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Smart Traffic Management System for Urban Congestion

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ABSTRACT

The rapid increase in vehicles has created major challenges in parking management and electric vehicle recharging in urban areas. To address this issue, this work proposes an AI-driven smart auto parking system with integrated recharging. The system uses IoT sensors, cameras, and embedded controllers to detect vehicle presence and identify available parking slots automatically. Artificial Intelligence is applied for efficient slot allocation and space optimization. Electric vehicles parked in designated slots are automatically connected to a recharging unit, enabling smart energy usage. Parking and charging data are sent to a cloud platform for real-time monitoring and user access. The proposed system reduces traffic congestion, saves time, and supports smart city development with an efficient and eco-friendly parking solution.

1. INTRODUCTION

In recent years, rapid advancements in autonomous vehicle technology have significantly transformed the global transportation sector. Developments in embedded systems, low-cost sensors, artificial intelligence, and battery-powered electric vehicles have enabled the realization of self- driving mechanisms even in small-scale and cost-sensitive platforms. In developing countries, auto-rickshaws remain a primary mode of urban transportation but face challenges such as fuel inefficiency, air pollution, traffic congestion, and dependence on human drivers.

The integration of AI-driven autonomous navigation with electric recharging systems presents a sustainable and intelligent solution to these challenges. By leveraging Arduino-based embedded control, ultrasonic and infrared sensors, and efficient decision-making algorithms, autonomous navigation can be achieved without relying on expensive industrial-grade hardware. Such an approach makes autonomous mobility systems more affordable and scalable for real-world deployment.

This paper presents the design and development of a smart autonomous electric auto prototype capable of obstacle detection, line following, intelligent motion control, and automatic docking for battery recharging. The system continuously monitors battery voltage and, upon detecting a low-charge condition, autonomously navigates to a charging station and initiates the charging process without human intervention. The proposed model demonstrates that low-cost microcontrollers and standard sensors can be effectively combined to create an intelligent, self-sustaining transportation system.

The presented work serves as a practical prototype for future self-driving electric auto- rickshaws, with potential benefits including reduced human workload, lower operational costs, decreased fuel dependency, and improved environmental sustainability, making it well suited for smart transportation and smart city applications

2. LITERATURE REVIEW

Autonomous mobility has been an active area of research for more than a decade. Early studies primarily focused on basic robotic navigation techniques such as line following and rule-based obstacle avoidance using simple sensors. With advancements in embedded systems, sensor technology, and artificial intelligence, recent research has shifted toward real-time sensor fusion, machine learning-based decision making, and advanced motion control algorithms for autonomous vehicles.

Several studies highlight the use of ultrasonic, infrared (IR), and LiDAR sensors for environment perception, obstacle detection, and navigation. While simple microcontroller-based systems rely on predefined paths and reactive control, advanced implementations utilize computer vision, neural networks, and localization algorithms to achieve higher accuracy. However, such systems often depend on high-cost processors and complex hardware, limiting their scalability for low-budget applications.

In the domain of electric vehicle (EV) charging, both conductive and inductive charging techniques have been widely explored. Conductive charging using metallic docking stations is considered reliable and cost-effective for small autonomous platforms due to its simplicity and ease of implementation.

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Recent smart parking research integrates IoT-based monitoring with AI-driven optimization to manage parking space allocation and EV charging schedules efficiently. These systems typically employ sensors for vehicle detection, wireless communication modules for cloud connectivity, and digital platforms for user interaction.

Arduino-based systems are frequently used in autonomous robotics research because of their open-source nature, low cost, and extensive development ecosystem. Many studies demonstrate Arduino's effectiveness in motor control, sensor data processing, and basic autonomous behaviors. However, most existing works focus either on autonomous navigation or on EV charging as separate problems. Very few studies combine low-cost autonomous navigation with automated self-charging in a compact and integrated prototype, particularly for auto-rickshaw-based models.

