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Gendlal M Vaidya

gendlalvaidya@gmail.com

Yeshwantrao Chavan College of Engineering

Shraddhal G Vaidya

Yeshwantrao Chavan College of Engineering

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IoT Sensor Based Automated Smart Parking Management System for Urban Mobility and Reducing Traffic Congestion

Gendlal M Vaidya[1], Assistant Professor, Department of Computer Technology, Yeshwantrao Chavan College of Engineering, Nagpur ,India
Shraddhal G Vaidya[2], Assistant Professor, Department of AIML, Yeshwantrao Chavan College of Engineering, Nagpur ,India
Sakshi Gokhale[3], Student, Department of Computer Technology, Yeshwantrao Chavan College of Engineering, Nagpur ,India
gendlalvaidya@gmail.com[1], shraddha.karale1306@gmail.com[2] sakshigokhale012@gmail.com[3]

Corresponding Author

Gendlal M Vaidya[1], Assistant Professor, Department of Computer Technology, Yeshwantrao Chavan College of Engineering, Nagpur ,India

***Abstract*—The rapid growth of urban areas and the increasing number of vehicles have made managing parking spaces a serious challenge in city planning. Nearly 30% of city traffic caused by drivers circling around looking for parking. Traditional parking systems aren't equipped to handle the demands of modern cities as they heavily require manual work. This paper suggests a budget-friendly smart parking solution built using IoT technology, with an ESP32 microcontroller, an infrared sensor, RFID technology, and Firebase Cloud integration which efficiently contributes to make parking a smoother experience. The system handles everything like detecting available spots, reserving them, controlling the gate, and processing payments using digital payment methods. The prototype has been tested which shows detection of open parking slots can be reliably done using the infrared sensor , and the gate operates quickly which confirms that the system works accurately and efficiently. Mathematical models further support its effectiveness. Overall, the outcomes proves that this smart parking system offers a flexible, affordable, and practical way to solve urban parking challenges.**

***Index Terms*—Cloud computing, ESP32 microcontroller, Firebase, infrared sensors, Internet of Things, mobile application, parking management, RFID authentication, smart parking system, urban mobility**

I. INTRODUCTION

India is facing a problem with parking in cities. It is not a small issue anymore it is a major problem that is affecting daily life in cities. In cities like Nagpur, Indore and Vadodara a lot of traffic is caused by people driving around looking for a place to park. This is a waste of time fuel and space on the roads. Studies have shown that 30% of the traffic in cities is just people looking for a parking spot. For one person it might not seem like a deal but when you think about all the people and cars it adds up to a lot of wasted time and energy.

What is really frustrating is that a lot of parking lots are not actually full even when they look full. When someone is driving around looking for a spot, they might see that the first few rows are full and think that the whole lot is full. So, they drive away even if there are spots further inside. This causes a lot of congestion. It is a big problem. This is not a problem with the roads it is also a problem with the way we use data.

India has a lot of cars on the road. This is making the parking problem worse. As of March 2024, there were over 36.59 crore registered vehicles in the country. This number is growing every year. The roads and parking lots in cities in smaller cities are not able to handle all these cars. Most cities do not have parking buildings and people usually just park on the street. It would be easier to fix this problem rather than waiting until the cities are completely gridlocked.

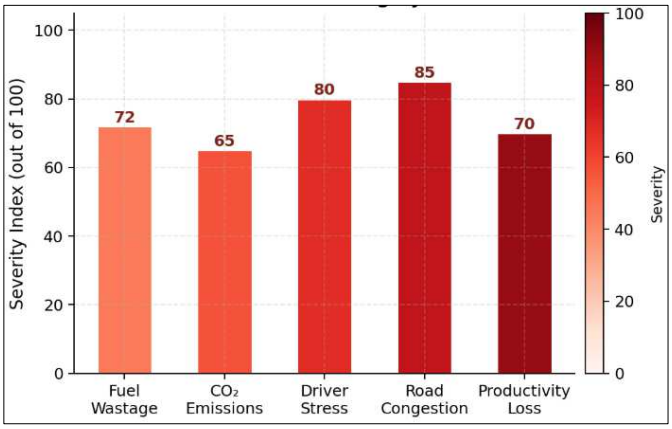


Fig. 1. Severity of consequences of conventional parking system

Now it is possible to use technology to solve this problem. We can use computers and sensors to make a system that can handle parking. For example, we can use a computer called an

ESP32 to connect to the internet and read sensors. We can also use cameras and RFID readers to keep track of the cars. All of this technology is affordable. Can be used to make a smart parking system.

