Control Systems and Optimization Letters, Vol. 3, No 3, 2025
ISSN: 2985-6116, DOI: 10.59247/csol.v3i3.219

A Systematic Design of a Low-Cost Real-Time Vehicle Tracking System for Enhanced Security and Location Monitoring

Hamzah M. Marhoon [1,*], Sabah Ali Sabah [2], Noorulden Basil [3], Benmessaoud Mohammed Tarik [4], Raghad Jassim Mohammed [5], Riyam Fadhil Abbas [6]
[1,2,5] Department of Automation Engineering and Artificial Intelligence, College of Information Engineering, Al-Nahrain University, Jadriya, Baghdad, Iraq
[3] Department of Electrical Engineering, College of Engineering, Mustansiriyah University, Baghdad, Iraq
[4] Electrical and Electronics Engineering Faculty, University of Sciences and Technology of Oran, USTO-MB, BP 1505, EL M'Naouer, Oran, 31000, Algeria
[6] Department of Computer Networks Engineering, College of Information Engineering, Al-Nahrain University, Jadriya, Baghdad, Iraq
Email: [1] hamzah.marhoon@nahrainuniv.edu.iq, [3] noorulden@uomustansiriyah.edu.iq, [4] tarik.benmessaoud@univ-usto.dz, [5] raghad.j.mohammed@nahrainuniv.edu.iq, [6] riyam.fadhil94@nahrainuniv.edu.iq
*Corresponding Author

Abstract—**The rapid development of vehicle tracking technology has significantly enhanced the safety and security of vehicles worldwide. This paper presents the design and implementation of a real-time vehicle tracking system utilising Global Positioning System (GPS) and Global System for Mobile Communication (GSM) technologies, based on the Arduino Uno platform. The proposed system enables vehicle owners to continuously monitor their vehicle's location, receiving instant SMS notifications for unauthorised movement, speed violations, and historical location data. The system's core components include an Arduino Uno microcontroller, interfaced with a SIM900A GSM module and a NEO-6 M GPS module, enabling real-time tracking via SMS alerts and Google Maps integration. Key features include automatic alerts for unauthorised car startups, exceeding speed limits, live tracking requests, and location history retrieval. The system stores the last five GPS coordinates in EEPROM memory and offers a user-friendly interface for retrieving data via SMS. The integration of Google Maps enhances the tracking experience by providing a visual representation of the vehicle's location. This solution offers a cost-effective and reliable means of vehicle monitoring, contributing to improved vehicle security and owner peace of mind.**

Keywords—***Vehicle Tracking, Mobile Communications, Control System, GPS***

I. Introduction

The integration of Global Positioning System (GPS) and Global System for Mobile Communication (GSM) technologies has revolutionised vehicle tracking systems, offering real-time monitoring and enhanced security for vehicle owners. These systems enable precise location tracking, facilitating applications such as fleet management, theft prevention, and personal vehicle monitoring. However, the rising sophistication of car theft, driven by advancements in technology, poses a growing challenge for vehicle owners and security systems worldwide [1], [2].

Historically, vehicle theft has been a significant concern, with criminals relying on traditional methods such as hot-wiring and manual bypassing of security systems. With the rapid development of technology, thieves have become increasingly organised, utilising modern tools such as signal jammers, key cloning devices, and hacking techniques to bypass existing anti-theft systems. This has led to a rise in vehicle thefts, particularly in urban areas, where the demand for high-value vehicles is high. Furthermore, older vehicles, which often lack modern security features, are more susceptible to theft. These cars are frequently targeted by thieves due to their simpler electronic systems and the absence of advanced anti-theft mechanisms, making them easier to steal compared to newer models equipped with state-of-the-art protection technologies [3]-[5].

The development of car alarm systems has been greatly impacted by the increasing demand for advanced vehicle security, which is being driven by the rise in auto theft. Steering wheel locks and other mechanical solutions were among the earliest attempts to deter theft. By physically stopping the steering wheel from turning, these gadgets served as a deterrent to opportunistic theft. These early mechanical solutions worked well for providing rudimentary protection, but they lacked the technological sophistication required to counteract more sophisticated and organised theft techniques [6], [7].

Car alarm systems were developed to meet these new challenges as car theft techniques became more organised and sophisticated. To make it harder for burglars to get past the alarms undetected, alarm systems started to include sensors that could detect motion, vibrations, and glass breaking. More sophisticated security features, such as remote keyless entry systems and immobilisers, were introduced in the 1990s. In addition to offering stronger security, these systems made it harder for criminals to access cars. The introduction of systems that could connect to remote transmitters marked yet another advancement in the development of automobile alarm systems [8], [9]. By the late 1990s, even when they were far away, car owners could get alerts when their vehicle was tampered with. Real-time notifications were made possible by these systems, enabling car owners to act right away in the event that their vehicle was compromised. This was a major turning point in automotive security, giving car owners more security and peace of mind [10]-[12].

Car smart systems have come a long way, especially in improving anti-theft security. Modern cars incorporate a variety of technologies, including the Body Controller, telecommunication systems, and specialised modules like anti-theft and keyless entry, as shown in the diagram in Fig. 1. Together, these systems offer cutting-edge theft protection. The Body Controller Unit, for example, controls lights and locks, making sure that doors stay firmly locked while the airbag and engine control systems keep an eye out for odd vehicle behaviour [13], [14].

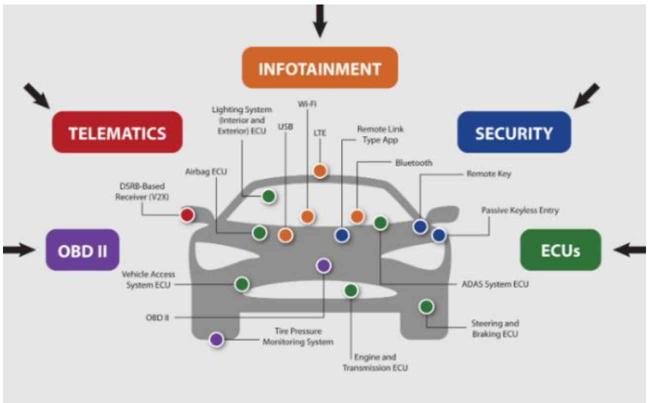

Fig. 1. Modern automotive control systems and connected units

The potential for the cyberattacks has increased with the development of in-vehicle networks, sensors, and connectivity choices of the recent technologies such Wi-Fi, Bluetooth, and cellular connections. Nowadays, cybersecurity measures are crucial to preventing unwanted access to these systems, especially from hackers who take advantage of holes in USB ports, SD card slots, on-board diagnostic (OBD) systems, and servers run by automakers. By enabling remote disabling of stolen vehicles, real-time location tracking, and even biometric identification, these cutting-edge features have completely changed anti-theft systems and made it more difficult for criminals to access and steal contemporary the automobiles [15], [16].

In this paper, we use the Arduino Uno, NEO 6M GPS module, and SIM900A GSM module to design and implement a real-time vehicle tracking system. Vehicle owners will be able to track the location of their vehicle, identify any unauthorised movement, and get real-time SMS alerts thanks to the system. Location tracking, speed limit alerts, and the capability to access historical data via SMS commands are some of the main features. An economical and practical solution for improved vehicle security is provided by the system's integration of Google Maps, which gives a visual depiction of the vehicle's location.

II. LITERATURE SURVEY

The development of advanced vehicle tracking systems has been greatly aided by the widespread availability of small, inexpensive electronic components, particularly Arduino microcontrollers, GPS modules, and GSM modules. This section explores several research initiatives that have used these technologies to develop a range of solutions for remote control, security improvement, and real-time vehicle monitoring. Together, these studies show how the field of vehicle tracking is changing, with a focus on user accessibility, accuracy, and affordability. These range from simple SMS-based location updates to integrated web platforms and smartphone applications. Numerous studies have been conducted in the literature; a few of these are reviewed as follows:

The authors Zeki *et al*. (2023) developed a real-time vehicle tracking system that leverages readily available hardware components to enhance vehicle security through continuous location monitoring. Their proposed system integrates an Arduino Uno R3 microcontroller with a NEO 6M GPS module for precise location acquisition and a SIM900A GSM module for communication. The core methodology involves establishing serial communication between the Arduino and these modules, enabling the system to transmit timely vehicle location updates via SMS. The reported results indicate that this system effectively provides accurate and real-time tracking capabilities, with SMS-based notifications significantly contributing to improved vehicle security [17].