From the literature, it is evident that current autonomous vehicle solutions often rely on expensive hardware and complex architectures. Challenges such as network latency, hardware compatibility issues, sensor failures, and security vulnerabilities further affect system reliability in smart parking and charging applications. These limitations reveal a clear research gap for developing an affordable, microcontroller-based autonomous auto system that integrates navigation, obstacle avoidance, and automatic charging within a single framework.

The present work addresses this gap by proposing an Arduino-controlled AI-driven autonomous auto prototype with self-charging capability, offering a practical, economical, and scalable solution suitable for smart transportation and smart city environments.

3. METHODOLOGY

Vehicle Detection and Sensing:

Infrared (IR) and ultrasonic sensors are used to detect vehicle presence, measure distance, and identify vacant parking slots. These sensors ensure accurate obstacle detection and safe vehicle movement within the parking area.

Image Capture and ANPR Processing:

An ESP32-CAM module captures vehicle number plate images at the entry and exit points. AI-based image processing techniques such as Optical Character Recognition (OCR) are applied to recognize and verify vehicle numbers automatically.

Data Processing and Decision Making:

The microcontroller processes sensor data and ANPR results to allocate available parking slots intelligently. AI algorithms optimize space utilization and guide vehicles to the nearest vacant slot.

Autonomous Parking Control:

DC motors and servo motors are controlled through motor drivers to perform automatic vehicle movement, steering, and precise parking without human intervention.

Battery Monitoring and Docking:

The system continuously monitors the vehicle battery level using voltage and current sensors. When the battery level falls below a predefined threshold, the system initiates autonomous docking using IR sensors for accurate alignment.

4. EXISTING SYSTEM

In the existing parking systems, vehicle parking is mostly managed manually or through basic automated mechanisms such as ticket-based or sensor-assisted parking. These systems rely on human intervention for vehicle guidance, parking slot allocation, and payment processing.

Conventional parking facilities do not provide intelligent slot optimization or real-time guidance, which results in increased time spent searching for parking spaces and higher traffic congestion. Most existing systems also lack automatic vehicle identification, making security and monitoring inefficient.

Electric vehicle charging in traditional parking lots is usually handled separately through wired charging stations. Users must manually connect charging cables, and charging operations are not integrated with parking management systems.

5. PROPOSED SYSTEM

The proposed system presents an AI-driven smart auto parking solution integrated with an automated electric vehicle recharging mechanism. The system uses IoT-based sensors such as infrared (IR) and ultrasonic sensors to detect vehicle presence, identify vacant parking slots, and ensure safe navigation within the parking area.

An ESP32-CAM module is employed for Automatic Number Plate Recognition (ANPR), enabling secure vehicle identification at entry and exit points. AI-based image processing algorithms analyze captured images to authorize vehicle access and maintain accurate parking records.

The Arduino-based control unit processes real- time sensor data and AI outputs to allocate parking slots intelligently and guide vehicles autonomously. DC motors and servo motors enable precise vehicle movement, steering, and automated parking without human intervention.

system continuously monitors the battery status of the vehicle. When a low battery condition is detected, the vehicle automatically navigates to a charging station using IR-based docking guidance. A relay-controlled wireless charging system is activated once proper alignment is achieved, ensuring safe and efficient recharging.

All parking, vehicle, and charging data are transmitted to a cloud platform, allowing users to monitor parking availability, vehicle status, and charging progress through a mobile or web application. This integrated approach improves parking efficiency, enhances user convenience, supports electric vehicle adoption, and contributes to smart and sustainable urban mobility

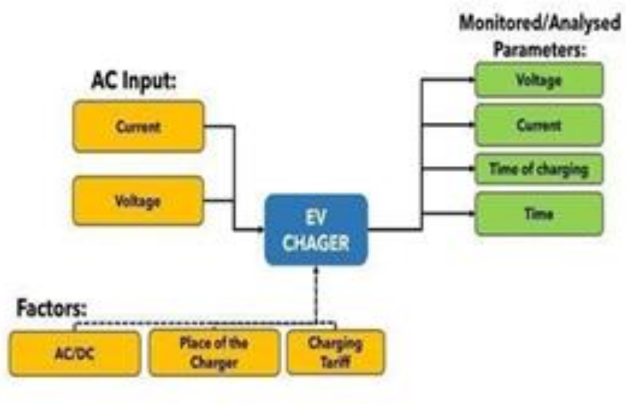

Figure 1- Block Diagram

6. SYSTEM DESIGN

The system design of the AI-driven smart auto parking with recharging is organized into interconnected modules that work together to achieve autonomous parking, secure vehicle identification, and automated electric vehicle charging.

