automated systems outperform traditional methods in terms of time and effort saved during parking and retrieval [6]. While the advancements in automated processes are promising, challenges remain in terms of scalability and integration with existing urban infrastructure, which may hinder widespread adoption. This study builds upon existing research in automated parking systems, utilizing the DE2i-150 FPGA board to manage and control the system's operations [8].

Several recent studies have explored a range of microcontrollers, including the ATmega16 [9], ATmega1280 [10], Arduino and PLCs [11], and the IC AT89S51 [12], each offering unique benefits. The control algorithms in these studies were often programmed in C, with simulations conducted using tools like PROTEUS to optimize control circuits. This research distinguishes itself by employing an FPGA as a System-on-Programmable-Chip (SoPC), aiming to provide a more efficient, flexible, and resource-optimized solution that outperforms traditional microcontroller- or PLC-based systems in speed, flexibility, and resource efficiency. System-on-Chip (SoC) technology has emerged as a pivotal innovation in modern electronic systems, integrating various components onto a single chip to enhance performance and efficiency. SoCs are foundational in a wide array of applications, from simple handheld devices to complex systems in the automotive, aerospace, and medical fields. The evolution of SoC design has been driven by the need for compactness, cost-effectiveness, and high-speed communication, particularly in the context of the Internet of Things (IoT) [13].

This research also considers the economic implications, practical applications, and potential for integrating advanced technologies to maximize the value of the proposed FPGA-based automated parking system. Economically, the system presents a cost-efficient solution by significantly reducing labor requirements through automation and optimizing resource usage. Its reliance on FPGA technology not only ensures lower power consumption compared to traditional microcontroller-based systems but also reduces maintenance costs due to its durable and reliable design. For urban planners and commercial operators, the compact and modular architecture of the system allows for efficient land utilization, particularly in high-density urban areas where real estate is at a premium. This makes the system highly suitable for deployment in environments such as metropolitan centers, airports, shopping malls, and public transport hubs.

The practical adaptability of the system to various configurations ensures its application across a broad spectrum of settings, including small-scale commercial parking lots, multi-level parking structures, and mixed-use developments. Its ability to scale seamlessly and handle diverse vehicle sizes and traffic volumes highlights its versatility in meeting the unique demands of different environments. Moreover, the potential integration of renewable energy sources, such as solar panels, can make the system energy self-sufficient, aligning it with global sustainability initiatives and reducing operational carbon footprints. Incorporating artificial intelligence (AI) could further enhance the system's performance by enabling predictive maintenance, optimizing parking space allocation, and improving traffic flow management. AI-driven analytics could also provide real-time data insights, aiding in better decision-making for both operators and users. By addressing economic, environmental, and technological dimensions, this research not only proposes an innovative solution for modern parking challenges but also positions the system as a forward-looking infrastructure component capable of adapting to evolving urban and sustainability needs.

2. Methodology

This section details the design of a rotating car parking system controlled on FPGA platform, focusing on an efficient and automated process to manage vehicle entry, storage, and retrieval. The methodology comprises three main components:

2.1 Vehicle Entry and Weight Verification

Initially, the system is implemented to assess each car's weight, determining whether it falls within acceptable parameters for entry. If the vehicle meets the required weight, it is allowed into the receiving bay; otherwise, access is denied. Once inside, the car is transferred from the receiving bay to the designated storage area. To distribute the weight load evenly, the system alternates the direction of the rotating mechanism with each vehicle entry, moving either to the right or left. This algorithm determines whether a car is allowed entry based on its weight distribution. The car’s total weight is calculated by assigning two-thirds of the weight to the front wheels and one-third to the rear wheels. A strain gauge pressure sensor is used to measure this weight accurately. The primary benefit of this system is to reduce stresses that could cause mechanical failure or collapse. Figure 1 shows the flow chart of weighing the car.

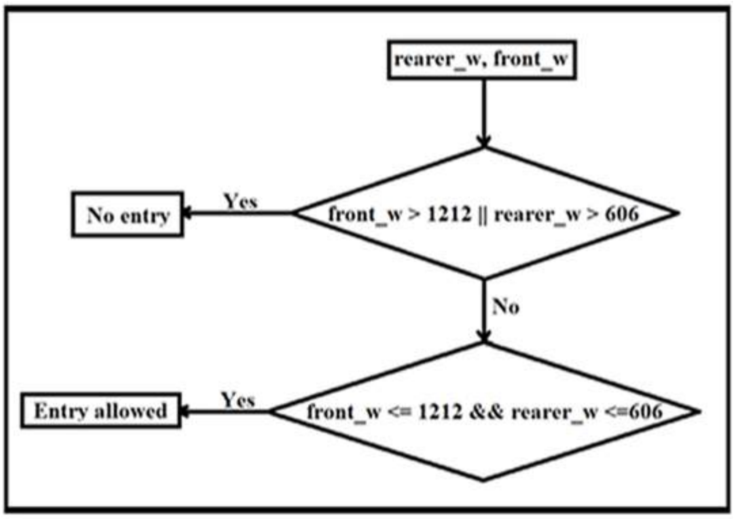

Figure 1. flow chart of the car weighing

2.2 Counting, Timing, and Departure Authentication

After a car enters the receiving bay, the system increments the internal car count, decreasing the count of available slots by one. Simultaneously, a time counter initiates, monitoring the car's duration in the system until a departure request is received. When a user initiates a departure, the system verifies the legitimacy of the request by requiring a unique room password. If an incorrect password is entered, the system maintains the counter without action. Upon correct password entry, the system locates the car using sensors installed throughout the mechanical structure, activating the motor to rotate left or right as needed for efficient car retrieval. This algorithm is designed to count the number of cars in a rotary parking system and calculate available spaces. It uses an infrared sensor to detect cars entering and exiting each room. When a car enters, the sensor increases the car counter by one. If the sensor detects a car leaving, the counter decreases by one. If the sensor remains unchanged, it means the car is still in the system and doesn't affect the count. To find the number of free spaces, the code subtracts the car counter from the total number of rooms (16 in our case). The result is shown to the user. Figure 2 illustrates the flowchart for the counting, timing, and departure authentication operations.