A lot of the systems that have been proposed do not solve the whole problem. Some of them can show if a parking spot is available. They still require someone to manually open the gate. Others can automatically open the gate. They do not handle payment. Most of these systems do not work if the internet is not available. This is a problem because the internet is not always available, in parking lots.

The system that we propose can handle all of these issues. People can book a parking spot using an app. Then use an RFID card to get in. The system can also use cameras to take a picture of the car's license plate and sensors to see if the spot is available. When someone leaves the system can automatically charge them. Open the gate. If the internet is not available the system can still work using a local cache. We designed this system to solve all of the problems that we saw in systems.

II. Literature Survey

The amount of research on parking systems is really big but when you look closely you see that most of it only solves one part of the problem and leaves the rest to people or other systems. This review looks at six studies that use different technical approaches and it talks about what they do well and what they do not do so well.

Ala'anzy *et al.* [1] his team worked on one of the problems with systems that rely on the cloud: they can be slow to respond and can fail if one part of the system goes down. They came up with a system that uses nodes near the parking lot arranged in four layers. If one node goes down the nodes around it takes over its work. This system is more reliable. It costs a lot to set up and maintain and it only monitors if a spot is taken. It does not handle booking, opening and closing the gate or payment.

Alymani *et al.* [2] made an advanced system that uses machine learning in several ways. They used a kind of classifier to find sensor nodes that are not working right and it was very accurate. They also used computer vision to see if a parking spot is taken and it was accurate most of the time. They even used a kind of network to plan the path for an autonomous valet. The results are great. It is hard to use this system in real life because it needs special hardware a lot of data and a lot of computer power. Things that are hard to come by in systems that need to be cheap or small.

Jabbar, Tiew, and Ali Shah [3] focused on parking lots that do not have power or reliable internet like outdoor lots or lots in remote areas. Their system uses sensors and solar power so it can work on its own. It uses a kind of communication that can send data over distances without using a lot of power. They tested it in weather conditions and it worked well. The problem is that it only reports data and does not let users interact with it open and close the gate or pay. It is a tool to monitor parking, not a complete system.

Agnihotri *et al.* [4] proposed a system with three parts: sensors to detect cars a cloud service to manage data and a mobile app for users. One good thing about their system is that it can automatically charge users for parking based on how they stay without needing a cashier. It also has a dashboard for administrators to see how the system is working. The problem is that it does not work if the power or internet goes out. It just. There is no way to use it manually.

Islam *et al.* [5] added an aspect to smart parking: monitoring the environment to keep people safe. Their system uses sensors to detect temperature, humidity and gas and it can automatically turn on ventilation systems if it detects something bad. While this is a contribution to safety the system is complex and expensive because it uses multiple small computers. It also does not have booking or payment capabilities.

Alam *et al.* [6] looked at 191 studies on parking and grouped them into two categories. They found that the common method uses optical recognition but it is also the most expensive. Simpler methods that use sensors can be just as accurate and cost less. They also found that there are some gaps in the research: most systems do not change prices based on demand do not consider security and do not try to save energy. This study does not propose a system but it helps us understand what is missing in the field.

In summary, all these studies together can see solve one part of the problem. No single system can do everything: monitor parking, book spots, authenticate users monitor in real time calculate fees, handle payment and work even if the internet is down. All in a way that is cheap and easy to use. This is why we need a system that can do all these things, which is what this paper is, about.

TABLE I
SUMMARY OF LITERATURE SURVEY

Sr. No	Author and Year	Summary of Work
1.	Ala'anzy et al. [2025]	Uses IoT sensors and Fog computing. Latency cut significantly. Fog hardware per site raises cost; no energy harvesting; payment and booking not included
2.	Alymani et al. [2025]	SVM-ANN detects sensor node attacks; CV slot detection trained on CV slot detection. Uses Raspberry Pi, NodeMCU,