1. Sensing Module

The sensing module consists of infrared (IR) sensors and ultrasonic sensors. IR sensors are used to detect parking slot availability and assist in precise docking alignment. Ultrasonic sensors measure the distance between the vehicle and surrounding obstacles to ensure safe and collision-free navigation.

2. Image Acquisition and AI Module

An ESP32-CAM module is installed at the parking entry and exit points to capture vehicle images. AI-based image processing techniques, such as Optical Character Recognition (OCR), are applied to perform Automatic Number Plate Recognition (ANPR). This module ensures secure vehicle identification and access control.

3.Control and Processing Module

The Arduino microcontroller acts as the central control unit of the system. It receives input from sensors and AI modules, processes the data, and makes decisions related to parking slot allocation, vehicle movement, and charging control.

4. Actuation Module

The actuation module includes DC motors for vehicle movement and servo motors for steering and barrier control. Motor drivers interface between the Arduino and motors to provide the required current and voltage levels.

5. Power Management and Charging Module

A rechargeable battery supplies power to the system. Voltage and current sensors continuously monitor battery status. When the battery level falls below a predefined threshold, the system initiates autonomous docking. Relay-controlled wireless charging pads are activated to recharge the vehicle safely.

6. Communication and Cloud Module

The system uses wireless communication to transmit parking status, vehicle identification data, and charging information to a cloud platform. Users can access this information through a mobile or web application for real-time monitoring and management.

7. MATLAB/SIMULINK MODEL

The simulation is carried out to examine the working behavior of the proposed AI-driven smart auto parking with recharging system before real- time hardware implementation. The simulation platform allows the system to be tested under different parking and battery conditions in a controlled and flexible environment. The simulation model consists of functional blocks representing sensor inputs, control logic, decision- making algorithms, vehicle movement, and charging operations.

In the simulation model, ultrasonic sensor inputs represent obstacle distances, IR sensor signals indicate parking slot availability and docking alignment, and battery voltage levels are modeled as variable input sources. These input signals are fed into a control block that simulates the operation of the Arduino microcontroller and AI-based decision logic.

The controller processes the sensor data and determines appropriate actions such as vehicle movement, steering control, parking slot selection, and docking initiation. When the battery voltage drops below the predefined threshold, the system automatically switches from parking mode to charging mode. The docking block ensures proper alignment, after which the relay-controlled charging unit is activated.