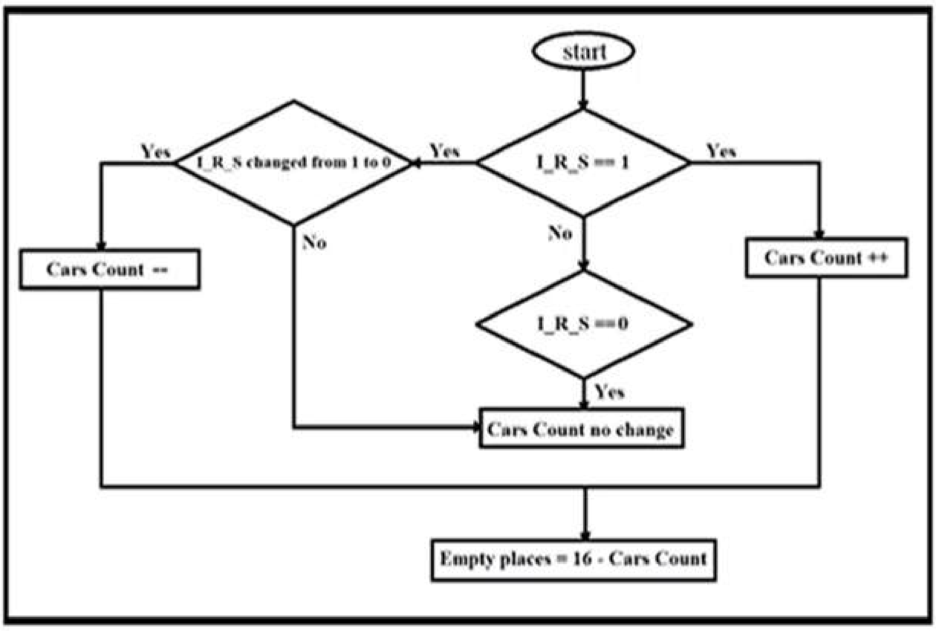

Figure 2. Flowchart for the counting, timing, and departure authentication operations

Another algorithm is designed for a rotary car parking system, which it lifts cars from an entry area to storage spaces. The system alternates the direction of movement—first to the right, then to the left—to evenly distribute the load. This balanced distribution reduces stress on one side of the mechanism, extending the system's lifespan and preventing excessive wear on its components. An infrared sensor called the Receiving Basket Sensor (RBS), detects when a car is in the entry area, prompting the lift motor to start its operation. Figure 3 illustrates the lift motor algorithm in detail.

2.3 Fire Detection and Extinguishing Mechanism

Each parking bay is equipped with a temperature sensor to monitor for potential fire hazards. If the temperature exceeds a predefined threshold, the alarm activates, and the water pump for the affected room engages to mitigate the risk. This fire suppression system remains active until the temperature sensor detects a safe level. This algorithm is designed to activate a fire extinguishing system if a fire

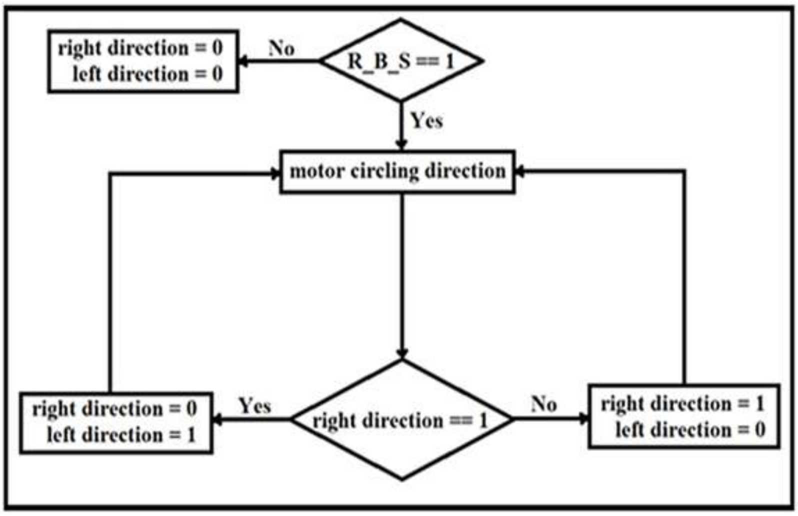

Figure 3. Car lift motor algorithm

breaks out in any room within the rotary car parking system. When a temperature sensor in a room detects an unusually high temperature, the controller sends a signal to turn on the room's pump, activating the fire suppression system and an alarm bell. Both the extinguishing system and the alarm remain active until the temperature returns to a safe level. Figure 4 illustrates the fire detection and extinguishing mechanism.

