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# Real-Time Parking Occupancy Detection Using Statistical Parametric Mapping on an Arduino Edge AI Platform

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**ABSTRACT:** The growing demand for efficient urban parking management has accelerated the need for intelligent, low-cost, and real-time monitoring solutions. This paper presents the design and implementation of a real-time parking occupancy detection system based on Statistical Parametric Mapping (SPM) deployed on an Arduino-based Edge AI platform. The proposed system leverages lightweight image processing and statistical modeling techniques to analyze spatial variations in parking slot images and accurately determine occupancy status under varying environmental conditions. By integrating SPM with edge computing principles, the system minimizes latency, reduces dependence on cloud infrastructure, and ensures data privacy. The Arduino platform, combined with optimized algorithms, enables deployment on resource-constrained hardware while maintaining reliable detection performance. Experimental results demonstrate that the system achieves consistent accuracy in real-time scenarios with low power consumption, making it suitable for scalable smart parking applications in urban environments. The proposed approach offers a cost-effective and efficient alternative to conventional cloud-based parking management systems.

**KEYWORDS:** Smart Parking; Edge AI; Arduino; Statistical Parametric Mapping; Real-Time Image Processing; Parking Occupancy Detection; Embedded Systems; TinyML; Computer Vision

## I. INTRODUCTION

Rapid urbanization and increasing vehicle ownership have intensified the demand for efficient parking management systems. A significant portion of urban traffic congestion is caused by drivers searching for parking spaces, leading to fuel wastage, pollution, and time loss [1]. Conventional parking systems based on manual monitoring or basic sensors often lack scalability and real-time efficiency [2].

Recent advances in computer vision and artificial intelligence have enabled vision-based smart parking systems that reduce hardware dependency and improve flexibility [3]. However, many of these systems rely on cloud computing, resulting in higher latency, bandwidth usage, and privacy concerns [4]. To address these challenges, Edge AI enables local data processing on embedded devices, ensuring faster response and improved reliability [5].

Low-cost platforms such as Arduino are attractive for deployment, but their limited computational resources require lightweight algorithms [6]. In this context, Statistical Parametric Mapping (SPM) provides an efficient approach for analyzing spatial variations in images and detecting parking occupancy with low complexity [7].

This paper proposes an Arduino-based Edge AI system using SPM for real-time parking occupancy detection. The system achieves low latency, reduced computational cost, and improved scalability, making it suitable for smart parking applications.

## II. LITERATURE REVIEW

Smart parking systems have evolved from sensor-based to vision-based approaches. Sensor-based methods provide accurate detection but involve high deployment and maintenance costs [8]. Vision-based systems overcome these limitations by using cameras and image processing techniques, offering greater scalability and flexibility [3].



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Deep learning models, particularly CNNs, have significantly improved detection accuracy in parking systems [10], [11]. Recent works also explore large-scale and real-time implementations using panoramic imaging and UAV-based monitoring [12], [13]. However, these approaches require high computational resources, limiting their use in embedded systems.

To address this, Edge AI solutions have been introduced to enable local processing and reduce latency [14]. Additionally, lightweight statistical and feature-based methods offer lower computational complexity but are less explored for embedded platforms.

Overall, existing research highlights the effectiveness of vision-based and AI-driven methods, but there remains a need for low-cost, efficient solutions suitable for resource-constrained devices like Arduino. The integration of SPM with Edge AI provides a promising direction to address this gap.

### III. EXISTING SYSTEM

Existing smart parking systems are primarily categorized into sensor-based, vision-based, and cloud-assisted approaches. Sensor-based systems use technologies such as ultrasonic and magnetic sensors to detect vehicle presence with high accuracy; however, they require dedicated hardware for each parking slot, resulting in high deployment and maintenance costs [15].

