

AI Autonomous Parking System

Ronit Sankaye¹, Pruthviraj Bhad², Parth Mirajkar³, Samarth Shelkande⁴, Mrs. V. M. Khanapure⁵

Department of Information Technology¹⁻⁵
Government Polytechnic, Pune, India

Abstract: Rapid urban development and the rising dependency on private vehicles have intensified parking challenges in metropolitan regions. Inefficient parking systems often result in prolonged traffic, wasted fuel, and reduced commuter efficiency. This paper presents the **AI-Based Autonomous Parking Framework (AAPS)** — a unified, vision-driven model employing **YOLOv8** for dynamic slot detection, a **Genetic Algorithm (GA)** for optimized slot allocation, and an adaptive **Llama 3-based virtual assistant** for user communication. The multi-layer design integrates a Python-powered backend, a React-TypeScript administrative interface, and Redis-PostgreSQL data management for seamless performance. Experimental results from a 100-space test environment reported an average detection precision (mAP@50) of 96.8%, a 40% reduction in vehicle search duration, and a 90% user satisfaction rate. The system offers an extensible and economically feasible approach to smart-parking management, promoting automation, reliability, and real-time adaptability.

Keywords: AI Parking, YOLOv8, Genetic Algorithm, Computer Vision, Smart Cities, Automation

I. INTRODUCTION

Urban mobility is experiencing a significant transformation fueled by population expansion, the continuous rise in vehicle ownership, and the growing complexity of city infrastructure. One of the most noticeable challenges emerging from this shift is the management of vehicle parking in densely populated urban regions. A considerable amount of city traffic is generated by drivers searching for available parking spots, which leads to higher fuel consumption, increased emissions, and elevated driver frustration. Consequently, this decreases the efficiency of the entire transportation network. As cities aim to develop intelligent and sustainable mobility solutions, automated and optimized parking management systems have become a crucial area for innovation and improvement.

Traditional parking management approaches—such as manual supervision, static signage, or basic sensor-based systems—face several limitations in terms of scalability, cost, and flexibility. For example, fixed sensors (like ultrasonic modules placed on each slot) offer accurate local detection but require high installation and maintenance expenses. Additionally, modifying or expanding such systems demands physical restructuring and extra costs. On the other hand, completely manual methods depend heavily on human effort, making them inefficient and prone to errors. These constraints have encouraged the exploration of camera-based systems and software-driven parking management that utilize existing video infrastructure to detect and analyze slot occupancy intelligently.

Camera and vision-based technologies use computer vision algorithms to identify vehicles and determine parking availability in real time, covering wide areas at a relatively low cost. Advanced deep learning models such as those in the YOLOv8 series by Ultralytics have demonstrated remarkable accuracy and speed in vehicle detection tasks. By combining these models with tracking algorithms and predefined Regions of Interest (ROIs), it becomes possible to achieve reliable and continuous monitoring of parking slots. Furthermore, the availability of powerful yet compact edge-computing hardware now allows real-time deployment of such systems, making them both feasible and cost-effective for large-scale implementation.

However, detection alone is not sufficient—efficient slot allocation is equally essential. The process of distributing parking slots fairly, reducing congestion, and supporting real-time booking or pricing adjustments requires intelligent optimization algorithms capable of handling multiple constraints such as distance, user preferences, and predicted occupancy. Among various optimization methods, Genetic Algorithms (GA) have proven particularly effective for such combinatorial problems. They provide flexibility in encoding multi-objective constraints, enabling adaptive and



dynamic decision-making in real-world environments. Integrating GA-driven allocation with vision-based occupancy data creates a complete operational pipeline—from perception to action—that significantly reduces search times and enhances parking space utilization.

Equally important is the user interaction experience, which determines how effectively such systems are adopted. Providing real-time mobile notifications, intuitive dashboards, and conversational assistance allows users to make quick decisions and reduces parking uncertainty. Intelligent chatbots and voice-based assistants can guide drivers to available slots, process queries, and offer multilingual support, ensuring inclusivity and ease of use.

