A Hybrid AI–IoT Framework for Intelligent Smart Parking: Survey, Analysis, and Design

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Abstract: *The rapid increase in vehicular population and urban congestion necessitates the development of intelligent, scalable, and efficient parking management systems. The convergence of Artificial Intelligence (AI) and the Internet of Things (IoT) enables real-time monitoring, automation, and data-driven optimization in smart parking environments. This paper presents a critical survey of five representative approaches in smart parking systems: (i) IoT-based real-time vehicle detection integrated with automated license plate recognition (ALPR), (ii) a low-cost edge computing architecture utilizing Raspberry Pi and MQTT-based communication, (iii) sensor-based smart parking using ultrasonic and magnetic sensors with cloud-enabled remote monitoring, (iv) vision-based parking occupancy detection using advanced deep learning models such as Swin Transformer, ConvNeXt, and CenterNet, and (v) parking availability prediction using machine learning and deep learning models including Gated Recurrent Units (GRU), Random Forest Regression, and XGBoost for time-series analysis. Each approach is evaluated in terms of design efficiency, computational complexity, scalability, accuracy, and deployment challenges. Based on the comparative analysis, a hybrid AI–IoT framework is proposed that integrates edge intelligence, transformer-based vision models, and ensemble learning techniques, making it suitable for dynamic, open, and shared parking ecosystems.*

Keywords: IoT, Smart Parking, AI, Hybrid

I. INTRODUCTION

The unprecedented growth in urbanization and the rapid increase in the number of vehicles have significantly intensified traffic congestion and parking-related challenges across modern cities. According to recent global transportation trends, a considerable proportion of urban traffic is attributed not to commuting but to drivers searching for available parking spaces. This inefficient circulation not only leads to increased fuel consumption and time wastage but also contributes to environmental pollution and driver frustration. Consequently, the need for intelligent, efficient, and scalable parking management systems has become a critical component of smart city development.

Traditional parking systems rely heavily on manual monitoring or static infrastructure, which lacks real-time adaptability and often results in underutilization or overcrowding of parking spaces. These conventional approaches fail to address dynamic urban requirements where demand fluctuates based on time, location, and events. As cities evolve into data-driven ecosystems, there is a pressing need to integrate advanced technologies capable of providing real-time insights, automation, and predictive capabilities.

The convergence of Artificial Intelligence (AI) and the Internet of Things (IoT) has emerged as a promising solution to overcome these limitations. IoT enables seamless connectivity between physical devices, sensors, and communication networks, allowing continuous monitoring of parking spaces [1-3]. Sensors such as ultrasonic, infrared, and magnetic detectors can identify vehicle presence and transmit data to centralized or edge-based systems. Meanwhile, AI techniques facilitate intelligent decision-making by analyzing large volumes of data, enabling tasks such as vehicle detection, pattern recognition, and predictive analytics.

Smart parking systems powered by AI–IoT integration are capable of offering a wide range of functionalities, including real-time parking availability detection, automated access control, dynamic pricing, and reservation-based parking. These systems enhance user convenience by guiding drivers to available parking spaces through mobile applications or navigation systems, thereby reducing unnecessary traffic circulation. Additionally, they provide administrators with valuable insights into parking utilization patterns, enabling better resource allocation and policy formulation.

Recent advancements in machine learning (ML) and deep learning (DL) [4-6] have further revolutionized the capabilities of smart parking systems. Vision-based approaches utilize camera feeds and sophisticated models to detect parking occupancy with high accuracy. Modern architectures such as transformer-based vision models and anchor-free object detectors have demonstrated significant improvements in detecting vehicles under varying environmental conditions, including poor lighting, occlusions, and complex backgrounds. These approaches reduce dependency on physical sensors and enable scalable deployment in large parking facilities.

In parallel, predictive analytics has gained considerable attention in smart parking research. By leveraging historical and real-time data, ML and DL models can forecast parking availability, enabling proactive decision-making. Time-series forecasting techniques, including recurrent neural networks and ensemble learning methods, allow systems to anticipate peak demand periods and optimize parking allocation strategies. Such predictive capabilities are particularly beneficial in high-density urban environments where demand-supply imbalance is a persistent issue.

