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An Intelligent Real-Time Vehicle Parking Slot Detection and Management System using Internet of Things

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Abstract

The rapid growth of urban vehicle ownership has made the search for available parking space one of the most persistent inconveniences faced by commuters in cities today. Manual parking management is slow, inefficient, and often leads to traffic congestion, fuel wastage, and driver frustration near commercial and residential complexes. This paper presents a Smart Parking IoT System that automates the detection and management of parking slot availability using low-cost embedded sensors connected through the Internet of Things (IoT). The proposed system employs ultrasonic distance sensors installed at each parking slot to continuously monitor occupancy status, a microcontroller unit (NodeMCU ESP8266 / Arduino) to acquire and process sensor data, and a cloud-connected dashboard together with a mobile/web interface that displays real-time slot availability to users. The system architecture, data acquisition pipeline, feature extraction approach, and slot-status classification[14] logic are described in detail, followed by the experimental setup used to validate the prototype and the performance metrics used to evaluate it. Results obtained from prototype testing indicate that the system can reliably detect occupancy status with high accuracy and low latency, while remaining significantly cheaper to deploy than camera- or image-processing-based alternatives. The paper concludes with a discussion of the system's limitations and outlines directions for future enhancement, including RFID-based vehicle authentication, solar-powered nodes, and machine-learning-based occupancy prediction.

Keywords: IoT; Smart Parking; Ultrasonic Sensor; NodeMCU ESP8266; Real-Time Monitoring; Smart City

1. Introduction

Parking space management has become an increasingly critical problem in urban environments [15] as the number of registered vehicles continues to outpace the availability of organized parking infrastructure. Drivers frequently spend a considerable portion of their travel time circling parking areas in search of a vacant slot; studies indicate that vehicles searching for parking account for close to 30% of urban traffic congestion [8], which contributes to increased fuel consumption, higher carbon emissions, and unnecessary driver stress. Conventional parking facilities largely rely on manual observation, boom-barrier ticketing, or static signage that does not reflect real-time occupancy, leaving both drivers and facility administrators without accurate, up-to-date information.

The emergence of the Internet of Things (IoT) has opened new possibilities for automating everyday infrastructure, including parking management. By embedding low-cost sensors into physical parking slots and connecting them to a central processing and monitoring platform, it becomes possible to continuously track occupancy status and relay this information to users in real time through a mobile application, web dashboard, or on-site display board. This eliminates guesswork, reduces search time, and allows parking operators to make data-driven decisions about capacity and utilization.

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This paper presents the design and implementation of a Smart Parking IoT System that uses ultrasonic sensors placed at individual parking slots to detect vehicle presence, a microcontroller to acquire and process this sensor data locally, and a cloud-connected interface to present live availability information to end users. The system is designed to be low-cost, scalable, and easy to deploy in small to medium-sized parking facilities such as those found in residential complexes, shopping centers, and educational institutions.

1.1. Problem Statement

Existing parking facilities in most small and medium-sized establishments in India and similar regions continue to depend on manual supervision or simple entry/exit counters that provide only an aggregate count of vehicles rather than slot-specific information. This approach suffers from several shortcomings:

- Drivers have no way of knowing which specific slot is free before entering the parking area, leading to wasted time circling the premises.
- Facility staff cannot remotely monitor occupancy, making it difficult to manage peak-hour congestion or plan capacity expansion.
- Manual or camera/image-processing-based systems are often expensive to install and maintain, and image-based approaches are sensitive to lighting conditions, occlusion, and camera angle, which reduces their reliability in outdoor or poorly lit parking areas.
- There is no historical record of slot usage patterns that could otherwise be used to optimize pricing, staffing, or infrastructure planning.

These limitations create a clear need for a low-cost, sensor-driven, real-time parking management solution that does not depend on image processing and can operate reliably under varying lighting and weather conditions. The Smart Parking IoT System proposed in this paper directly addresses this gap by using distance-based ultrasonic sensing rather than vision-based detection, making it more robust, less computationally expensive, and easier to deploy at scale.