The authors Al-Hilali *et al*. (2022) advanced the field of vehicle tracking by developing a smart system that integrated real-time monitoring with smartphone accessibility. Their solution utilised an Arduino UNO as the central processing unit, coupled with a GPS module for accurate positioning and a GSM module for communication. A key innovation of their work lay in the smartphone integration, which facilitated enhanced user interaction. The system operated by transmitting location updates via SMS, which were then visualised on Google Maps through a dedicated smartphone application. The experimental results demonstrated the system's efficacy in real-time vehicle tracking and location display on a smartphone, thereby significantly improving user experience and overall vehicle management capabilities [18].

The authors Alquhali and Roslee (2018) focused on developing a real-time vehicle tracking system that leveraged web-based technologies for remote monitoring. Their system incorporated an Arduino Uno R3, a GPS module for location acquisition, and a GSM module for data transmission. The methodology involved transmitting vehicle data via the GSM network, with the vehicle's location then being displayed on a web interface utilizing platforms such as ThingSpeak and Freeboard. The results indicated a successful implementation of real-time vehicle location tracking through a web-based platform, demonstrating its effectiveness for remote vehicle monitoring [19].

The authors Tummanapally and Sunkari (2021) developed a smart vehicle tracking system that emphasised the use of affordable hardware for real-time location monitoring. Their research integrated an Arduino UNO microcontroller with a GPS NEO-6M module for precise positioning, a GSM 900A module for communication, and a 16x2 LCD for on-device display. The system's operational method involved sending location updates via SMS, with visual tracking further enhanced through Google Maps integration. The results demonstrated the system's effectiveness in real-time vehicle tracking, highlighting its reliance on low-cost components, which rendered it a practical and affordable solution for widespread implementation [20].

Ghatul et al. (2024) designed a real-time vehicle tracking system that extended beyond mere monitoring to include remote vehicle control, leveraging GPS and GSM technologies. Their system integrated a GPS module for accurate location determination and a GSM module for communication, all managed by an AT89C51 microcontroller. The methodology involved transmitting location updates via SMS, while also enabling vehicle control through SMS commands. The reported results indicated the successful implementation of both real-time vehicles tracking and remote-control functionalities, thereby providing enhanced security measures for vehicle owners [21].

The author Morallo (2020) presented the design of a vehicle tracking system that combined the capabilities of Arduino with GPS and GSM technologies for real-time monitoring and location tracking. The system's hardware consisted of an Arduino Uno, a GPS module for acquiring location data, and a GSM module for communication. The methodology involved sending vehicle location updates via SMS, with Google Maps employed for visual representation of the vehicle's position. The results demonstrated successful real-time vehicle tracking with accurate location updates, ultimately contributing to enhanced vehicle security [22].

The authors, Mustafa *et al.* (2020), proposed a comprehensive vehicle security system aimed at both intrusion detection and theft control, integrating GSM, GPS, and microcontroller technologies. The system's hardware comprised a GPS module for location tracking, a GSM module for communication, a microcontroller for processing, and a relay for control functionalities. The methodology involved detecting intrusions through integrated sensors, while vehicle control was made possible via SMS-based commands. The results demonstrated the successful implementation of a functional vehicle security system that offered both tracking and control features for enhanced vehicle protection [23].

The authors Ibraheem and Salam (2018) focused their work on developing a modern low-cost, secure vehicle tracking system that leveraged GPS, GSM, and XBee technologies for communication, with Google Earth integration for location visualisation. The system's hardware consisted of a GPS module for location acquisition, a GSM module for broader communication, an XBee module for local wireless data transmission, and an Arduino microcontroller. The methodology involved transmitting data via XBee, with the vehicle's location then being visualised using Google Earth. The results demonstrated the successful implementation of a system that offered both enhanced security and cost-efficiency, alongside improved location tracking capabilities [24].

The author Al-Khedher (2012) introduced a hybrid GPS-GSM localisation system specifically designed for automobile tracking, which integrated Google Earth for effective location visualisation. The system's hardware consisted of a GPS module for precise positioning, a GSM module for data transmission, and an Arduino microcontroller for processing. The methodology involved sending location data via GSM, which was then visualised on Google Earth for comprehensive tracking. The reported results indicated the achievement of accurate and reliable vehicle tracking, with enhanced localisation accuracy, thus providing a robust tracking solution [25].

The authors Sahoo and Rath (2013) integrated GPS, GSM, and cellular phone systems to create a comprehensive solution for vehicle location tracking and monitoring, specifically targeting security applications. The system's hardware comprised a GPS module for positioning, a GSM module for communication, and a cellular phone for user interaction. The methodology involved sending SMS-based location updates, with the vehicle's path visually displayed on both a dedicated monitor and the cellular phone. The results demonstrated the effective implementation of vehicle location tracking and monitoring, ultimately enhancing overall vehicle security [26]. The overview of the current car tracking systems covered in the previous studies is summarised in Table 1.

Table 1. Overview of vehicle tracking systems in the literature [17]-[26]

Authors	Proposed Method	Application
Zeki *et al.* (2023)	Real-time vehicle tracking using Arduino Uno, GPS, and GSM for SMS-based location updates to enhance vehicle security.	Vehicle security and real-time tracking
Al-Hilali *et al.* (2022)	Integrated vehicle tracking with smartphone access, using Arduino, GPS, and GSM for SMS updates, visualized on Google Maps via an app.	Enhanced user experience and vehicle management
Alquhali and Roslee (2018)	Web-based vehicle tracking using Arduino, GPS, and GSM. Data displayed on ThingSpeak and Freeboard for remote monitoring.	Remote vehicle monitoring through web interface
Tummanapally and Sunkari (2021)	Affordable tracking system with Arduino, GPS, GSM, and LCD for SMS-based location updates and Google Maps integration.	Affordable and practical real-time vehicle tracking
Ghatul *et al.* (2024)	Combines real-time tracking and remote-control using GPS, GSM, and AT89C51 microcontroller. Vehicle control through SMS commands.	Enhanced security with tracking and remote control
Morallo (2020)	Vehicle tracking with Arduino, GPS, and GSM for real-time tracking, SMS location updates, and visualization on Google Maps.	Vehicle security and location tracking
Mustafa *et al.* (2020)	Vehicle security system using GSM, GPS, and microcontroller for intrusion detection and vehicle control via SMS-based commands.	Intrusion detection and vehicle theft control
Ibraheem and Salam (2018)	Low-cost vehicle tracking system using GPS, GSM, and microcontroller for real-time location tracking with a focus on affordability.	Secure, low-cost vehicle tracking
Al-Khedher (2012)	Hybrid GPS-GSM localisation system with Google Earth visualisation	Automobile tracking
Sahoo and Rath (2013)	GPS, GSM, and cellular phone integration with SMS-based updates and monitoring	Vehicle location and security

III. Proposed Methodology

The working mechanism of a standard vehicle tracking system, which is essentially dependent on the smooth integration of GPS and GSM technologies, is fully depicted in Fig. 2. The procedure starts when GPS satellites send out signals, which a car with a specialised tracking device precisely receives. The precise geographic coordinates of the vehicle are determined by processing the signals received by this strategically placed onboard unit. The SIM900 GSM module then uses the existing cellular network infrastructure to send this crucial positional data to a GSM mobile tower. The GSM tower then sends this data to the designated user's device, like a computer or smartphone, usually in the form of an SMS message. As the Google Maps icon in the mentioned illustration clearly illustrates, the user can then easily view the vehicle's current position and trajectory on a digital mapping platform after receiving it. The diagram's visual flow effectively delineates this process: initiating with GPS satellite signal transmission (indicated by a dashed blue arrow) to the vehicle, followed by the vehicle's communication with the GSM mobile tower (solid blue arrow), and culminating in the SMS delivery to the user's device for Google Maps visualization. This robust system facilitates accurate and dynamic tracking of vehicle movements and finds widespread application across diverse domains, including fleet management, personal vehicle security, and logistics, thereby playing a pivotal role in enhancing safety, control, and operational efficiency.

Fig. 2. Graphical illustration for the proposed methodology

This paper proposes the design and implementation of a real-time vehicle tracking system based on Arduino, utilising Global System for Mobile Communications (GSM) and Global Positioning System (GPS) technologies. The proposed system consists of three key stages, which are outlined below:

- **Location Stage:** In order to track the location of the vehicle, navigation technologies like GPS and GSM are used during this stage. The system is built into the car so the owner can keep an eye on its location in real time. The GPS module is in charge of obtaining the car's geographic coordinates. The vehicle's precise location on the surface of the Earth is determined by a GPS receiver, the 6M-Neo module, which communicates with orbiting satellites to obtain precise latitude and longitude data for car's position.
- **Processing Stage:** An Arduino microcontroller receives the raw GPS data and uses it to interpret the location data. After processing the data, the microcontroller transforms the geographic coordinates into a format that is easy to use, typically a URL. The location of the car can then be conveniently tracked using a smartphone or other web-enabled device by opening this URL in a mapping app, like Google Maps.
- **Stage of Communication:** In the last step, a GSM module sends the location data that has been processed to the car owner. This module connects to a cellular network so that it can send an SMS with the exact location of the vehicle and a link to Google Maps. Real-time location tracking is made possible by this communication, giving the car owner convenient remote access to updates.