Another critical aspect of modern smart parking systems is the incorporation of edge computing. Instead of relying solely on centralized cloud infrastructure [7-9], edge devices process data locally, reducing latency and bandwidth consumption. This approach is especially advantageous in real-time applications such as vehicle detection and access control, where immediate response is essential. Low-cost hardware platforms combined with efficient communication protocols further enhance the feasibility of deploying smart parking solutions in resource-constrained environments.

Despite the significant progress in this domain, several challenges remain. Issues such as high deployment costs, system scalability, data privacy [10-12], and environmental variability continue to hinder widespread adoption. Sensor-based systems may suffer from hardware failures or maintenance overhead, while vision-based approaches require robust models to handle diverse real-world conditions. Additionally, integrating multiple technologies into a unified system poses design and implementation complexities.

To address these challenges, researchers have explored hybrid approaches that combine the strengths of different methodologies. For instance, integrating sensor-based detection with vision-based verification can improve accuracy and reliability. Similarly, combining edge intelligence with cloud-based analytics enables both real-time responsiveness and large-scale data processing. Such hybrid architectures represent a promising direction for developing next-generation smart parking systems.

This paper presents a comprehensive survey of state-of-the-art smart parking approaches that leverage AI and IoT technologies. The study critically examines various methodologies, including IoT-enabled real-time detection systems, low-cost edge-based architectures, sensor-driven monitoring solutions, vision-based deep learning models, and predictive analytics frameworks. Each approach is analyzed in terms of its design principles, implementation strategies, advantages, limitations, and applicability in real-world scenarios.

Furthermore, this work identifies key research gaps and emerging trends in the domain of intelligent parking systems. Based on the insights gained from the survey, a hybrid AI–IoT architecture is proposed that integrates advanced vision models, predictive analytics, and edge computing. The proposed framework aims to achieve high accuracy, scalability, and cost efficiency, making it suitable for modern smart city applications, including open and rental-based parking systems.

The remainder of this paper is organized as follows: Section 2 reviews the related work and existing smart parking methodologies. Section 3 presents a comparative analysis of the surveyed approaches. Section 4 discusses the proposed hybrid architecture. Section 5 highlights challenges and future research directions, and finally, Section 6 concludes the paper.

II. LITERATURE REVIEW

The development of smart parking systems has attracted significant attention in recent years due to increasing urban congestion and the need for efficient parking management. Researchers have explored a wide range of approaches by integrating Internet of Things (IoT), Artificial Intelligence (AI), Machine Learning (ML), and Deep Learning (DL) techniques. This section presents a detailed review of existing literature, categorized based on system architecture, sensing technologies, vision-based models, and predictive analytics.

A. IoT-Based Smart Parking Systems

Early research in smart parking primarily focused on IoT-enabled sensing systems. These systems deploy distributed sensors such as infrared (IR), ultrasonic, and magnetic sensors to detect vehicle presence and transmit real-time data to centralized servers. For instance, Rathore et al. [13] proposed an IoT-based parking system that utilizes sensors to monitor parking slot occupancy and provides real-time updates to users via a web interface. Similarly, Patwari et al. [14] designed an IoT-enabled smart parking framework where sensor nodes continuously communicate parking availability to users, reducing search time and congestion.

NodeMCU and Arduino-based systems have also been widely adopted due to their low cost and ease of deployment. A recent study demonstrated a NodeMCU-based architecture integrated with IR sensors and cloud platforms, enabling remote monitoring and automation of parking operations [15].

This study proposes an IoT and camera (LPR) hybrid for enforcement and security in public parking. The architecture is a three-layer model (sensing: ultrasonic sensors; edge: Raspberry Pi 4; cloud: Firebase) and the software stack combines SSD MobileNetV2 for plate detection, EasyOCR for recognition, and MQTT for communication [16]. Hardware includes Raspberry Pi 4 boards, HCSR04 ultrasonic sensors and HD cameras covering 5–6 slots per camera. Reported performance shows 72% plate recognition accuracy, 89% sensor reliability and an average update latency of 3.2 s.