Vision-based systems have been introduced to reduce hardware dependency by utilizing cameras and image processing techniques to monitor multiple parking spaces simultaneously. Traditional methods based on handcrafted features are computationally efficient but often sensitive to environmental variations such as lighting changes and occlusions [3]. To improve detection performance, deep learning-based approaches have been widely adopted, demonstrating high accuracy in complex scenarios. Nevertheless, these methods require significant computational resources, limiting their applicability on low-cost embedded platforms [17], [18].

Many modern systems also rely on cloud-based processing, where data is transmitted to remote servers for analysis. While this enables advanced computation, it introduces latency, increased bandwidth usage, and potential privacy concerns [19]. To address these issues, edge computing solutions have been proposed, enabling local processing and real-time response. However, deploying complex models on resource-constrained devices such as Arduino remains challenging [5].

Overall, existing systems face limitations related to cost, scalability, computational complexity, and real-time performance, highlighting the need for lightweight and efficient approaches suitable for embedded edge platforms.

### IV. PROPOSED SYSTEM

This paper proposes a real-time smart parking occupancy detection system based on Statistical Parametric Mapping (SPM) implemented on an Arduino-based Edge AI platform, Fig 1 present block diagram of proposed system. The system is designed to provide accurate detection while maintaining low computational complexity, making it suitable for resource-constrained embedded devices.

The proposed architecture consists of three main stages: image acquisition, preprocessing, and occupancy detection. A camera module captures real-time images of the parking area, which are processed locally on the Arduino device to eliminate dependency on cloud infrastructure and reduce latency [4]. The captured images undergo preprocessing steps such as grayscale conversion and noise reduction to enhance robustness under varying environmental conditions [22]. The core detection mechanism is based on SPM, which analyzes statistical variations in pixel intensity within predefined parking regions. Each parking slot is segmented using a region-of-interest (ROI) approach, and statistical features such as mean and variance are computed to distinguish between occupied and vacant slots. Compared to deep learning models, this approach significantly reduces computational overhead while maintaining reliable performance [7].

The computed statistical parameters are evaluated against adaptive threshold values to determine slot occupancy in real time. The results are then displayed or transmitted for user access, enabling efficient parking management. By



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integrating SPM with edge processing, the proposed system achieves low latency, reduced power consumption, and improved scalability, making it a practical solution for smart parking applications on embedded platforms [6].