IV. Utilised Hardware Components

The careful selection and integration of numerous hardware components is essential to the successful deployment of vehicle tracking and security systems. Microcontrollers, the main processing units in these systems, are in charge of managing data and controlling peripheral devices. While Global System for Mobile Communications (GSM) modules offer vital communication features, such as sending SMS alerts and relaying data to web-based platforms, the integration of GPS modules is essential for precise real-time vehicle location determination. The hardware components used in this system will be thoroughly discussed in the following section, with an emphasis on their functions and roles within the overall design.

A. Arduino Microcontroller

Based on the ATmega328P microcontroller, the Arduino UNO is an affordable microcontroller board. The GPS module is directly interfaced with the Arduino UNO, which serves as the system's central control unit. Since our application does not require onboard data storage, we chose this board because it has enough input/output pins to meet our system requirements and a sufficient amount of memory. The Arduino UNO is also well known for being inexpensive, easy to use, and having a large community. The Arduino UNO serves as the "brain" of the system, controlling data processing, enabling communication between linked modules, and carrying out commands that have been programmed by the user. The board has six analogue input channels and 14 digital input/output pins, six of which support pulse width modulation (PWM). A 16 MHz ceramic resonator, a USB port for programming and serial communication, a power jack for an external power source, in-circuit serial programming headers for more complex programming options, and a reset button are among its features [27], [28]. Fig. 3 represent the Arduino Uno microcontroller with its features.

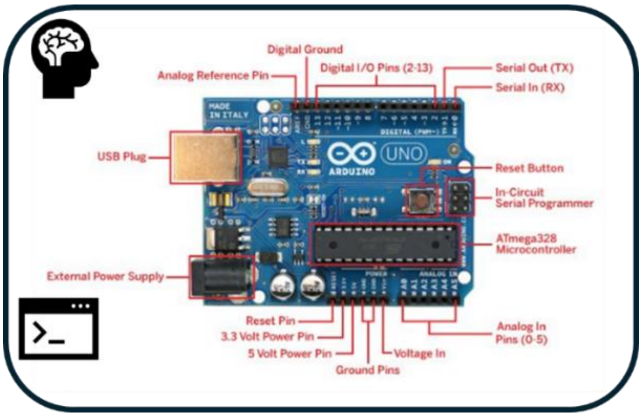

Fig. 3. Arduino Uno microcontroller board [28]

The processing power and memory limitations of Arduino are frequently adequate for applications such as vehicle tracking systems. Its capabilities are sufficient for the real-time tracking, simple data processing, and communication tasks needed in these systems, even though it might not be appropriate for sophisticated optimisation algorithms or high-performance tasks. For these kinds of applications, where sophisticated computational requirements are low, Arduino's affordability and ease of use make it a viable option [28]-[37].

B. GPS 6M-NEO Module

Usually using a default baud rate of 9600 bps, the module connects to microcontrollers through a common UART (serial) interface. It provides location data in the NMEA (National Marine Electronics Association) sentence format, including latitude, longitude, altitude, speed, and time, as seen in Fig. 4. The NEO-6M module's salient characteristics include [38], [39]:

- **Positioning accuracy:** typically, 2.5 meters
- **Cold start time:** ~27 seconds
- **Warm start time:** ~25 seconds
- **Hot start time:** ~1 second
- **Operating voltage:** 3.3V (with onboard regulation for 5V logic)
- **Data protocol:** NMEA 0183 or U-Blox binary

The NEO-6M GPS module is a great option for applications like vehicle tracking, personal navigation, and geofencing systems because of its dependable performance and simplicity of integration with microcontrollers like the Arduino UNO [40].

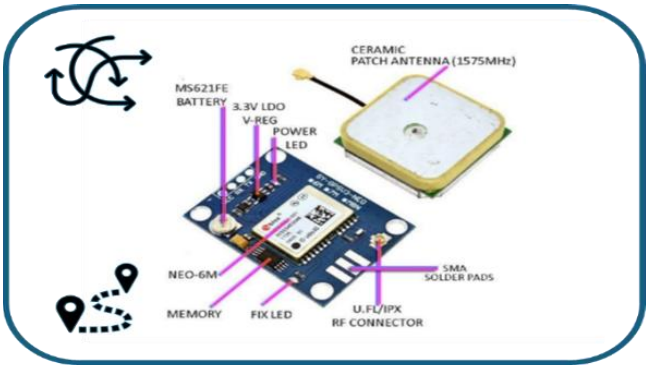

Fig. 4. GPS 6M-Neo module [13]

C. GSM SIM 900 Module

The GSM SIM900 shield, a modular hardware interface designed to facilitate cellular communication in embedded systems and microcontroller-based projects, is depicted in Fig. 5. The SIM900 GSM/GPRS module is integrated into this shield to enable data transmission via GPRS protocols, SMS messaging, and voice calls. This module operates within the standard GSM frequency bands (900/1800 MHz). Its architecture includes essential subsystems for signal processing, power management, and peripheral interfacing, ensuring robust operational stability across a range of applications, including remote monitoring and Internet of Things deployments [41]. A voltage regulator is incorporated into the shield's structural design to reduce external oscillations and ensure consistent power delivery. Power management is further improved, and seamless switching between primary and backup sources is made possible by a power key control circuit and a DC jack for power supply selection. For radio frequency connectivity, a specialised antenna interface ensures optimal signal transmission and reception. The shield enables extensive microcontroller integration through GPIO, PWM, and ADC pins, enabling digital control and analogue sensor interfacing. Microphone and earphone jacks provide audio channels for voice-based applications, while UART serial communication enables AT-command-based module configuration. Additionally, configurability is offered by serial port select jumpers, and NetLight and Status LEDs visually convey operational status by displaying network connectivity and system activity, respectively [42].

The GSM SIM900 shield serves as a stand-alone communication platform by abstracting the complexities of GSM protocols into a standardised hardware interface. Its design, which prioritises compatibility with development boards (like Arduino) while ensuring adherence to telecommunications standards, makes it an essential component of scalable, low-power wireless systems [43].

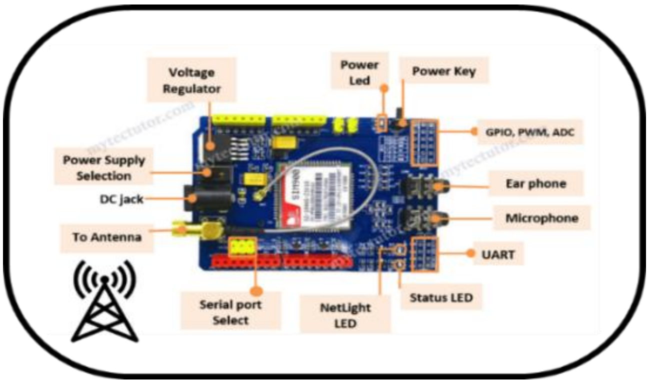

Fig. 5. SIM900 GSM module [44]

V. PROPOSED SYSTEM IMPLEMENTATION

Fig. 6 illustrates the operational block diagram of the proposed real-time vehicle tracking system, which uses GPS and GSM technologies to remotely track the location of vehicles. The system gets precise spatiotemporal coordinates directly from satellite constellations using a 6M-NEO GPS module that is mounted inside the target vehicle. This geolocation information is subsequently processed and relayed by an integrated GSM module, which establishes a cellular connection with the nearest base station. The module provides the owner's mobile device with the coordinates as a formatted SMS and embeds a dynamic hyperlink to Google Maps. This link enables continuous real-time tracking by providing the authorised user with immediate visual access to the vehicle's current location on a digital map.

The Arduino Uno microcontroller, which controls communication between a SIM900 GSM module and a NEO 6M GPS module, is the major component of the proposed real-time vehicle tracking system. The Arduino, which serves as the brain of the system, analyses location data from the GPS module, while the NEO 6M continuously determines the latitude and longitude of the vehicle by locking onto satellite signals. The SIM900 GSM module then transmits this crucial positioning data over cellular networks, sending coordinates to the owner's mobile device via SMS, which contains the latitude and the longitude of the car's position. Owners can see the vehicle's current location at a glance thanks to the instant SMS alerts that include both the raw geographic data and a clickable Google Maps link. A thorough depiction of the hardware arrangement is shown in Fig. 7, which shows how the parts are methodically assembled and housed inside the enclosure.

