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Design of an Embedded System based on strain gauges to mitigate automotive vehicle thefts, Lima 2023

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From October to December 2023, there was a 19.8% increase in vehicle thefts, reaching 2025 reports, compared to the same period in 2022, according to a report from the INEI. This represents a significant challenge for both affected individuals and authorities in their recovery efforts. An Embedded System based on strain gauges was developed to mitigate automotive thefts in Lima. This system sends an alert to a cell phone interface when it detects weight on the driver's seat. To achieve this, the requirements of the Embedded System were determined, the electronic system was designed, the microcontroller was programmed, and it was implemented both in simulation and physically for testing purposes. For the tests, simulators, an Arduino UNO microcontroller, NEO-6M GPS module, SIM900D module, HX711 converter, strain gauge bridge, resistors, capacitors, transistors, and a SIM card were used. The results demonstrated an effectiveness exceeding 98%, with optimal response times, indicating that the project can be implemented on a large scale. In the future, it is expected to patent the design of the embedded system.

Keywords: Embedded system, microcontroller, strain gauges, vehicular security system.

1. Introduction

Crime and criminality are issues that afflict most Peruvians, as a significant portion of the population experiences some form of such acts daily. According to [1], crime statistics reveal that one of the most significant problems faced by Peruvians is citizen insecurity, which affects the right of every individual to life, liberty, and security. As reported at [1], in the year 2020, 23.4% of the population aged 15 and over in the urban areas of the country reported being victims of some criminal act that threatened their security during the twelve months prior to the day they were interviewed.

Subsequently, in a study conducted by INEI, the National Institute of Statistics and Informatics from Peru, in 2022 "Peru: Statistical Yearbook of Crime and Citizen Security, 2017 - 2021" [2], a detailed breakdown of police reports is provided, showing that 247,672 were "crimes against property". Additionally, in [3], it is observed that, in 2022, only in the Lima district, 17,153 crimes were recorded, of which 12,296 are classified as crimes against property, representing 71.68% of the total. On the other hand, [4] indicates that between October and December 2023, there was a 19.8% increase in vehicle thefts, reaching 2025 reports, compared to the same period in 2022.

Within crimes committed against property, theft and robbery or assault are included. It is important to highlight the difference between them, as they are separately prosecuted in the Peruvian Penal Code [5]. In the same, theft is defined as the act of unlawfully seizing a movable property, totally or partially belonging to another, to benefit from it, by removing it from the place where it is located. On the other hand, in robbery or assault, violence is used against the person, or they are threatened with imminent danger to their life or physical integrity.

At the same time, in [6], theft and robbery of vehicles are defined as: The unlawful appropriation of a movable property, wholly or partially belonging to another, by abruptly taking it or without the owner's knowledge; it encompasses theft or robbery of vehicles such as: car, van, truck, motorcycle taxi, motorcycle, bicycle. Additionally, theft of automotive parts and accessories (headlights, grilles, hood, tires, rims, bumpers, doors, stereo equipment, etc.) is also considered. In addition to the mentioned incidents, attempted crimes are also considered. It is worth noting that, regardless of the crime committed, many go unreported. As a result, more citizens may have been victims of these crimes, and they are not reflected in the statistics.

With the rapid increase in car theft, many owners install security systems in their vehicles. Each system used incorporates technologies such as alarms, motion detectors, and a password to prevent theft. However, vehicle theft remains a persistent problem due to the variety of methods used by thieves. This phenomenon has had an adverse impact on society [7].

Over the past 200 years, the invention of automobiles has been one of the most significant for humanity. Since then, they have evolved every day, becoming increasingly popular and a necessity for the population, also causing concern for the safety of the vehicle and its occupants. Hence, studies and research are continuously conducted focused on seeking security for the vehicle and its users, aiming to prevent thefts and robberies. Therefore, the design of an embedded system based on strain gauges was proposed to mitigate automotive vehicle thefts. In this research work, background reviews on the mentioned topic were conducted. It was found that there are no applications of embedded systems for detecting people in vehicle seats based on strain gauges that could be used in security systems.

It is also important to mention that strain gauges are passive transducers that, when applied to a specimen, allow measuring the force exerted on it from the resulting deformation [8]. Based on the uses of strain gauges in control systems over the last 5 years, and applying their operating principle, the best way to implement them in the embedded system design was identified.

