RESEARCH ARTICLE

An Intelligent Smart Parking Framework Using Machine Learning–Based Automatic License Plate Recognition for Enhanced Security

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Abstract

Urban parking inefficiency has become a critical challenge in modern cities, leading to increased traffic congestion, higher fuel consumption, and greater environmental impact. This paper proposes an intelligent smart parking management system that integrates hardware sensing, machine learning, and computer vision to enable real-time parking monitoring and automated vehicle identification. The system combines infrared sensors, camera modules, and microcontroller-based control with vision-based parking space detection and automatic license plate recognition (ALPR). Experimental results demonstrate that the parking space detection module achieves an accuracy of 93.97%, while the license plate recognition module attains 84.93% accuracy. Extensive testing under real-world conditions confirms the system's reliability and practicality. The proposed approach enhances parking space utilization, reduces parking search time, and offers a scalable, cost-effective foundation for future smart city parking infrastructure.

Keywords: smart parking, ALPR, machine learning, image processing, IoT automation.

1 Introduction

Urban transportation systems are being stretched by the explosion in vehicles and lack of parking infrastructure, which makes parking inefficiency a constant challenge in current cities. A large fraction of the urban traffic flow congestion is the time required for drivers to search for available parking locations, which results in unnecessary fuel consumption, time, and carbon emissions [1]. Conventional parking management approaches, usually relying on static allocation, manual supervision or isolated sensing mechanisms, are unable to respond dynamically to fluctuations of the real-time demand. As a result, these systems fail to deliver accurate and timely information regarding the availability of parking reducing the overall transportation efficiency.

To solve these challenges, smart parking systems have become an important part of smart city systems, using Internet of Things (IoT) technologies to

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monitor and distribute information about parking spaces in real-time [2]. While IoT-based solutions provide better connectivity and accessibility, some of the limitations of these solutions are related to scalability issues, infrastructure costs, and reliance on centralized cloud platforms. Sensor-based occupancy detection techniques, though cost-effective, are sensitive to environmental effects such as ambient lighting conditions, weather conditions and sensor misalignment, and can produce considerable degradation in the detection accuracy [3]. Vision-based parking systems provide better spatial awareness and context understanding but the systems are often flawed in their robustness under the real-world condition without proper integration with complementary sensing mechanism [4].

Another key limitation of current parking management system does not include integrated vehicles identification. Many are constrained to identify vacant parking spaces without considering the identification of vehicles, which is essential to enable access control, security enforcement and operational traceability [5]. License plate recognition has been extensively examined in traffic surveillance and toll management applications; nevertheless, it has not yet been adopted in the parking management system to a great extent and on a relatively fragmented basis. The lack of any common framework that combines parking occupancy detection and vehicle identification makes current solutions less effective and reliable.

Motivated by these gaps, this paper proposes an intelligent smart car parking management system based on low-cost hardware sensing technology and the machine learning drive computer vision techniques to allow accurate real-time parking occupancy detection and automatic license plate recognition. The proposed scheme involves a combination of infrared sensors, camera modules along with a microcontroller-based control unit for localized processing reducing the dependency on cloud infrastructure [6]. By combining the domains of sensing, perception, and control in a single architecture, the system can improve detection reliability, provide better scalability and increase security of operations. Experimental validation in real-world scenarios is an indication of the practicality and effectiveness of the proposed approach towards a practical solution forecast for next-generation smart parking infrastructures in line with intelligent urban mobility systems [7].

1.1 Novelty and Contributions of the Proposed System

Unlike many existing smart parking systems that rely solely on sensor-based occupancy detection or vision-only approaches, the proposed system introduces a hybrid and unified architecture that integrates low-cost infrared sensing with lightweight computer vision techniques to achieve simultaneous parking space detection and automatic license plate recognition within a single operational framework. The key contributions of this work are summarized as follows:

1. integration of region-based pixel density analysis with hardware sensing to improve robustness against environmental variations,
2. localized edge-level processing to minimize cloud dependency and system latency, and
3. inclusion of vehicle identification functionality to enhance security, access control, and operational traceability.

In contrast to deep learning–centric smart parking solutions that require high computational resources and extensive training datasets, the proposed approach achieves competitive performance using computationally efficient algorithms, making it suitable for cost-sensitive, scalable, and real-world smart city deployments.