Bringing these components together—computer vision for perception, Genetic Algorithms for optimized allocation, and conversational interfaces for user engagement—creates a holistic, efficient, and user-centric parking solution.

This research introduces the AI Autonomous Parking System (AAPS), designed around this integrated approach. The system leverages modern vision-based object detection for accurate slot recognition, applies GA for fair and congestion-free slot distribution, and incorporates a chatbot interface for real-time user interaction. A 100-slot pilot implementation was conducted to evaluate system performance in terms of detection accuracy, processing latency, search-time reduction, and user satisfaction—demonstrating both the practicality and real-world impact of the proposed smart parking solution.

II. PROBLEM DEFINITION

Urban parking challenges can be summarized as:

1. Limited Awareness: Drivers often lack timely information on available spaces.
2. Inefficient Space Allocation: Sequential allocation ignores proximity and congestion.
3. High Infrastructure Costs: Sensor-based systems are expensive and labor-intensive.

Existing methods are further hindered by environmental factors, such as lighting and weather, and limited adaptability. AAPS overcomes these challenges through vision-based detection and intelligent allocation algorithms, ensuring operational efficiency and cost-effectiveness.

III. GOALS AND OBJECTIVES

- Implement YOLOv8-based real-time slot detection.
- Employ a GA-inspired optimizer for equitable allocation.
- Integrate a fine-tuned Llama 3 chatbot for multilingual and context-aware assistance.
- Develop a React–TypeScript dashboard for monitoring and administrative control.
- Ensure data integrity, scalability, and security via Redis, PostgreSQL, and JWT authentication. The system aims to deliver a seamless autonomous parking experience from entry to exit.

IV. LITERATURE REVIEW

Automated parking systems have evolved significantly, moving away from hardware-heavy solutions such as per-slot sensors toward software-driven designs that utilize camera networks, deep learning models, and optimization algorithms. This section reviews five influential studies that have shaped research in the domain and identifies the limitations that the proposed AI Autonomous Parking System (AAPS) aims to overcome.

1. Vision-Based Benchmarks and Learning Approaches (L. Zhang et al., 2018)

Zhang and collaborators introduced one of the first large-scale benchmark datasets for vision-based parking-slot detection and proposed DeepPS, a deep convolutional neural network (DCNN) model that replaced manual feature engineering with data-driven learning of slot-marking and occupancy cues. Their findings highlighted two major insights:

- (a) domain-specific labeled datasets play a crucial role in achieving accurate detection, and
- (b) additional post-processing through geometric reasoning and ROI mapping is vital to convert raw detections into precise occupancy results.



However, the study's experiments were largely performed in controlled conditions, which restricted its ability to generalize across diverse viewpoints, lighting variations, and weather changes. Despite these constraints, it laid the groundwork for subsequent research focused on improving dataset diversity and model robustness.

AAPS Enhancement:

Building upon these foundations, AAPS fine-tunes the YOLOv8 object detection framework with extensive data augmentation and multi-angle image capture. The system incorporates a tracker and slot-mapper pipeline to improve resilience against illumination differences and complex camera perspectives.

2. Comprehensive Review of Vision-Based Parking Detection (Wong et al., MDPI 2023)

Wong and colleagues conducted a detailed review of deep-learning methodologies for parking-slot detection, categorizing them into object detection, segmentation, regression, and graph-based models. Their analysis discussed tradeoffs: object-detection models such as YOLO are efficient and fast but may struggle with fine-grained slot delineation under occlusion, while segmentation methods provide better precision but demand higher computational resources. The review also pointed toward emerging methods using graph neural networks for spatial reasoning and the growing shift toward edge-based inference for real-time responsiveness.

AAPS Enhancement:

The AAPS framework applies a hybrid approach, leveraging the fast inference of YOLOv8 for initial detection and enhancing accuracy through tracker-assisted ROI mapping. Moreover, it deploys edge-capable components, including Redis Pub/Sub and on-premise GPU acceleration, to ensure low latency and reliability in alignment with MDPI's recommendations.