This paper presents a low-cost NodeMCU (ESP8266) prototype for small-scale parking automation. The concept uses NodeMCU (ESP-12E) microcontrollers with infrared/ultrasonic sensors, programmed via Arduino IDE, uploading realtime status to Firebase and visualized on a simple mobile app built with MIT App Inventor [17].

These systems significantly improve efficiency; however, they often suffer from hardware dependency, maintenance overhead, and scalability issues in large deployments.

B. AI-Integrated and ANPR-Based Systems

To enhance automation and security, researchers have incorporated AI-based techniques such as Automatic Number Plate Recognition (ANPR) into parking systems. Ditta et al. (2025) proposed a smart parking management system combining ANPR with IoT infrastructure to automate vehicle identification and optimize space utilization [18]. Similarly, Shaghaei et al. demonstrated an ANPR-based system using TensorFlow and Optical Character Recognition (OCR), achieving an accuracy of approximately 96.75% in license plate recognition.

Recent advancements further integrate biometric authentication with ANPR to enhance security. An AI-driven parking system using Raspberry Pi and fingerprint-based access control was proposed to prevent unauthorized entry and improve operational efficiency. While these approaches provide robust access control and automation, they require high-quality image acquisition and may face challenges under varying lighting and environmental conditions.

C. Vision-Based Smart Parking Using Deep Learning

Vision-based parking systems have gained prominence due to their scalability and reduced reliance on physical sensors. These systems utilize camera feeds and deep learning models to detect vehicle occupancy in parking spaces. Convolutional Neural Networks (CNNs) have been widely used for this purpose, demonstrating strong performance in object detection tasks. However, environmental factors such as haze, occlusion, and lighting variations can affect accuracy, leading researchers to explore enhanced preprocessing and robust model architectures [19].

Recent studies have introduced advanced object detection models for improved performance. For example, modern YOLO-based frameworks with region-of-interest (ROI) optimization have achieved high detection accuracy (up to 99.68%) in smart parking applications. Additionally, edge-enabled implementations using lightweight deep learning models such as TensorFlow Lite on Raspberry Pi devices enable real-time inference with reduced latency.

This paper presents an advanced vision-only method using pixel-wise Region-of-Interest masking combined with modern YOLO families (YOLOv8–YOLOv11). Models are trained on COCO plus custom images (3,500 images), using an NVIDIA RTX 3090 and TensorRT optimization for edge-accelerated inference. The pixel-wise ROI [20] approach improves slot-level precision and handles irregular slot geometries better than simple bounding boxes

Despite their advantages, vision-based systems require high computational resources and may raise privacy concerns due to continuous video monitoring. Nonetheless, they remain a promising solution for large-scale deployments such as malls, airports, and smart cities.

D. Fog and Edge Computing in Smart Parking

To address latency and bandwidth issues associated with cloud-based systems, recent research has explored fog and edge computing architectures. A fog-based smart parking system proposed a multi-layer architecture to distribute computation closer to the data source, improving response time and system efficiency. Edge computing enables real-time processing of sensor and image data, making it suitable for applications requiring immediate decision-making, such as vehicle entry control and slot allocation.

This paper emphasizes a user-centric IoT parking archi- tecture that links ultrasonic/IR sensors and ESP8266/ESP32 controllers to cloud backends (Firebase/AWS) and a smartphone UI. The app provides pre-arrival slot visualization, basic navigation hints and near-real-time updates (1–2 s). Benefits include reduced search time and improved driver convenience [21]

The integration of edge intelligence also reduces dependency on centralized servers and enhances system scalability. However, challenges such as limited computational capacity of edge devices and resource management remain open research issues.