2 Related Work

Smart parking research has progressed from simple occupancy sensing to more extensive and sophisticated city-wide smart infrastructure, aimed at addressing problems in traffic circulation and pollution (emissions), user experience. A significant amount of research has been conducted on smart parking as an IoT-driven service, where sensing nodes and communication layers feed the availability data to the users and operators in real-time [3]. However, no. of deployments, several studies highlight recurring challenges with regard to system done functionality of the network in interoperability, as well as reliability in environmental variability and cost-associated with maintaining the dense sensing networks. Survey driven work even shows that though IoT architectures offer visibility and automation, many systems are limited by practical issues involving scalability bottlenecks, privacy concerns and poor integration between detection and downstream decision modules [2].

Beyond connecting, however, more researchers are considering smart parking as an optimization problem with potential benefits in both economic and environmental terms. Intelligent parking systems have been found to lower cruising behavior around parking facilities and decrease congestion and emissions when the occupancy information within a parking facility is accurate and timely [8]. However, inherited limitations exist in traditional sensor units-only design approaches because of noise, misalignment or degradation of sensing units with the passage of time, stimulates interest in seeing unit theses and designing hybrid systems with a capacity of comprehending contextual information [5, 9, 10]. In addition, reservation-oriented parking frameworks represent ways in which the higher-level control strategies can reduce uncertainty and enhance utilization, but they add complexity to operations and dependable validation of occupancy and vehicle presence in real-time [10–12]. In recent times, there is more emphasis on machine learning and computer vision to enhance (deep learning) occupancy detection, especially for mission areas where it isn't applicable to install sensors for every single slot. AI-based smart parking techniques have shown great potential in estimating the parking availability from video feed, nevertheless, robustness is one of the concerns given the changing illumination, occlusion and diverse parking layout [13, 14]. Parallel researches have been undertaken on cloud-based architecture for smart parking to maintain large deployment and analytics, while cloud dependency often leads to latency, infrastructure cost, and availability issues, particularly in the context of bandwidth constraint [5, 8]. Such gaps represent a continuously ascertained requirement for pragmatically deployable systems that combine reliable sensing with perceptions generated from vision by limiting the requirement of infrastructure. The first part of present work is to design and validate a unified architecture of smart parking that integrates the occupancy detection and vehicle identification into one operation pipeline.

3 Proposed System Architecture

The proposed smart car parking management system is developed into an integrated hybrid system which incorporated hardware sensing and machine learning-aided computer vision to perform real-time parking occupancy and automated vehicle identification. Figure 1 displays the overall architecture of the system and it was used in the thesis to demonstrate final system implementation. This architecture has been designed in a way that makes it be modular, low latency, and practically deployable in a real-life parking scenario.

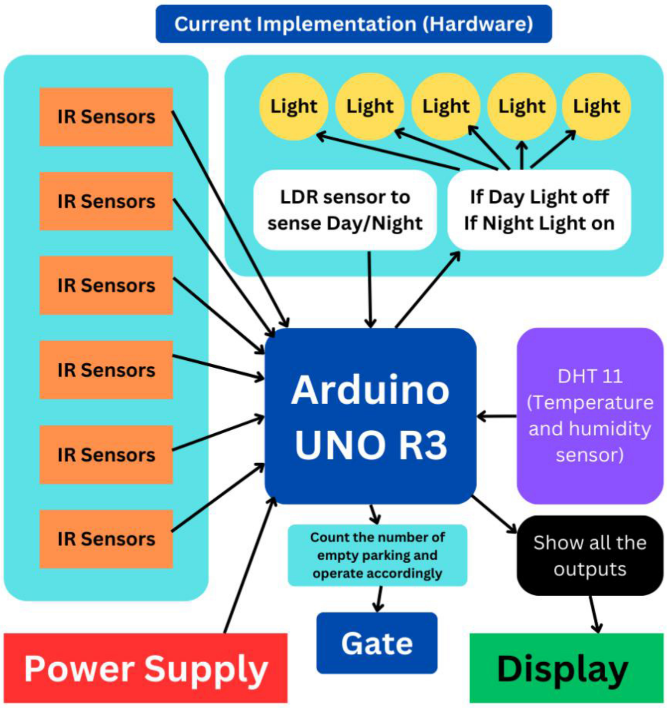

Figure 1. Architecture of the proposed smart car parking management system.