An embedded system is a set of connected devices for performing a specific task. In the view of Pérez [9], an embedded system has 3 fundamental parts: Hardware, main application, and supervisory operating system. Furthermore, Salas Arriarán [10] indicates that embedded systems are not equivalent to computer systems used in laptops or desktop computers, as embedded systems often have limited resources and specific applications. In this regard, Pérez [9] highlights that an embedded system is designed under 3 constraints: small amount of memory, limited processing capacity, and the need to limit power consumption.

Embedded systems execute specialized and repetitive programs, have low energy costs, and are capable of process data in real time. Therefore, embedded systems are highly efficient and reliable in specific applications, but they have a significant deficit in multitasking. The hardware design of an embedded system is fundamental to its operation. This design defines the system's specialization in a task. The architecture of embedded systems usually considers the following aspects, as described in [11] and shown in Fig. 1.

1-The processor is responsible for processing the input and output signals of the system. It is determined by its speed, application, among other factors. 2- The I/O interface is responsible for connecting the processor to the real world through sensors and actuators. 3-The AD/DA converter converts analog signals to digital, and vice versa, to condition the signals transmitted within the system. 4- RAM is a memory that only stores data when powered by electricity. 5-ROM is a non-volatile memory used to store routines for frequently used functions. [9]. 6-DMA refers to the network device's ability to reduce processor usage by directly moving packets to system memory. [12]. 7- ASIC (Application Specific Integrated Circuits) are integrated circuits built for a specific application. They are essential for improving system speed and reliability. [13]

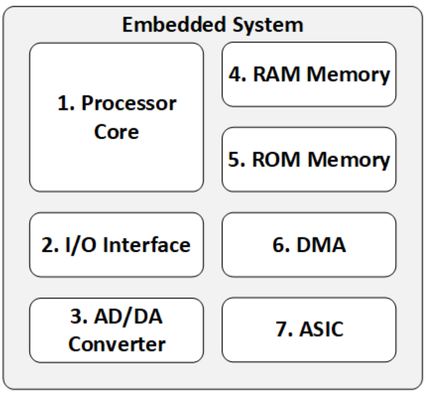

Fig. 1 Typical Design of an Embedded System

A. Anti-Theft Security System for Vehicles

For a successful car theft, only 15 seconds are enough. For this reason, it is necessary to take security measures to prevent thefts. Some of these measures include avoiding parking in public areas between 8 pm and 10 pm from Thursday to Saturday, as this is the time when most thefts occur; having vehicle insurance with theft coverage; and acquiring anti-theft security systems. [14]

Anti-theft security systems prevent thefts in a timely manner, providing greater security for vehicle owners thanks to new technological advances [15].

In [16] some of the most important anti-theft systems used today are listed:

1. Engine immobilizer. A smart key is used to send an electrical signal to the vehicle to allow the engine to start.

2. Mechanical security systems. Refers to physical objects placed inside or outside the car to hinder theft. Among these systems, we can find steering wheel locks, wheel clamps, handbrake and gear lever locks, and pedal locks.

3. Kill switch. Consists of a switch inside the vehicle that cuts off the power to the engine. The car will not start until this switch is activated.

4. Tracking and geolocation systems. This system does not prevent theft but locates the vehicle through GPS tracking, allowing real-time visualization of its position.

5. Security nuts. It consists of unique bolts with a special pattern that can be installed and removed with a single key, making it difficult to steal the vehicle's tires.

6. Security films. Involves applying a special film to the windows to increase their resistance to potential impacts and glass splintering.

Similarly, there are several types of alarms available in the market, as explained in [17]. These include:

1. GPS Alarm System. Tracks the exact location of the vehicle and sends this data to the owner and the police, depending on the configuration. These devices operate within GSM coverage and can be installed in any type of vehicle.

2. Basic Alarm System. Emits an audible alert when someone tries to force the vehicle or detects sudden movement.

3. Immobilizer Alarm System. Blocks some vehicle functions, preventing ignition or movement. It is considered one of the most reliable systems, as it can be activated and deactivated from a computer, phone call, or text message.

4. Unidirectional Alarm. Only allows communication in one direction.

5. Bidirectional Alarm. Allows data exchange between the alarm and other external devices. There are alarms that even allow listening to conversations that occur inside a vehicle.