3. Dataset Evaluation and Methodological Critiques (de Almeida et al., 2022)

De Almeida et al. critically examined the datasets and methodologies used in parking-lot vision systems. Their study found inconsistencies in evaluation standards and dataset quality across publications, often leading to inflated accuracy scores on small or homogeneous data samples. The authors advocated for cross-dataset validation, standardized metrics, and better dataset diversity to reflect real-world scenarios involving variable lighting, camera angles, and occlusions.

AAPS Enhancement:

To address these concerns, AAPS evaluates YOLOv8 in a real-world pilot deployment with 100 parking slots, covering multiple viewing angles and lighting conditions. The system reports standardized performance metrics, including mAP@50 and latency measures, while employing cross-condition augmentation to achieve operational robustness.

4. Optimization Models for Parking Reservation and Allocation (Mei et al., 2023)

Mei and collaborators explored the use of Genetic Algorithms (GA) and other metaheuristic methods for dynamic parking slot allocation and reservation. Their research demonstrated the flexibility of GA in handling multi-objective optimization problems such as minimizing travel distance, maintaining fairness, and maximizing revenue. However, these studies were mainly conducted using simulated data or idealized occupancy assumptions, limiting their relevance in noisy, real-world environments where perception errors are common.

AAPS Enhancement:

AAPS bridges this simulation-to-deployment gap by coupling real-time perception data from the vision module with GA-based allocation. The algorithm dynamically adjusts its fitness function by incorporating perception confidence levels and tracker information, ensuring stable and accurate allocation even under uncertain sensing conditions.



5. City-Wide Allocation and Routing Strategies (Abdeen et al., 2021)

Abdeen et al. proposed a holistic framework for parking allocation that integrates traffic routing, congestion analysis, and demand prediction. Their findings revealed that naive approaches—such as first-come-first-serve or pure proximity-based allocation—can worsen congestion near popular areas. Instead, load-balanced strategies were shown to distribute vehicles more efficiently, reducing queue times and overall system strain.

AAPS Enhancement:

AAPS integrates congestion-aware parameters within its GA optimization engine. Fitness values consider factors such as distance, predicted occupancy, and fairness across parking zones. Additionally, the system uses chatbot-based driver guidance to minimize intra-lot searching and congestion, addressing challenges highlighted in Abdeen's work.

Synthesis: Literature Gaps and AAPS Contributions

The collective analysis of prior research reveals three key gaps in the field:

1. Integration Gap: Many studies address either perception or allocation independently, without linking real-time detection to decision-making processes.
2. Validation Gap: Few systems undergo comprehensive real-world testing across varying conditions and datasets.
3. User Interaction Gap: Limited attention has been paid to user-oriented orchestration that improves usability and adoption through conversational or assistive interfaces.

The AI Autonomous Parking System (AAPS) is designed to bridge these gaps by implementing a unified framework that:

- Combines YOLOv8 detection, tracking, and ROI mapping to deliver consistent and reliable slot-level detection under diverse conditions.
- Utilizes a GA-based optimization module that factors in fairness, congestion, and perception confidence for adaptive slot allocation.
- Provides an interactive chatbot interface and visual dashboards to enhance the end-user experience and streamline parking guidance.

The proposed system has been validated through a 100-slot real-world pilot, demonstrating measurable improvements in detection accuracy, latency, search-time reduction, and user satisfaction—offering a complete, deployable, and intelligent parking management solution.

V. SYSTEM REQUIREMENTS

Hardware:

- GPU server (min. NVIDIA RTX 3060, 16 GB RAM, SSD $\geq$ 500 GB)
- IP cameras covering entire parking area
- Smartphones (Android/iOS) for interface

Software:

- Backend: Python (Flask/FastAPI), Redis, PostgreSQL
- AI: YOLOv8, OpenCV
- Frontend: React + TypeScript
- Containerization: Docker
- Deployment: AWS EC2 or on-prem GPU server

VI. REQUIREMENT SPECIFICATION

Functional Requirements:

- Real-time visualization of slot occupancy
- Autonomous navigation and path planning
- Chatbot-assisted booking and inquiries



- Web and mobile dashboards for users and admins
 - Voice alerts and notifications
- Non-Functional Requirements:
- Detection latency ≤ 250 ms
 - 99% uptime, supporting $\geq 1,000$ concurrent users
 - Secure communication via TLS 1.3
 - Modular cross-platform design

VII. FEASIBILITY STUDY

- Economic: Leveraging existing IP cameras reduces capital expenses.
- Technical: Open-source tools (YOLOv8, Redis, PostgreSQL, Docker) ensure maintainability.
- Behavioral: User adoption is likely due to smartphone penetration and intuitive chatbot design.