At the hardware sensing layer, infrared (IR) sensors are installed at the individual parking slots in order to detect the presence of vehicles with low computational costs. These sensors are part of the immediate binary occupancy signal, which allows for the fast response of these sensors for continuous monitoring. In parallel, camera modules are set up at strategic places to record video streams on the parking area, reactions to provide the required of accessible visual data for conducting higher-level perception duties. All the sensing components are interfaced with a microcontroller-based control unit, which is responsible for coordinating the data acquisition and communicating with perception and control modules. The specifications of the main hardware components used in the system implementation are summarized in Table 1.

Table 1. Hardware components and specifications.

Component	Specification
Camera Module	HD USB/ IP Camera (≥ 720)
Infrared Sensor	IP Proximity Sensor
Microcontroller	Arduino/ ESP-based controller
Processing Unit	Local edge device (PC/ SBC)
Communication Interface	USB/Serial/Wired

The perception layer is composed of two coupled modules of computer vision. The first module realizes parking space detection based on video frames corresponding to predefined parking spaces. Through image preprocessing and evaluation of pixel density, each slot is classified as occupied or vacant, and the system can be used for the validation and complement of sensor-based detection. The second module used for license plate recognition, vehicle entry and exit lines, detected plate regions at the entrance and exit of the entrance are extracted and processed to be used to get the alphanumeric content. By placing these two perception tasks in the same framework, the system is able to deal with parking availability and vehicle identification simultaneously. The control and decision layer blend the information from the IR sensors and vision modules and produces actions for the entire system. Based on the results of real-time occupancy status and vehicle identification, the controller updates the parking availability information, controls the operation gate, and for monitoring and security purposes, also records the vehicle data. By choosing to run processing close to the devices instead of relying on execution on the cloud, the system reduces its communication overhead and enhances operational reliability especially in an environment with restricted network connectivity.

Overall, the promoted architecture brings sensing, perception and control together in a cohesive and scalable structure. By using inexpensive hardware and intelligence through vision systems, the system fulfills the major shortcoming in some existing smart parking solutions and lays a promising foundation for its use in the intelligent transportation system and the future smart city infrastructure.

4 Methodology – Parking Space Detection

4.1 System Workflow Overview

The proposed parking space detection method aims to identify occupied and vacant parking slots in real time using a structured vision-based pipeline. The complete workflow of the proposed detection process is illustrated in Figure 2, which also presents the parking space counting mechanism and the overall process diagram included in the thesis. This workflow systematically organizes the sequential steps, from video acquisition to final occupancy classification, ensuring methodological consistency and reproducibility. As a result, the detection process becomes standardized, reliable, and repeatable.

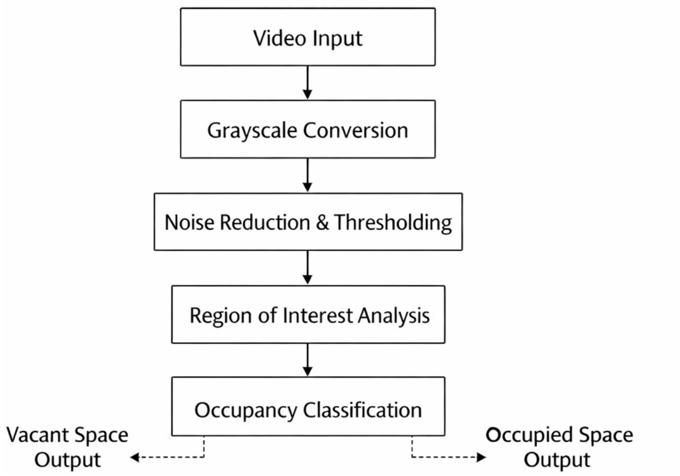

Figure 2. Workflow of the vision-based parking space detection module.