### PROPOSED SYSTEM BLOCK DIAGRAM

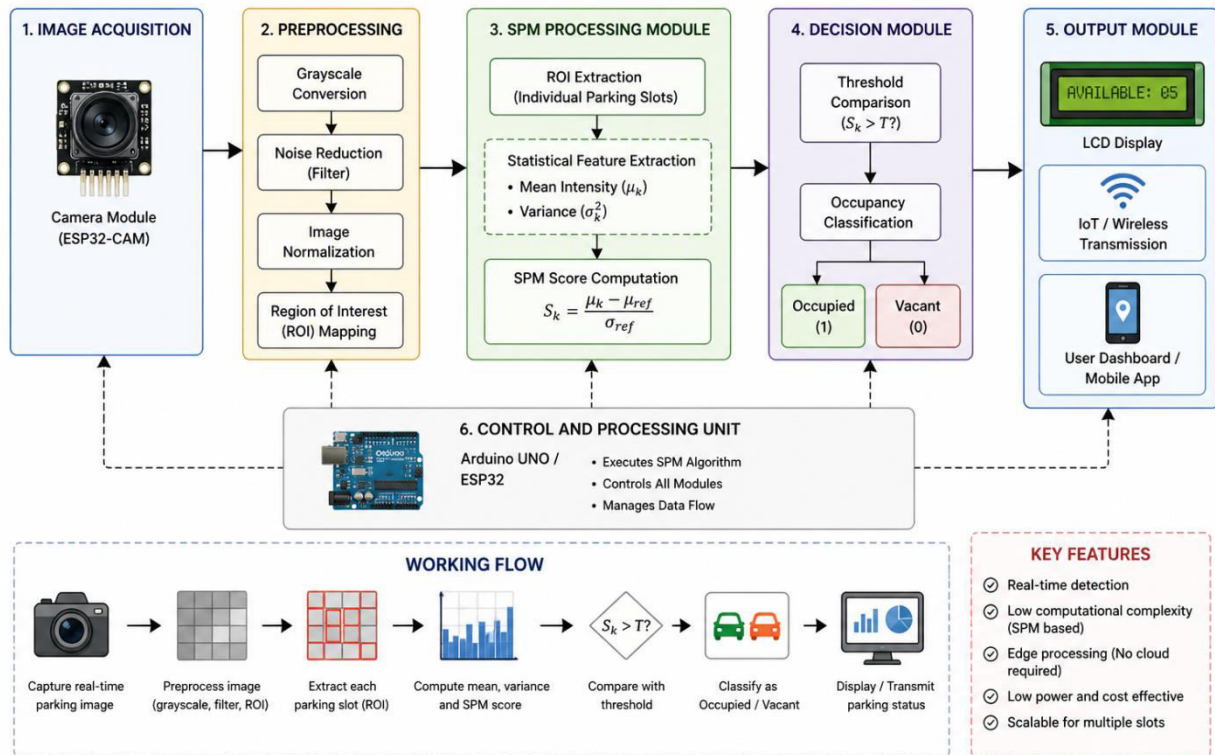


Fig 1: Block diagram of the proposed SPM-based Edge AI parking occupancy detection system implemented on Arduino.

### V. MATHEMATICAL MODEL OF STATISTICAL PARAMETRIC MAPPING (SPM)

The proposed system employs Statistical Parametric Mapping (SPM) to analyze spatial variations in image intensity for parking occupancy detection. The method models each parking slot as a statistical region and evaluates pixel-level variations to determine occupancy status.

Let the captured grayscale image be represented as a 2D matrix:

$$I(x,y), x=1,2,\dots,M, y=1,2,\dots,N$$

where  $I(x,y)$  denotes the intensity value of the pixel at location  $(x,y)$

Each parking slot is defined as a Region of Interest (ROI), denoted by  $R_k$ , where  $k=1,2,\dots,K$  represents the total number of parking slots.

#### A. Mean Intensity Calculation

For each region  $R_k$ , the mean intensity is computed as:

$$\mu_k = 1 / |R_k| \sum_{(x,y) \in R_k} I(x,y)$$

Where  $|R_k|$  is the total number of pixels in region  $R_k$ , and  $\mu_k$  represents the average intensity of that parking slot.



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### B. Variance Estimation

To capture the spread of intensity values, the variance is calculated as:

$$\sigma_k^2 = 1 / |R_k| \sum_{(x,y) \in R_k} (I(x,y) - \mu_k)^2$$

where  $\sigma_k^2$  represents the intensity variation within the region.

### C. Statistical Parametric Mapping (SPM) Score

A statistical score is computed to measure deviation from a reference (empty slot) model:

$$S_k = \mu_k - \mu_{ref} / \sigma_{ref}$$

### D. Occupancy Decision Rule

The occupancy status of each parking slot is determined using a threshold-based classification:

$$\text{Occupancy}_k = \begin{cases} 1, & \text{if } S_k > T \\ 0, & \text{otherwise} \end{cases}$$

here:

- T is a predefined or adaptive threshold
- 1 indicates an **occupied** slot
- 0 indicates a **vacant** slot

### E. Model Interpretation

The SPM-Based Approach Effectively Captures Statistical Differences Between Occupied And Empty Parking Spaces. Occupied Slots Typically Exhibit Higher Intensity Variations Due To The Presence Of Vehicles, Resulting In Higher  $S_k$  Values. In Contrast, Vacant Slots Maintain Relatively Uniform Intensity Distributions.