2. Materials and Methods

A. Materials

Within the materials used in the design of the embedded system, the Proteus Design Suite software was employed, which combines ease of use with a powerful set of features to enable rapid design, testing, and layout of professional printed circuit boards [18]. It is used for developing PCB schematics, circuit simulations, and IoT Builder. In the present study, the Proteus software was applied for the virtual simulation of the embedded system. Additionally, a microcontroller board of an Arduino UNO was used, which is based on ATmega328P (datasheet). It has 14 digital input/output pins (of which 6 can be used as PWM outputs), 6 analog inputs, a 16 MHz ceramic resonator (CSTCE16M0V53-R0), a USB connection, a power jack, an ICSP header, and a reset button [19]. It contains everything needed to support the microcontroller; it simply connects to a computer with a USB cable or powers up with an AC to DC adapter or a battery to get started. Finally, a GPS module for Arduino was used. This Global Positioning System (GPS) utilizes signals sent by satellites in Earth's space and ground stations to accurately determine its position on Earth [20]. In the case of this design, the NEO-6M GPS receiver module was selected, which uses USART communication to communicate with the microcontroller or PC terminal and receives information such as latitude, longitude, altitude, UTC time, etc., from satellites in the form of NMEA strings [20].

B. Methods

1) Data Collection Procedure

Fig. 2 depicts the flowchart of the embedded system based on strain gauges to mitigate automotive vehicle thefts.

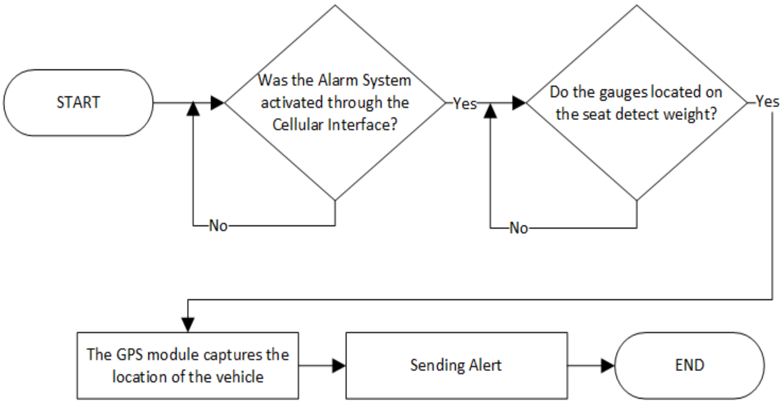

Fig. 2 Flowchart of the process

To collect data and validate the efficiency of the embedded system for detecting individuals in automotive anti-theft security systems, the following steps were undertaken:

First, the design of the embedded system for detecting individuals in automotive anti-theft security systems was developed. Next, the design was implemented in Proteus software. This was done to validate the correct design of the system. Subsequently, necessary modifications were made to the design for optimal functioning of the embedded system for detecting individuals in automotive anti-theft security systems. Then, the virtual simulation was run in Proteus software. The simulation was run 10 times. Afterward, the physical simulation of the system was implemented, and 40 tests were conducted on it. Finally, the results of the tests were analyzed.

TABLE I. 2) Data Analysis

Before proceeding with the analysis, all the data obtained from the tests were organized using Microsoft Excel software. Subsequently, a quantitative descriptive analysis method was applied, in which graphs were created to summarize the results for better organization and understanding of the tests.

Next, a comparison of the results obtained with the objectives set was carried out, and the consistency between them was determined. Additionally, the effectiveness of the design was verified by calculating the percentage of person detection using the following formula:

$$\text{Effectiveness} = \frac{\text{People detected}}{\text{Number of tests done}} x100\% \qquad (1)$$

Finally, the results were presented considering alignment with the established objectives.

3. Results

A. Analysis and Interpretation of the Results obtained by Determining the design requirements of the system.

The design of the embedded system based on strain gauges to mitigate vehicle thefts was implemented in the Proteus software. In this program, it was verified that the proposed design would function virtually according to the project requirements:

7. Weight detection in the strain gauge array
8. Reception of the global position of the circuit
9. Sending alert when the alarm system is activated

The system begins to operate as soon as installation is completed, and it is powered on. The GPS module continuously receives the location while the system is operating. Then, the circuit validates that the strain gauge array has deformed, indicating that there is a person leaning or sitting on the driver's seat. Subsequently, if the validation is successful, an alert is sent to the mobile interface with the current position of the vehicle, notifying the owner of a possible vehicle theft.