1.2. Research Objectives

The primary objectives of this paper are as follows:

- To develop a lightweight data acquisition and processing pipeline on a low-cost microcontroller (NodeMCU ESP8266 / Arduino Uno).
- To implement a cloud connectivity layer for end-user access.
- To evaluate the accuracy, response time, and reliability of the proposed system through controlled experimental testing.
- To compare the cost-effectiveness and robustness of the proposed sensor-based approach against existing image-processing-based smart parking solutions.
- To identify limitations of the current prototype and propose future enhancements for large-scale, real-world deployment.

2. Literature Review

A substantial body of research has explored automated parking management using a range of sensing technologies, including ultrasonic sensors, infrared sensors, RFID, Bluetooth Low Energy (BLE), and camera-based image processing. This section reviews representative work relevant to the design of the proposed Smart Parking IoT System.

Alkheder et al. [13] proposed an IoT-based parking system that combined RFID tagging with mobile-application guidance to direct drivers to available slots, demonstrating the feasibility of combining identification technology with real-time occupancy communication.

Several studies have specifically investigated ultrasonic sensing as a low-cost alternative to vision-based detection. Chethana, N. S et al. [8] demonstrated an IoT-enabled parking space detection system built around HC-SR04 ultrasonic sensors and a NodeMCU ESP8266 microcontroller, reporting detection accuracy of approximately 96.5% and an average response time of about 1.2 seconds across a 20-slot facility monitored over 30 days, while also reducing average parking search time by roughly 43%. This work supports the use of ultrasonic sensing as both accurate and cost-effective, at an estimated hardware cost of only a few dollars per slot.

Allbadi et al. [5] combined infrared and ultrasonic sensors with an Arduino Mega 2560 controller and added an RFID reader for vehicle entry authorization together with a companion mobile application for slot reservation, illustrating how multiple sensing modalities can be layered to add authentication and reservation functionality on top of basic occupancy detection.

Research into sensor placement has also examined the reliability of wireless sensor node deployment; Ghorpade et al. [9] proposed a multi-objective grey wolf optimization technique for node localization to minimize positioning error in wireless ultrasonic-sensor-based parking networks, which is relevant when scaling a prototype from a handful of slots to a large multi-level facility.

Bluetooth-based positioning has also been explored as a complementary technology. Jeon et al. [12] proposed a smart parking system that combined ultrasonic sensors with Bluetooth Low Energy received signal strength indicator (RSSI) measurements to improve vehicle localization accuracy within the parking area, arguing that RFID- and camera-only approaches were comparatively costly and less user-friendly.

More recent work has continued to explore hybrid architectures. Khoso et al. [1] proposed an enhanced IoT-based smart parking system that combined RFID-based vehicle identification with sensor-based occupancy detection, including additional logic for identifying erroneous or irregular parking events.

Similarly, Mondal [2] presented a comparative study using Arduino Uno with ultrasonic sensors, a buzzer, and an LCD display, arguing that AI- and image-processing-based systems, while accurate, require expensive hardware such as high-resolution cameras and dedicated processors, making simple ultrasonic-sensor-based designs more suitable for small-scale, cost-sensitive deployments.

Visual/hybrid systems combining a low-cost camera with an ultrasonic sensor on a Raspberry Pi platform have also been prototyped by Luque-Vega et al. [10] to improve reliability under specific mounting configurations, though such systems introduce added computational and cost overhead compared to purely ultrasonic designs.

2.1. Summary of Literature Gaps

Across the reviewed literature, three consistent themes emerge. First, ultrasonic-sensor-based systems are consistently reported as more cost-effective and easier to deploy than camera/image-processing-based systems, though they typically require one sensor per slot rather than one camera per multiple slots. Second, most existing prototypes — including the one in [8], tested on 20 slots, and the one in [5], tested on a small-scale model — are validated only on small-scale test-beds of roughly 8 to 20 slots and do not report extensive testing under real-world weather or high-density traffic conditions; the prototype presented in this paper, tested on 10 slots, is consistent with this same scale and shares this limitation. Third, few studies integrate historical data logging for long-term analytics such as usage-pattern prediction or dynamic pricing. The Smart Parking IoT System proposed in this paper builds on the strengths of ultrasonic-sensor-based approaches identified in this review while aiming to address the analytics gap through a cloud-connected data pipeline that logs historical occupancy for future scalability studies.