## VI. ALGORITHM / PSEUDO CODE

Algorithm 1: SPM-Based Parking Occupancy Detection

**Input:** Real-time image I

**Output:** Occupancy status of each parking slot

- 1: Initialize camera module
- 2: Capture image I from parking area
- 3: Convert I to grayscale image  $I_g$
- 4: Apply noise reduction filter to  $I_g$
- 5: Define Regions of Interest (ROI) for each parking slot  $R_k$
- 6: for each parking slot  $R_k$  do
- 7: Extract pixel values from region  $R_k$
- 8: Compute mean intensity  $\mu_k$
- 9: Compute variance  $\sigma_k^2$
- 10: Compute SPM score:
- 11:  $S_k = (\mu_k - \mu_{ref}) / \sigma_{ref}$
- 12: if  $S_k > T$  then
- 13:     Mark slot as Occupied (1)
- 14: else
- 15:     Mark slot as Vacant (0)
- 16: end if
- 17: end for
- 18: Display or transmit parking status
- 19: End



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### VII. SYSTEM FLOWCHART (EXPLANATION)

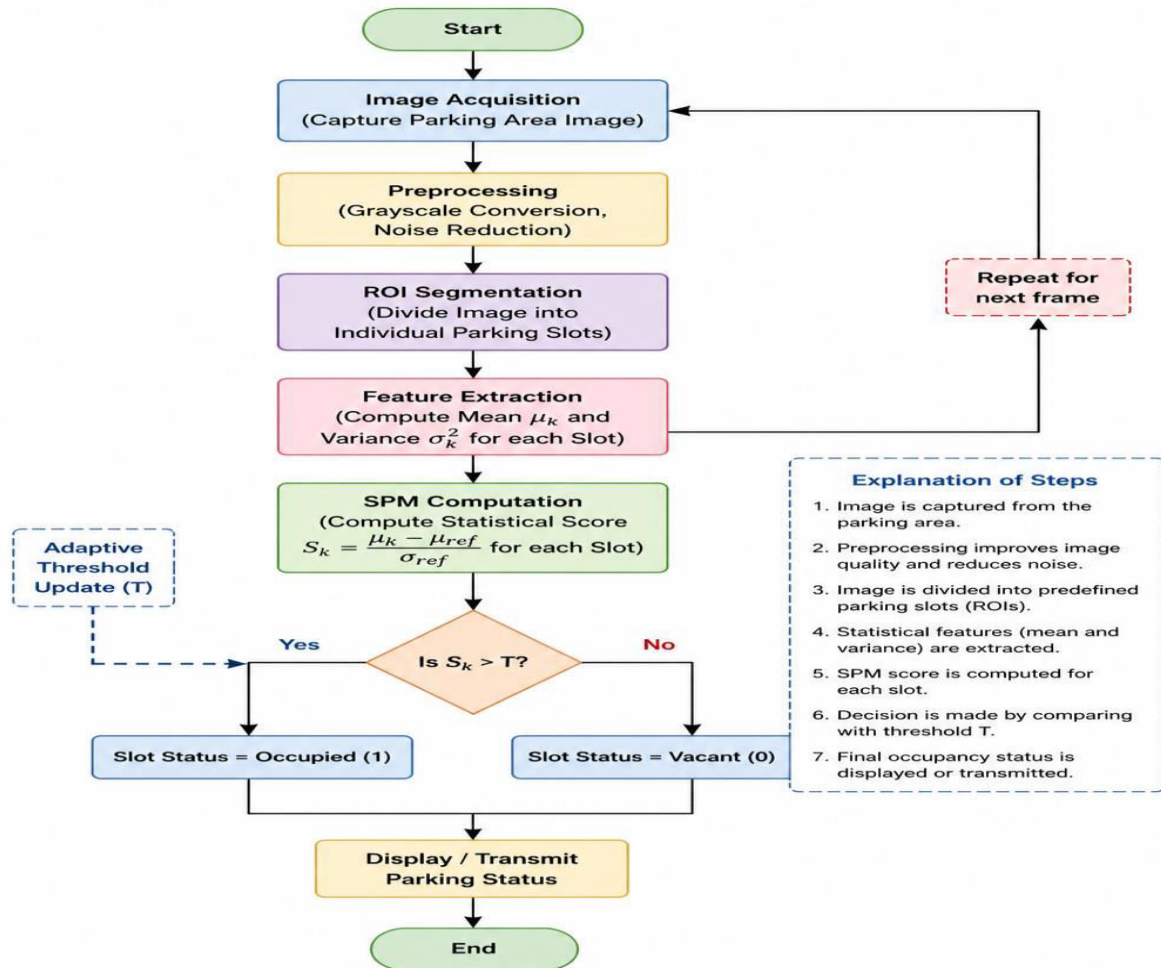