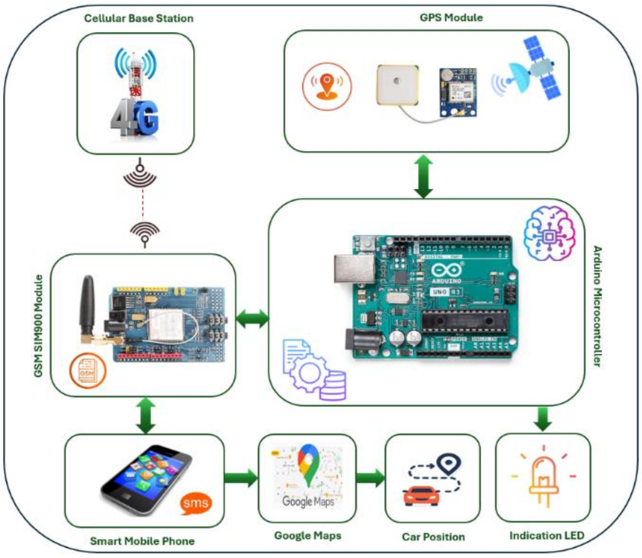

Fig. 6. Graphical illustration for the proposed system

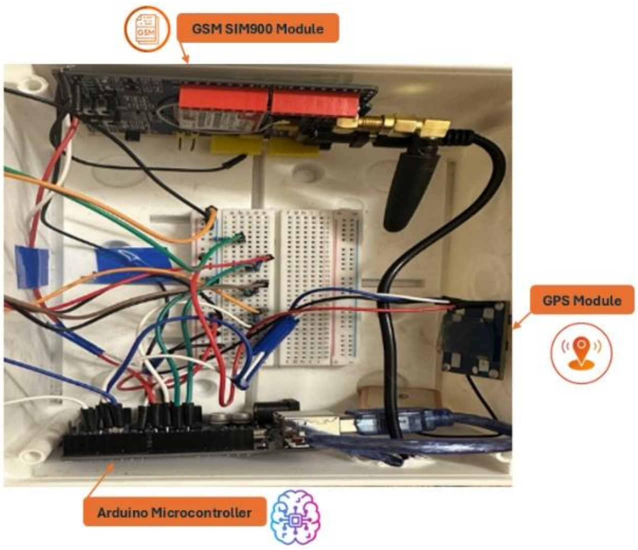

Fig. 7. Internal view of the implemented proposed system

To achieve optimum performance, the SIM900 GSM module requires a peak current of up to 2A. Instead of depending just on the Arduino's 5V pin, which might not be enough to meet the module's power requirements, it is advised to use an external power source, such as a 12V 2A adapter, to guarantee steady performance. By means of particular wiring connections, the Arduino Uno communicates with the GPS and GSM modules, allowing for location tracking and real-time data exchange. As shown in Fig. 8, the wiring configuration connects the GPS module's RX pin to pin 3 of the Arduino and its TX pin to pin 4 of the Arduino.

In a similar arrangement, as illustrated in Fig. 9, the GSM module's RX pin is connected to pin 7 of the Arduino, and its TX pin is connected to pin 8 of the Arduino. With this configuration, the Arduino can send data to the GSM module and receive data from the GPS module. In order to guarantee dependable signal transmission, all modules also share a common ground. Location information is recorded by the GPS module, formatted into a system-specific packet, and sent to the user via SMS.

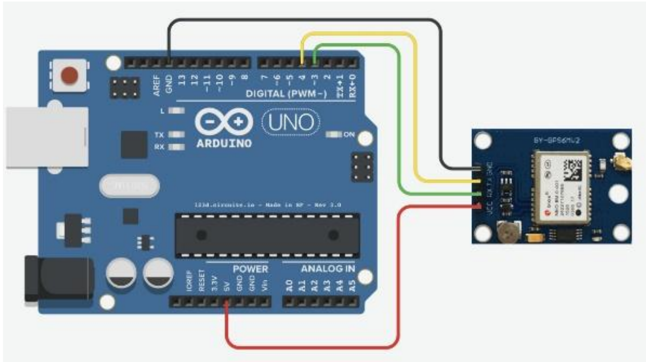

Fig. 8. Connection diagram of Arduino Uno with GPS

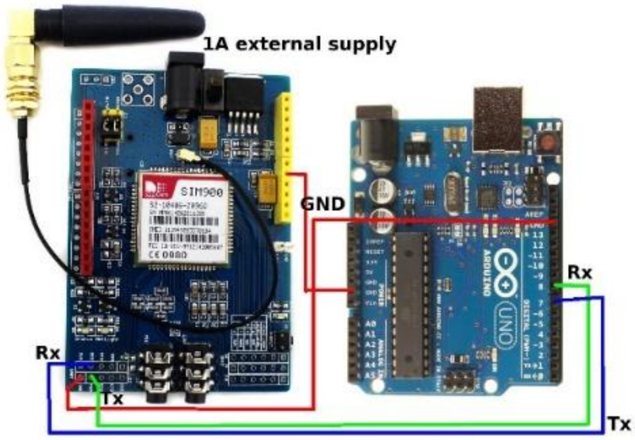

Fig. 9. Connection diagram of Arduino Uno with GPS

After that, three LEDs, each with a specific function, are connected to the Arduino Uno once the GPS, GSM, and Arduino microcontroller wiring is finished. The first LED illuminates to show that the system is operating correctly when it is turned on. To save power, the second LED indicates whether the system is in sleep mode. Notably, the Arduino starts this sleep mode when the system is not in use. When the SMS is successfully sent by the system, the third LED is finally turned on. A tiny push button that simulates starting the car's engine initiates this process. The system provides the owner with an SMS message that includes a link to the vehicle's current location on Google Maps when the button is pressed, indicating that the engine of the car is running. The third LED turns on to show that the SMS message was sent successfully after the location information has been successfully sent to the vehicle owner. The constructed system inside its enclosure is shown in Fig. 10.

VI. Obtained Results and Discussion

The results obtained in this section of the paper show that the vehicle tracking system works as planned, sending SMS alerts based on predefined conditions like:

- Location Updates
- Speed Violations, and
- Unauthorised Movement

The real-time tracking and alert notifications were made possible by the Arduino Uno's dependable integration of the

GPS and GSM modules. By switching to sleep mode when not in use, the system also efficiently reduces power consumption. The project's overall objective of developing a useful and effective vehicle tracking system was met, though there is room for additional advancements in response time and accuracy. The system instantly sends a brief message to the car owner's mobile phone after starting the vehicle and pressing the push button, which simulates a theft attempt. The Google Maps URL that shows the car's current location is included in this message, along with the warning prefix "UNAUTHORISED MOVEMENT" to warn the owner of the possible theft. As demonstrated in Fig. 11, the system's responsiveness to these inputs shows how well it works to give the vehicle owner timely information and guarantee that security measures are actively maintained.

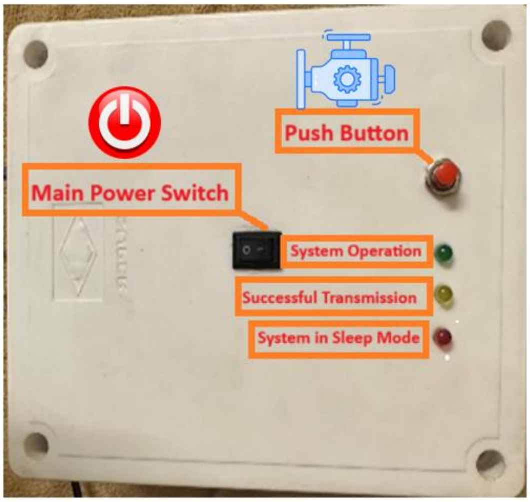

Fig. 10. The implemented car tracking system

The GPS tracks the car's speed continuously. The system automatically sends an SMS with the alert message "Alert: Speed Limit Exceeded!" and the vehicle's current coordinates if the speed of the vehicle surpasses 80 km/h. Fig. 12, which shows the received alert message, demonstrates this functionality. The system has been enhanced with an additional feature that enables it to switch to live tracking mode when it receives an SMS command that includes the word "track." Following receipt of this command, the system will transmit the location of the vehicle every 60 seconds for a maximum of five updates. The owner of the car can follow the movement of the vehicle in almost real-time thanks to this feature. Fig. 13 shows the procedure and the live tracking capability of the system. The final feature of the proposed system is that the current latitude and longitude are saved in the EEPROM memory each time the GPS data is updated. The last five locations are saved by the system and can be retrieved by sending the SMS command "history." The user can easily access the vehicle's past locations by clicking on links to Google Maps that are sent back to them from these stored locations. Fig. 14, which displays the location history sent to the user, serves as an example of this functionality.

