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A Data-Driven IoT Framework for Real-Time and Predictive Smart Parking Management in Urban Cities

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Abstract

Urbanization and increasing vehicles have led to parking challenges, causing traffic congestion, pollution, and wasted time searching for parking spots. Traditional parking systems are inefficient due to the lack of real-time data. This project presents an IoT-based smart parking system that monitors and manages parking spaces in real time, optimizing space utilization and improving user convenience. The system uses IoT sensors to detect space occupancy and transmit the data to a central server. Users can access this information via a mobile app that displays available parking spots in real time. The system also includes automated entry and exit as well as digital payment options, reducing the need for manual intervention and streamlining the process. In tests, the system improved parking efficiency by 30%, reducing the time spent finding parking spots. Additionally, vehicle idling was minimized, leading to a 20% reduction in carbon emissions in congested areas. This IoT-based smart parking system provides a scalable solution to enhance urban mobility, offering a more sustainable and efficient approach to managing city parking.

Keywords: Internet of things, Smart parking, Real-time monitoring, Urban mobility, Parking management, Sensors, Digital payment.

1 | Introduction

Urbanization has led to a significant increase in vehicle numbers on the road, exacerbating traffic congestion and parking shortages in modern cities [1]. Traditional parking systems often rely on manual management

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and are inefficient in terms of both space utilization and user convenience [2]. With the advent of IoT, smart parking systems have been developed to improve parking availability, reduce traffic congestion, and enhance user experiences by providing real-time data on parking space occupancy [3].

The core principle of IoT-based smart parking systems is the integration of sensors, communication networks, and data processing technologies to monitor and manage parking spaces efficiently [4]. These systems use real-time data collection and processing to help drivers find available parking spaces, reduce unnecessary driving, and optimize the use of available parking infrastructure [3], [5].

1.1 | Variables and Equations

N_total: total number of parking spots in the parking area.

N_available(t): number of available parking spots at time t.

N_occupied(t): number of occupied parking spots at time t.

S_i: status of parking spot i (1 if occupied, zero if vacant)

T_search: time taken by a vehicle to find a parking spot.

T_idle: time spent by vehicles idling while searching for parking.

F_idle: fuel consumption rate during vehicle idling (liters per second).

CO2_idle: carbon emissions during vehicle idling (grams per second).

E_system: energy consumption of the IoT system (sensors, data transmission) over time (Joules).

R_system: system response time for detecting a change in parking spot occupancy (seconds).

U_efficiency: parking utilization efficiency (ratio of occupied spots to total spots).

I. Parking spot availability: the number of available spots at any time t is calculated as:

$$N\_available\ (t) = N\_total\ - N\_occupied\ (t),$$

Where the number of occupied spots is given by:

$$N\_occupied\ (t) = i = 1 \sum N\_total\ \ Si\ (t). \quad (1)$$

II. Parking efficiency: parking utilization efficiency at time t is:

$$U\_efficiency\ (t) = (N\_total / N\_occupied\ (t))\ \times 100. \quad (2)$$

III. Time to find parking (search time): the average time to find a parking spot can be modeled as a function of availability:

$$T\_search\ = f(N\_available\ (t)). \quad (3)$$

IV. Fuel consumption during idling: total fuel consumed during vehicle idling while searching for a parking spot:

$$F\_total\ = F\_idle\ \times T\_idle. \quad (4)$$

V. Carbon emissions during idling: total carbon emissions during vehicle idling while searching for a parking spot:

$$CO2total\ = CO2idle\ \times Tidle. \quad (5)$$

VI. Energy consumption of the IoT system: energy consumed by the IoT system is modeled as:

$$E\_system = P\_sensor \times T\_active. \quad (6)$$

VII. System response time: the system's response time to detect parking spot changes:

$$R\_system = T\_detecion + T\_transmission. \quad (7)$$

2 | Literature Review

2.1 | Introduction to Smart Parking Systems

Smart parking systems utilize modern technologies to improve parking management in urban environments [4]. Traditional parking methods often lead to inefficiencies such as traffic congestion and wasted time, prompting the need for innovative solutions [5]. Internet of Things (IoT) technology is crucial in developing smart parking systems, enabling real-time data collection and communication between devices.

2.2 | Challenges of Traditional Parking Systems

Traditional parking management systems face various challenges, including:

I. Inadequate information: drivers often lack real-time information about available parking spaces, resulting in longer search times [2].

II. Inefficient resource utilization: many parking lots operate below capacity due to inefficient management [8].

III. Environmental impact: increased traffic caused by drivers searching for parking contributes to higher fuel consumption and emissions.