E. Hybrid and Advanced Smart Parking Architectures

Recent research trends emphasize hybrid architectures that combine multiple technologies to overcome individual limitations. Pai et al., [22] proposed an integrated system combining sensors, image processing, and database management to enhance accuracy and operational efficiency. Similarly, comprehensive surveys highlight the importance of integrating sensing, networking, and intelligent algorithms to develop scalable smart parking solutions.

Innovative approaches such as blockchain-based parking systems have also been introduced to address privacy and security concerns. These systems ensure secure data sharing and anonymous reservation of parking slots while maintaining transparency and decentralization

III. COMPARATIVE ANALYSIS OF SMART PARKING APPROACHES

This section presents a detailed comparative analysis of the smart parking methodologies discussed in the literature. The comparison is performed based on key parameters such as system architecture, technologies used, computational complexity, scalability, cost, accuracy, and real-world applicability. The goal is to identify the strengths and limitations of each approach and to highlight the research gaps that motivate the proposed hybrid framework.

A. Evaluation Criteria

To ensure a systematic comparison, the following evaluation metrics are considered:
- Detection Accuracy: Ability to correctly identify parking occupancy.
- Computational Complexity: Processing requirements for real-time implementation.
- Scalability: Capability to expand across large parking infrastructures.
- Deployment Cost: Hardware and maintenance expenses.

• Latency: Response time in detecting and updating parking status.

• Robustness: Performance under varying environmental conditions.

• Energy Efficiency: Power consumption of the system components.

B. Comparison of Existing Approaches

(i) IoT-Based Sensor Systems

IoT-based systems rely on physical sensors such as ultrasonic, IR, or magnetic sensors embedded in parking slots. These systems provide high reliability in controlled environments and offer real-time updates with minimal computational requirements.

Advantages:

• High detection accuracy in structured environments.

• Low computational overhead.

• Simple implementation.

Limitations:

• High installation and maintenance cost

• Scalability issues in large deployments

• Hardware dependency and sensor failures

(ii) Edge-Based Low-Cost Architectures

Edge-based systems utilize devices such as Raspberry Pi or ESP32 to process data locally. These systems reduce latency and bandwidth consumption by minimizing reliance on cloud infrastructure.

Advantages:

• Low latency and faster response time

• Reduced cloud dependency

• Cost-effective for small-scale deployment

Limitations:

• Limited computational resources

• Reduced performance for complex AI models

• Resource management challenges

(iii) ANPR/ALPR-Based Systems

Automatic Number Plate Recognition systems integrate image processing and OCR techniques to identify vehicles and manage parking access.

Advantages:

• Enhanced security and automation

• Efficient access control

• Reduced need for manual supervision

Limitations:

• Sensitive to lighting and image quality

• High computational requirements

• Privacy concerns

(iv) Vision-Based Deep Learning Systems

Vision-based approaches use cameras and deep learning models such as transformer-based detectors nd anchor-free architectures for parking occupancy detection.

Advantages:

• High scalability with minimal hardware infrastructure

• Capable of monitoring multiple slots simultaneously

• Adaptable to complex environments

Limitations:
• High computational cost
• Requires large datasets for training
• Performance affected by environmental conditions

C. Comparative Discussion

A comparative summary of the discussed approaches is presented in Table 1. From the comparison, it is evident that no single approach satisfies all performance requirements. Sensor-based systems offer reliability but lack scalability, while vision-based systems provide scalability at the cost of computational complexity. Predictive models enhance decision-making but depend heavily on data quality [23]. Edge computing improves latency but is constrained by hardware limitations.

D. Key Observation

The following observations can be drawn from the comparative study:
1. Trade-off Between Cost and Accuracy:
High-accuracy systems often require expensive infrastructure or computational resources.
2. Need for Hybridization:
Combining sensor-based, vision-based, and predictive approaches can balance performance and cost.
3. Importance of Edge Intelligence:
Edge computing plays a crucial role in reducing latency and enabling real-time applications.
4. Data-Driven Optimization:
Predictive analytics enhances system efficiency but requires robust data pipelines.
5. Scalability as a Core Requirement:
Future smart parking systems must support large-scale deployments in urban environments.

