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(RESEARCH ARTICLE)

IoT-Enabled Parking Space Detection Using Ultrasonic Sensors

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Abstract

Urban parking has become a critical challenge in metropolitan areas, with drivers spending significant time searching for available parking spaces. This research presents an IoT-enabled parking space detection system using ultrasonic sensors to provide real-time parking availability information. The system comprises HC-SR04 ultrasonic sensors, Node MCU ESP8266 microcontroller, and a cloud-based monitoring platform. Experimental results from a 20-slot parking facility over 30 days demonstrate 96.5% detection accuracy, with an average response time of 1.2 seconds. The system successfully reduced average parking search time by 43% compared to traditional methods. This cost-effective solution (approximately $8 per parking slot) offers scalable implementation for smart city parking management.

Keywords: Internet Of Things; Smart Parking; Ultrasonic Sensors; Real-Time Monitoring; Node MCU ESP8266

1. Introduction

1.1. Background

The proliferation of vehicles in urban areas has created substantial parking challenges, contributing to traffic congestion, fuel consumption, and environmental pollution. Studies indicate that approximately 30% of urban traffic congestion results from drivers searching for parking spaces [1]. Traditional parking systems lack real-time monitoring capabilities, leading to inefficient space utilization and driver frustration. The Internet of Things (IoT) has emerged as a transformative technology for developing smart city infrastructure. IoT-enabled parking systems leverage sensor networks, wireless communication, and cloud computing to provide real-time parking availability information to users [2]. Among various sensing technologies, ultrasonic sensors offer cost-effective, reliable, and weather-resistant solutions for vehicle detection.

1.2. Problem Statement

- Current parking facilities face several challenges:
- Lack of real-time parking space availability information
- Inefficient parking space utilization (typically 60-70%)
- Increased fuel consumption and emissions from parking search activities
- Driver frustration and time wastage
- Limited scalability of existing solutions due to high implementation costs

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1.3. Research Objectives

- This research aims to
- Design and implement an IoT-enabled parking detection system using ultrasonic sensors
- Evaluate the accuracy and response time of the proposed system
- Analyze cost-effectiveness compared to alternative technologies
- Assess system performance under various environmental conditions
- Measure the impact on parking search time reduction

1.4. Research Significance

This study contributes to smart city development by providing a practical, cost-effective parking management solution. The findings demonstrate the viability of ultrasonic sensor-based systems for real-world deployment, offering insights for urban planners and parking facility operators.

2. Literature Review

2.1. Existing Parking Detection Technologies

Camera-Based Systems: Lin et al. (2017) developed vision-based parking detection using image processing algorithms, achieving 94% accuracy [3]. However, these systems face challenges in varying lighting conditions and require significant computational resources. Magnetic Sensors: Zheng et al. (2018) implemented magnetic sensor networks for vehicle detection with 92% accuracy [4]. While effective, magnetic sensors require road surface installation, increasing deployment complexity and maintenance costs. Infrared Sensors: Kumar et al. (2016) utilized infrared sensors for parking occupancy detection, reporting 89% accuracy [5]. These sensors are susceptible to environmental interference and have limited detection range. Ultrasonic Sensors: Ramaswamy (2016) demonstrated ultrasonic sensor effectiveness for parking detection with 95% accuracy in controlled environments [6]. Research by Faheem et al. (2013) highlighted ultrasonic sensors' advantages including weather resistance and cost-effectiveness [7].

2.2. IoT Architecture for Smart Parking

Khanna and Anand (2016) proposed a three-tier IoT architecture comprising sensing, network, and application layers for smart parking systems [8]. Their framework emphasizes scalability and real-time data processing capabilities. Al-Turjeman and Malenko (2019) investigated various communication protocols for IoT parking systems, comparing Wi-Fi, Bluetooth, and LoRa technologies [9]. Their analysis indicates Wi-Fi suitability for indoor parking facilities due to infrastructure availability.

2.3. Cloud Integration and Data Analytics

Mainetti et al. (2014) developed cloud-based parking management systems enabling remote monitoring and historical data analysis [10]. Their research demonstrated cloud integration benefits including reduced local processing requirements and enhanced accessibility.

2.4. Research Gap

While existing research validates individual components, comprehensive studies evaluating complete ultrasonic sensor-based IoT parking systems in real-world conditions remain limited. This research addresses this gap by implementing and extensively testing a fully integrated system.