2.3 | Role of IoT in Parking Management

IoT technologies solve these challenges by enabling connectivity and data exchange between the parking infrastructure and users [6]. Key components of IoT-based parking systems include:

I. Sensors: Various sensors (e.g., ultrasonic, infrared) are deployed in parking spaces to detect real-time occupancy status [4].

II. Cloud Computing: Centralized data processing allows for efficient parking data management and analysis.

III. Mobile Applications: User-friendly applications provide drivers with information on available spaces, reducing search time and enhancing user experience [10].

2.4 | Algorithms Used in IoT-Based Smart Parking Systems

Various algorithms are employed in smart parking systems to manage data effectively and enhance functionality:

2.4.1 | Occupancy detection algorithms

These algorithms process sensor data to determine whether a parking space is occupied or vacant. For instance, ultrasonic sensors use signal processing algorithms to analyze distance data and detect occupancy [4], [7].

Initialize OCCUPIED_DISTANCE_THRESHOLD to 10 cm

Initialize NUM_PARKING_SPACES to N // Total number of parking spaces

FUNCTION read_ultrasonic_sensor(space_id):

I. Trigger the ultrasonic sensor

II. Measure the time for the echo to return

III. Calculate distance using formula: Distance = (Time × 34300) / 2

IV. RETURN distance

FUNCTION check_parking_spaces():

I. Initialize occupancy_status as an empty list

II. FOR space_id FROM 0 TO NUM_PARKING_SPACES - 1:

- distance = read_ultrasonic_sensor(space_id)
- IF distance < OCCUPIED_DISTANCE_THRESHOLD THEN

occupancy_status[space_id] = "Occupied"

- ELSE

occupancy_status[space_id] = "Available"

- RETURN occupancy_status

WHILE true:

I. occupancy_status = check_parking_spaces()

II. PRINT occupancy_status

III. WAIT for 5 seconds

2.4.2 | Data processing algorithms

Cloud-based data processing algorithms aggregate and analyze sensor data to provide users with real-time occupancy information. These algorithms may involve machine learning techniques to improve prediction accuracy over time.

I. Initialize the cloud environment and database.

II. FUNCTION ingest_sensor_data():

- Collect data from sensors
- Store data in a cloud database

III. FUNCTION aggregate_data():

- Retrieve historical occupancy data
- Aggregate data by time intervals
- Calculate average occupancy rates
- RETURN aggregated data

IV. FUNCTION feature_engineering(data):

- Extract relevant features
- RETURN engineered dataset

V. FUNCTION train_model(features, labels):

- Split data into training and test sets
- Choose a machine learning algorithm
- Train model

- Save the trained model

VI. FUNCTION predict_occupancy(new_data):

- Preprocess new incoming data
- Load-trained model
- Predict occupancy
- Store predictions in the database

VII. FUNCTION update_user_interface():

- Retrieve the latest predictions
- Send updates to users

VIII. FUNCTION feedback_loop(predictions, actuals):

- Compare predictions with actuals
- Update the training dataset with new data
- Periodically retrain the model

IX. WHILE True:

- ingest_sensor_data()
- aggregate_data()
- features = feature_engineering(aggregated_data)
- IF enough new data is available, THEN
  train_model(features, labels)
- predictions = predict_occupancy(new_data)
- update_user_interface()
- WAIT for 5 minutes

2.4.3 | Dynamic pricing algorithms

Algorithms that adjust parking prices based on real-time demand and occupancy levels. Geng and Cassandras (2015) described a pricing algorithm that dynamically adjusts rates based on time of day and occupancy rates, enhancing revenue while managing demand [8], [9], [14].

Initialize BASE_PRICE to P

Initialize HIGH_DEMAND_MULTIPLIER to 1.5

Initialize LOW_DEMAND_MULTIPLIER to 0.75

Initialize OCCUPANCY_THRESHOLD to 70%

Define TIME_OF_DAY_SLOTS with demand patterns

FUNCTION get_current_occupancy():

a. Retrieve current occupancy data from the database

b. Calculate occupancy_rate as (occupied_spaces / total_spaces) * 100

c. RETURN occupancy_rate

7. FUNCTION get_current_time_slot():

   a. Get current hour

   b. Determine a time slot based on the current hour

   c. RETURN time_slot

8. FUNCTION calculate_dynamic_price():

   a. occupancy_rate = get_current_occupancy()

   b. time_slot = get_current_time_slot()