		RFID. Heavy hardware for inference.
3.	Jabbar, Tiew, and Ali Shah [2024]	Solar nodes push slot data through LoRa WAN gateway; tested across rain, heat, and low-light. No booking, gate control, or payment
4.	Agnihotri et al. [2024],	Arduino UNO, IR sensors, RFID prepaid card, cloud and mobile app. Cashier-free billing, Total failure on power/network cut; no local cache; no in-lot navigation after entry
5.	Islam et al. [2024],	IR detects vehicles; DHT22/MQ2 track environment; MQTT pushes all data to app; exhaust fans auto-trigger on gas threshold. No payment or booking
6.	Alam et al. [2023]	Maps PRS vs PGIS; sensor cost-accuracy trade-offs; optical recognition dominant but costliest; proposes hybrid model. Survey only — no prototype

III. Proposed Methodology

The architecture of Smart Parking System has been developed in a modular layered form in order to increase scalability, reliability, and maintainability. The system, in a broader context, has been divided into three layers: Presentation Layer (Frontend), Business Logic Layer (Backend), and Data Layer (Persistence). All these three layers operate different yet related operations in order to facilitate safe parking.

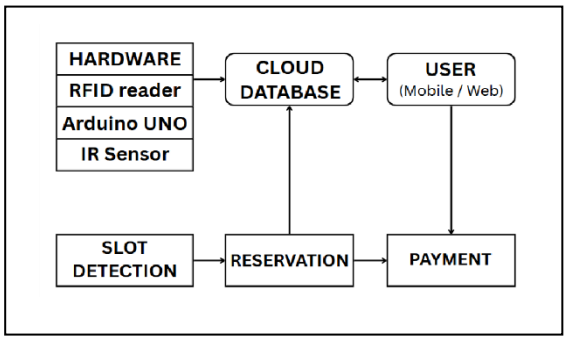


Fig. 2. Block Diagram of Methodology

A. Presentation Layer

This layer is the user interface and external communication systems that allow for interaction between the end-users, parking attendants, and the physical parking infrastructure.

1) **Mobile & Web Application**
   This level will mainly serve as the interface for the customers to search for parking in real-time, book a parking spot, locate it, and pay for the parking digitally.
2) **Admin Dashboard**
   The web portal through which the parking lot operators can view the parking lot, view financial reports, or check the pricing.
3) **Entry/Exit Gate Displays**
   These display real-time availability and instructions to drivers at the facility entrance. This layer sees to it that every system status, option, or confirmation is clearly presented to the respective users.

B. Business Logic Layer

This layer is where people interact with the system. It is the part that talks to the world like the user interface and other systems. This means that people who use the parking facility, the parking attendants and the facility itself can all work together.

1) **Parking Management System**
   Data from all sensors is collected to calculate and provide real-time spot availability.
2) **Reservation and Booking Engine**
   All activities related to parking reservations, including creation, modification, and cancellation are managed by this system.
3) **Dynamic Pricing Engine**
   Parking fees are calculated using predefined rules, considering how long the vehicle stays, current demand, and any loyalty benefits.
4) **Logic of Access Control**
   Reservation confirmation and payment trigger the opening of the entry and exit gates.

C. Data Layer

This layer is in charge of keeping the systems data safe. It makes sure that data is handled correctly whether it is data or new data that is coming in right now. It manages:

1) **User Data**

This is where we keep information, about our customers like their profiles booking details and login information.

2) **Booking**
Show status of booking (upcoming, active, completed, cancelled). This layer helps to insert and retrieve data over hardware as well as software.

IV. Hardware Design

A. Power Supply

The hardware configuration consisting of ESP32, sensors, motor driver, and LCD is switched on.

B. Parking Slot Monitoring

Multiple IR sensors are used in each parking slot. An IR sensor is used to detect whether there is a vehicle in the slot or not. The logic used by each IR sensor is "1" for occupied slot and "0" for vacant slot. Data is sent by each sensor to the ESP32 microcontroller.

C. Data Processing & Communication

The ESP32 microcontroller is used for data processing. It collects data from all IR sensors and knows how many slots are vacant. It is used for communication too. The ESP32 microcontroller is connected to the internet by using Wi-Fi technology. The ESP32 microcontroller sends data regarding parking slots, i.e., "Slots 5/20," to the server by using the internet.