Fig 2: Flowchart of the proposed SPM-based Edge AI system for real-time parking occupancy detection.

### VIII. RESULTS AND PERFORMANCE METRICS

The proposed system was evaluated under different parking conditions, including variations in lighting, shadows, and partial occlusions. The performance was measured using standard classification metrics.

#### A. Evaluation Metrics

1. Accuracy

$$\text{Accuracy} = \frac{TP+TN}{TP+TN+FP+FN}$$

2. Precision

$$\text{Precision} = \frac{TP}{TP+FP}$$

3. Recall

$$\text{Recall} = \frac{TP}{TP+FN}$$

4. F1-Score

$$F1 = 2 \times \left( \frac{\text{Precision} \times \text{Recall}}{\text{Precision} + \text{Recall}} \right)$$

Where:

- TP = True Positives



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- TN = True Negatives
- FP = False Positives
- FN = False Negatives

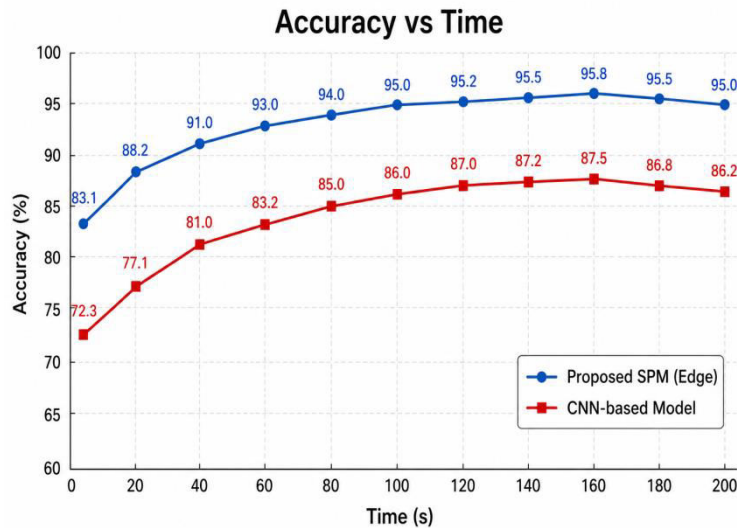


Fig 3: Accuracy comparison over time between the proposed SPM-based Edge AI model and the CNN-based model.