4.2 Data Acquisition and Camera Configuration

Video data are recorded by a camera with fixed position installed in order to cover whole parking area. The camera is angled so there is a minimum distortion of the perspective as well as a good view of all parking slots. Continuous streams of video frames are split into simple frames, which are processed independently to maintain the responsiveness of the connectivity in real time. This from this frame-based processing, this system can dynamically update the parking occupancy real-time without having any buffering delay.

4.3 Image Preprocessing

Each frame acquired undergoes a series of preprocessing operations in order to make the acquired frames robust to the noise and illumination varies. First, frames are converted to grayscale to decrease the computational complexity as well as avoid the effect of color dependency. After this, a Gaussian blurring is done to suppress the frequencies (actual high frequencies) and flatten the changes in intensity. Adaptive thresholding is used in order to make the foreground objects different from the other and therefore obtain the reliable segmentation of the vehicles under the conditions of different lights. Morphological operations such as median filtering, dilation is used to enhance the contour of the objects and also reduce fragmentation induced due to shadows or surface irregularities.

4.4 Parking Slot Region Definition

Parking slots are defined as static areas of interest from the physical point of view of the parking area. Slot boundaries are annotated by hand one-time during initialization of the system and without change during system operation. This predefined region-based strategy is employed for the system to restrict the analysis to the relevant regions and hence reduce the computational overhead considerably. By associating each region with a unique slot identifier, the system has consistent slot-level tracking across the operation of the system.

4.5 Occupancy Classification Strategy

For each predefined parking slot region, the occupancy is determined by using the pixel density analysis. Preprocessing Number of non-zero pixels in each region are obtained after preprocessing. A slot is defined as occupied or vacant by counting the pixel number in it, by comparing it with a value set for the same. Higher pixel density indicates the presence of a vehicle and a low density indicates an empty slot. This threshold-based classify method makes a stable performance possible and eliminates the complexity of deep learning models thus making it suitable for real-time deployment of multiple core classifications on resource constrained hardware.

Although a fixed pixel-density threshold is used in this implementation for computational simplicity, the threshold value can be adapted based on parking layout, camera placement, and illumination conditions. In practical deployment, an initialization-phase calibration may be applied to improve robustness under shadowing effects, partial occlusions, or lighting variations.

4.6 Real-Time Visualization and Status Update

The occupancy status of each parking space is visually presented by overlaying bounding boxes onto the video stream. Vacant and occupied slots are differentiated using distinct visual markers, as illustrated in Figure 3, which shows sample detection results obtained from the implemented system. The occupancy data from all parking spaces are then aggregated to determine the overall parking availability. Subsequently, this information is transmitted to the control module for display updates and system-level decision-making.

4.7 Mathematical Formulation

Let an input image captured by the camera be represented as a grayscale image $I(x, y) \in [0, 255]$, Here x and y are the coordinates that are the spatial pixel locations. Each parking slot is modelled as a fixed region of interest (ROI) which is defined as:

$$ROI_i = \{(x, y) \mid x_1 \leq x \leq x_2; y_1 \leq y \leq y_2\} \quad (1)$$

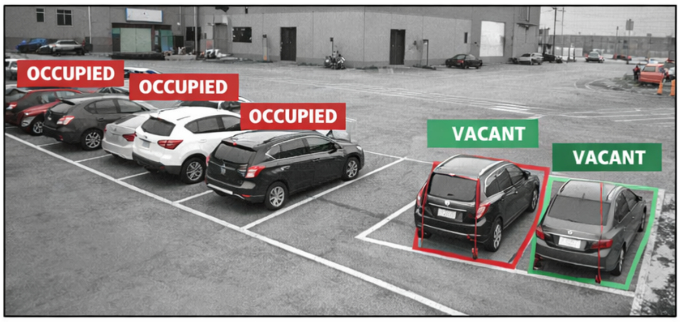

Figure 3. Sample output of parking space detection showing occupied and vacant slots.