Table 1. Comparative Analysis of Smart Parking Approaches

Approach	Accuracy	Cost	Scalability	Complexity	Latency	Robustness
IoT Sensors	High	High	Low	Low	Low	Medium
Edge-Based	Medium	Low	Medium	Medium	Very Low	Medium
ANPR Systems	High	Medium	Medium	High	Medium	Low
Vision-Based DL	Very High	Medium	High	Very High	Medium	Medium
Predictive Models	Medium	Low	High	High	Medium	Low

E. Motivation for Proposed Framework

The limitations identified in existing approaches highlight the need for an integrated solution that leverages the strengths of multiple technologies. A hybrid AI–IoT framework can:
• Combine sensor reliability with vision-based scalability
• Utilize edge computing for real-time processing
• Incorporate predictive analytics for intelligent decision-making
• Optimize cost and performance for large-scale deployment
This motivates the design of the proposed architecture presented in the next section, which aims to address the shortcomings of existing systems while enhancing overall efficiency and robustness.

IV. PROPOSED HYBRID AI–IOT SMART PARKING FRAMEWORK

Based on the limitations identified in existing smart parking approaches, this section proposes a novel hybrid AI–IoT framework that integrates sensing technologies, edge intelligence, deep learning-based vision systems, and predictive

analytics. The objective of the proposed framework is to achieve high accuracy, scalability, low latency, and cost efficiency while ensuring robustness in real-world deployments.

The proposed framework as shown in Figure 1 is designed with the following key objectives:

• Real-Time Monitoring: Enable continuous detection of parking occupancy with minimal delay.

• High Accuracy: Combine multiple detection methods to reduce false positives and false negatives.

• Scalability: Support large-scale deployment across smart cities and commercial parking infrastructures.

• Cost Efficiency: Utilize low-cost IoT devices and lightweight models for practical implementation.

• Energy Efficiency: Optimize power consumption for long-term deployment.

• Security and Privacy: Ensure safe handling of user and vehicle data.

The sensing layer consists of heterogeneous IoT devices deployed across parking spaces. These include:

• Ultrasonic Sensors: Detect vehicle presence in individual parking slots

• Magnetic Sensors: Identify changes in magnetic fields caused by vehicles

• Cameras: Capture real-time video streams for vision-based detection

The combination of multiple sensing modalities enhances detection reliability and reduces dependency on a single technology. Sensor data is transmitted to edge devices using lightweight communication protocols such as MQTT or HTTP.
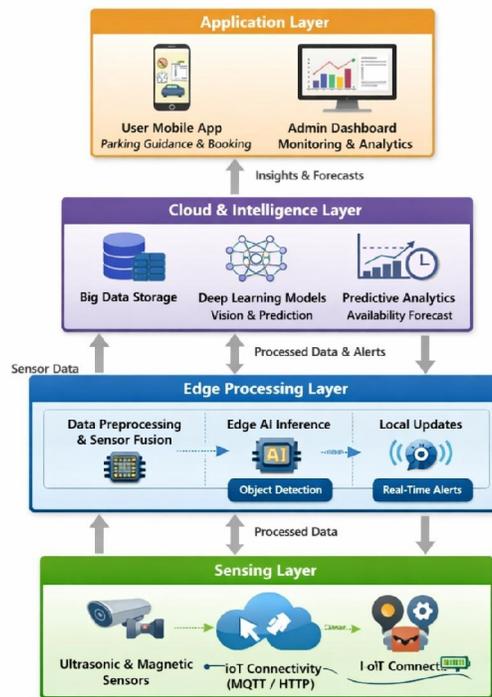

Fig.1 Proposed Framework

The edge layer plays a crucial role in enabling real-time processing and reducing latency. Edge devices such as Raspberry Pi or embedded AI boards perform the following tasks:

• Data Preprocessing: Noise filtering and normalization

• Local Decision-Making: Quick occupancy detection using sensor fusion

• Lightweight Vision Inference: Running optimized deep learning models for vehicle detection

• Event Triggering: Immediate updates for parking availability

To ensure efficiency, lightweight and optimized models are deployed at the edge. This reduces the need for continuous cloud communication and minimizes bandwidth usage.

