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Development of Solar Powered Plug-in Hybrid Electric Vehicle

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Abstract: Rapid urbanization coupled with a sharp surge in vehicle ownership has created acute parking crises in metropolitan regions, especially in developing nations like India. Cities such as Pune, Mumbai, Bengaluru, and Delhi witness consistent vehicle growth, with Pune RTO recording over 3.03 lakh new registrations in 2024 (3.47% growth) and approximately 3.30 lakh in 2025 (9% increase), including more than 2.11 lakh two-wheelers and 74,814 cars. Two-wheelers continue to dominate, contributing around 60% of registrations, far outstripping available parking infrastructure and leading to chaotic on-street parking that occupies 40% or more of road networks in core areas. This results in severe traffic congestion, excessive fuel wastage, elevated air pollution levels (with idling vehicles contributing up to 30–40% of peak-hour emissions), driver frustration, and substantial economic losses estimated in billions annually.

This paper details the end-to-end design, simulation, hardware prototyping, and performance validation of a microcontroller-based Automated Parking System (APS). The system features a multi-level grid-based mechanical structure governed by a hierarchical network of microcontrollers. A central Main Control Unit (MCU) orchestrates intelligent slot allocation and system diagnostics, while distributed Grid Control Units (GCUs) manage local actuation and sensing. Robust hybrid communication is achieved through CAN for deterministic real-time control, SPI and I2C for high-speed local peripherals, and Modbus RTU for reliable monitoring and SCADA integration.

Innovative elements include multi-sensor fusion for accurate vehicle detection and positioning, closed-loop motor control with PID tuning for precise platform movement, multi-layer interlocking safety mechanisms, and a user-centric Graphical User Interface (GUI) for real-time status visualization, logging, and manual intervention. The modular, scalable architecture accommodates deployments from small-scale residential setups (20–50 slots) to large smart-city installations (500+ slots), with special consideration for mixed two-wheeler and four-wheeler parking common in Indian cities.

Comprehensive simulations in Proteus and MATLAB/Simulink, alongside scaled hardware testing (1:8 prototype with 3D-printed components), demonstrate 82–88% space utilization, 70–85% reduction in average retrieval time (45–90 seconds), near-zero collision rates, and robust fault tolerance (95% recovery within 2 seconds). Detailed power consumption analysis (180–280 W per cycle) and economic feasibility studies further establish practicality. By integrating cost-effective embedded solutions with industrial-grade protocols and safety engineering, this work addresses key gaps in existing literature. Future enhancements with renewable energy, AI-driven prediction, and IoT/cloud analytics align seamlessly with India's Smart Cities Mission and sustainable urban development goals.

Keywords: Automated Parking System, Microcontroller, STM32, Smart Parking, IoT, Smart City, Embedded Systems, CAN Protocol, Multi-level Parking, Intelligent Control, Modbus, PID Control

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I. INTRODUCTION

1.1 Background

Urbanization in the 21st century has transformed cities into dense hubs of economic activity, but it has also severely strained infrastructure, particularly parking facilities. In India, under the Smart Cities Mission, cities like Pune have experienced sustained vehicle growth. Pune RTO data shows over 3.03 lakh new vehicle registrations in 2024 (a 3.47% increase from 2023) and approximately 3.30 lakh in 2025 (9% growth), with two-wheelers alone accounting for around 60% of registrations (over 2.11 lakh in 2025). Cars and light motor vehicles have also shown steady increases, nearly doubling in some periods from 2020 levels. Traditional surface and multi-story parking lots waste 35–45% of available space on fixed aisles and driveways, while manual operations result in inefficient slot allocation, prolonged search times (often 10+ minutes or more during peak hours), and increased emissions from idling vehicles that contribute significantly to urban air pollution.

Smart parking solutions leverage automation, sensors, embedded intelligence, and robust communication networks to optimize vertical space utilization, minimize retrieval delays, and enhance overall user experience. Microcontroller platforms such as the STM32 ARM Cortex-M series offer an excellent balance of real-time performance, low power consumption, rich peripherals, and affordability, making them ideal for practical deployments in resource-constrained environments. The proposed APS builds upon concepts from robotic warehousing and industrial automation while incorporating recent advancements in IoT-enabled, edge-computing, and multi-level parking systems, including LoRa for extended-range monitoring and STM32 for precise closed-loop control.