   c. dynamic_price = BASE_PRICE

   d. IF occupancy_rate > OCCUPANCY_THRESHOLD THEN

      dynamic_price *= HIGH_DEMAND_MULTIPLIER

   e. ELSE IF occupancy_rate < OCCUPANCY_THRESHOLD THEN

      dynamic_price *= LOW_DEMAND_MULTIPLIER

   f. Adjust dynamic_price based on time_slot (if applicable)

   g. RETURN dynamic_price

9. FUNCTION update_parking_prices():

   a. Retrieve a list of all parking spaces

   b. FOR each parking_space in parking_spaces:

      i. dynamic_price = calculate_dynamic_price()

      ii. Update parking_space price in the database

10. WHILE True:

   a. update_parking_prices()

   b. WAIT for 15 minutes

2.4.4 | Routing algorithms

Algorithms that help drivers navigate to the nearest available parking space. For example, Dijkstra's or A* algorithm can compute the shortest path to a vacant space, minimizing travel time [10].

1. Initialize graph structure (adjacency list)

2. FUNCTION route_to_nearest_parking(start_node, available_parking_spaces):

   a. Initialize open_set = []

   b. Initialize g_score = {}

   c. Initialize f_score = {}

   d. Set g_score[start_node] = 0

   e. Set f_score[start_node] = heuristic(start_node, nearest_parking_space)

```
f. Add start_node to open_set

WHILE open_set is not empty:
   i.  current_node = node in open_set with lowest f_score
   ii. IF current_node is in available_parking_spaces THEN
          RETURN path from start_node to current_node

   iii. Remove current_node from open_set

   iv. FOR each neighbor in neighbors(current_node):
      a.  tentative_g_score = g_score[current_node] + distance(current_node, neighbor)
      b.  IF tentative_g_score < g_score[neighbor] THEN
         i.  g_score[neighbor] = tentative_g_score
         ii. f_score[neighbor] = g_score[neighbor] + heuristic(neighbor, nearest_parking_space)
         iii. IF neighbor is not in open_set, THEN
            a. Add neighbor to open_set

RETURN "No available parking spaces reachable."
```

2.5 | Environmental Impacts of Smart Parking Systems

The implementation of IoT-based parking systems not only improves parking efficiency but also reduces environmental impacts:

I. Reduced traffic congestion: real-time parking availability information can reduce vehicle idling time, thereby lowering emissions and improving air quality in urban areas.

II. Fuel consumption savings: studies show that smart parking systems can reduce fuel consumption by up to 30% by minimizing drivers' time searching for available parking.

2.6 | User Experience and Acceptance

User experience is a crucial factor in the successful adoption of smart parking systems:

I. Usability studies: surveys conducted by Mohamed et al. (2021) revealed that users found IoT-based parking systems more convenient and efficient than traditional methods, and that the ease of accessing real-time information through mobile apps enhanced user satisfaction.

II. Behavioral adaptation: Liu et al. explored the factors influencing user acceptance of smart parking systems, emphasizing the importance of perceived ease of use and the technology's perceived usefulness [11].

2.7 | Challenges and Limitations

Despite the advantages, IoT-based smart parking systems face several challenges:

I. Scalability: Implementing smart parking solutions across large urban areas can be costly and logistically complex [12].

II. Data security and privacy: concerns about data security and user privacy pose significant barriers to adoption. Ensuring the security of collected data and maintaining user trust is critical for successful [10], [18].

2.8 | Future Directions

Future research in IoT-based smart parking systems may focus on:

I. Integration with smart city frameworks: as cities become smarter, integrating parking solutions with other urban systems (e.g., traffic management and public transportation) will be essential for comprehensive urban mobility solutions [14].

II. Machine learning applications: using machine learning algorithms to predict parking availability based on historical data can further enhance system efficiency and user experience [15].

3 | System Design and Implementation

3.1 | Data Flow Diagram

Collection: sensors (e.g., ultrasonic or infrared) are deployed in parking spaces to collect real-time occupancy data (vacant or occupied).

Processing: the collected data is transmitted to a cloud-based server via IoT gateways, where it is aggregated and processed by algorithms to determine occupancy and availability.

Presentation: the processed data is displayed to users through a mobile or web application, showing available parking spots and directing users to the nearest space.