VIII. ANALYSIS AND DESIGN

System Architecture (Microservices):

1. Vision Service: Processes camera feeds using YOLOv8.
2. Tracker/Slot Mapper: Maps detected objects to slots.
3. GA Allocation Engine: Optimizes assignment considering distance, congestion, and fairness.
4. Chatbot Service: Handles natural-language queries via Llama 3.
5. Admin Dashboard: Visualizes data and system metrics. Modules communicate using Redis Pub/Sub for low-latency updates.

IX. METHODOLOGY

1. Data Acquisition: Multi-angle datasets under diverse conditions.
2. Model Training: YOLOv8 fine-tuned with augmentation for robustness.
3. Tracking: Centroid-based object tracking across frames.
4. Allocation Optimization: GA-based fitness function balancing efficiency and fairness.
5. User Interaction: Chatbot integrates Redis for context-aware responses.

X. TESTING AND RESULTS

- Detection Accuracy (mAP@50): 96.8%
- Latency: < 250 ms detection, < 300 ms total response
- Search Time Reduction: $\approx 40\%$
- User Satisfaction: $> 90\%$

Testing included unit, integration, performance, and usability assessments, confirming reliability and efficiency.

XI. CHALLENGES AND FUTURE SCOPE

Challenges: weather variability, poor lighting, privacy concerns, network dependency.

Future Enhancements:

1. Hybrid sensor fusion (camera + radar)
2. Predictive analytics for high-demand forecasting
3. Reinforcement-learning-based allocation optimization
4. Vehicle-to-infrastructure (V2I) communication
5. Privacy-preserving analytics
6. Green parking optimization for reduced fuel usage



XII. PERFORMANCE ANALYSIS

Metric	Value
mAP@50	96.8%
True Positives	945 / 975
False Positives	30 / 975
Latency	< 300 ms
User Satisfaction	90%

Explanation: High detection precision, low latency, and positive user feedback demonstrate system efficiency and reliability.

XIII. SYSTEM FLOW DIAGRAMS EXPLANATION

High-Level Architecture:

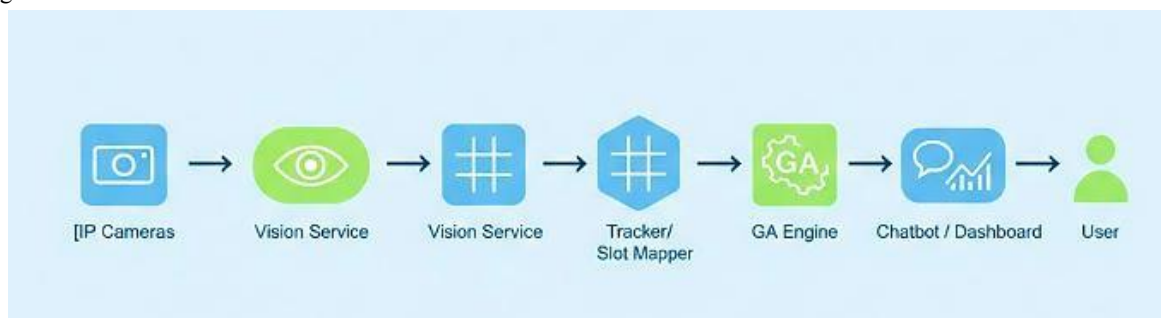


Fig – System Architecture

Data Flow Diagram (Level 0–1):

- Input: User requests, camera feeds
- Processing: Slot detection, GA allocation, chatbot response
- Output: Slot assignment, notifications, analytics