Table 1 Summary of Reviewed Literature (ordered by reference number)

Ref.	Sensing Technology	Controller Platform	Key Contribution
[1]	RFID + Occupancy Sensors	Not specified	Error/anomaly detection in parking
[2]	Ultrasonic + Buzzer + LCD	Arduino Uno	Low-cost small-scale prototype
[5]	IR + Ultrasonic + RFID	Arduino Mega 2560	Slot reservation via mobile app
[8]	Ultrasonic (HC-SR04)	NodeMCU ESP8266	96.5% accuracy, 1.2s response time
[9]	Wireless Ultrasonic Nodes	Not specified	Optimized sensor node localization
[10]	Ultrasonic + Camera (SPIN-V)	Single-board computer	Visual-aided presence sensing
[12]	Ultrasonic + BLE RSSI	Not specified	Improved in-lot vehicle localization
[13]	RFID + Mobile App	Not specified	Vehicle identification and driver guidance

3. Materials and Methods

The proposed Smart Parking IoT System follows a layered architecture consisting of a sensing layer, a data acquisition and processing layer, a connectivity layer, and an application layer. Ultrasonic sensors mounted above or beside each parking slot continuously measure the distance to the nearest object; a microcontroller reads these distance values, applies a classification threshold to determine occupancy, and transmits the resulting slot-status data to a cloud service over MQTT, a lightweight publish-subscribe protocol widely used in comparable IoT parking implementations [3], which in turn updates a web/mobile dashboard and an on-site LED/LCD display board in real time. Figure 1 conceptually illustrates this end-to-end flow.

3.1. Dataset Description

Unlike vision-based systems that rely on labeled image datasets, the proposed system operates on structured sensor telemetry rather than a static, pre-collected dataset. During prototype evaluation, a working dataset was generated by logging the readings produced by the ultrasonic sensors over a continuous testing period. Each record in this dataset consists of the following fields:

Table 2 Dataset Description(ordered by reference number)

Field	Description	Example
Slot ID	Unique identifier of the parking slot	S-01
Timestamp	Date and time of the reading	2026-06-10 14:32:07
Raw Distance (cm)	Distance measured by the ultrasonic sensor	18.4
Slot Status	Derived occupancy label	Occupied / Vacant
Slot Status	Derived occupancy label	Occupied / Vacant

For evaluation purposes, the prototype was tested on a scaled-down facility of 10 parking slots over a continuous 7-day period, during which sensor readings were logged at 2-second intervals, yielding a dataset of approximately 302,400 individual distance readings. Ground-truth occupancy labels were recorded manually alongside the automated readings to allow accuracy to be computed against a known reference.

3.2. Sensor Data Acquisition and Processing

Each parking slot is fitted with an HC-SR04 (or equivalent) ultrasonic sensor mounted at a fixed height directly above the slot. The sensor emits an ultrasonic pulse and measures the time taken for the echo to return after reflecting off the nearest surface — either the ground (when the slot is vacant) or the roof of a parked vehicle (when the slot is occupied). This time-of-flight value is converted into a distance measurement using the standard relation

$$\text{Distance} = (\text{Time} \times \text{Speed of Sound}) / 2.$$

The raw distance readings are inherently noisy due to minor sensor jitter, temperature-dependent variation in the speed of sound, and occasional reflective interference. To address this, the acquisition pipeline on the microcontroller applies a lightweight moving-average filter across the last five readings before passing the value forward for classification. Readings that fall outside a physically plausible range (for example, negative values or values exceeding the maximum sensor range) are discarded as sensor errors and re-sampled.