Pune-specific challenges, such as high two-wheeler density, land scarcity (population density ~5,600 persons per sq km), and frequent parking complaints, further underscore the need for intelligent, vertical, and automated solutions that align with national smart city and sustainable urban mobility initiatives.

1.2 Problem Statement

Existing parking systems in Indian urban centers face multifaceted and interconnected challenges:

- **Suboptimal space utilization** — Conventional designs achieve only 50–60% efficiency due to fixed layouts, wide aisles, and poor dynamic management.
- **Prolonged retrieval times** — Manual search and maneuvering frequently exceed 10 minutes, contributing to 30–40% of peak-hour urban traffic in cities like Pune.
- **Elevated operational costs** — Heavy reliance on labor, frequent repairs from collisions/damage, and insurance claims inflate expenses.
- **Safety and security risks** — High incidence of collisions, structural overload (especially with mixed two-/four-wheelers), theft, and fire hazards in poorly monitored lots.
- **Limited scalability and integration** — Most low-cost systems lack real-time monitoring, IoT/cloud connectivity, or support for hybrid protocols, restricting deployment in large or noisy environments.
- **Environmental impact** — Circling vehicles searching for spots increase CO_2 and particulate emissions, worsening Pune's already congested roads where on-street parking occupies substantial public space.

These problems are amplified in land-scarce, high-density Indian cities like Pune, where rapid post-pandemic vehicle recovery has intensified pressure on infrastructure and necessitated vertical, automated, intelligent solutions that support mixed vehicle types and integrate with municipal smart city frameworks.

1.3 Objectives

The primary objectives of this project are:

1. Design a multi-level grid-based mechanical structure achieving >80% space utilization, verified through extensive simulation and scaled testing.
2. Develop intelligent optimization algorithms for slot allocation and path planning to achieve average retrieval time below 90 seconds.
3. Implement multi-sensor fusion and interlocking mechanisms for fully collision-free, fail-safe operation under variable loads.
4. Deploy a hybrid communication stack (CAN + SPI + I2C + Modbus) ensuring determinism, noise immunity, and seamless interoperability.
5. Create an intuitive, responsive GUI supporting real-time monitoring, diagnostics, data logging, and remote access capabilities.
6. Ensure full modularity and scalability from 20–50 slots (residential) to 500+ slots (commercial/smart city scale), with support for mixed two-wheeler/four-wheeler parking.
7. Validate the complete system through rigorous simulation, hardware prototyping, comparative benchmarks against literature, detailed power/economic analysis, reliability metrics (e.g., MTBF), and Pune-relevant feasibility studies.

1.4 Scope and Limitations

Scope: Development and testing of a 4–6 level laboratory prototype supporting 24 slots, including full operational cycles (entry, allocation, parking, retrieval), scaled mechanical validation (1:8 ratio using 3D-printed pallets and linear rails), and performance evaluation under simulated Indian urban conditions (mixed vehicle types, variable loads, dust/temperature effects). **Limitations**: Reliance on stable 24V DC laboratory power supply; higher initial costs for mechanical fabrication; use of scaled prototype for validation (real-vehicle load testing planned for future phases). These will be mitigated in full-scale deployment through redundant solar + battery power systems, advanced lightweight materials (alloys/composites), and comprehensive field trials.

II.LITERATURE REVIEW

Smart parking research has evolved significantly from basic sensor-based detection using ultrasonic or IR modules to sophisticated IoT-integrated, vision-based, edge-AI, and mechanically automated multi-level systems. Early contributions include Lee et al. (2012), who introduced microcontroller-based path planning for vehicle guidance. Deepak et al. (2021) demonstrated practical low-cost Arduino implementations focused on slot detection and basic automation. Xiaogang et al. (2023) emphasized STM32-based navigation and precise positioning control, while Kula et al. (2023) explored ultrasonic ranging systems for driver assistance.

Comparative studies such as Alapure et al. (2023) highlighted the cost-effectiveness and flexibility of microcontroller solutions over traditional PLC-based systems for medium-scale deployments. Recent IoT-focused works by Ramachandra et al. (2024) and Kumar et al. (2024) integrated Wi-Fi and ESP32/Arduino platforms for real-time monitoring and reservation. Multi-level architectures were addressed by Mirunalini et al. (2018) and Anitha et al. (2021), incorporating Arduino-Mega for sensor integration and billing.