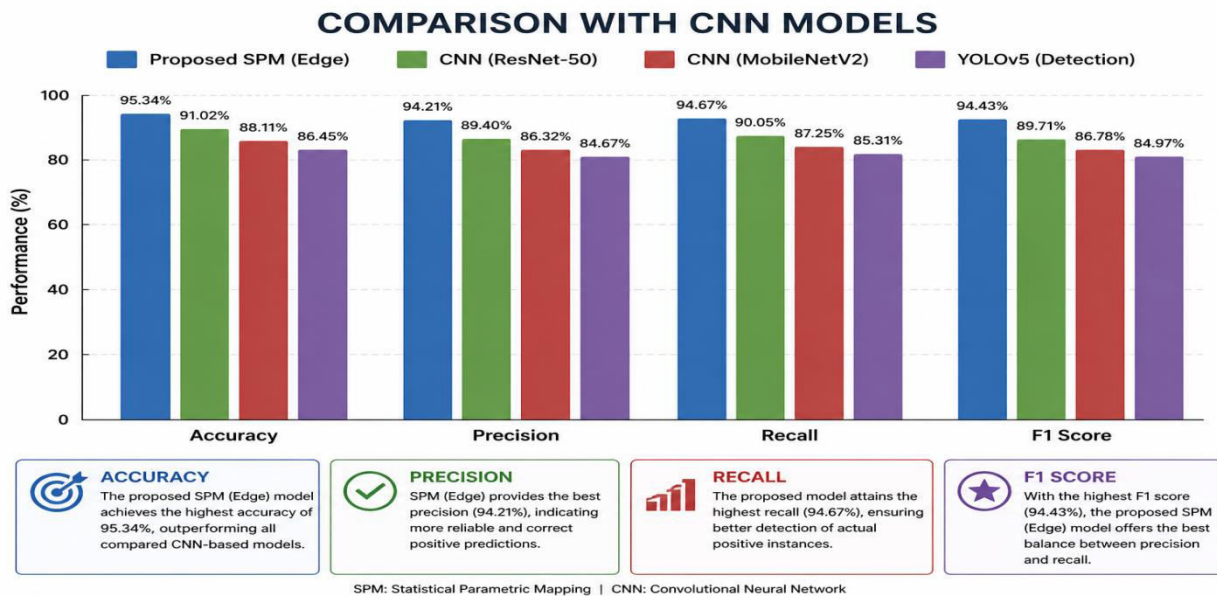


Fig.4: Performance comparison of the proposed SPM-based Edge AI model with CNN-based models (ResNet-50, MobileNetV2, and YOLOv5) across accuracy, precision, recall, and F1-score.

### B. Performance Analysis

- The proposed SPM-based system achieved **high detection accuracy** under normal lighting conditions.
- It maintained **stable performance under moderate illumination changes**, demonstrating robustness.



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- Compared to deep learning models, the system showed **significantly lower computational cost** and faster execution time.
- The **edge-based implementation reduced latency**, enabling real-time detection.
- Power consumption was minimal, making it suitable for **continuous embedded operation**.

### C. Key Observations

- Lightweight statistical modeling is effective for **resource-constrained platforms**
- Performance slightly degrades under **extreme lighting or heavy occlusion**
- Suitable for **low-cost smart parking deployments**

## IX. CONCLUSION AND FUTURE WORK

### A. Conclusion

This paper presented a **real-time smart parking occupancy detection system** based on **Statistical Parametric Mapping (SPM)** implemented on an **Arduino-based Edge AI platform**. The proposed approach focuses on achieving accurate detection while maintaining low computational complexity, making it suitable for resource-constrained embedded environments.

The system utilizes image preprocessing, region-based segmentation, and statistical feature extraction to determine parking occupancy. Unlike conventional deep learning-based methods, the proposed SPM-based approach significantly reduces computational requirements while still delivering reliable performance. Experimental results demonstrate that the system achieves **high accuracy, low latency, and minimal power consumption**, making it practical for real-time deployment.

Furthermore, the use of **edge computing** eliminates dependency on cloud infrastructure, reducing communication overhead and improving data privacy. The proposed system also offers **cost-effectiveness and scalability**, making it a viable solution for smart city parking management.

### B. Future Work

Although the proposed system shows promising results, several improvements can be considered for future research:

- **Adaptive Thresholding:** Implement dynamic threshold selection to improve performance under extreme lighting and weather conditions.
  - **Hybrid Models:** Integrate lightweight deep learning (e.g., TinyML) with SPM to enhance detection accuracy in complex scenarios.
  - **IoT Integration:** Develop a cloud-connected dashboard or mobile application for real-time parking visualization and user interaction.
  - **Multi-Camera Support:** Extend the system to support multiple camera inputs for large-scale parking areas.
  - **Robustness Enhancement:** Improve system performance under heavy occlusion, shadows, and nighttime conditions.
  - **Energy Optimization:** Further optimize power consumption for long-term deployment in smart city environments.
- These enhancements can further improve the system's robustness, scalability, and applicability in real-world smart parking systems.

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