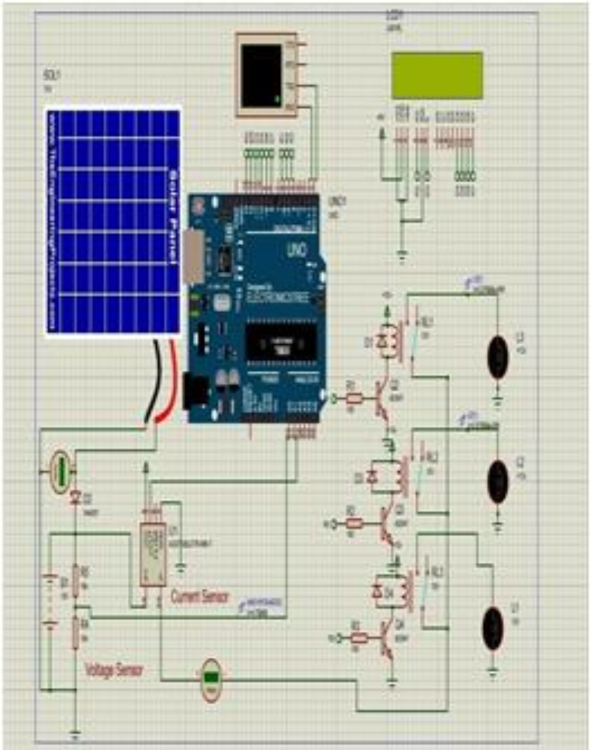

Figure 2- MATLAB Simulation Model

The simulation results demonstrate that the vehicle successfully detects vacant parking slots, avoids obstacles, parks autonomously, and initiates automatic recharging when required. This confirms the correctness, reliability, and efficiency of the proposed smart parking and recharging system before physical implementation.

8. SIMULATION RESULTS

The Simulink model was evaluated under different operating conditions by varying obstacle distances, parking slot availability, and battery charge levels. The results demonstrate that when a vacant parking slot is detected, the control system accurately guides the vehicle using sensor feedback to perform autonomous parking without collision.

When the battery voltage falls below the predefined threshold, the system automatically switches from navigation mode to charging mode. The docking mechanism aligns the vehicle precisely with the charging station, after which the relay-controlled charging unit is activated. After the recharging process, the battery level shows a significant increase, and the system returns to normal operational mode.

These results verify that the proposed system is capable of continuously monitoring parking conditions and battery status while ensuring safe navigation and efficient energy management in real time. Therefore, the simulation confirms the suitability of the proposed AI-driven smart auto parking with recharging system for smart parking facilities, commercial buildings, and urban environments.

The controller responds quickly to variations in distance measurements and parking availability, ensuring smooth vehicle movement and accurate decision making. No false parking detection or charging errors were observed during testing, which indicates good coordination between sensing, control, and charging modules. This confirms that the system can operate reliably in dynamic parking environments.

9. CONCLUSION

The AI-driven smart auto parking with recharging system provides an efficient and intelligent solution for modern parking challenges. By integrating IoT sensors, AI- based number plate recognition, autonomous navigation, and automated charging, the system minimizes human intervention and improves parking space utilization.

Simulation results demonstrate that the system can accurately detect available parking slots, safely guide vehicles for automatic parking, and initiate recharging when the battery level is low. The cloud-based monitoring feature enables real-time tracking of parking and charging status, enhancing user convenience and management efficiency. The proposed system supports sustainable electric vehicle usage and is suitable for implementation in smart parking facilities, commercial buildings, and smart city environments.

The proposed prototype also demonstrates the feasibility of integrating parking management and vehicle charging within a single automated framework. By combining sensing, decision- making, and energy management in one system, it improves overall operational efficiency and reduces dependency on manual supervision. This approach contributes to smarter infrastructure development and promotes the adoption of intelligent transportation systems in future urban environments

10. FUTURE SCOPE

The proposed AI-driven smart auto parking wither charging system has significant potential for further development and real- world applications. Future enhancements may include:

1. Integration with Smart City Infrastructure:

The system can be connected to city-wide traffic and parking management networks to provide real-time guidance and optimize overall traffic flow.

2. Advanced AI Algorithms:

Machine learning models can be used to predict parking slot availability, optimize vehicle routing, and reduce waiting time during peak hours.

3. Enhanced Security Features:

Integration of facial recognition or RFID-based vehicle authentication can improve access control and prevent unauthorized entry.

4. Renewable Energy Integration:

Wireless charging stations powered by solar panels or other renewable energy sources can make the system more sustainable.

5. Fleet Management Applications:

The system can be scaled to manage autonomous fleets, enabling smart scheduling, monitoring, and charging of multiple electric vehicles simultaneously.

6. Mobile App and IoT Expansion:

Future development can allow full user control via mobile apps, including real-time booking, navigation assistance, and monitoring of vehicle charging remotely.

These enhancements can make the system more intelligent, energy-efficient, and scalable, contributing to the development of sustainable and smart urban transportation systems.

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