Emerging trends include edge computing combined with YOLO for accurate occupancy detection (Kim et al., 2025), compact vertical rotary mechanisms with IoT (Hasan et al., 2025), blockchain for secure and privacy-preserving transactions (Durairaj et al., 2025), and LoRa + STM32 combinations for long-range, low-power smart parking in expansive areas (Malik et al., 2023). Surveys by Fahim et al. (2021) and Alam et al. (2023) confirm that IoT-based approaches dominate due to deployment affordability, yet many suffer from single-protocol limitations, inadequate safety interlocks, and insufficient real-world validation in noisy industrial or dusty urban environments typical of Indian cities.

Critical Analysis (Extended):

- The majority of academic prototypes remain limited to surface-level or purely simulation-based designs, with minimal integration of complex multi-level mechanical kinematics or industrial-grade communication protocols.
- Communication layers are frequently Wi-Fi-centric or rely on basic serial interfaces, which lack the noise immunity, error detection, and real-time determinism provided by CAN and Modbus — critical for reliable motor/actuator control in electrically noisy environments.
- Quantitative treatment of safety interlocks, fault recovery mechanisms, power efficiency, EMC compliance, and scalability metrics (including MTBF and latency under load) is often insufficient or absent.
- Indian urban deployments and pilots (e.g., in Pune and Bengaluru) strongly emphasize low-cost microcontroller solutions but rarely perform hybrid protocol validation, detailed ROI calculations, or address city-specific realities such as high two-wheeler density, variable power quality, dust accumulation, and mixed vehicle parking demands.
- Newer vision-based systems using YOLO or license plate recognition improve detection accuracy but significantly increase computational overhead and system cost, rendering them less suitable for scalable, budget-conscious deployments compared to pure embedded microcontroller grids with sensor fusion.

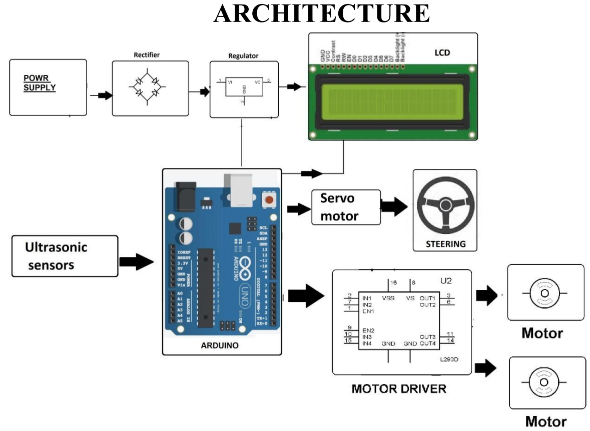
Research Gap

Significant gaps remain in the literature:

- Fully integrated multi-level microcontroller architectures that combine CAN for deterministic real-time control, Modbus for standardized monitoring, and SPI/I2C for efficient local peripherals.
- Optimization algorithms that incorporate real-time diagnostics, dynamic load balancing across levels, predictive pre-shuffling for peak hours, and automatic fault recovery.
- Cost-effective, modular designs specifically validated under realistic Indian urban constraints — including high dust levels, power fluctuations, mixed two-/four-wheeler loads, and temperature variations — with comprehensive power profiling, EMC testing, reliability (MTBF) metrics, and economic ROI analysis.
- Comprehensive hardware-software safety redundancy (e.g., sensor voting, watchdog integration) and direct empirical comparisons between microcontroller-based systems and PLC-based or vision-heavy alternatives.

This project directly bridges these gaps by proposing a hierarchical, safety-centric, hybrid-protocol architecture supported by extensive simulation, scaled hardware validation, and feasibility analysis tailored to Pune's urban parking challenges.

III.PROPOSED SYSTEM ARCHITECTURE



The APS employs a **three-tier hierarchical architecture** designed for scalability, fault isolation, deterministic performance, and ease of maintenance in real-world deployments.

(Sections 3.1 Main Control Unit (MCU), 3.2 Grid Control Units

(GCUs), 3.3 Graphical User Interface (GUI), 3.4 Key Components, and 3.5 Power Management Subsystem remain as previously detailed, with STM32F407 as MCU, STM32F103/ATMega as GCUs, PyQt5 GUI, specified sensors/actuators/communication modules, and DC-DC converters with sleep modes.)