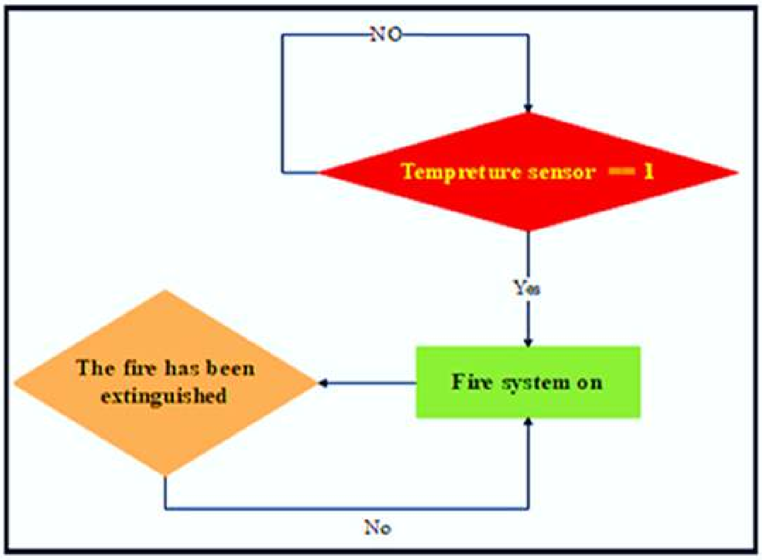

Figure 4. Fire detection and extinguishing mechanism

2.4 Shortest Path Detection

This algorithm determines the direction in which the motor should rotate left or right to retrieve a car from the rotary parking system based on its storage location. As shown in Figure 5 a and b, If the car is parked in spaces 1 to 8, the motor rotates left; if the car is in spaces 9 to 15, it rotates right. Sensors installed at each parking spot help the controller locate the car. When a user requests their car, the controller identifies its position using these sensors, selects the correct rotation direction, and then moves the motor until the car reaches the entry area for pickup.

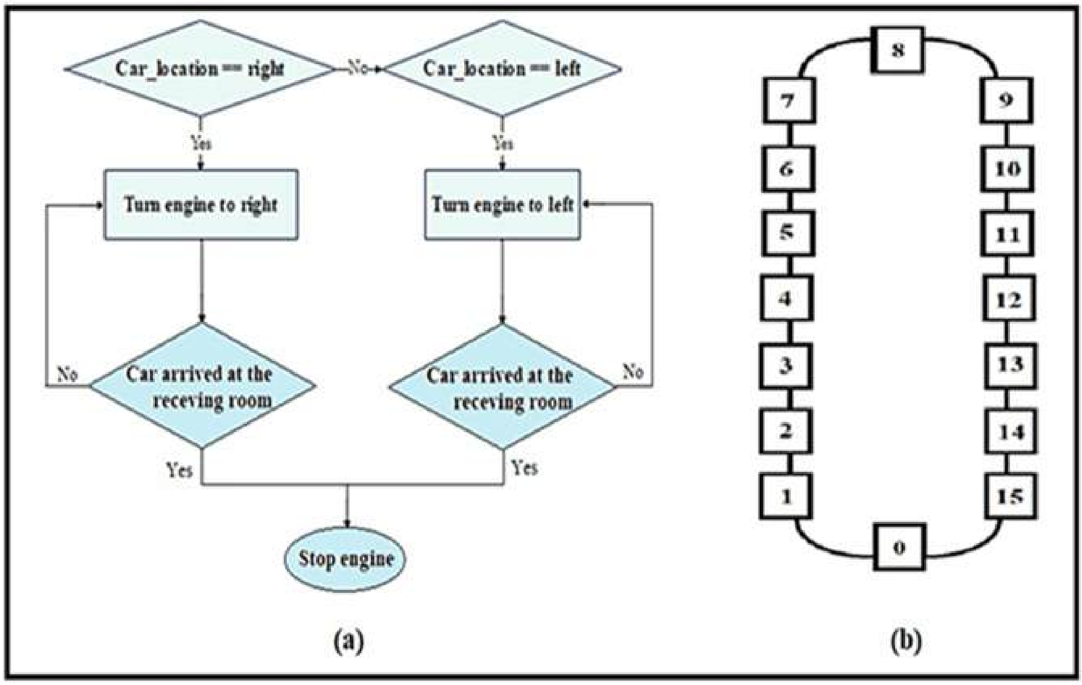

Figure 5. Shortest path detection

2.5 Parking Time Count

This algorithm calculates the time a car spends in the parking system and determines the cost when an exit request is made. To process the exit, the user must first enter the correct password for the car's storage room. The cost is then calculated based on a per-hour rate, which can be easily adjusted within the program. If the exit request occurs before a full hour has passed, any time exceeding a quarter-hour is rounded up to the next hour. If the user enters an incorrect password, the timer continues to run, and the exit request is denied. Figure 6 shows the flow of the time calculation algorithm.

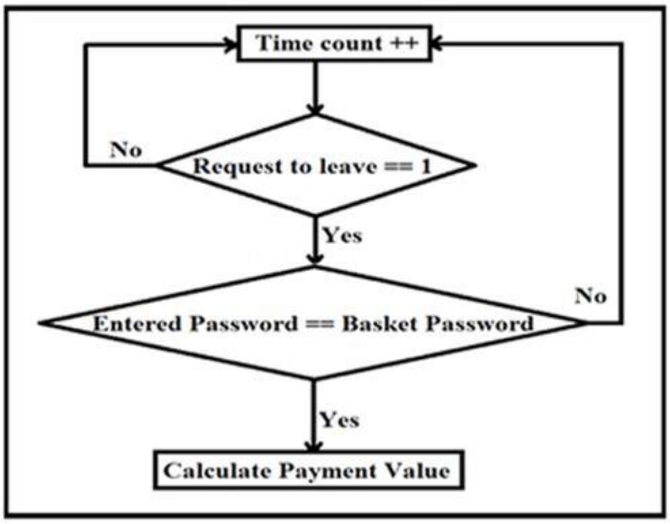

Figure 6. Parking time count

The operational flow of this system, from vehicle entry to emergency response, is illustrated in the Figure 7, providing a comprehensive overview of the automated process.