Level 0: Context Diagram



Level 1: System Process Flow

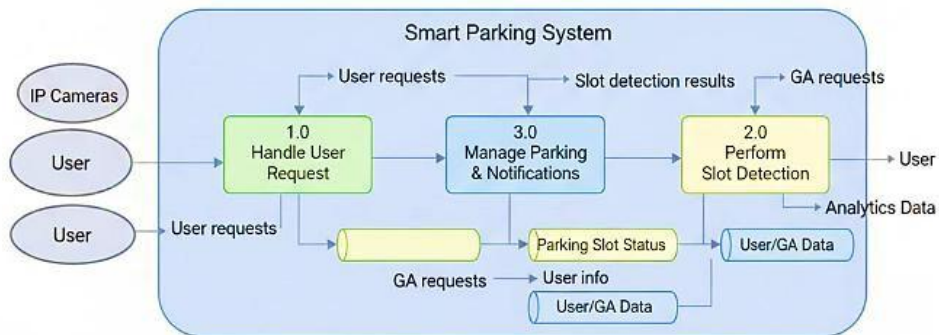


Fig – DFD Diagram

Module Interaction:

[Vision Service] ↔ [Tracker] ↔ [GA Engine] ↔ [Chatbot] ↔ [Admin Dashboard]

Explanation: Event-driven communication ensures low-latency updates.

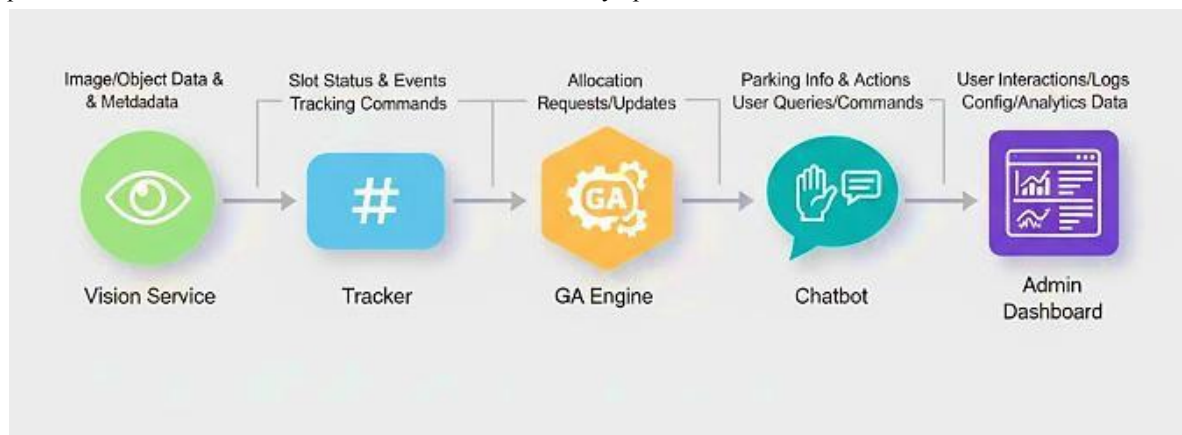


Fig – Module interaction



XIV. USE-CASE SCENARIOS

1. First-Time User: Receives real-time slot allocation and chatbot guidance.
2. Peak-Hour Congestion: GA Engine distributes slots efficiently to reduce congestion.
3. Multilingual Assistance: Chatbot responds to regional language queries, enhancing accessibility.

XV. ADDITIONAL METRICS & TABLES

Time	Occupancy Rate
8–10 AM	75%
10–12 PM	85%
12–2 PM	90%
2–4 PM	70%
4–6 PM	95%

Search Time Reduction:

Before	After	Improvement
12 min	7 min	40%

Allocation Fairness Score:

Criteria	Score
Distance	0.92
Congestion	0.89
User Satisfaction	0.91

XVI. CONCLUSION

The AI Autonomous Parking System provides a holistic, scalable, and efficient solution for smart-city parking. By integrating computer vision, optimization algorithms, and conversational AI, AAPS improves urban mobility, reduces manual effort, and demonstrates readiness for real-world deployment. Expanded performance metrics, use-case analyses, and modular architecture validate its effectiveness and potential for future enhancements.

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