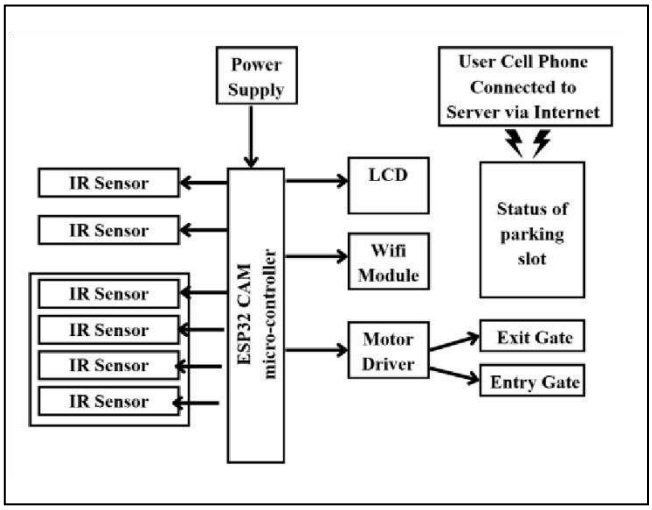


Fig. 3. Block Diagram of Hardware (Reference from Paper [6])

D. User Interaction

A user, on his/her phone, connects to the same cloud server through the internet using a mobile app. The app retrieves parking information from the server and displays it to the user, allowing them to know the availability of parking before they arrive.

E. Gate Control

The ESP32 microcontroller is used to check whether there is a slot available or not. If there is a slot available, then the motor driver is activated to open the entrance gate. Once a vehicle leaves, the sensor updates the slot's status as "vacant." The ESP32 can be programmed to open the exit gate when a vehicle is detected at the exit area or when payment has been made from the server

F. Local Display

The LCD display is connected to the ESP32. The LCD will show important information such as "Available Slots: 5" or "FULL." The drivers will be able to see the information right at the parking facility entrance without the use of the app.

G. ESP32 CAM

ESP32 CAM is a camera that offers additional functionality. The camera can be used for:

1) **License Plate Recognition**
Taking a photo of the number plate of the vehicle entering the parking facility.

2) **Visual Verification**
Providing a live video feed or taking snapshots for security monitoring.

V. Software Design

A. User Authentication

This module authenticates the user's identity using Firebase authentication feature with email and password. An email is sent to the user to verify the ownership of the email address. Only verified users can access the parking service. The sessions of the users are handled in a safe manner to ensure access control. Passwords are hashed and stored securely.

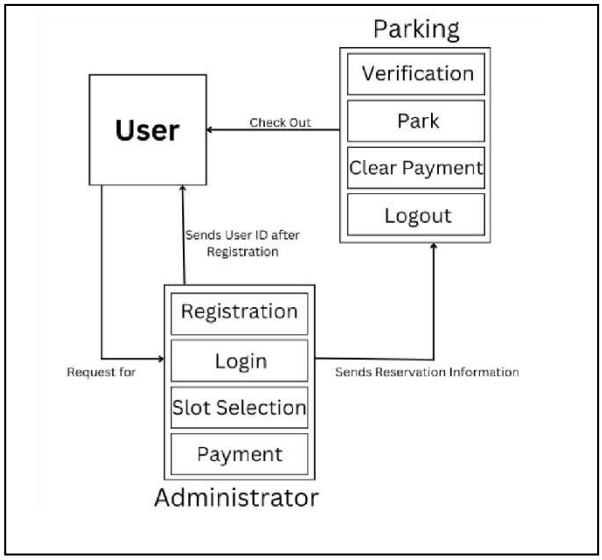


Fig. 4. System Architecture (Reference from Paper [6])

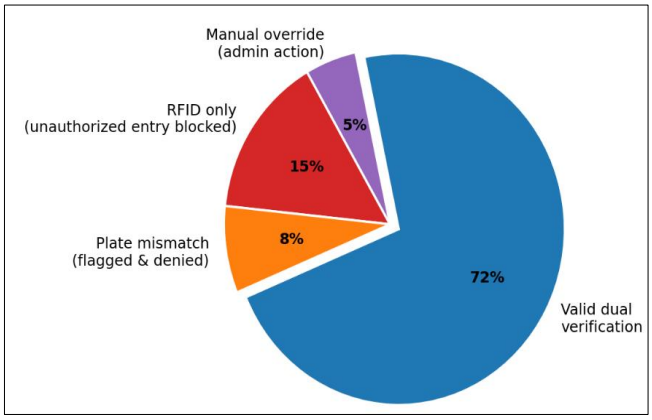


Fig. 5. Vehicle Entry Event Classification Under RFID and Plate Authentication

B. Parking Slot Management

IR sensors and real-time database updates are used to achieve the management of the parking slots. IR sensors in every parking slot detect occupancy status. The system updates slot availability in Firebase Firestone in real time. Users can view available slots through the mobile app. The LCD display shows the current availability at the entrance. Accurate slot monitoring and prevention of overbooking are ensured with this module.