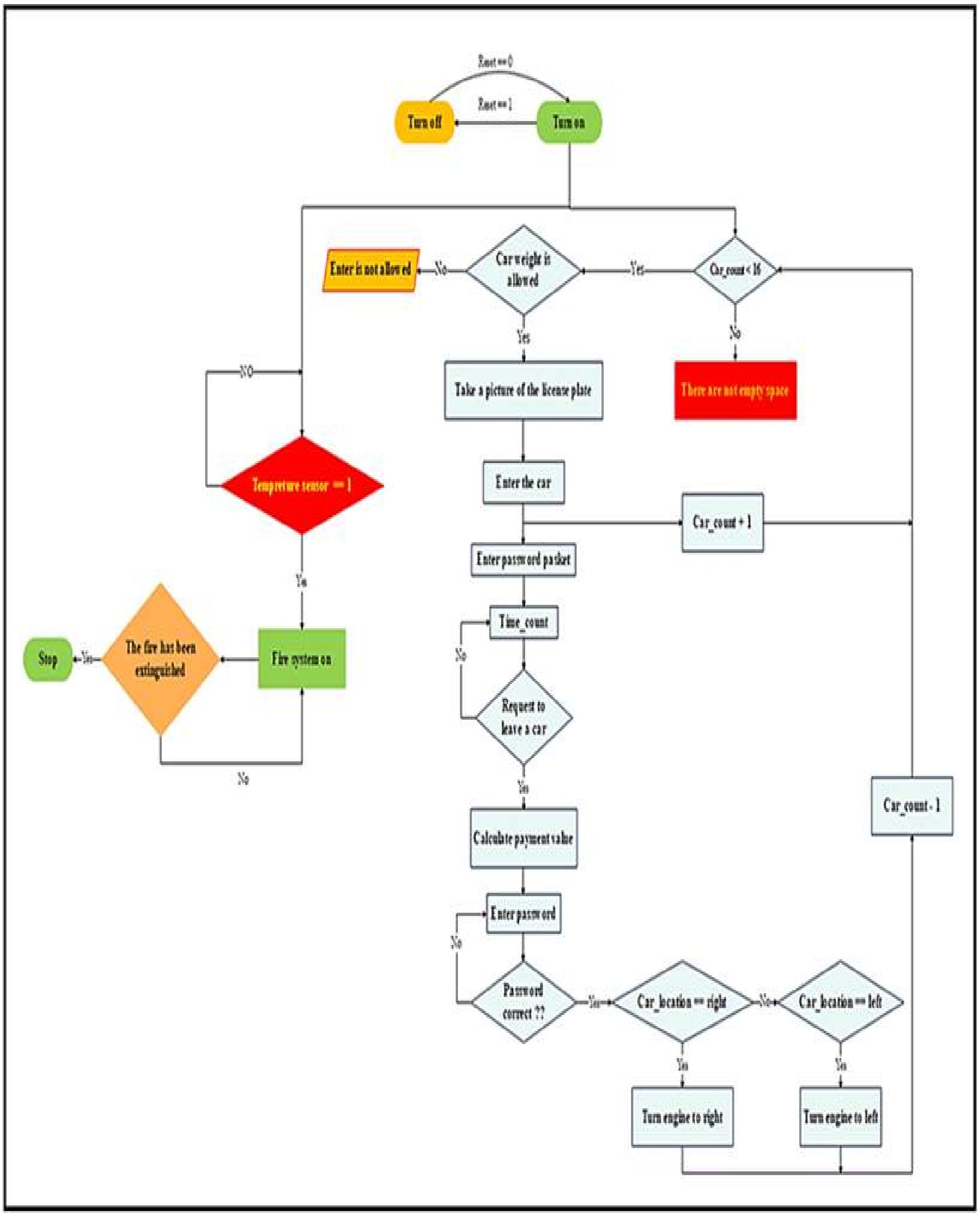

Figure 7. Comprehensive overview of the automated process

3. Results And Discussions

The initial testing phase used ModelSim Advanced simulation and debugging to validate the design before loading it onto an FPGA board, and it performed successfully, as illustrated in the figures below. Figure (8) demonstrates the car counting functionality: each time one of the sixteen sensors changes from "1" to "0," the counter for available spaces decreases by one, indicating that a car has entered the parking system and occupied a slot. Conversely, when the sensor changes from "0" back to "1," the empty spaces counter increases by one, indicating that a car has exited the system, freeing up a slot.