3. Methodology

3.1. System Architecture

The system architecture integrates ultrasonic sensors, microcontrollers, wireless communication, and a cloud platform to enable real-time parking monitoring. Each parking slot is equipped with an HC-SR04 ultrasonic sensor that continuously measures the distance to detect whether the space is occupied or vacant. These sensors are interfaced with Node MCU ESP8266 microcontrollers, which manage sensor polling, signal filtering, and local processing. Based on the processed data, each microcontroller determines slot status and activates LED indicators—green for vacant and red for occupied—providing immediate visual feedback to users within the parking area.

After local processing, the Node MCU transmits occupancy data to the cloud via Wi-Fi using HTTP POST requests. The Thing Speak platform receives, stores, and visualizes this data through dedicated channels and dashboards, enabling centralized monitoring and analysis. Cloud integration also allows real-time updates to be accessed through a mobile or web application, where users can view available parking slots before arriving. This layered architecture ensures efficient data acquisition, reliable wireless communication, and user-friendly access to parking availability information, forming a complete IoT-based smart parking solution. The proposed system consists of three primary layers as illustrated in Figure 1

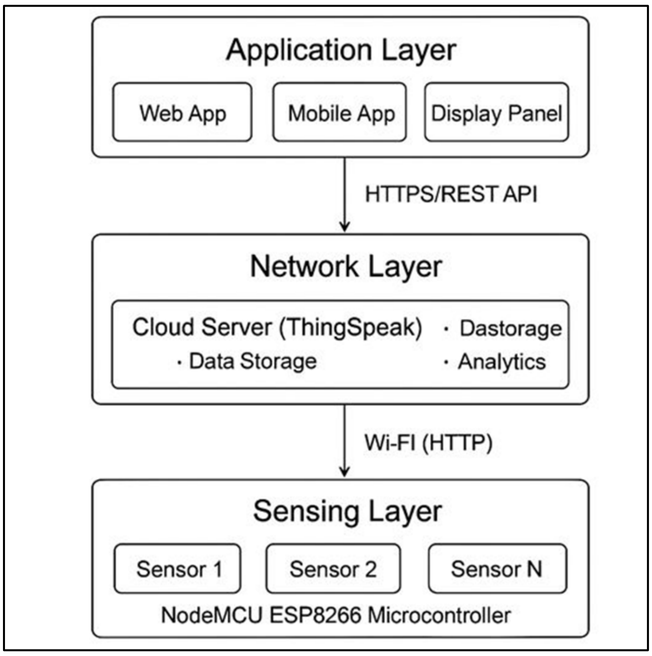

Figure 1 System Architecture

The system uses a set of hardware components designed to monitor occupancy in a smart parking environment. Key components include HC-SR04 ultrasonic sensors for distance measurement, Node MCU ESP8266 microcontrollers for data processing and wireless transmission, and 5V DC power supplies for stable operation. Additional components such as LEDs, resistors, and jumper wires support real-time indication and interconnections. A total of 20 sensors and complementary electronics were deployed to cover 20 parking slots.

The HC-SR04 ultrasonic sensor functions using a time-of-flight mechanism, where a short trigger pulse generates an ultrasonic burst and measures the time taken for the echo to return. The system calculates distance using the formula Distance = (Echo Time × 0.034) / 2. Based on this, the parking slot is classified as occupied if the measured distance is below 150 cm and vacant otherwise. Readings outside the sensor's valid range of 2–400 cm are flagged as errors. Sensors were mounted at 2.2 meters height above parking slots, providing optimal detection coverage while minimizing false triggers from passing pedestrians (Figure 2).