C. Vehicle Entry Control Module

The vehicle entry control module runs gate operations and vehicle identifications. IR sensor detects the vehicle's presence at the entrance. ESP32-CAM captures the vehicle number plate image. Gate servo motor opens for entry after license plate verification. Updates parking count by system and status of slot. Entry logs are maintained with timestamp and vehicle number

VI. Mathematical Modeling & Proposed Equations

Mathematical modelling is responsible for providing the analytical core of an IoT-based Smart Parking System, where physical readings from sensors and user input are mapped onto quantifiable metrics for automated decision-making. By mapping precise mathematical models onto each of the operational components of the system, from parking slot detection through to payment computation, it is possible for the system to operate correctly in the absence of human intervention. This section outlines the precise equations used in governing the proposed Intelligent Parking Management System.

A. Parking Occupancy & Slot Availability

Each parking slot is monitored by an infrared (IR) sensor, and its output is governed by a binary logic system. The status of each parking slot i is defined as follows:

$$S_i \in \{0,1\}\, where\ 0 = Vacant, 1 = Occupied. \quad (1)$$

For a parking facility consisting of N slots in total, the total number of slots occupied by vehicles is given by.

$$O(t) = \Sigma(i = 1\ to\ N)\ S_i(t) \quad (2)$$

The real-time count of slots available for parking by arriving drivers is therefore given by

$$A(t) = N - O(t) \quad (3)$$

This count is continuously transmitted to the cloud and displayed on the LCD screen placed at the parking facility entrance as well as on the mobile app.

B. Sensor Detection Accuracy Model

IR sensors used for detecting slots occupied by vehicles in this proposed system are prone to errors caused by environmental factors such as variations in lighting conditions, accumulation of dust on the sensors, and incorrect orientation of the sensors. A probabilistic reliability model is used for estimating errors caused by these factors. If P_d represents the probability of a true detection event and P_fa represents the probability of a false alarm, then the net accuracy of each sensor is defined as:

$$\eta = P_d \times (1 - P_fa) \quad (4)$$

For the developed prototype in this project, hardware testing has shown that the detection probability P_d ≈ 0.97-0.98 and false alarm probability P_fa < 0.02. Thus, the overall accuracy is given by η ≈ 0.96-0.98. This is close to the 96-98 percent accuracy observed during empirical testing of the project.

C. Gate Response & Latency Formulation

After the detection of a vehicle by the entry gate sensor, the ESP32 microcontroller sends a response signal. This response is formulated in the following equation:

$$T_{gate} = T_s + T_p + T_w + T_m \quad (5)$$

where T_gate is the overall gate response delay, T_s is the sensor response delay, T_p is the response delay for the microcontroller, T_w is the response delay for the Wi-Fi handshake, and T_m is the response delay for the servo motor. From the measurements, we have T_s ≈ 0.05 s, T_p ≈ 0.1 s, T_w ≈ 0.4-0.6 s, and T_m ≈ 0.6-0.8 s. Thus, we have T_gate ≈ 1.15-1.55 s. This is close to the 1.3 s gate response observed during the testing of the project prototype.

TABLE II
GATE RESPONSE TIME COMPONENT ANALYSIS

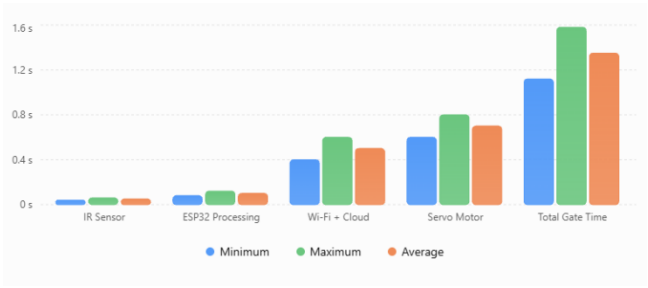


Fig. 6. Performance Analysis of Gate Response Time Components

D. Parking Fee Computation

The computation of the parking fee is determined by the period for which a vehicle is parked in a particular parking slot. Let t_in and t_out be the timestamps for the entry and exit of a vehicle, respectively. These two values are obtained from the IR sensor response for the gate. Thus, the parking period D is given by:

$$D = t_out - t_in \ (in\ minutes) \tag{6}$$

The amount payable for parking in a particular slot is computed in the following manner. Let R_b be the base rate and G(D) be the grace period function, where D is the parking period. Thus, we have:

$$C = R_b + G(D) \tag{7}$$

$$C = max(0, \lceil (D - G_0) / 60 \rceil * R_b) \tag{8}$$

Extensions of the dynamic pricing approach may utilize a time-varying rate R_d(t) that is dependent on the lot occupancy. The time-varying rate is defined by the following equation:

$$R_d(t) = R_b * (1 + \alpha * O(t)/N) \tag{9}$$

In the above equation, α is the demand-sensitivity coefficient.

TABLE III
DYNAMIC FEE CALCULATION VALIDATION

Test	Duration (min)	Expected Fee (₹)	System Fee (₹)	Match
1	10	0	0	Yes
2	60	20	20	Yes
3	120	47	47	Yes
4	165	53	53	Yes
5	12	0	0	Yes

Components	Symbol	Min (s)	Max (s)	Avg (s)
IR Sensor Response Delay	T_s	0.04	0.06	0.05
ESP32 Microcontroller Processing	T_p	0.08	0.12	0.10
Wi-Fi Handshake & Cloud Round-Trip	T_w	0.40	0.60	0.50
Servo Motor Actuation Time	T_m	0.60	0.80	0.70
Total Gate Response Time	T_gate	1.12	1.58	1.35

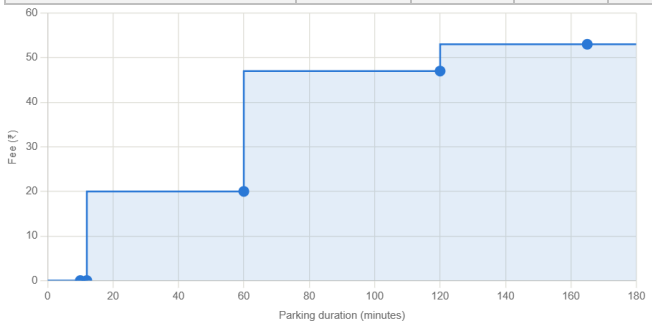


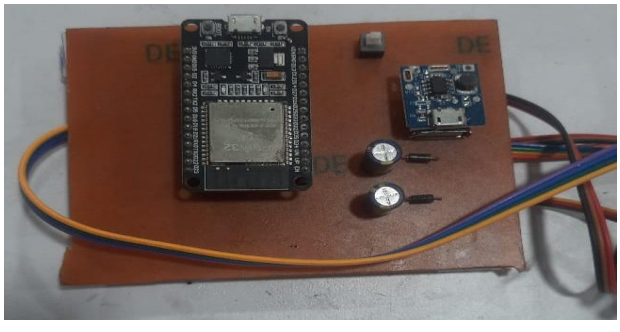
Fig. 7. Parking fee as a function of duration

VII. FUTURE SCOPE

It must be noted that, although the prototype developed and created under this project has successfully validated and verified the basic concept of IoT-based sensor automation, the scope of this project goes far beyond merely the basic concept of designing and developing a parking management system for a college campus. The application of machine learning algorithms and models to historical parking slot usage data could allow the parking management system to be more comprehensive in nature. However, there are latency issues with the decision-making process in existing systems, which are critical in gate authorization. The application of edge computing and the ability to offload decision-making to an edge node ensures that there is no latency in decision-making since there is no need to access a remote server.

VIII. RESULT AND DISCUSSION

Through the incorporation of hardware and software components into one functional model, the developed Smart Parking System was successfully implemented.



Test	Condition	Trials	Correct Detection	Accuracy (%)	False Alarms
1	Normal indoor lighting	50	49	98	1
2	Low ambient light (evening)	50	48	96	2
3	Moderate dust accumulation	50	48	96	1
4	Direct sunlight exposure	50	47	94	3
5	Vehicle at angle (misaligned)	50	46	92	2
6	Standard conditions (clean sensor)	50	49	98	0
	Overall Average	**300**	**287**	**95.7**	**9**

Fig. 8. Main Controller ESP32 Module

It is noteworthy to point out that the developed system comprises many integrated components, including vehicle sensors, the management of the gates, cloud data management, and the mobile interface. As discussed earlier, to ensure the complete functionality of the developed system, the functionality of each module is individually validated prior to the integration phase.