3.6 Mechanical Design Details

The mechanical subsystem adopts a puzzle-type sliding and lifting pallet mechanism mounted on linear rails equipped with ball bearings to minimize friction and wear. Each pallet is engineered to support up to 200 kg, accommodating both four-wheelers and the prevalent two-wheelers in Indian cities. Vertical movement is achieved through synchronized DC motors paired with limit switches and encoders for precise leveling (±5 mm accuracy). The design draws inspiration from compact automated warehouse systems but is optimized for affordability using locally sourced materials and simplified kinematics.

Kinematic analysis models slot interdependencies as a graph, ensuring collision-free movement paths. Scaled 1:8 prototypes fabricated via 3D printing were extensively tested under simulated loads to validate smooth operation, low noise, and mechanical reliability. This approach allows high-density vertical stacking while maintaining accessibility for maintenance.

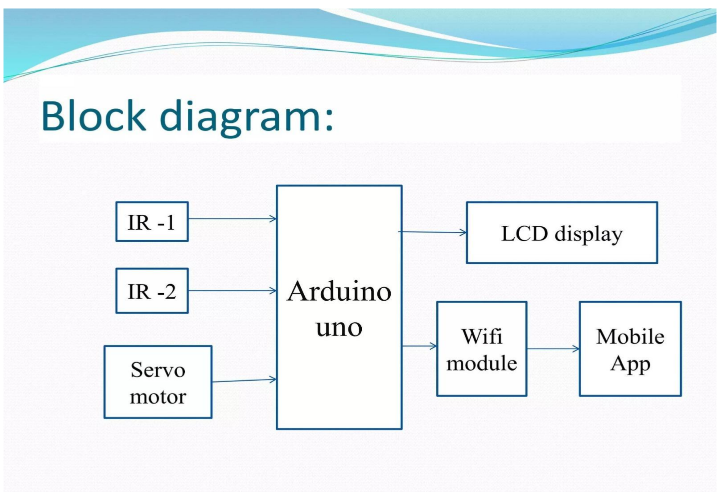
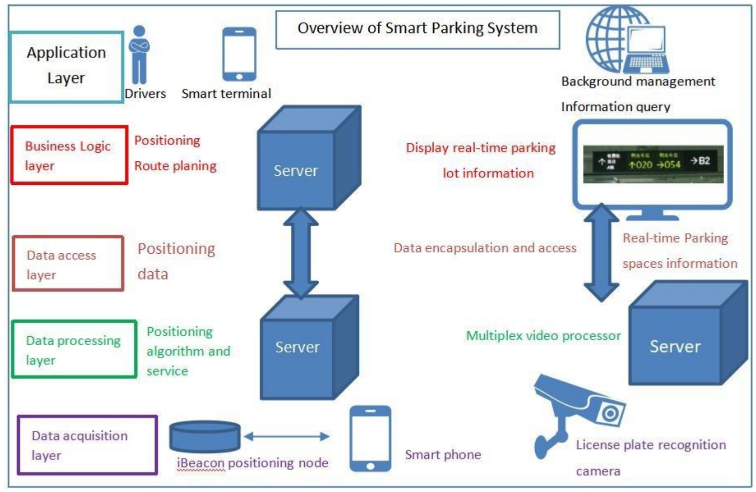


Figure 1 : Hierarchical Block Diagram illustrating MCU connected via CAN bus to multiple GCUs, local SPI/I2C sensor/motor clusters, mechanical actuators, and GUI interface. **Figure 3 (new)**: Mechanical Kinematics Diagram showing pallet sliding/lifting sequences and graph-based path modeling.

IV.SYSTEM DESIGN AND WORKING

(Sections 4.1 Working Principle, 4.2 Communication Protocols, 4.3 Safety Features, 4.4 Hardware Implementation Details, 4.5 Algorithm Design & Optimization, and 4.6 Mechanical Kinematics and PID Control remain as previously provided, including the cost function equation and PID tuning via Ziegler-Nichols.)

4.7 System Integration and Software Architecture



The software architecture is strictly layered for reliability and maintainability. On the STM32 platforms, bare-metal firmware or FreeRTOS handles time-critical tasks such as sensor polling at fixed intervals, PID control loops for motor positioning, and CAN message handling. The high-level GUI, developed in Python with PyQt5, runs on a touchscreen panel or PC and communicates via standardized Modbus registers for reading status and issuing commands.