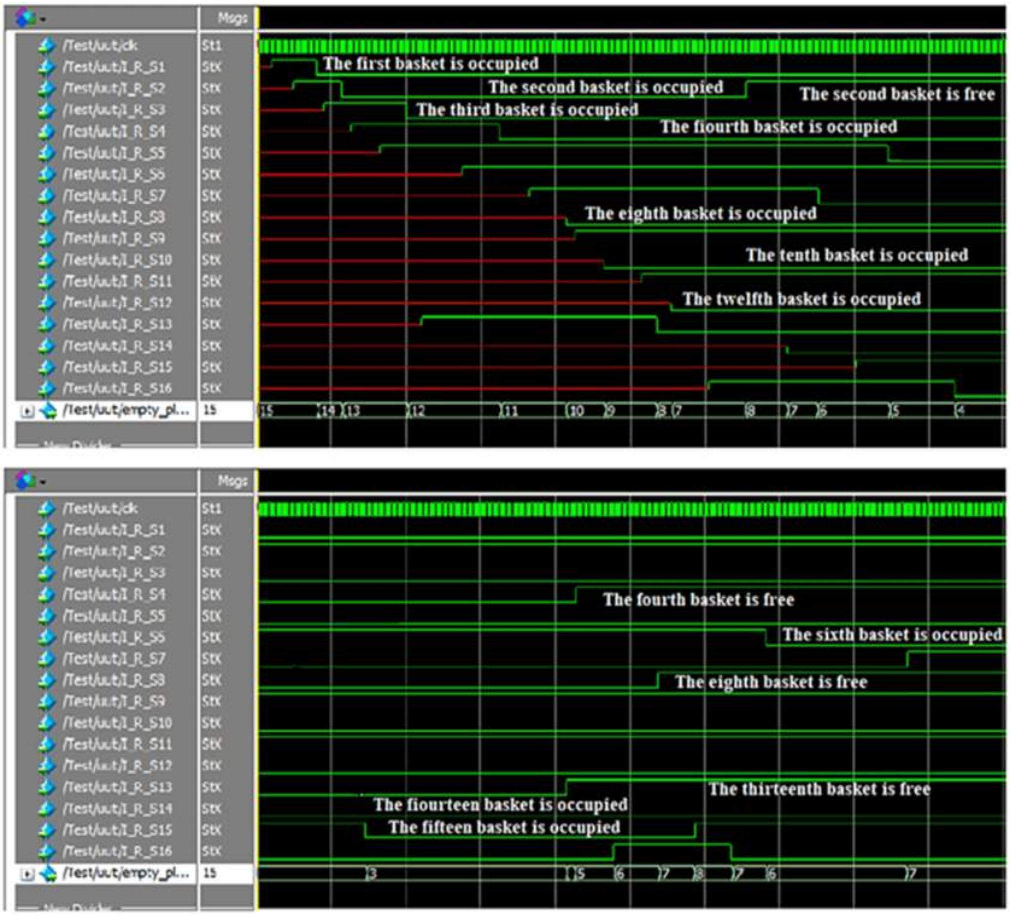

Figure 8. Car count module simulation

Figure 9 shows the fire-extinguishing functionality. When the temperature sensor in a room detects a temperature of 50°C or above, both the alarm bell and water pump activate, indicating a fire. These remain active until the temperature falls below 50°C, at which point both the alarm and pump turn off.

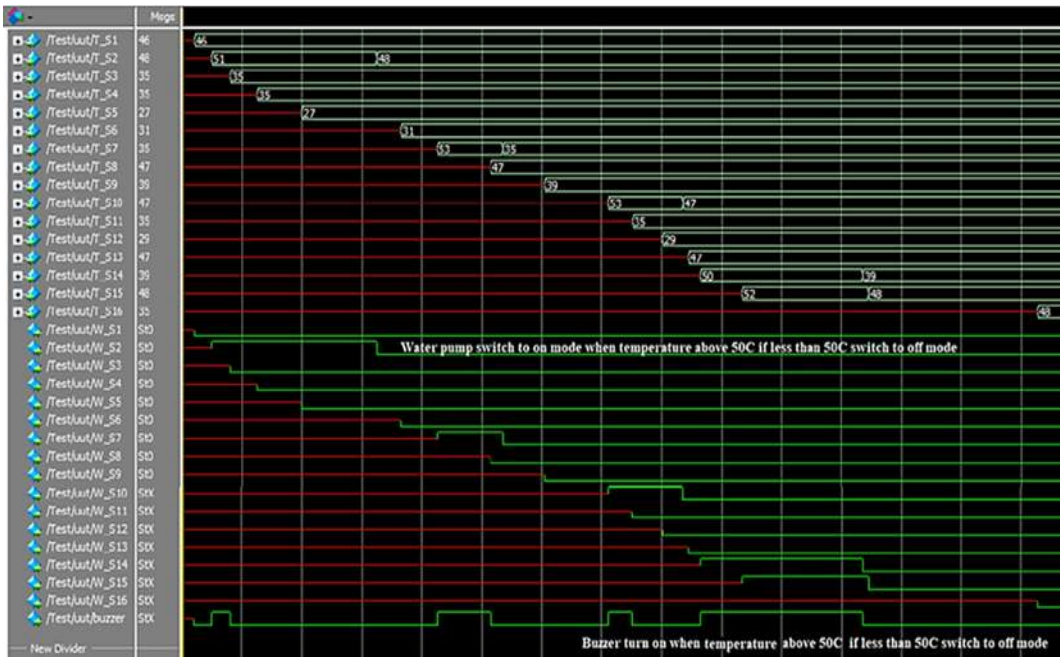

Figure 9. Fire extinguishing module simulation

Figure 10 illustrates the car weight control feature. The system checks the weight on the car's front and rear wheels using pressure sensors. If the weight on either the front or rear wheels exceeds the designer's specified limits—1212 kg for the front wheels and 606 kg for the rear—the system denies entry to the rotary car parking. These weight limits were set based on the average weight of sedan cars. If the measured weight is within these limits, the car is allowed to enter.