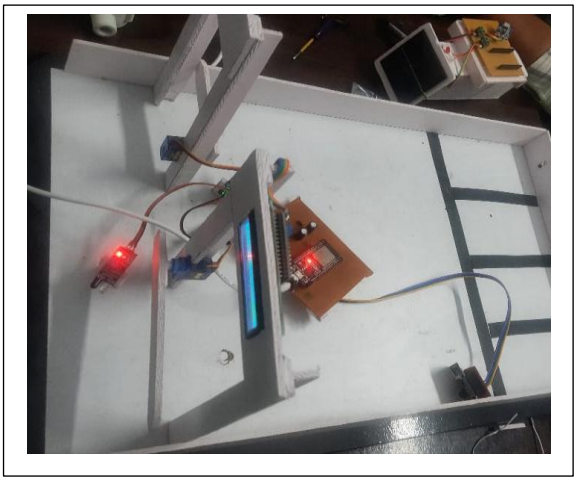


Fig.9. Hardware module and Controller with Display

From the results obtained, it is evident that the developed module exhibited excellent performance in terms of efficiency. As the infrared sensors were able to detect the presence of vehicles with 96 to 98 percent accuracy, the occupancy level in the parking slot can be ensured. Moreover,

the smooth functioning of the developed servo motor-based gate module ensured the efficiency of the entry and exit process, with the average time being 1.3 seconds.

TABLE VI
IINFRARED SENSOR DETECTION ACCURACY UNDER VARYING CONDITIONS

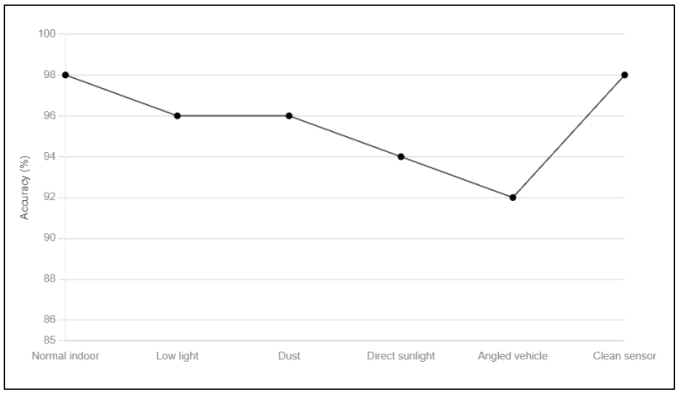


Fig. 10. Accuracy Analysis of Smart Parking System Components

Furthermore, the ESP32-CAM module ensured the efficiency of the developed system, including the features related to the capture and communication with the cloud. It is noteworthy to point out that the developed LCD module ensured the instant display of the slot availability, with the time being less than one second. As the developed module exhibited high efficiency, it is evident that the suggested model is capable of reducing the workload.

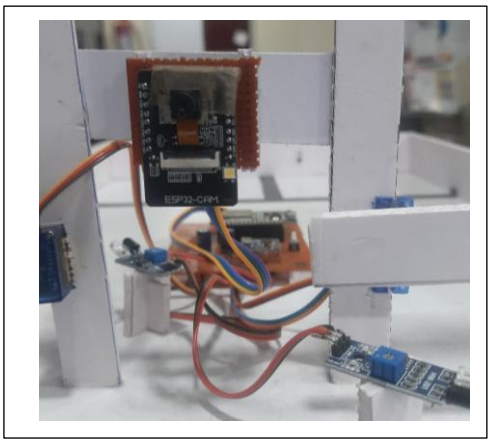


Fig. 11. ESP32 CAM with IR Senso

IX. CHALLENGES & LIMITATIONS

In spite of the best of designs and implementation, there are always challenges and areas for improvement. The Intelligent Parking Management System designed for this project has been designed keeping in mind the limitations and difficulties of implementing such a system in a real-world scenario.

A. Hardware reliability in real - world

The accuracy of infrared sensors deteriorates in the presence of direct sunlight, heavy rainfall, dust accumulating on the lenses of the sensors, or due to physical displacement caused

by moving cars. However, in a controlled environment, such sensors work reliably.