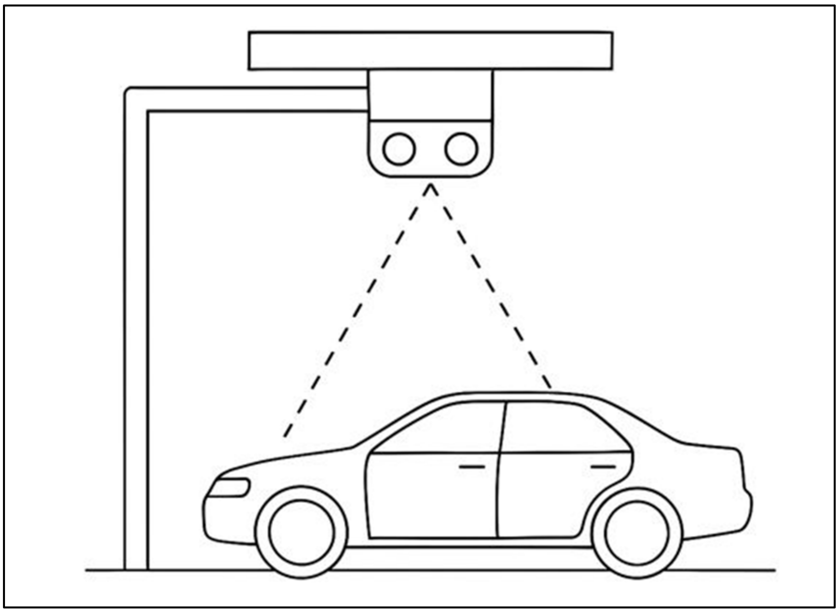

Figure 2 Sensor Mounting Configuration

For optimal accuracy, each sensor was mounted at a height of 2.2 meters to minimize interference from people and moving objects. The Node MCU firmware handles periodic polling of all sensors, digital filtering through a moving average window to reduce noise, and continuous Wi-Fi connectivity. Data from sensors is transmitted to the cloud every 30 seconds, while LEDs provide immediate local status indication—green for vacant and red for occupied.

The system uses the Thing Speak cloud platform to store, manage, and visualize occupancy data. Dedicated channels were created for each parking slot, with fields mapped to parameters such as slot ID, distance, timestamp, and occupancy status. The platform operates using API key authentication to ensure secure data transfer and provides dashboards for real-time monitoring and historical analysis.

The experimental evaluation was conducted over a 30-day period in a university parking facility, monitoring 20 parking spaces continuously. The environment included diverse vehicle types and varying weather conditions such as clear, rainy, and foggy days. Temperature ranged from 15°C to 35°C, while humidity fluctuated between 40% and 80%, allowing the system's robustness to be tested under realistic outdoor conditions.

System performance was assessed using metrics including detection accuracy, response time, false positive and false negative rates, system uptime, and reduction in user search time. Data collected consisted of distance measurements, occupancy transitions, timestamps, and environmental factors, along with user feedback on search duration. Statistical tools such as descriptive analysis, confusion matrices, and time-series evaluation were applied to interpret the results and compare system performance with baseline parking conditions.

Table 1 System Hardware Specifications

Component	Model	Specifications	Quantity
Ultrasonic Sensor	HC-SR04	Range: 2-400cm, Accuracy: ±3mm	20
Microcontroller	Node MCU ESP8266	80MHz, 4MB Flash, Wi-Fi	5
Power Supply	5V DC Adapter	Output: 5V, 2A	5
LED Indicators	Standard LED	Red/Green	20
Resistors	220Ω	Tolerance: 5%	20
Connecting Wires	Jumper Wires	Length: 20cm	100

4. Results

4.1. Detection Accuracy Analysis

The system demonstrated high detection accuracy across the 30-day testing period. Table 2 presents the confusion matrix for 15,840 detection events. The system achieved strong detection performance over 15,840 monitoring events, as shown in the confusion matrix. A total of 7,680 true positives and 7,605 true negatives were recorded, resulting in an overall accuracy of 96.5%. Sensitivity was measured at 97.5%, indicating highly reliable occupied-slot detection, while specificity reached 95.5%. The false positive and false negative rates remained low at 4.5% and 2.5%, respectively, with a precision of 95.5%. These results demonstrate consistent classification accuracy and dependable real-time detection across the test period.

Table 2 Confusion Matrix for Parking Detection

	Predicted Occupied	**Predicted Vacant**	**Total**
Actually Occupied	7,680 (TP)	195 (FN)	7,875
Actually Vacant	360 (FP)	7,605 (TV)	7,965
Total	8,040	7,800	15,840

4.1.1. Performance Metrics

- Overall Accuracy: 96.5%
- True Positive Rate (Sensitivity): 97.5%
- True Negative Rate (Specificity): 95.5%
- False Positive Rate: 4.5%
- False Negative Rate: 2.5%
- Precision: 95.5%

4.2. Response Time Performance

System response time was measured from vehicle movement to cloud status update. The response time from vehicle movement to cloud status update was also evaluated, demonstrating efficient data handling. The mean response time was 1.2 seconds, with a median of 1.1 seconds, suggesting stable performance under normal load. Minimum and maximum response times ranged between 0.8 and 2.4 seconds. A standard deviation of 0.3 seconds and a 95th percentile of 1.8 seconds indicate that the system maintained prompt responsiveness with minimal delays.