Post processing for preprocessing and thresholding is then used to calculate the pixel density in a parking slot, calculated as:

$$D_i = \sum_{(x,y) \in ROI_i} B(x, y) \quad (2)$$

where the binary function $B(x, y)$ is defined as:

$$B(x, y) = \begin{cases} 1, & \text{if pixel belongs to foreground} \\ 0, & \text{otherwise} \end{cases} \quad (3)$$

The occupancy state of a parking slot is classified based on a predefined threshold T as follows:

$$S_i = \begin{cases} \text{Occupied}, & D_i \geq T \\ \text{Vacant}, & D_i < T \end{cases} \quad (4)$$

License plate detection is modeled as:

$$LP = f(I)_v \quad (5)$$

where $f(\cdot)$ denotes the Haar Cascade classifier. Optical character recognition is applied as:

$$C = g(LP)_v \quad (6)$$

System performance is evaluated using accuracy, defined as:

$$\text{Accuracy} = \frac{(TP + TN)}{(TP + TN + FP + FN)} \quad (7)$$

5 Methodology - License Plate Recognition

The License Plate Recognition (LPR) module is designed to automatically identify vehicles entering and exiting the parking area by extracting alphanumeric information from captured images. This module complements the parking space detection process by enabling vehicle-level identification, access control, and traceability. The overall workflow of the proposed license plate recognition process is illustrated in Figure 4, which has already been presented in the thesis and is reproduced here without modification.

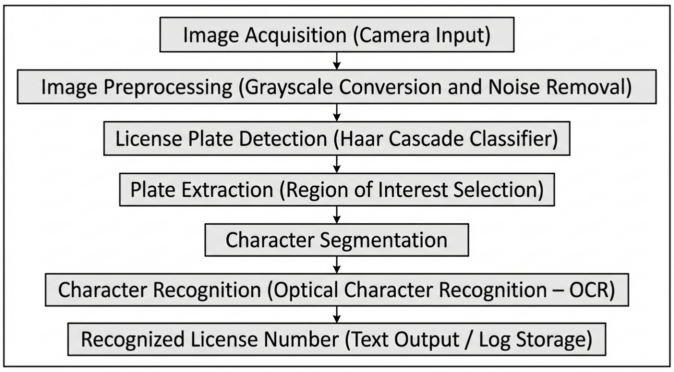

Figure 4. Workflow of the license plate recognition module.

5.1 Image Acquisition

Images are obtained with a fixed camera that is installed at the entry and exit points of the parking. The camera is placed so as to provide frontal or near-frontal views of vehicles, decreasing the amount of perspective distortion and occlusions of license plate. Captured frames are analyzed on real-time basis for immediate identification of vehicles without interrupting the traffic flow.

5.2 Image Preprocessing

To increase the visibility of the license plates and lessen the environmental noises, the captured frame will go through a preprocessing phase. The image is first converted to grayscale to reduce the computation complexity as well as to eliminate the dependency of color. Noise reduction techniques are used to process the image such as through the use of the gaussian filter to reduce background artifacts and enhance edge clarity. These preprocessing steps are done to enhance the robustness of the plate detection in different lighting conditions as well as different weather environments.

5.3 License Plate Detection

License plate regions are detected by using a Haar Cascade classifier model which is trained and scanned by the preprocessed image to find rectangular regions similar to the structure of license plate texts. After it is detected, vocation with bounding box equivalent to license plate becomes a region of interest (ROI). This step separates the plate area, then the rest of the image, so the following processing attached to the appropriate image area, namely.

5.4 Character Segmentation and Recognition

The extracted license plate ROI image is further processed to segment the individual characters in it. Thresholding and contour detection techniques are used to detect separation of characters from the background. Each segment of a character is then passed to an optical character recognition (OCR) engine which turns the visual symbolic representation into machine-readable alphanumeric text. The recognized license number is stored to be used for system-level operations such as access logging and monitoring.

Recent studies have demonstrated higher recognition performance using deep learning–based license plate recognition models. However, such methods often demand substantial computational resources and large annotated datasets. The Haar Cascade and OCR-based approach adopted in this work offers a lightweight alternative that balances accuracy with real-time performance, particularly suitable for edge-based and low-cost deployments.

5.5 Output Generation and System Integration

The complete recognition results are visually presented by overlaying bounding boxes and the recognized license plate text onto the original image, thereby providing intuitive feedback to system operators. Sample results of the implemented license plate recognition process are illustrated in Figure 5, which is directly reproduced from the thesis.

Figure 5. Sample output of license plate recognition showing detected plate and recognized characters.