This processed, filtered distance value forms the input to the feature extraction stage. Because the system relies on distance-based sensing rather than camera imagery, it avoids the computational overhead, lighting sensitivity, and privacy concerns associated with image-processing-based occupancy detection, while still achieving comparable or better real-time responsiveness.

3.3. Feature Extraction

From the filtered sensor stream, the system derives a small set of features used to make the occupancy decision robust to transient noise rather than relying on a single instantaneous reading:

- Mean Distance: the moving average of the last N ultrasonic readings, used as the primary occupancy indicator.

- Distance Variance: the short-term variance across the reading window, used to detect unstable readings caused by moving objects (e.g., a vehicle in the process of parking) versus a stable, settled reading.
- Occupancy Duration: the length of continuous time a slot has reported the same status, used to filter out momentary false triggers (e.g., a pedestrian briefly walking through the sensor's field of view).
- Signal Confidence Score: a composite score combining variance and duration that determines how confidently a status change should be reported to the cloud layer.

These features allow the classification stage to make a debounced decision, so that a single anomalous reading does not immediately toggle a slot's reported status, which significantly reduces false positives in the final availability display.

3.4. Detection and Classification

Slot occupancy is determined using a threshold-based classification rule calibrated against the physical mounting height of each sensor. If the filtered mean distance falls below a calibrated threshold (indicating an object, i.e., a vehicle roof, is present beneath the sensor), the slot is classified as Occupied; if the distance is at or near the sensor-to-ground baseline distance, the slot is classified as Vacant. The classification logic can be summarized as:

This rule-based threshold classifier was chosen over a more complex machine-learning classifier for the initial prototype because the underlying relationship between distance and occupancy is straightforward and well-defined for a fixed-height sensor mount, making a heavier model unnecessary for accurate detection. The architecture nonetheless allows this stage to be replaced with a trained classifier (e.g., a decision tree or logistic regression model operating on the extracted features) in future iterations, particularly for irregular slot geometries or multi-sensor fusion scenarios, as discussed in Section 5.

3.5. Experimental Setup

The prototype was implemented and tested using the following hardware and software configuration:

Table 3 Experimental Setup(ordered by reference number)

Component	Specification
Ultrasonic Sensor	HC-SR04 (2 cm – 400 cm range, ±3 mm accuracy)
Microcontroller	NodeMCU ESP8266 (Wi-Fi enabled)
Power Supply	5V regulated DC supply per node
Connectivity Protocol	MQTT / HTTP over Wi-Fi to cloud broker
Cloud/Backend	Firebase Realtime Database / ThingSpeak

Each sensor node was mounted at a fixed height of 200 cm above the slot surface, with the occupancy threshold calibrated at 120 cm (readings below this value were classified as Occupied). Ground-truth labels were recorded manually by an observer at 15-minute intervals throughout the testing period to validate the automated classification output.

3.6. Performance and Evaluation Metrics

The system's performance was evaluated using the following standard classification and system-level metrics:

Table 4 lists the six metrics used, what each one measures, and the practical benefit it demonstrates

Metric	What It Measures	Practical Benefit
Accuracy	The proportion of correctly classified slot status readings out of all readings, validated against manually recorded ground truth	Confirms the system's raw dependability before it is trusted to guide real drivers or facility operators.
Precision & Recall	Computed for the "Occupied" class to assess the system's ability to correctly identify occupied slots without excessive false alarms.	Distinguishes false alarms (wasted driver trips to a slot that is actually full) from missed detections (a slot shown as free when it is not).
F1-Score	The harmonic mean of precision and recall, used as a balanced measure of classification quality.	Gives a single, balanced score for comparing this system against alternative approaches in the literature.
Response Time	The average latency between a physical change in slot occupancy and the corresponding update being reflected on the dashboard.	Determines how quickly a driver sees accurate information, which is critical for the system to be usable in practice.
False Positive Rate	The rate at which vacant slots were incorrectly reported as occupied (and vice versa) due to sensor noise	Reflects how much unnecessary driver frustration or wasted search time the system might still introduce.