1) System Components

The embedded system for detecting individuals in automotive vehicles was developed with the components listed in TABLE I.

TABLE II. EMBEDDED SYSTEM COMPONENTS

Quantity	Component
1	Arduino UNO
1	GPS NEO-6M Module
1	HX711
1	Strain Gauge Bridge
1	SIM900D Module
2	Resistors
2	Capacitors
1	NPN Transistor
1	SIM
1	Power Supply

B. System Requirements

For the proper operation of the system and its components, the characteristics listed in TABLE II. were considered.

TABLE III. CHARACTERISTICS OF COMPONENTS

Component	Feature	Value
Arduino UNO	Power Supply	7 - 12V
	Current	410 mA
	I/O Pins	14
	Output Pins	6
	Flash Memory	32 K
GPS NEO-6M Module	Power Supply	3.3V
	Current	20 - 50 mA
Strain Gauge Load Cell	Resistance	350 Ohms
	Sensitivity (mV/V)	2
HX711	Power Supply	2.6 – 5.5V
	Resolution	24 bits
	Current	1 – 2 mA

C. Analysis and Interpretation of the Results obtained in the Design of the Embedded System and programming.

In the circuit design, the Arduino UNO microcontroller was used, which allows programming of the different modules required for the development of the embedded system.

The circuit consists of three independent systems working together: Strain gauge system, GPS system, and SIM system. Each system was designed and simulated separately before final integration. For this purpose, each independent system of the embedded system based on strain gauges to reduce vehicle thefts was designed and programmed separately.

1) Strain Gauge System

The strain gauge system was developed considering the information these can provide and the requirements of the final embedded system. For its integration with the Arduino, it was decided to use an HX711 module, responsible for amplifying and transmitting the load cell readings to the microcontroller, allowing it to be reliable and accurate.

Fig. 3, Fig. 4, Fig. 5 show the output readings of the HX711 module at different simulated weights in Proteus software.