The results of the practical assessment of the suggested real-time vehicle tracking system demonstrate a swift and effective response in various test scenarios. In normal operating conditions, the system's 2.5-meter horizontal positioning accuracy ensures accurate and dependable location tracking. Real-time data updates are supported for both standard and high-speed applications by the navigation update rate of 1 Hz, which can be increased to 5 Hz. In addition, the system's sensitivity of -161 dBm guarantees stable operation even in situations where GPS signal reception is poor, increasing its dependability under trying circumstances. When it came to initialisation, the system showed a 27-second cold start time and a 1-second hot start time. A cold start, which usually results in a longer initialisation period, is the amount of time it takes the system to acquire satellite signals when no previous position or satellite information is available. On the other hand, a hot start occurs when the system has stored satellite data from earlier operations in a cache, which allows for much faster satellite signal acquisition and a much shorter waiting time. Fig. 15 provides a summary and visual representation of these important system features, highlighting the system's capabilities for improved security and real-time vehicle monitoring. Regarding the limitations of the suggested system, Fig. 16 offers a thorough summary of the difficulties faced during the real-time vehicle tracking system, which makes use of the Arduino Uno and GPS 6M-Neo modules.

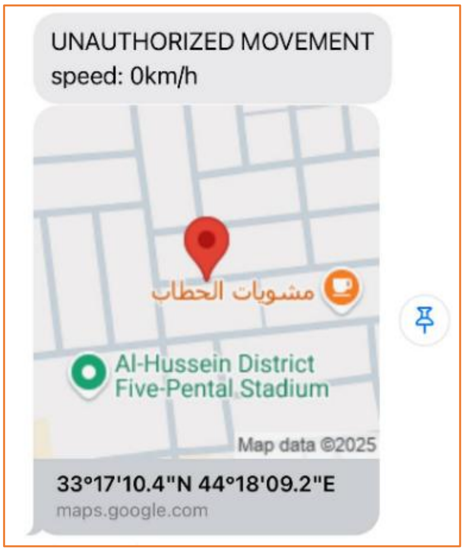

Fig. 11. Alert SMS received by car owner

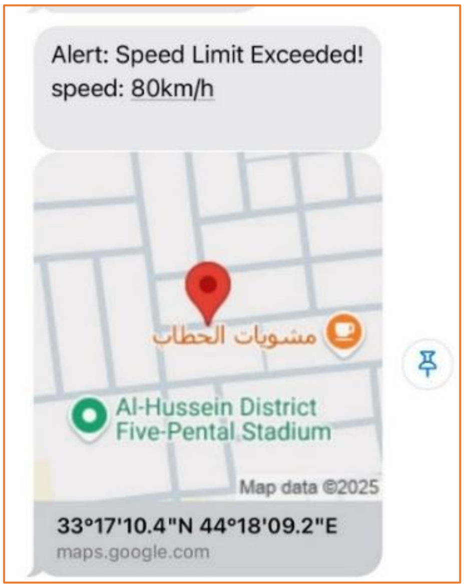

Fig. 12. Speed limit exceeded alert SMS with car position

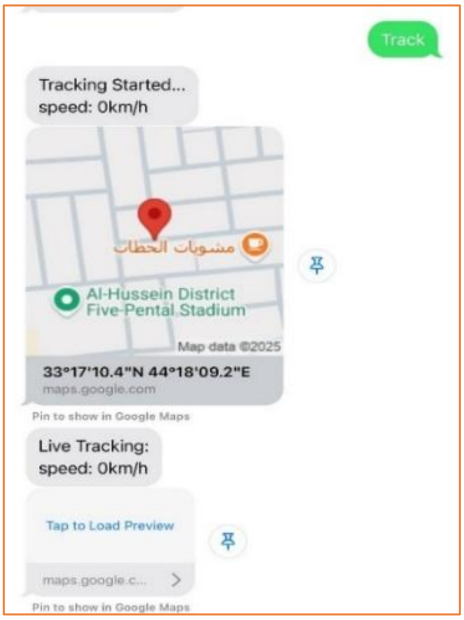

Fig. 13. Live tracking mode with vehicle location updates

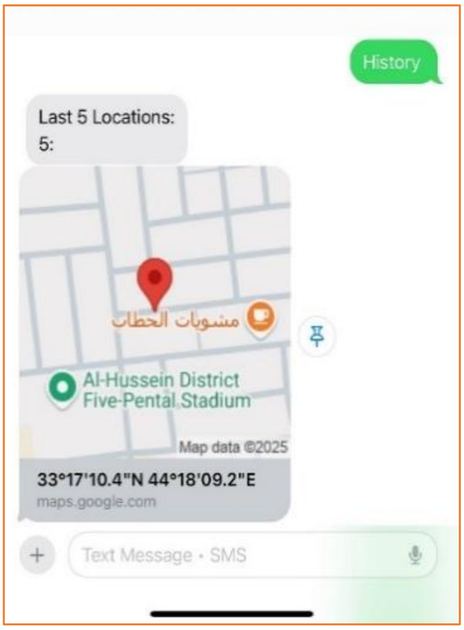

Fig. 14. Location history sent to user with Google maps links

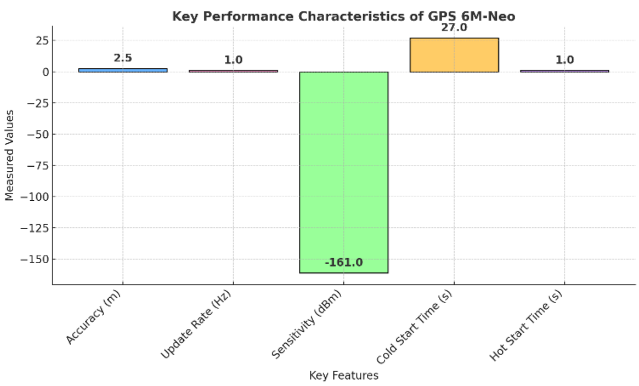

Fig. 15. Performance Metrics of the Real-Time Vehicle Tracking System

This system underwent a battery of demanding tests intended to evaluate its functionality in a range of operational scenarios. A number of significant limitations emerged during the testing process, pointing out areas where the system's dependability and efficiency could be further enhanced. The following provides a thorough examination of the elements that affected the system's overall functionality, as the limitations found during these trials have been methodically categorised:

- **Limited Processing Power:** In situations requiring high computational demands, such as sophisticated route planning or real-time data analysis, the Arduino Uno's comparatively low processing power limits its capacity to carry out more intricate computations or manage several tasks at once.
- **Problems with GPS signal reception:** The system's capacity to sustain a steady GPS connection is severely impacted in locations with low satellite visibility, such as urban canyons or densely forested areas, which may result in inaccurate or lost position data.
- **Accuracy restrictions:** Although the GPS 6M-Neo has a 2.5-meter horizontal position accuracy, this may not be enough for applications that need high-precision location tracking, like auto navigation or applications where accuracy down to the centimetre is crucial.
- **Limitations on the power supply:** When the system is powered by a battery, its total power consumption—which includes the Arduino Uno and the GPS module—may lead to a short operating time. This calls for effective power management techniques, especially in applications that need to run continuously without requiring recharging.
- **Environmental Sensitivity (Temperature Effect):** Both the GPS 6M-Neo and Arduino Uno may perform less well in extremely hot or cold temperatures. When exposed to high temperatures, the Arduino Uno in particular may become unresponsive or even "hang," which could cause instability in the system. In a similar vein, high temperatures may result in decreased accuracy or slower GPS signal acquisition. Therefore, stable environmental conditions are essential for the system's dependability, especially in outdoor applications.
- **Cold Start Time Delay:** The 27-second cold start time of the GPS 6M-Neo could cause a lag before the system receives its first reliable satellite signal. When quick position fixes are needed, like in real-time vehicle tracking or emergency response situations, this delay is more apparent.

VII. Comparative Analysis of Microcontrollers: Effectiveness, Cost, and Complexity

The performance of three different microcontroller options, the Arduino Uno, PIC, and Raspberry Pi, was compared in order to assess the efficacy of the suggested Real-Time Vehicle Tracking System. The Arduino Uno performs better than the PIC in the majority of categories, as shown in Fig. 17, but it scored highest in ease of use and community support. According to [45], the Arduino Uno is well-known for its simplicity, which makes it perfect for rapid prototyping and educational applications. However, as [46] and [47] demonstrate, the Raspberry Pi offers substantially more computational power and is better suited for complex tasks, so it lags in terms of real-time processing and processing speed. Despite being extremely effective and power-efficient, the PIC received lower scores for real-time processing and ease of use, suggesting that it is more appropriate for low-power applications but may need more time and experience to develop [48]. Overall, the Raspberry Pi is better suited for sophisticated, resource-intensive applications, the Arduino Uno offers a well-balanced choice for simple systems, and the PIC fills specialized use cases where low power consumption is essential, as explained by [49] and [50].