The recognized license plate information is passed to the central control module and may be linked to parking occupancy information and gate control decisions as well as logs. By incorporating license plate recognition in addition to parking space detection, the proposed system guarantees efficient parking management as well as increased operational security.

6 Results and Performance Evaluation

This section presents the experimental results that obtained from the implementation of the proposed smart car parking management system. The evaluation is being addressed in two major aspects of the system: parking space detection and license plate recognition. Performance is evaluated in terms of practical test scenarios to show the reliability, the accuracy and the practical use of the proposed approach.

The experimental evaluation was conducted over multiple operational sessions under real parking conditions, including variations in lighting, traffic density, and vehicle positioning. The dataset consisted of several hundred parking occupancy events and license plate captures collected during routine parking operations. This diversity ensures that the reported accuracy values reflect realistic deployment scenarios rather than controlled laboratory environments.

6.1 Parking Space Detection Performance

The performance of the parking space detection module was assessed in real operating condition using continuous video streams obtained from the deployed camera set up. Each parking slot was monitored in real time and the parking slots were classified as occupied or vacant based on the pixel density-based decision rule described in the methodology. As an example, the detected results were visually validated with the bounding box overlay that is shown in Figure 3, in which occupied and vacant slots are clearly distinguished.

Experimental results show that the proposed parking space detection method has a high level of accuracy in the detection of slot occupancy. The system correctly detects vehicle presence in various lighting conditions and parking layouts and on the robustness against moderate illumination change and shadow effect. The overall detection accuracy obtained for parking space occupancy is 93.97% which proves the good effectiveness of the vision-based approach combined with region-based analysis.

6.2 License Plate Recognition Performance

The license plate recognition module was tested in parking entry and exit points. The system was able to identify the regions of license plate using Haar Cascade classifier and characterize the alpha numeric letters using OCR engine. Results of recognition were visually confirmed by a bounding box overlays and extracted text as shown in the corresponding thesis figure for license plate output.

Through the experimental evaluation, the overall recognition accuracy of the license plate recognition module is 84.93%. Recognition performance depends on factors like image resolution, viewing angle, and lighting conditions; about the operating performance the system is found to have consistent performance under normal parking operation environment. These results show that the proposed approach is a reliable compromise between recognition accuracy and computational efficiency.

6.3 Quantitative Performance Summary

A look at the performance summary for the system is presented in Table 2, which highlights accuracy achieved by each of the modules.

Table 2. Performance evaluation of the proposed system.

Module	accuracy (%)
Parking Space Detection	93.97
License Plate Recognition	84.93

The results show that parking space detection module outperforms license plate recognition module with respect to accuracy, which is also expected as there is more complexity in detecting characters. However, acceptable performance for real-time implementation in smart parking settings is achieved by both components.

6.4 Discussion

The experimental results show the successful combination of parking space recognition and vehicle identification in the proposed system. The accuracy of parking occupancy detection is high and thus directly contributing to improve the use of parking spaces, as well as the time spent searching for a parking location for the driver. Meanwhile, the license plate recognition module is a nice addition to enhance the security and traceability of the systems by the potential of automating the identification of vehicles. By depending on lightweight computer vision methods and localized processing, it escapes

Table 3. Comparative summary of smart parking systems.

Feature	Sensor-based	vision-based	Cloud-centric	proposed system
Real-time occupancy detection	Yes	Yes	Yes	Yes
Vehicle Identification	No	No	Partial	Yes
Cloud dependency	Low	Low	High	Low
Computational Complexity	Low	Medium	High	Low-Medium
Deployment cost	Medium	Medium	High	Low

the overhead constructing for cloud-depending or deep learning-based techniques, being appropriate for cost-efficient and simpler deployment.

7 Comparative Analysis with Related Work

A comparative analysis of the proposed smart car parking management system to the existing studies brings forward some important distinctions in the context of the system design, functionality and practical deployment. Early smart parking solutions largely depended on sensor-based architectures as the solution, for example extended ultrasonic and infra-red sensors, to ascertain parking occupancy. While these systems had shown some basic effectiveness, they were often undermined by issues of scalability, regular maintenance needs, as well as having lower reliability under environmental variation. On the contrary, the proposed system combines vision-based analysis and region-based occupancy detection, which allows for rich understanding of the context with limited dependence on the hardware. This hybrid approach enhances the robustness of detection processes without having to undertake the large infrastructure cost exerted so commonly by high density sensor deployments. A comprehensive comparison of key features across different system approaches is presented in Table 3.