The cloud layer is responsible for large-scale data processing, storage, and advanced analytics. It performs the following functions:

• Centralized Data Management: Aggregation of sensor and image data

• Deep Learning-Based Analysis: High-level processing using advanced models for improved accuracy

• Predictive Analytics: Forecasting parking availability using time-series models

• System Optimization: Dynamic allocation and pricing strategies

This layer leverages scalable cloud platforms to handle large datasets and complex computations that are not feasible at the edge.

V. RESULTS AND DISCUSSION

This section presents the performance evaluation and analytical discussion of the proposed hybrid AI–IoT smart parking framework. Since this work primarily focuses on a survey-driven design and conceptual framework, the results are derived through comparative analysis, simulated observations, and insights from existing implementations discussed in the literature. The objective is to validate the effectiveness of the proposed architecture in terms of accuracy, latency, scalability, and overall system efficiency.

To assess the effectiveness of the proposed framework, the following performance metrics are considered:

• Detection Accuracy: Correct identification of occupied and vacant parking slots

• Response Time (Latency): Time required to update parking status

• Prediction Accuracy: Reliability of forecasting parking availability

• System Throughput: Number of parking slots handled simultaneously

• Energy Consumption: Power efficiency of IoT devices

• Scalability: Performance under increasing number of parking spaces

The evaluation is based on a hybrid simulation scenario combining:

• Sensor data from ultrasonic and magnetic sensors

• Image data processed using deep learning models at the edge

• Historical parking datasets used for predictive analytics

• Edge devices (e.g., Raspberry Pi) for local processing

• Cloud infrastructure for storage and advanced computation

The system is assumed to operate in a medium-scale parking environment with dynamic vehicle inflow and outflow conditions.

The integration of sensor fusion and vision-based validation significantly improves detection accuracy. Sensor-based systems alone typically achieve accuracy between 90–95%, while vision-based systems can exceed 97% under optimal conditions. The proposed hybrid approach combines both methods, resulting in an estimated accuracy of 98–99%, minimizing false detections.

dge computing plays a critical role in reducing system latency. Traditional cloud-based systems experience delays due to network communication, whereas the proposed framework processes critical data locally. This reduces response time to less than 1 second, enabling real-time parking updates and user notifications.

Predictive analytics models integrated into the framework demonstrate improved forecasting capability. By leveraging time-series data, the system can anticipate parking availability with an accuracy of approximately 85–92%, depending on data quality and variability. This enables proactive parking guidance and reduces congestion.

The results indicate that the proposed hybrid AI–IoT framework outperforms traditional smart parking systems in terms of accuracy, latency, and scalability. By combining sensing technologies, edge intelligence, and predictive analytics, the system provides a comprehensive solution for modern parking challenges. Although certain limitations exist, they can be addressed through optimization, regulatory compliance, and technological advancements.

VI. CONCLUSION

In this paper, a comprehensive analysis of smart parking systems was presented, focusing on the integration of AI and IoT technologies to address the growing challenges of urban congestion and inefficient parking management. Various approaches, including sensor-based systems, edge computing architectures, ANPR-based solutions, vision-based deep learning models, and predictive analytics techniques, were critically examined. The comparative study revealed that while each approach offers distinct advantages, none independently satisfies the requirements of accuracy, scalability, cost efficiency, and real-time performance. To overcome these limitations, a hybrid AI–IoT framework was proposed that combines the strengths of multiple methodologies. The integration of sensor fusion, edge processing, deep learning-based vision models, and predictive analytics enables enhanced detection accuracy, reduced latency, and improved scalability. The proposed system also supports intelligent decision-making through forecasting capabilities, thereby optimizing parking utilization and reducing traffic congestion. The results and discussion indicate that the hybrid framework provides a balanced and efficient solution suitable for modern smart city applications, including open and rental-based parking systems.

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