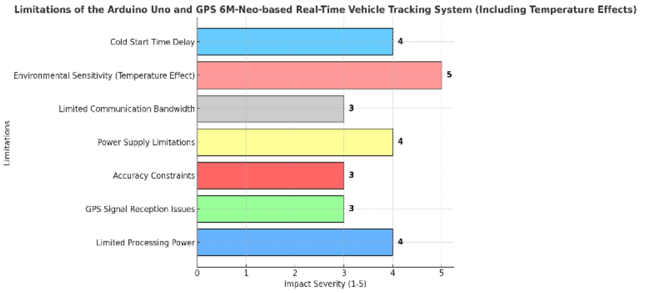

Fig. 16. Limitations of the proposed tracking system

When choosing the best platform for real-time vehicle tracking systems, the price of microcontrollers is a major consideration. At about $10, the Arduino Uno is the most economical option, as seen in Fig. 18, which makes it a great choice for low-budget projects and educational applications. With prices usually starting at $5, the PIC microcontroller is a little less expensive, making it a desirable option for straightforward embedded systems requiring little processing power [51]. However, the Raspberry Pi is much more costly; models usually run about $35. Its higher cost, however, is justified by its increased computational capacity, adaptability, and suitability for more complicated, resource-intensive applications like networking, multimedia, and real-time data processing [52] and [53]. Therefore, the Raspberry Pi justifies its higher price with enhanced capabilities that are advantageous for complex tasks requiring advanced processing power and connectivity, while the Arduino Uno and PIC offer affordable options for simpler and cost-sensitive applications [54].

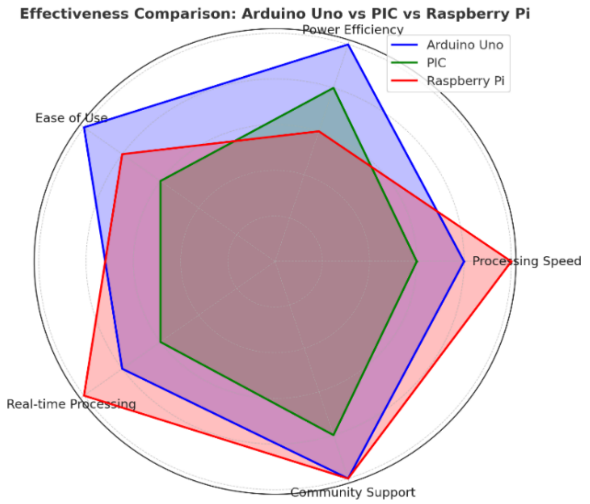

Fig. 17. Effectiveness comparison of Arduino Uno, PIC, and Raspberry Pi

In terms of development time, resources, and scalability, microcontroller complexity is a significant consideration when choosing the best platform for a particular application. With the smallest development complexity score, the Arduino Uno is the most straightforward microcontroller, as shown in Fig. 19. It is perfect for novices and quick prototyping in educational environments because it is easy to use and has extensive documentation [55]. Despite being power-efficient, the PIC microcontroller is comparatively more complicated, necessitating a deeper comprehension of its hardware interface and assembly language for development [56]. The PIC is appropriate for applications requiring low power and minimal resource usage due to its increased complexity, but it might not be the best choice for quick development or non-expert users. With more processing power, network capabilities, and a large library, the Raspberry Pi is the most sophisticated of the three. Although it works well for more complex tasks, simple embedded systems are less suited for it due to the additional setup, programming, and resource management complexity [57] and [58]. Consequently, the PIC and Raspberry Pi offer more sophisticated functionality at the expense of greater development complexity, making them appropriate for more demanding applications, even though the Arduino Uno is still the most user-friendly.

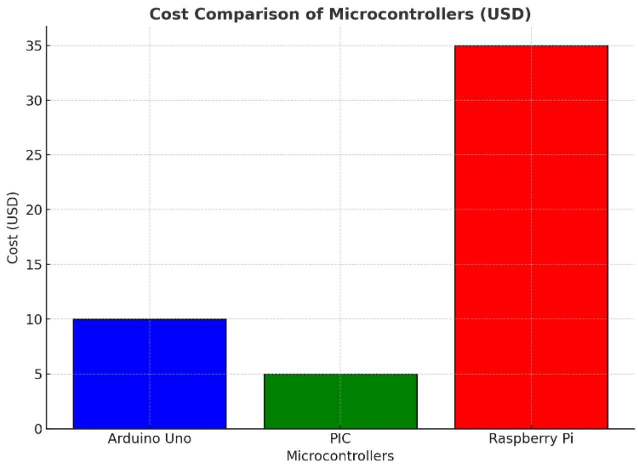

Fig. 18. Cost Comparison of Arduino Uno, PIC, and Raspberry Pi (USD)

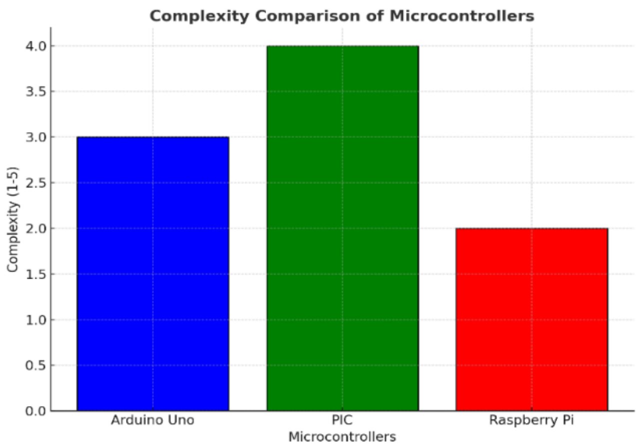

Fig. 19. Complexity Comparison of Arduino Uno, PIC, and Raspberry Pi

VIII. Conclusion

This paper illustrates the design and implementation of an economical and effective vehicle tracking system that makes use of GPS, GSM, and Arduino Uno microcontroller modules. Real-time tracking, speed monitoring, alert notifications for illegal movement, speed limit violations, and location updates are some of the system's primary features. The system simulates a theft attempt and sends an SMS alert with a link to the car's location on Google Maps when the engine is started. The system also tracks the vehicle's speed and notifies the user if it surpasses 80 km/h. By sending an SMS command to activate live tracking mode, which sends location updates every 60 seconds, the car owner can also follow the movement of the vehicle in almost real-time. Additionally, the "history" command allows the owner to access the last five GPS locations that the system has stored in EEPROM memory. In this work, the sleep mode exploit is triggered when the system is not in use, which in turn reduces the power consumption of the system. The system is made accessible and reasonably priced by the design's use of inexpensive and user-friendly hardware components, including the Arduino Uno, GPS and GSM modules, and simple electronic components. This vehicle tracking system successfully satisfies its goals of delivering location history retrieval, real-time tracking, and timely alerts while guaranteeing vehicle security and consuming minimal power. Together with the system's functionality, the hardware components' affordability and ease of use make it the perfect way to improve vehicle security at a reasonable cost.

REFERENCES

[1] Z. Abbas, B. Ahmad, J. Abbas, A. Akbar, and R. Batool, "A fingerprint based students attendance system with SMS alert to parents," *Iraqi Journal of Information and Communications Technology (IJICT)*, vol. 6, no. 3, 2023, https://doi.org/10.31987/ijict.6.3.271.

[2] A. H. Mukalaf, H. M. Marhoon, I. Suwarno, and A. Ma'arif, "Design and Manufacturing of Smart Car Security System with IoT-Based Real-Time Tracking," *International Journal of Intelligent Systems and Applications in Engineering*, vol. 11, no. 6s, pp. 745–752, 2023, https://ijisae.org/index.php/IJISAE/article/view/2909.

[3] N. Alsaedi and A. S. A. Jalal, "Energy aware smart car parking system based Internet of Spatial Things," *Iraqi Journal of Information and Communication Technology*, vol. 7, no. 1, pp. 1–10, 2024, https://doi.org/10.31987/ijict.7.1.241.

[4] K. Lappanitchayakul, "Anti-theft device for car: Alert system using radio wave," in *2019 International Conference on Intelligent Informatics and Biomedical Sciences (ICIIBMS)*, pp. 351-355, 2019, https://doi.org/10.1109/ICIIBMS46890.2019.8991531.

[5] H. M. Marhoon, A. I. Alanssari, and N. Basil, "Design and implementation of an intelligent safety and security system for vehicles based on GSM communication and IoT network for real-time tracking," *Journal of Robotics and Control (JRC)*, vol. 4, no. 5, pp. 708-718, 2023, https://doi.org/10.18196/jrc.v4i5.19652.