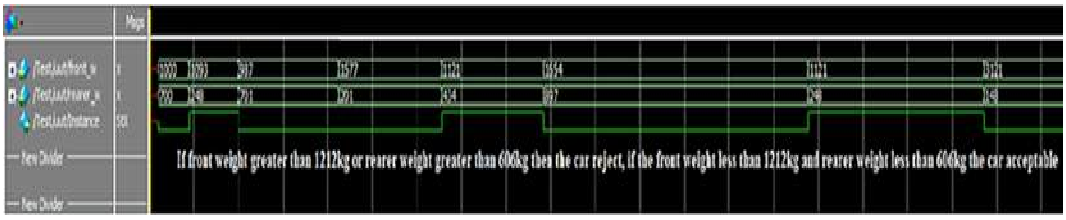

Figure 10. Car weight module simulation

Figures 11 and 12 demonstrate the shortest path algorithm for the motor's rotation in the parking system. When a user requests their car, the system checks the room location: if it's between 9 and 15, the motor rotates to the right; if it's between 1 and 8, it rotates to the left. Before the motor activates, the system verifies the user's password. If the password is incorrect, the motor will not operate. For instance, in the case of room number 12, an exit request was received, and the motor was supposed to turn to the right. However, because the password was incorrect, the motor did not start.

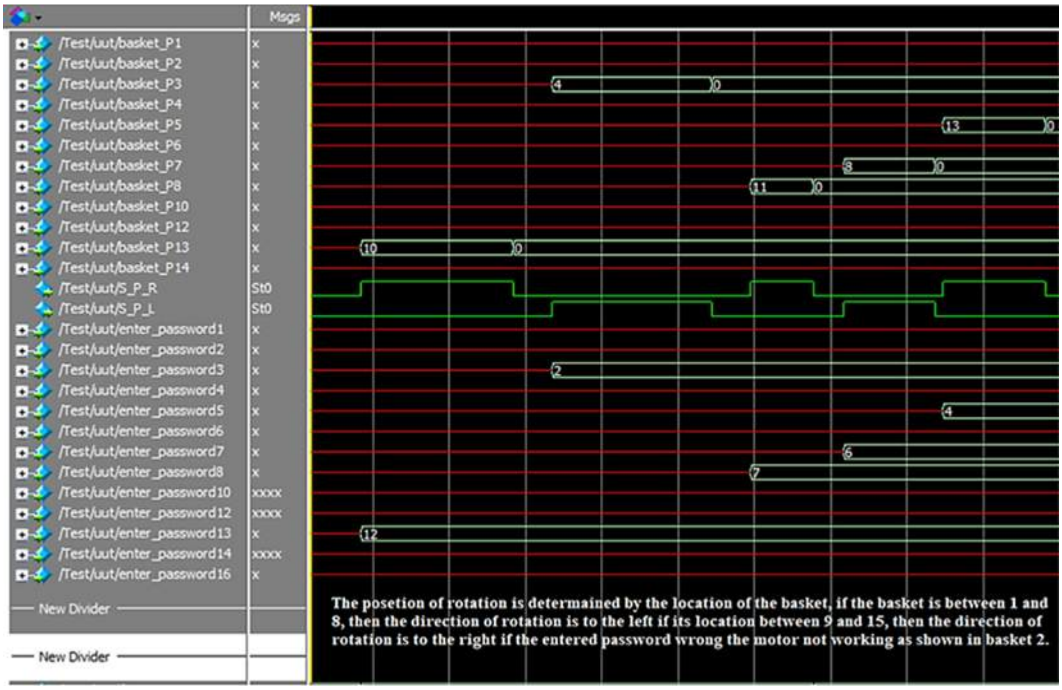

Figure 11. Shortest path module simulation

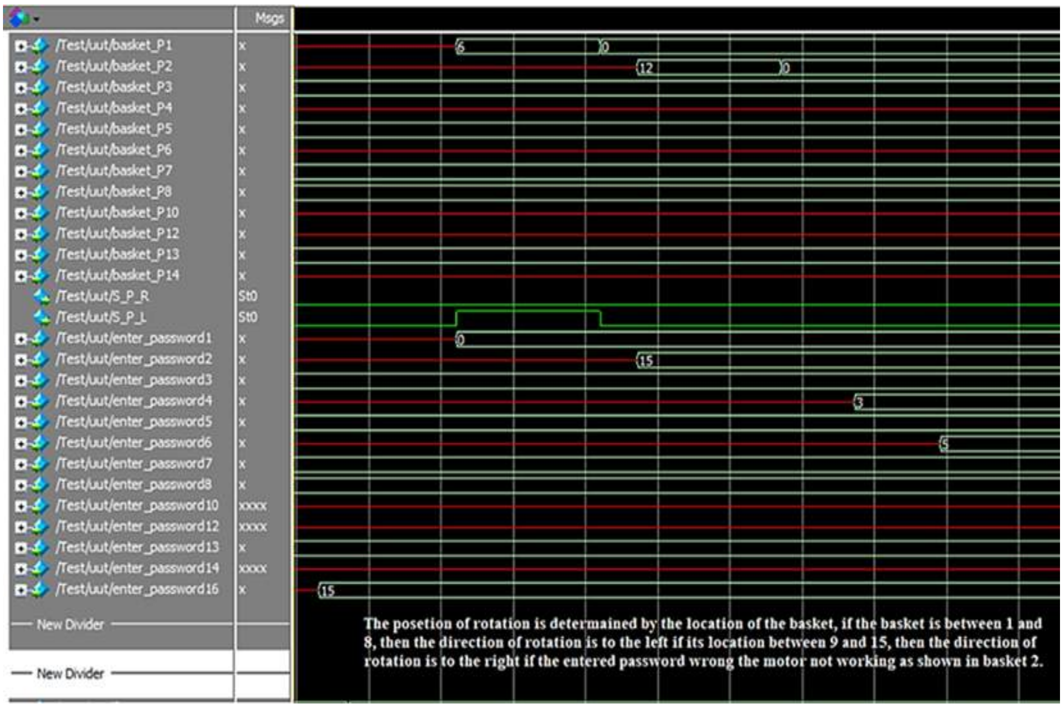

Figure 12. Shortest path module simulation

Figure 13 shows the operation of the car lift motor. When a signal is received indicating that a car has entered the receiving area, the motor activates to move the car to its storage location. With each new entry, the motor alternates its rotation direction switching between right and left to balance the load distribution in the system.