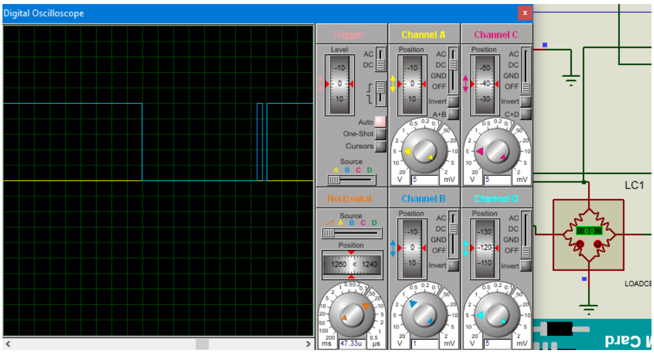

Fig. 3 Output signal of the HX711 at 0.00 kg

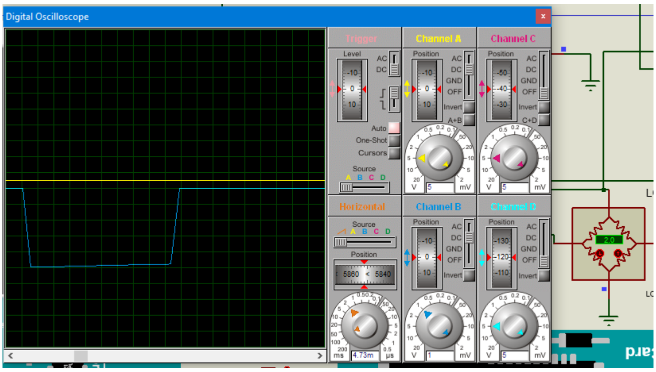

Fig. 4 Output signal of the HX711 at 2.00 kg

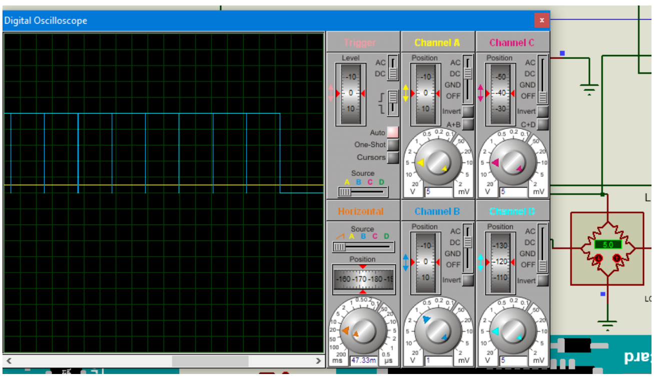

Fig. 5 Output signal of the HX711 at 5.00 kg

In TABLE III. , the actions that the system performs with the data obtained from the strain gauge system readings are described.

TABLE IV. ACTIVATION OF THE NEXT STEP OF THE SYSTEM

Weight detected in the strain gauge system	Activation of the GPS system
Yes	Yes
No	No

Next, in Fig. 6, the design of the embedded system's GPS system in Proteus is shown.

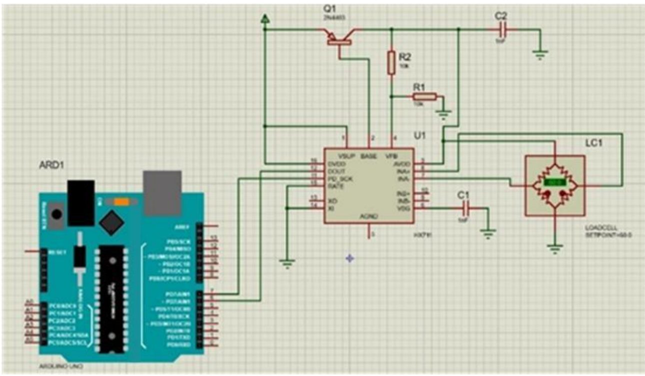

Fig. 6 Schematic of the strain gauge system for the embedded system for person detection

2) GPS System

The GPS System was designed using the GPS NEO-6M receiver module, which allows receiving latitude, longitude, date, time, etc., of the current module position. In TABLE IV. , the actions that the system performs with the data obtained from the GPS module readings are described.

TABLE V. ACTIVATION OF THE NEXT STEP OF THE SYSTEM

Activation of the strain gauge system	Sending the car's location taken from the GPS
Yes	Yes
Not	Not

Next, in Fig. 7, the design of the GPS system of the embedded system in Proteus is shown.

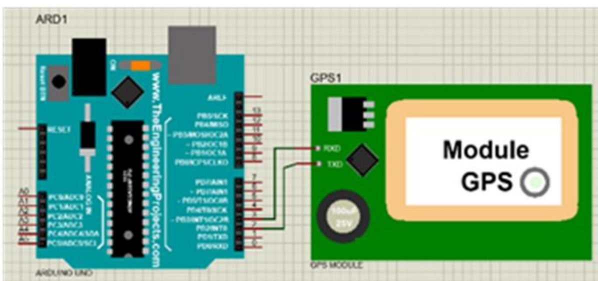

Fig. 7 Schematic of the GPS system for the embedded system for person detection

3) Alarm System/SIM

The Alarm System was designed using the SIM900D transmitter module, which allows sending and receiving information from a SIM card. This system will activate whenever the GPS system detects vehicle movement, and the load cell system detects a weight greater than 0 kg. The alarm system is controlled from an interface with two functions: turning the alarm on and off and triggering the alarm when the system is activated. Fig. 8 shows the mobile interface developed for the system.

When the system is on, the vehicle's location can be checked at any time (See Fig. 8. (a)). When the system detects a suspicious weight and the alarm is triggered, three actions will be displayed: accept and dismiss the alarm, show the vehicle's location, and call emergency services (See Fig. 8. (b)). If the option to view the vehicle's location is selected, a map marked with the vehicle's location will be displayed (See Fig. 8. (c)).