[6] S. C. Mathi, S. R. Jambula, D. A. Surat, M. C. Maridinapalli, M. P. V., and V. Sailaja, "Development of an Intelligent Fuel Monitoring and Theft Detection System Equipped with GPS & GSM Integration, State of Charge Monitoring and Realtime Alarm Generation," in *2024 International Conference on Inventive Computation Technologies (ICICT)*, pp. 2095-2102, 2024, https://doi.org/10.1109/ICICT60155.2024.10544646.

[7] S. A. Mohammed, "Designing rules to implement reconnaissance and unauthorized access attacks for intrusion detection system," *Iraqi Journal of Information and Communication Technology*, vol. 2, no. 2, pp. 25–43, 2019, https://doi.org/10.31987/ijict.2.2.67.

[8] Shatgar, and P. B. Metri, "Smart Anti-Theft Control System Using IoT," in *2024 IEEE North Karnataka Subsection Flagship International Conference (NKCon)*, pp. 1-5, 2024, https://doi.org/10.1109/NKCon62728.2024.10774803.

[9] D. Dhrumil, D. Vaithiyanathan, P. Verma, and B. Kaur, "Implementation and Experimental Analysis of Anti-Theft Alarm System," in *2024 First International Conference on Electronics, Communication and Signal Processing (ICECSP)*, pp. 1-7, 2024, https://doi.org/10.1109/ICECSP61809.2024.10698192.

[10] M. Pathak, K. N. Mishra, and S. P. Singh, "An intelligent integrated vehicle surveillance system for controlling the vehicle thefts/hacking using IoT and facial recognition," *Int. J. Syst. Assur. Eng. Manag.*, vol. 16, pp. 468–493, 2025, https://doi.org/10.1007/s13198-024-02654-8.

[11] C. Hong and S. Guo, "Design of automotive anti-theft system based on IoT and multisensor fusion," in *International Conference on Mechatronics and Intelligent Control (ICMIC 2024)*, vol. 13447, pp. 264-268, 2025, https://doi.org/10.1117/12.3055086.

[12] K. Shashidhar, A. Kumar Dharmireddy, and C. M. Rao, "Anti-theft fingerprint security system for motor vehicles," in *Blockchain Technology for IoT and Wireless Communications*, pp. 89-101, 2023, https://doi.org/10.1201/9781003269991-8.

[13] H. M. Marhoon, A. Ma'arif, H. D. K. Aljanabi, A. I. Alanssari, and I. Nadheer, "IoT-based low-cost children tracker system," *Signal and Image Processing Letters*, vol. 5, no. 1, pp. 72-79, 2023, https://doi.org/10.31763/simple.v5i1.62.

[14] T. A. Devi, G. Sanjeev, K. V. Govardhan Rao, T. V. Sai Kalyani, R. Nittala, and M. K. Kumar, "GSM based Vehicle Security Theft Control System," in *2024 3rd International Conference on Computational Modelling, Simulation and Optimization (ICCMSO)*, pp. 165-169, 2024, https://doi.org/10.1109/ICCMSO61761.2024.00043.

[15] N. Papadakis, N. Koukoulas, I. Christakis, I. Stavrakas, and D. Kandris, "An IoT-Based Participatory Antitheft System for Public Safety Enhancement in Smart Cities," *Smart Cities*, vol. 4, no. 2, pp. 919-937, 2021, https://doi.org/10.3390/smartcities4020047.

[16] R. S. Rathore, C. Hewage, O. Kaiwartya, and J. Lloret, "In-Vehicle Communication Cyber Security: Challenges and Solutions," *Sensors*, vol. 22, no. 17, p. 6679, 2022, https://doi.org/10.3390/s22176679.

[17] T. Islam, M. A. Sheakh, A. N. Jui, O. Sharif, and M. Z. Hasan, "A review of cyber attacks on sensors and perception systems in autonomous vehicles," *Journal of Economy and Technology*, vol. 1, pp. 242-258, 2023, https://doi.org/10.1016/j.ject.2024.01.002.

[18] F. Zeki, "Vehicle tracking system by using GPS, GSM, and Arduino technology," in *Proceedings of the 4th International Conference on Communication Engineering and Computer Science (CIC-COCOS 2022)*, pp. 157–161, 2022, https://doi.org/10.24086/cocos2022/paper.833.

[19] M. E. A. Osman and H. Hassan, "GPS and GSM-Based Vehicle Tracking System," *Progress in Engineering Application and Technology*, vol. 5, no. 1, pp. 23-31, 2024, https://publisher.uthm.edu.my/periodicals/index.php/peat/article/view/14763.

[20] A. H. Y. Alquhali and M. B. Roslee, "A Novel Real-Time Vehicle Tracking System Using Arduino," *Engineering International*, vol. 6, no. 2, pp. 93–106, 2018, https://doi.org/10.18034/ei.v6i2.228.

[21] S. S. Tummanapally and S. Sunkari, "Smart Vehicle Tracking System using GPS and GSM Technologies," *Available at SSRN 3884903*, 2021, https://doi.org/10.2139/ssrn.3884903.

[22] S. Jeevan, K. K. S, J. Sharma, Mohana, M. Moharir and A. K. A R, "GPS Based Efficient Real Time Vehicle Tracking and Monitoring System Using Two Factor Authentication and Internet of Things (IoT)," *2024 Second International Conference on Intelligent Cyber Physical Systems and Internet of Things (ICoICI)*, Coimbatore, India, 2024, pp. 473-478, 2024, https://doi.org/10.1109/ICoICI62503.2024.10696765.

[23] N. T. Morallo, "Vehicle tracker system design based on GSM and GPS interface using Arduino as platform," *Indonesian Journal of Electrical Engineering and Computer Science*, vol. 23, no. 1, pp. 258–264, 2021, https://doi.org/10.11591/ijeecs.v23.i1.pp258-264.

[24] A. Mustafa, H. Jameel, M. Baqar, R. A. Khan, Z. M. Yaqoob, Z. Rahim, and S. S. Hussain, "Vehicle intrusion and theft control system using GSM and GPS: An advance and viable approach," *arXiv preprint arXiv:2004.04864*, 2020, https://doi.org/10.48550/arXiv.2004.04864.

[25] I. K. Ibraheem and S. W. Hadi, "Design and Implementation of a Low-Cost Secure Vehicle Tracking System," *2018 International Conference on Engineering Technology and their Applications (IICETA)*, pp. 146-150, 2018, https://doi.org/10.1109/IICETA.2018.8458096.

[26] A. Mustafa, M. I. Aal-Nouman, and O. A. Awad, "Cloud-based vehicle tracking system," *Iraqi Journal of Information and Communication*

Technology, vol. 2, no. 4, pp. 21–30, 2019, https://doi.org/10.31987/ijict.2.4.81.

[27] H. A. Qaisi and M. F. Al-Gailani, "Experimental realization of quantum cryptography by Arduino," *Iraqi Journal of Information and Communication Technology*, vol. 6, no. 1, pp. 1–8, 2023, https://doi.org/10.31987/ijict.6.1.204.

[28] H. Setiawan, A. Ma'arif, H. M. Marhoon, A.-N. Sharkawy, and A. Çakan, "Distance Estimation on Ultrasonic Sensor Using Kalman Filter," *Buletin Ilmiah Sarjana Teknik Elektro*, vol. 5, no. 2, pp. 210–217, 2023, https://doi.org/10.12928/biste.v5i2.8089.

[29] A. A. Sahrab and H. M. Marhoon, "Design and fabrication of a low-cost system for smart home applications," *Journal of Robotics and Control (JRC)*, vol. 3, no. 4, pp. 409-414, 2022, https://doi.org/10.18196/jrc.v3i4.15413.

[30] I. A. Taha and H. M. Marhoon, "Implementation of controlled robot for fire detection and extinguish to closed areas based on Arduino," *TELKOMNIKA (Telecommunication Computing Electronics and Control)*, vol. 16, no. 2, pp. 654-664, 2018, https://doi.org/10.12928/telkomnika.v16i2.8197.

[31] N. Basil, A. F. Mohammed, B. M. Sabbar, et al., "Performance analysis of hybrid optimization approach for UAV path planning control using FOPID-TID controller and HAOAROA algorithm," *Sci Rep*, vol. 15, p. 4840, 2025, https://doi.org/10.1038/s41598-025-86803-4.

[32] N. Basil, H. M. Marhoon, D. F. Sahib, et al., "Accelerated black hole optimization algorithm with enhanced FOPID controller for omni-wheel drive mobile robot system," *Neural Comput & Applic*, pp. 1-32, 2025, https://doi.org/10.1007/s00521-025-11310-6.

[33] Z. S. Bakr, H. M. Marhoon, and A. Alaythawy, "An Enhanced Image Segmentation Technique-Based on Motion Detection Algorithm," *Journal of Applied Engineering and Technological Science (JAETS)*, vol. 6, no. 1, pp. 69–85, 2024, https://doi.org/10.37385/jaets.v6i1.6080.