Recent IoT-based smart parking frameworks have focused on real-time data transmission and centralized data monitoring; but few of these systems are strong cloud-based, and therefore their latency is large, the costs of operation are higher, and reliability issues in bandwidth-limited scenarios can arise. Compared to such approaches, the proposed one emphasizes on the localized processing which is enabled for taking real-time decisions without the continuous connectivity to the cloud. In this design choice, the system is more responsive and the design is more appropriate to be used in resource constrained or semi-urban environments. Furthermore, unlike reservation-based parking accountability systems that require pre-recording and centralized coordination, the framework proposed here is dynamic responding to real-time system occupancy without constraining users with additional requirements.

Vision-based parking detection techniques reported in the literature tend to concentrate solely on parking occupancy and overlook the identification of vehicles. Although these methods provide acceptable detection accuracy, the lack of integrated security and traceability mean that having these ones is limited in their practical application. The proposed system overcomes this lack by incorporating license plate recognition in the same operational pipeline, which allows use for both parking management and vehicle identification. This unified design has the advantage over current works by treating occupancy detection and license plate recognition as independent modules or separate systems.

In terms of the performance, the success rate for parking space detection (93.97%) in the proposed system compares well with the results from the various smart parking system-based pilot tests reported in the literature with more complex models (deep learning-based models) that deliver higher accuracy. Although the accuracy in license plate recognition (84.93%) is affected by various factors such as illumination, and viewing angle, the accuracy remains competitive with similar approaches based on OCR and reported in the literature. More importantly, the system achieves this performance using lightweight algorithms and low-cost hardware body which re-enforces its suitability for real-world deployment.

Overall, the comparative analysis shows that the proposed system is an effective balance in terms of accuracy, computation efficiency, and deploy ability. By bringing the challenges of parking two-state detection and vehicle identification in one localized framework, the system addresses some of the limitations of current sensor-only, vision-only and cloud-based approaches. These characteristics make the proposed approach a realistic alternative who aim at success, for the sake of intelligent parking management in emerging smart city environments.

8 Conclusion and Future Work

This paper introduced an intelligent smart car parking management system which combines vision-based technique to detect parking space with automated license plate recognition to solve the main issues of today's parking infrastructure. By reliving lightweight computer vision techniques, region-based analysis and localized processing, the proposed provides reliable real-time functionality while being cost-effective and real-world deployable. Experimental evaluation shows that parking space detection module achieves a high accuracy of 93.97% and license plate recognition module achieves an accuracy of 84.93%, which proves that the proposed method has a good effect under the practical operating conditions. The combination of occupancy detection and vehicle identification in a unified scheme enables both improved parking efficiency and improved operational security, and is distinctively different from what are currently available as sensor-only or vision-only solutions.

Despite these promising results, there are a number of opportunities for further improvement. Future work might examine the combination of deep learning detection models to make them more robust to the extreme lighting variations, heavy occlusion and complexity of background. Adaptive thresholding methods and dynamic region-of-interest updating could be useful to increase the accuracy of parking occupancy detection for various parking layouts. On top of that, the introduction of cloud-assisted analytics and mobile application support would allow for large-scale deployment with analysis of historical data and real-time interaction with users. Extending the system to enable high-dimensional fusion of multiple cameras and automate payment or reservation processes may be further expanded to a wide range of uses in smart cities. These extensions would make the proposed system a robust and intelligent solution in the future of urban parking management that can be scaled.

Among the proposed future directions, improving robustness under extreme illumination variations and introducing adaptive thresholding mechanisms are considered immediate priorities. Subsequent efforts may focus on cloud-assisted analytics, mobile application integration, and large-scale deployment for intelligent urban mobility systems.

Data Availability Statement

Data will be made available on request.

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Conflicts of Interest

The authors declare no conflicts of interest.

AI Use Statement

The authors declare that no generative AI was used in the preparation of this manuscript.

Ethical Approval and Consent to Participate

Not applicable.

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