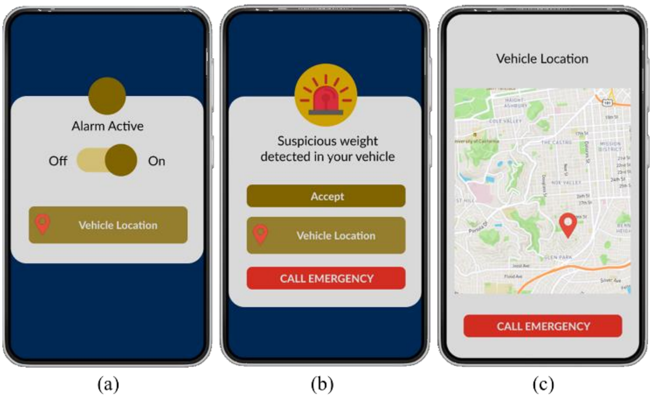

Fig. 8 Cell phone Interface. (a) Alarm system on/off. (b) Alert message. (c) Vehicle location.

The design of the embedded system's SIM module in Proteus is shown in Fig. 9.

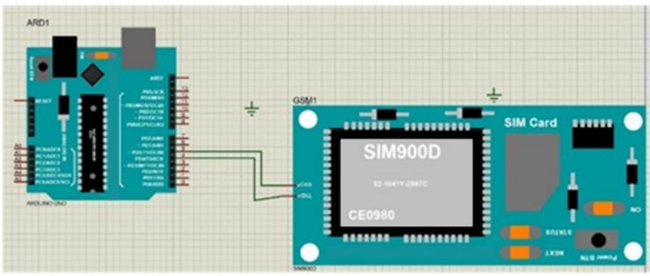

Fig. 9 Schematic of the SIM system for the embedded system for person detection

D. Analysis and Interpretation of the Results Obtained from the Integration of the Embedded System.

After validating the functionality of each system separately, the integration of the embedded system based on strain gauges to mitigate vehicle theft was carried out. To achieve system integration, the step-by-step process developed by the embedded system was initiated. Fig. 10 outlines the workflow performed by the integrated embedded system for alarm activation.

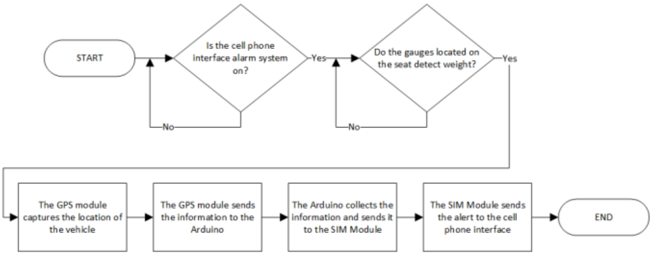

Fig. 10 Flowchart of the Embedded System Process

The integrated and simulated electronic circuit in Proteus is shown in Fig. 11.

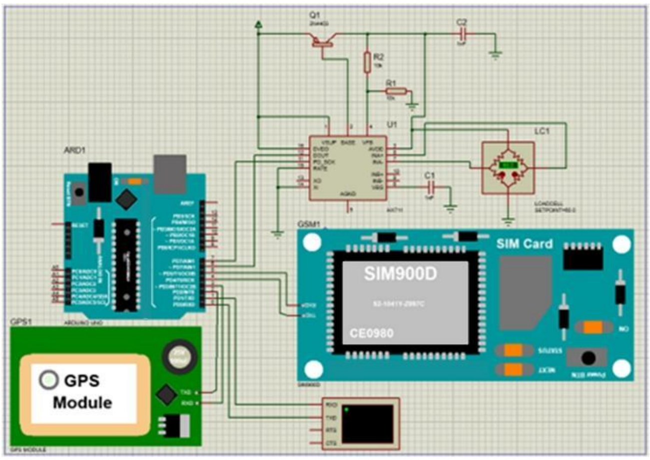

Fig. 11 Schematic of the embedded system for person detection

E. Analysis and Interpretation of the Results Obtained in the Validation of the Embedded System Design.

The design implemented in the Proteus software was simulated on several occasions. In these runs, it was validated that the system operates correctly following the following criteria:

1. The Arduino microcontroller detects the resistance variation of the strain gauge through the HX711 module.

2. The Arduino microcontroller can receive the location detected by the GPS NEO-6M module.

3. The Arduino microcontroller efficiently integrates the data provided by the GPS NEO-6M module into a user-friendly alert message and sends it to the SIM 900D module.

4. The SIM 900D module sends the message provided by the Arduino microcontroller to the virtual terminal, which in the simulation performs the function of the receiving phone.