[34] N. Basil and H. M. Marhoon, "Correction to: selection and evaluation of FOPID criteria for the X-15 adaptive flight control system (AFCS) via Lyapunov candidates: Optimizing trade-offs and critical values using optimization algorithms," *e-Prime-Advances in Electrical Engineering, Electronics and Energy*, vol. 8, p. 100589, 2024, https://doi.org/10.1016/j.prime.2024.100589.

[35] N. Basil, H. M. Marhoon, and A. F. Mohammed, "Evaluation of a 3-DOF helicopter dynamic control model using FOPID controller-based three optimization algorithms," *Int. J. Inf. Technol.*, pp. 1-10, 2024, https://doi.org/10.1007/s41870-024-02373-0.

[36] A. F. Mohammed, H. M. Marhoon, N. Basil, and A. Ma'arif, "A New Hybrid Intelligent Fractional Order Proportional Double Derivative+ Integral (FOPDD+ I) Controller with ANFIS Simulated on Automatic Voltage Regulator System," *International Journal of Robotics & Control Systems*, vol. 4, no. 2, 2024, https://doi.org/10.31763/ijrcs.v4i2.1336.

[37] N. Basil, H. M. Marhoon, M. R. Hayal, E. E. Elsayed, I. Nurhidayat, and M. A. Shah, "Black-hole optimisation algorithm with FOPID-based automation intelligence photovoltaic system for voltage and power issues," *Australian Journal of Electrical and Electronics Engineering*, vol. 21, no. 2, pp. 115-127, 2024, https://doi.org/10.1080/1448837X.2024.2308415.

[38] T. M. Salman, H. N. Abdullah, H. M. Marhoon, and Z. A. Karam, "Design and Fabrication of a Smart Monitoring System for Liquefied Petroleum Gas-Operated Cars Based on Global System Mobile," *International Journal of Online & Biomedical Engineering*, vol. 19, no. 11, 2023, https://doi.org/10.3991/ijoe.v19i11.41937.

[39] K. B. Poovanna, A. Rai and S. Roy, "Personal Safety and Health Monitoring System for Emergency Assistance using IOT," 2024 3rd International Conference on Artificial Intelligence For Internet of Things (AIIoT), pp. 1-6, 2024, https://doi.org/10.1109/AIIoT58432.2024.10574638.

[40] P. Chinnasamy, P. P. S, C. Sivakrishnaiah, T. Sathiya, I. Alam and D. P. Degala, "Design and Implementation of an IoT-based Emergency Alert and GPS Tracking System using MQTT and GSM/GPS Module," *2025 5th International Conference on Trends in Material Science and Inventive Materials (ICTMIM)*, pp. 1286-1291, 2025, https://doi.org/10.1109/ICTMIM65579.2025.10987939.

[41] V. T. M, V. S. N, U. G. D, S. B. L, and J. R. Munavalli, "Real-Time Global Parcel Tracking System in the Supply Chain Using RFID and GPS," in *2025 International Conference on Intelligent and Innovative Technologies in Computing, Electrical and Electronics (IITCEE)*, pp. 1-5, 2025, https://doi.org/10.1109/IITCEE64140.2025.10915357.

[42] Z. Abbas, B. Ahmad, J. Abbas, A. Akbar, and R. Batool, "A fingerprint based students attendance system with SMS alert to parents," *Iraqi Journal of Information and Communications Technology*, vol. 6, no. 3, 2023, https://doi.org/10.31987/ijict.6.3.271.

[43] M. Murad, O. Bayat, and H. M. Marhoon, "Design and implementation of a smart home system with two levels of security based on IoT technology," *Indonesian Journal of Electrical Engineering and Computer Science*, vol. 21, no. 1, pp. 546-557, 2021, https://doi.org/10.11591/ijeecs.v21.i1.pp546-557.

[44] H. M. Marhoon, N. Basil, and B. B. Q. Elias, "Design and Manufacturing of an Efficient Low-Cost Fire Surveillance System Based on GSM Communications and IoT Technology," in *Proceedings of Third International Conference on Computing and Communication Networks (ICCCN 2023)*, vol. 917, 2024, https://doi.org/10.1007/978-981-97-0892-5_6.

[45] D. Rani, A. Kaur, R. Mittal, A. Kaur and N. Garg, "Exploring Arduino Board Applications in Embedded Systems: The Role of AI, Cloud Computing, and Edge Computing," *2025 3rd International Conference on Communication, Security, and Artificial Intelligence (ICCSAI)*, pp. 1730-1734, 2025, https://doi.org/10.1109/ICCSAI64074.2025.11063918.

[46] G. Vieira, J. Barbosa, P. Leitão and L. Sakurada, "Low-Cost Industrial Controller based on the Raspberry Pi Platform," *2020 IEEE International Conference on Industrial Technology (ICIT)*, Buenos Aires, Argentina, 2020, pp. 292-297, 2020, https://doi.org/10.1109/ICIT45562.2020.9067148.

[47] S. Karthikeyan, R. A. Raj, M. V. Cruz, L. Chen, J. L. A. Vishal and V. S. Rohith, "A Systematic Analysis on Raspberry Pi Prototyping: Uses, Challenges, Benefits, and Drawbacks," in *IEEE Internet of Things Journal*, vol. 10, no. 16, pp. 14397-14417, 2023, https://doi.org/10.1109/JIOT.2023.3262942.

[48] D. Yadav, B. Raj, and B. Raj, "Design and simulation of low power microcontroller for internet of things applications," *Sensor Letters*, vol. 18, no. 5, pp. 401-409, 2020, https://doi.org/10.1166/sl.2020.4241.

[49] H. Wu, C. Chen, and K. Weng, "An energy-efficient strategy for microcontrollers," *Applied Sciences*, vol. 11, no. 6, p. 2581, 2021, https://doi.org/10.3390/app11062581.

[50] M. R. Idris, M. N. Irdayanti, and M. Ramlee, "A review of microcontroller design in future industrial revolution," In *AIP Conference Proceedings*, vol. 2750, no. 1, p. 050031, 2023, https://doi.org/10.1063/5.0149679.

[51] A. Villar-Martínez, L. Rodríguez-Gil, I. Angulo, P. Orduña, J. García-Zubía and D. López-De-Ipiña, "Improving the Scalability and Replicability of Embedded Systems Remote Laboratories Through a Cost-Effective Architecture," in *IEEE Access*, vol. 7, pp. 164164-164185, 2019, https://doi.org/10.1109/ACCESS.2019.2952321.

[52] L. I. Minchala, J. Peralta, P. Mata-Quevedo, and J. Rojas, "An approach to industrial automation based on low-cost embedded platforms and open software," *Applied Sciences*, vol. 10, no. 14, p. 4696, 2020, https://doi.org/10.3390/app10144696.

[53] P. Coelho, C. Bessa, J. Landeck, and C. Silva, "The Potential of Low-Power, Cost-Effective Single Board Computers for Manufacturing Scheduling," *Procedia Computer Science*, vol. 217, pp. 904-911, 2023, https://doi.org/10.1016/j.procs.2022.12.287.

[54] S. Wang, S. Vallurupally, R. Mitra, S. S. Nuguri, K. Salah and P. Calyam, "Cost-Performance Trade-Offs in Fog Computing for IoT Data Processing of Social Virtual Reality," *2019 IEEE International Conference on Fog Computing (ICFC)*, pp. 134-143, 2019, https://doi.org/10.1109/ICFC.2019.00025.

[55] D. Miller, "The best practice of teach computer science students to use paper prototyping," *International Journal of Technology Innovation and Management (IJTIM)*, vol. 1, no. 2, pp. 42-63, 2021, https://doi.org/10.54489/ijtim.v1i2.17.

[56] A. Fanariotis, T. Orphanoudakis, and V. Fotopoulos, "Reducing the power consumption of edge devices supporting ambient intelligence applications," *Information*, vol. 15, no. 3, p. 161, 2024, https://doi.org/10.3390/info15030161.

[57] S. Safari *et al.*, "A Survey of Fault-Tolerance Techniques for Embedded Systems From the Perspective of Power, Energy, and Thermal Issues,"

in *IEEE Access*, vol. 10, pp. 12229-12251, 2022, https://doi.org/10.1109/ACCESS.2022.3144217.

[58] G. K. Walia, M. Kumar and S. S. Gill, "AI-Empowered Fog/Edge Resource Management for IoT Applications: A Comprehensive Review, Research Challenges, and Future Perspectives," in *IEEE Communications Surveys & Tutorials*, vol. 26, no. 1, pp. 619-669, 2024, https://doi.org/10.1109/COMST.2023.3338015.