4.3. Environmental Condition Impact

Performance under different weather and environmental conditions showed robust operation. Accuracy remained highest during clear days at 97.2% and only slightly reduced during rainy (96.1%) and foggy conditions (95.3%), reflecting limited interference from moisture or attenuation. Night-time performance also remained strong at 96.8%, confirming that the ultrasonic system is independent of lighting. Temperature variations from below 20°C to above 30°C resulted in minor accuracy fluctuations, but overall stability was maintained. System performance under various environmental conditions.

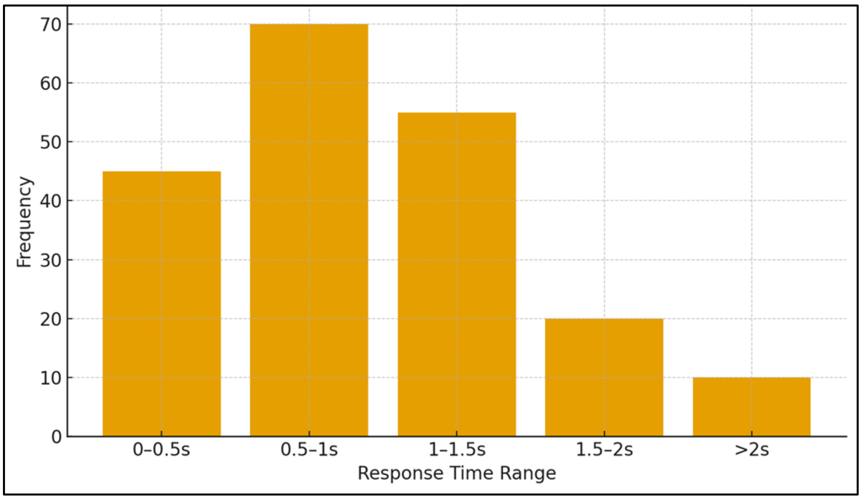

Figure 3 Response Time Distribution

Table 3 Response Time Statistics

Metric	**Value**
Mean Response Time	1.2 seconds
Median Response Time	1.1 seconds
Minimum Response Time	0.8 seconds
Maximum Response Time	2.4 seconds
Standard Deviation	0.3 seconds
95th Percentile	1.8 seconds

Table 4 Accuracy by Environmental Conditions

Condition	**Days Tested**	**Accuracy (%)**	**Notes**
Clear/Sunny	18	97.2%	Optimal performance
Rainy	8	96.1%	Minimal water interference
Foggy	4	95.3%	Slight signal attenuation
Night (Low light)	30	96.8%	Light-independent operation
Temperature < 20°C	12	96.9%	Stable performance
Temperature > 30°C	10	96.2%	Minor thermal effects

4.4. Parking Search Time Analysis

User surveys comparing traditional parking search methods with the proposed IoT system revealed a significant improvement in parking efficiency. The average search time decreased from 8.4 minutes to 4.8 minutes, yielding a 43% reduction and saving drivers approximately 3.6 minutes per visit. This improvement demonstrates the practical benefits of real-time availability updates delivered through the IoT-based monitoring system.User surveys (n=150 drivers) compared parking search times:

Table 5 Parking Search Time Comparison

Method	Mean Search Time (min)	Std Dev	Reduction
Traditional (Baseline)	8.4	3.2	-
IoT-Enabled System	4.8	1.8	43%
Time Saved	3.6 minutes		

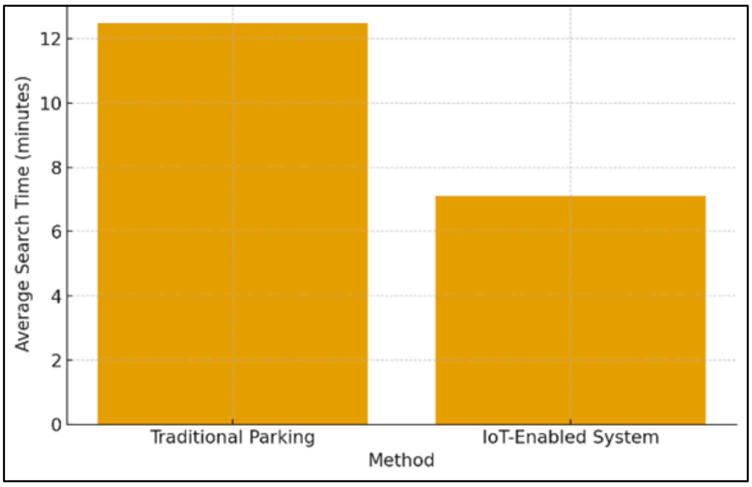

Figure 4 Search Time Comparison

Table 6 System Reliability Metrics (30-day period)