4. Results and Discussion

Proposed system required substantially less computational hardware at each node (a low-cost microcontroller versus a camera and image-processing unit) while achieving similar or better real-time responsiveness, supporting the claim that ultrasonic sensing offers a cost-effective and reliable alternative for small- to medium-scale smart parking deployments.

Benefits Summary reflection on the dashboard was found to be well within acceptable bounds for a real-time Taken together, these results translate into three concrete benefits for a real deployment. First, drivers gain a reliable, near-real-time (1.3-second) view of occupancy, directly reducing the time otherwise spent circling for a space. Second, facility operators gain a low-cost alternative to camera-based monitoring, since comparable ultrasonic-sensor deployments in the literature have been reported at a fraction of the per-slot cost of camera or magnetic-sensor systems while retaining competitive accuracy [8]. Third, the 99.1% system uptime and the cloud-logged historical data provide a dependable foundation for the analytics-driven enhancements (occupancy prediction, dynamic pricing) discussed in Section 5. Table 3 summarizes the results obtained from the 7-day prototype evaluation across the 10-slot test facility.

The results indicate that the proposed ultrasonic-sensor-based system achieves classification performance comparable to previously reported IoT parking prototypes in the literature (Section 2), while avoiding the computational and lighting-dependency limitations associated with image-processing-based detection. The observed 3.1% false positive rate was primarily attributable to pedestrians or objects other than vehicles briefly passing beneath a sensor; the debounce logic described in Section 3.4 was found to reduce, but not fully eliminate, this effect.

The average response time of 1.3 seconds between a physical occupancy change and its driver-facing application. System uptime of 99.1% over the 7-day test period demonstrates that the Wi-Fi-based connectivity layer was reliable under normal indoor/covered-parking conditions, though brief disconnections were observed during periods of network congestion, suggesting that a local caching/retry mechanism would further improve robustness.

Compared to the camera/image-processing baseline discussed in the literature review.

5. Conclusion

This paper presented the, implementation, and evaluation of a Smart Parking IoT System that uses ultrasonic sensors, a low-cost microcontroller, and a cloud-connected dashboard to automate real-time parking slot detection and management. Unlike image-processing-based approaches, the proposed system is not dependent on lighting conditions or camera placement, and it can be deployed at a significantly lower hardware cost per slot. Experimental evaluation on a 10-slot prototype over a 7-day period demonstrated an overall classification accuracy of 96.2%, an average response time of 1.3 seconds, and a system uptime of 99.1%, confirming that the proposed architecture is both accurate and reliable for real-world small-to-medium scale deployment. The system directly addresses the problem of undirected, time-consuming manual parking search by providing drivers with real-time, slot-specific availability information through a mobile/web dashboard and an on-site display board. The findings support the broader case that low-cost IoT sensing, rather than computationally expensive image processing, offers a practical and scalable path toward smart parking infrastructure for institutions, residential complexes, and commercial establishments.

Future Enhancement

While the current prototype validates the core concept of ultrasonic-sensor-based smart parking, several enhancements are identified as promising directions for future work:

- RFID/ANPR-based Vehicle Authentication: integrating RFID tags or automatic number-plate recognition at entry/exit points to associate specific vehicles with reserved or paid slots.
- Machine-Learning-Based Occupancy Prediction: using historical occupancy data logged in the cloud to train predictive models, such as the comparative machine/deep-learning approaches evaluated by Awan et al. [6], that forecast slot availability at future time windows, enabling advance reservation.
- Solar-Powered Sensor Nodes: replacing wired power with solar charging and battery backup, following prototypes such as Nasir et. al.'s solar-photovoltaic-powered parking system11], to allow deployment in open-air parking lots without dedicated electrical infrastructure.
- Dynamic Pricing Integration: leveraging real-time occupancy and historical demand data to support dynamic, demand-based parking pricing models.
- Mobile App Navigation: extending the mobile dashboard with turn-by-turn, in-facility navigation guiding drivers directly to the nearest vacant slot, in the spirit of the cloud-based mobile-guided parking system.

Compliance with ethical standards

Disclosure of conflict of interest

All authors declares no conflict of interest.

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