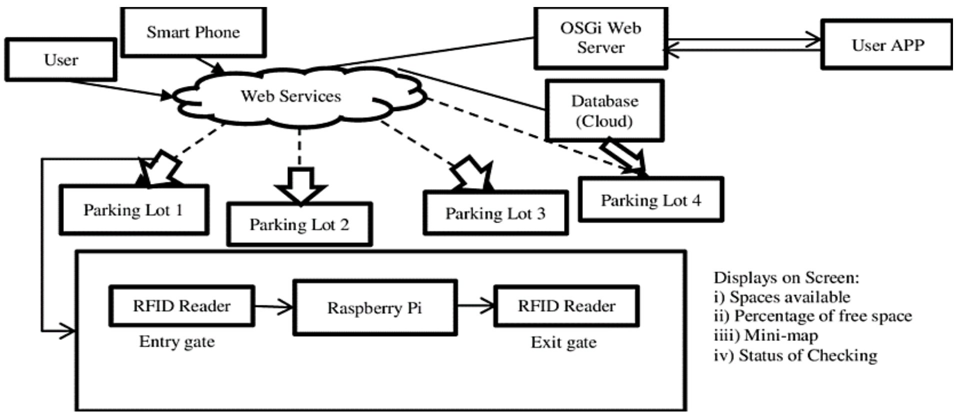

Fig. 1. Data flow diagram.

3.2 | Hardware Setup

Sensors: Ultrasonic or infrared sensors are installed in each parking spot to detect vehicle presence.

Gateways: IoT gateways collect sensor data and send it to the cloud for processing.

Connectivity: wireless protocols (e.g., Wi-Fi, LoRa, or ZigBee) transmit data between sensors and gateways [16].

Cloud infrastructure: a cloud server processes sensor data, applies algorithms for real-time analysis, and integrates with a user interface for communication with drivers [16]

Requirements: nodemcu, IR sensor, Camera, LDR, DC motor.

3.3 | System Workflow

Step 1. A driver opens the parking application and requests available parking.

Step 2. The system collects real-time sensor data and identifies vacant spaces.

Step 3. The application provides directions to the nearest available spot using the routing algorithm.

Step 4. The driver parks in the assigned spot, and the sensor detects the vehicle, updating the system in real-time [14].

Step 5. Dynamic pricing is applied based on occupancy levels, and the driver is billed accordingly.

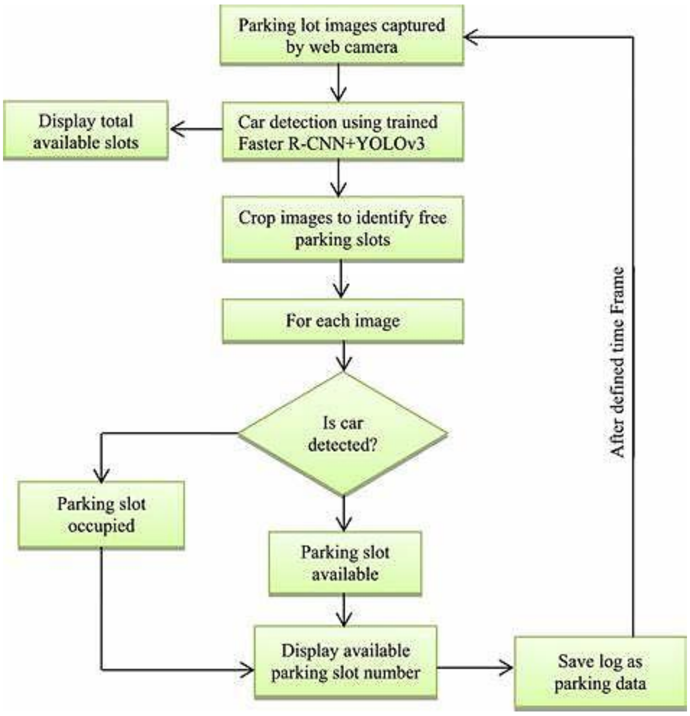

Fig. 2. System workflow.

4 | Conclusion

Implementing an IoT-based smart parking system effectively addresses the growing challenges of urban parking management by leveraging real-time sensor data to monitor space occupancy. This system optimizes parking space utilization, reduces traffic congestion, and enhances user experience by efficiently guiding drivers to available spots. Key components, including sensor networks, cloud-based data processing, and user-friendly mobile applications, work in sync to provide seamless parking solutions. Integrating dynamic pricing models, predictive algorithms, and routing mechanisms improves system efficiency and scalability. Future developments could enhance AI-driven predictive models for occupancy and integrate renewable energy sources to create more sustainable parking infrastructure.

This system represents a significant step towards smart city development, offering environmental and economic benefits by reducing fuel consumption, emissions, and operational costs. As IoT technology evolves, these systems will likely become more sophisticated and prevalent, transforming urban mobility.

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Data Availability

The data used and analyzed during the current study are available from the corresponding author upon reasonable request.

Conflicts of Interest

The author declares no conflicts of interest related to this research on the IoT-based smart parking system. No personal circumstances or interests could be considered to have an inappropriate influence on the presentation or interpretation of the reported research findings.

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