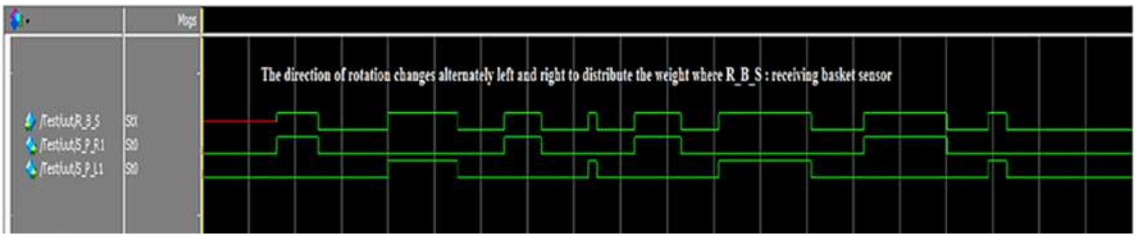

Figure 13. Car lift motor module simulation

Figure 14 illustrates the time count functionality, using three example cases: rooms 1 and 2, the system calculates time by counting seconds until they reach 59, at which point the minutes counter increases by one. Similarly, when the minutes counter reaches 59, the hours counter increases by one. For clearer demonstration, the counters are sped up: the minutes counter increases when seconds reach 10, and the hours counter increments when minutes reach 5. When seconds hit 10, they reset, and the counting restarts, as with the minutes counter at 5.

When a user requests an exit, the total time in hours is multiplied by the hourly rate—in this case, 10 dinars—to calculate the fee. However, if the user enters an incorrect password, the counter continues but no payment is calculated, as shown in the example for room 2.

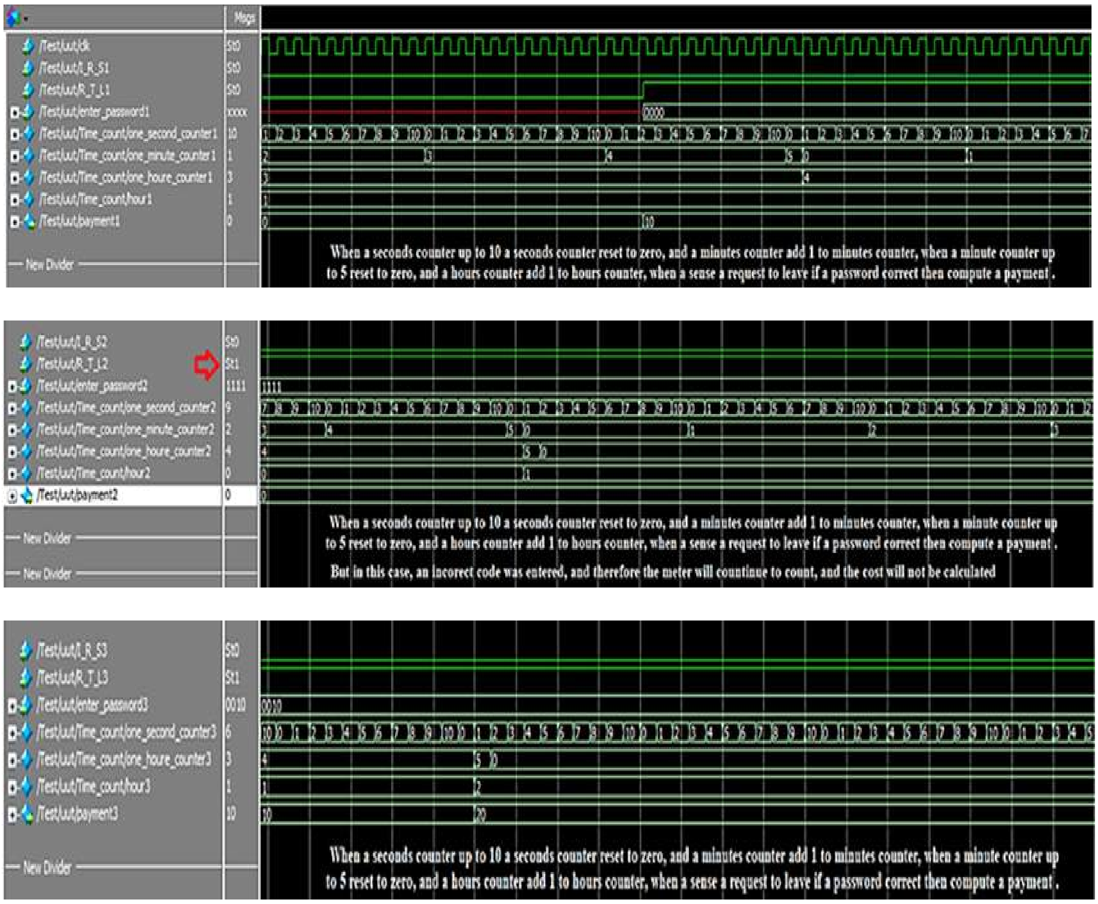

Figure 14. Time count module simulation

Figure 15 displays the system's response in three situations: when the user enters an incorrect room code, when there are no available spaces in the rotary parking system, or when an exit request is made for an already empty room. In each case, specific commands or error messages are shown to inform the user of the issue.