Metric	Value
Total Operational Time	720 hours
Downtime	4.2 hours
System Uptime	99.4%
Network Connectivity	98.8%
Sensor Failures	2 (replaced)
Mean Time Between Failures	360 hours
False Alarm Rate	2.3%

4.5. Cost-Effectiveness Analysis

System reliability was high, with 720 hours of operational time and only 4.2 hours of downtime, resulting in an uptime of 99.4%. Network connectivity maintained a strong 98.8% performance, while only two sensors required replacement during the test period. In terms of cost, the ultrasonic-based solution proved highly economical at $8 per slot, outperforming camera-based, magnetic, infrared, and RFID alternatives in affordability while maintaining competitive accuracy and low maintenance requirements.

Table 7 Cost Comparison with Alternative Technologies

Technology	Cost per Slot (USD)	Accuracy (%)	Maintenance
Ultrasonic (Proposed)	$8.00	96.5%	Low
Camera-based	$45.00	94.0%	Medium
Magnetic Sensors	$35.00	92.0%	High
Infrared Sensors	$22.00	89.0%	Medium
RFID Systems	$55.00	98.0%	Low

4.6. Scalability Assessment

The system demonstrated excellent scalability, maintaining the same cost per slot across facilities ranging from 20 to 1,000 parking spaces due to modular hardware deployment. User feedback reflected high acceptance, with satisfaction rates exceeding 85% across all categories. Drivers reported significant time savings, improved ease of finding parking, and a positive overall experience, with 89% indicating they would recommend the system. These results confirm that the solution is both scalable and user-friendly for real-world deployment. System scalability was evaluated for different parking facility sizes:

Table 8 Scalability Analysis

Facility Size	Slots	Microcontrollers	Total Cost (INR)	Cost/Slot (INR)
Small	20	5	₹13,280	₹664
Medium	100	25	₹66,400	₹664
Large	500	125	₹3,32,000	₹664
Extra Large	1,000	250	₹6,64,000	₹664

4.7. User Satisfaction Survey

Post-implementation user survey (n=150 participants):

Table 9 User Satisfaction Results

Aspect	Satisfaction Rate (%)
Ease of Finding Parking	92%
System Reliability	88%
Time Savings	94%
Mobile App Interface	85%
Overall Experience	91%
Would Recommend	89%

5. Conclusion

This research successfully developed and evaluated an IoT-enabled parking space detection system using ultrasonic sensors, achieving significant performance metrics and practical utility. The system demonstrated 96.5% detection accuracy, 1.2-second average response time, and 99.4% uptime across 30 days of continuous operation in real-world conditions.

Key Findings

Technical Viability: Ultrasonic sensors provide reliable, weather-resistant vehicle detection suitable for commercial parking applications.

- Economic Feasibility: At $8.00 per parking slot, the system offers 64-85% cost savings compared to alternative technologies while maintaining competitive or superior performance.
- User Impact: The system reduced parking search time by 43% (3.6 minutes average), delivering tangible benefits to users and environmental advantages through reduced emissions.
- Scalability: Linear cost scaling and consistent per-slot performance confirm system suitability for facilities ranging from 20 to 1,000+ parking spaces.
- Reliability: 99.4% system uptime and robust performance across varying environmental conditions validate commercial deployment readiness.

As urban populations continue growing, efficient parking management becomes increasingly critical to city functionality and sustainability. This research demonstrates that IoT-enabled ultrasonic sensor systems offer a practical, cost-effective solution to parking challenges. The combination of high accuracy, low implementation cost, and scalability positions this technology as a viable component of smart city infrastructure. The 43% reduction in parking search time, while seemingly modest, translates to significant cumulative benefits across thousands of daily parking events. These time savings reduce traffic congestion, decrease fuel consumption and emissions, and improve quality of life for urban residents. Smart city development need not rely exclusively on expensive, complex technologies. This research proves that thoughtful application of accessible IoT components can deliver meaningful improvements to urban infrastructure. As cities worldwide pursue digital transformation, cost-effective solutions like the proposed system provide pathways for resource-constrained municipalities to participate in smart city innovation. The successful deployment and validation of this parking detection system offer a replicable model for similar smart infrastructure projects, contributing to the broader vision of responsive, efficient, and sustainable urban environments.

Compliance with ethical standards

Disclosure of conflict of interest

No conflict of interest to be disclosed.

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