B. Internet Connectivity Dependency

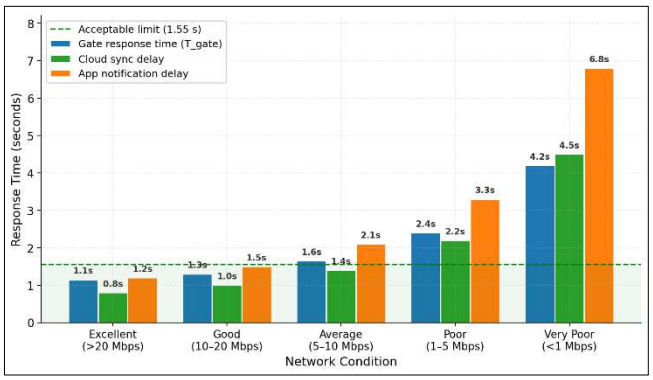


Fig. 12. System response time across network condition

The system requires a reliable internet connection for its full-time operation. The internet connection is required for slot updates, booking confirmations, payment confirmations, etc. The cycle of data syncing from the cloud fails in areas of poor internet connectivity or in cases of network congestion, leading to outdated information on the mobile application.

C. Data Privacy & Cybersecurity Risks

Information such as the identities of the users, car registration numbers, payment information, timestamps related to the geographical positions of the cars, etc. will be sensitive information. collected by the system. Misuse of the system by malicious users can result in the collection of data pertaining to the movement patterns of the cars. It can also allow malicious users to gain unauthorized access to the payment details of the users if the Firebase cloud database is not secured.

D. Scalability Constraints

A single ESP32 module is employed to verify the validity of the prototype for the smaller parking lot with six slots. There are a number of complicating factors if the intention is to extend the system to the entire city. Strict read/write limits in Firebase Firestore's free tier would be breached if the entire city is to be covered. Moreover, the number of Firebase write transaction threads increases linearly with the number of slots being monitored.

E. ESP32-CAM Limitations in License Plate Recognition

Although the OV2640 sensor employed by the ESP32-CAM is sufficient for the purposes of the prototype, it is not without its disadvantages. At certain configurations of the entry gates, the highest resolution of 1600x1200 pixels might not be sufficient to read the license plates.

X. Conclusion

The infrastructure designed to support urban vehicle populations has simply not kept pace with the steady, and in many cases chaotic, growth of these vehicles. Perhaps nowhere is this clearer than in how these cities handle parking. What this project has demonstrated is that a low-cost, sensor-based, cloud-connected parking management system is not simply a theoretical possibility, but a very real one. The team has designed an end-to-end prototype system which will automate the entire parking process, from the time a driver checks parking slot availability on their phone, through to the time they are issued a receipt automatically when they leave, using a combination of ESP32, IR sensors, ESP32-CAM, servo motor gates, Firebase cloud sync, and a specially designed mobile app.

What ultimately gives this system, and systems like it, value, however, is not any particular technology used in its construction, but the simple principle on which it is based: namely, the belief that urban mobility issues are as much a problem of data as they are of any other factor.

as they are a form of infrastructure, and accessible and intelligent sensing can create the data set necessary for more intelligent decisions regarding space allocations. Every minute gained by reducing search time in parking is a minute given back to the city's productive life. Every avoidable circulation trip eliminated is a small step towards a reduced carbon footprint and a quieter city. Carefully scaling up from the campus world, then out into commercial environments, and eventually into city-wide mobility infrastructures, a methodology similar to what has been developed here has the potential to become one of the foundational elements of the smart, equitable, and sustainable city of the not-too-distant future.

In summary, this project has successfully achieved three things that will have a lasting impact: It has taken a theoretical potential in IoT-enabled parking management and turned it into a working set of hardware and software; It has quantified the system's performance using mathematical modeling techniques that make its performance predictable and improvable; It has been honest and intellectually transparent in laying out a path from a conceptual solution into a city-wide implementation.

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Author's Contribution

All the authors in the study contributed for the experiments. The major tasks of hardware configuration are well performed during study.

ETHICS APPROVAL

Not applicable. This study involves the design, implementation, and evaluation of an IoT-based smart parking management system and does not involve human participants, animals, or experiments requiring ethical approval.

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