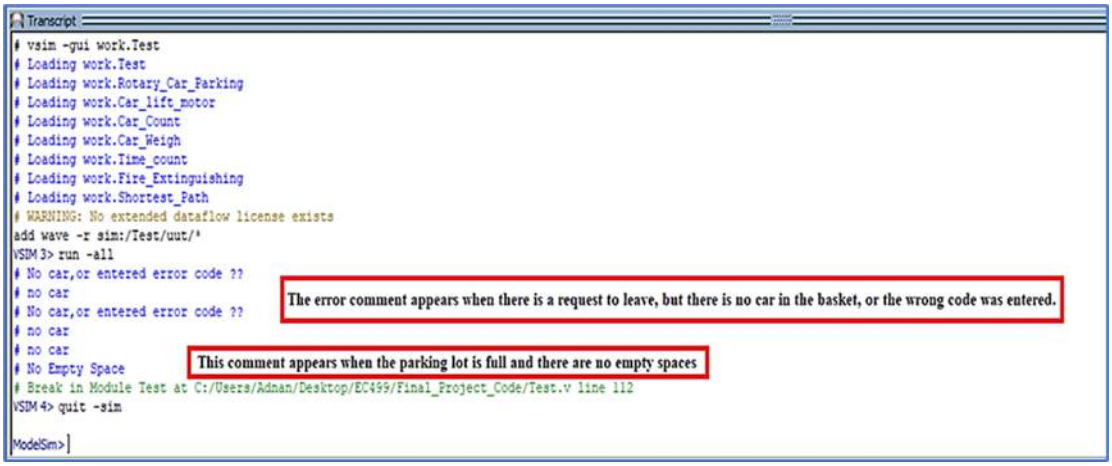

Figure 15. System's response simulation

The final testing phase was conducted on an FPGA development board, where various system functions were mapped to keys and LEDs to simulate real operations:

- Car Count Test: Key 0 and Key 1 acted as infrared sensors, while LEDs 7, 8, and 9 displayed the count of empty spaces.
- Car Weight Test: Keys 2 and 3 represented the car's front weight, and Keys 4 and 5 represented the rear weight. LED0 indicated whether the car's weight was within the acceptable range for entry.
- Shortest Path Test: Keys 7, 8, and 9 represented the basket's location (1–7), with LED1 showing right rotation and LED2 showing left rotation for the motor.
- Motor Rotation Test: Key 6 indicated a car entering the receiving area, with the motor's operation shown on LED5.
- Time Count and Payment Calculation: LEDs 10–15 displayed the parking fee, while Key 17 served as the "request to leave" button.

In Figure 16, the output (011110) in binary, equivalent to 30 in decimal, represents a 3-hour stay with a rate of 10 coins per hour, resulting in a total fee of 30 coins.

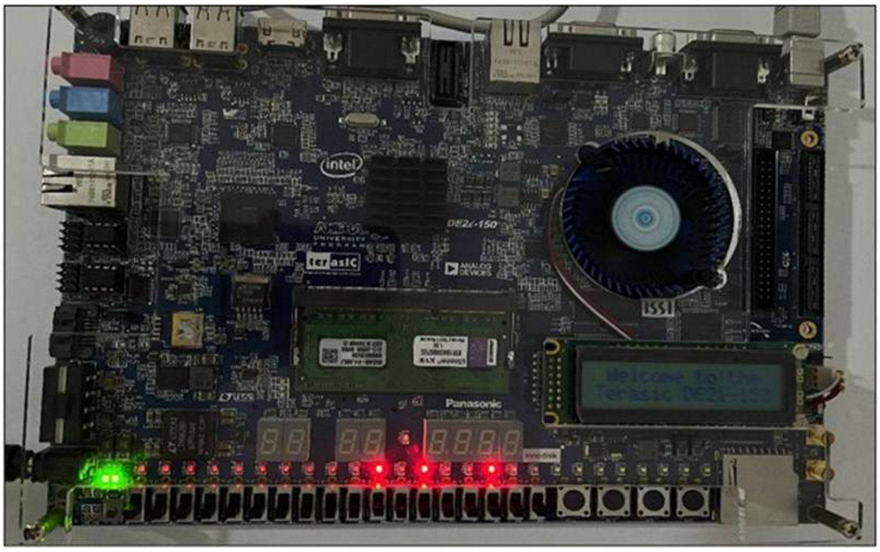

Figure16. Final testing phase on FPGA development board

4. Conclusions

In conclusion, this research demonstrates significant advancements in FPGA-based automated parking systems, offering a comprehensive solution that integrates real-time control, enhanced safety features, and adaptability to diverse parking configurations. By leveraging FPGA technology, the system achieves superior operational efficiency and safety through innovations like weight compliance monitoring, password-protected vehicle retrieval, temperature sensors for fire safety, and precise vehicle tracking via directional sensors. Its scalable and flexible design makes it particularly suitable for dense urban environments, addressing the limitations of traditional microcontroller and PLC-based systems. Experimental results validate its effectiveness in optimizing parking operations, highlighting its practical applicability. While the system excels in automation and safety, it also provides a distinct approach compared to alternative designs that focus more on user interaction and IoT integration, thereby contributing to a broader spectrum of solutions in the domain of smart parking systems.

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