After verifying the correct operation in the virtual simulation, the circuit was implemented on a breadboard, where physical simulation was conducted. In this simulation, 40 tests were performed.

During the operational tests, the proper functioning of each independent system (strain gauge system, GPS system, and SIM system) was corroborated. Likewise, the functioning of the embedded system as a whole was tested, validating that it complies with the workflow outlined in Fig. 10. These tests were successfully passed. Therefore, it is confirmed that the embedded system passed the validation of operation in both virtual and physical simulations, validating the design of the embedded system based on strain gauges to mitigate vehicle theft.

4. Discussion

Firstly, it was necessary to research which elements could function with the selected microcontroller, which was the Arduino UNO. Then, their characteristics, prices, and availability in the market had to be identified. Subsequently, the schematic design was carried out in Proteus, and simultaneously the code was developed for the microcontroller. The latter step was the most complicated since certain parameters were required that could not be obtained due to being a virtual simulation, such as the location obtained from the GPS module and the sending of alerts to a cellphone with the interface. These two points could only be obtained through physical simulation. Due to the encountered inconveniences, a code was developed that, when uploaded to a physical Arduino UNO, would function normally, but in the Proteus program, it provided random locations focused on Lima, in a way that would not interfere with reality. Additionally, the serial terminal of the same software was utilized to reflect the alert and location, as a model of the text message that would be sent to a cellphone, in a physical simulation.

Finally, the program was run several times, consistently obtaining good results in the simulations. This provides us with the confidence that the project can be implemented physically, leading to the continuation of the physical simulation of the system. For this purpose, the embedded system was implemented using the same methodology as in the virtual simulation. Starting with the implementation of each system separately on the breadboard, ensuring proper functionality. Then, the system was tested as a whole, responding with great success.

Throughout our research process, various articles and theses were evaluated for the design of this system. It is important to mention that although the following researchers designed embedded systems using microcontrollers, none were found that employed both strain gauges and GPS simultaneously in vehicle security systems. However, research was found where anti-theft security systems for vehicles were developed with objectives aligned with the present investigation.

For example, Lin et al. [21] developed a vehicle security system based on Internet + GPS, connecting the vehicle monitoring system with the WeChat application. Another example is Lv et al. [22], who designed an anti-theft security system for a vehicle based on a fingerprint detector and the Internet of Things. Similarly, Subektu et al. [23] created an anti-theft security system using an Arduino UNO as a microcontroller and a presence sensor. Additionally, Castilla et al. [24] chose to develop a system for detecting and monitoring infants within a vehicle using temperature and oxygen sensors.

In the analyzed research, control systems were developed using strain gauges for data capture. An example of this is Correa Hernández [25], who used these devices attached to the cardan joints to measure the torque generated by rotodynamic equipment and then send that data to multiple devices using the Internet of Things communication protocol. Similarly, Valeev et al. [26] applied strain gauges and pulse control to locate defects in multirotor machines. Also, Bohórquez & Ushiña [27] developed a semi-automatic cheese press, where strain gauges were used to control the force exerted by the machine when pressing the cheese. Likewise, Sacoto & Zaruma [28] implemented a control system using strain gauges for monitoring vertical deformations in metal beams of a bridge located over the Machángara River in Cuenca, Ecuador. Similarly, Adarsh et al. [29], developed seismic response control of structures using strain gauges based on a 4-story building model, concluding with a highly effective algorithm for controlling the seismic responses of structures. Finally, Soto [30], who designed a food dosing system, used a controller that received signals from strain gauges, and depending on its configuration, certain signals were sent to the actuators.

5. Conclusions

The tests conducted verified that the system design functions correctly. These tests were carried out in simulators and on physical devices. To determine the design requirements, a preliminary investigation was conducted where the needs that the design had to fulfill based on the objectives were identified. The electronic system was designed and programmed for person detection in anti-theft security systems in automotive vehicles. A simulation software was used for electronic design, and the Arduino IDE was used for programming the control system. The embedded system for person detection was integrated through a simulation, where the GPS location system, alert sending system, and weight detection system using strain gauges were combined. Tests were conducted in the virtual simulation to verify the correct design and communication among all system components. This system was implemented in a physical simulation, where the results in the virtual simulations were confirmed. The effectiveness in response times reached 98%, which represents an optimal result and indicates that it can be reproduced on a larger scale.

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