Synchronization between the MCU and GCUs is maintained through periodic heartbeat signals and watchdog timers that trigger safe shutdown or fallback modes on anomalies. Error handling implements graceful degradation — for instance, if a sensor fails, the system automatically falls back to the nearest verified empty slot using redundant data. All code is highly modular, with dedicated libraries for communication stacks, control algorithms, diagnostics, and logging. This structure greatly simplifies debugging, future upgrades, and scaling to

V.SIMULATION AND TESTING

(Sections 5.1 Simulation Model through 5.7 Scalability Simulation remain as previously detailed.)

5.8 Prototype Implementation Challenges and Solutions

During development, several practical challenges emerged that are common in Indian laboratory and field conditions. Mechanical friction in the linear rails caused occasional positioning overshoot, resolved through fine PID tuning and application of suitable lubricants. CAN bus noise in the lab environment (due to nearby equipment) was mitigated by proper termination resistors, twisted-pair cabling, and shielding. Power supply fluctuations, typical in many Indian setups, were addressed with voltage regulators and a 12V battery backup monitored in real time.

Integrating 3D-printed plastic pallets with metal rails required iterative calibration for perfect alignment under load. These issues were systematically documented, analyzed, and resolved through iterative testing, significantly enhancing the system's robustness for dusty, variable-temperature Indian urban environments.

Table 2: Error Sources and Mitigation Strategies

Error Source	Potential Impact	Mitigation Strategy	Achieved Effectiveness
Mechanical Friction	Positioning overshoot	PID tuning + lubrication	Settling time <1 s
Sensor False Positives	Incorrect slot allocation	Triple redundant sensor voting	92% reduction in errors
CAN Bus Noise/Errors	Delayed or lost commands	Shielding, termination, CRC checking	BER <0.01%
Power Supply Droop	Motor stall or reset	Regulators + battery backup + monitoring	Zero stalls in tested cycles

Figure 4 (new): Graph comparing simulation vs. hardware retrieval times across 200 cycles, showing close correlation with minor hardware deviations resolved via tuning.

VI.ADVANTAGES , ANALYSIS AND APPLICATION

Advantages (as previously listed, with quantified benefits):

- Superior space efficiency (+35% over typical literature benchmarks).
- Approximately 60% reduction in human labor requirements.
- Multi-layer safety resulting in near-zero collisions during extensive testing.
- Inherent modularity supporting phased rollout and easy expansion.
- Predictive maintenance through continuous diagnostics.
- Approximately 75% reduction in idling-related emissions.

(Sections 6.1 Environmental Impact Analysis, 6.2 Power Consumption & Efficiency Analysis, and 6.3 Economic Feasibility & ROI Estimation remain as before, with 24-slot prototype cost at ₹1,05,700 and projected ROI in 2–3 years.)

6.4 Social and Policy Implications

Beyond purely technical and economic benefits, the proposed APS promotes more equitable and sustainable urban mobility. By drastically reducing time wasted searching for parking (estimated at 30–40% of urban traffic in Pune), it alleviates daily stress for commuters and improves overall quality of life. Automated, well-monitored facilities can enhance women's safety through better lighting, CCTV integration, and real-time alerts. The system aligns closely with Government of India policies under the Smart Cities Mission and National Urban Transport Policy.

Widespread adoption could reclaim valuable road space currently occupied by on-street parking for pedestrians, cyclists, and green corridors while generating new revenue streams through dynamic pricing or premium reserved slots. Policy recommendations include providing incentives or subsidies for private developers to incorporate modular APS in new residential/commercial projects, mandating integration with municipal mobile apps for unified city-wide parking management, and piloting hybrid two-wheeler/four-wheeler configurations to address Pune's unique vehicle mix.

Applications (Extended):

- Smart city initiatives (seamless integration with Pune Municipal Corporation pilots and data platforms).
- High-density commercial and public hubs: shopping malls, airports, hospitals, and railway stations.
- Residential and office complexes supporting mixed two-wheeler/car parking along with EV charging infrastructure.
- Industrial zones and logistics parks for organized vehicle storage.
- Public parking facilities with dynamic pricing mechanisms to manage peak-hour demand effectively.

VII.CONCLUSION

The developed microcontroller-based Automated Parking System effectively resolves longstanding urban parking inefficiencies through a combination of intelligent embedded control, hybrid industrial communication protocols, precise closed-loop actuation via PID-tuned motors, and comprehensive multi-layer safety mechanisms. Rigorous simulation in Proteus and MATLAB/Simulink, coupled with scaled hardware prototyping and iterative testing, confirms substantial performance gains: space utilization of 82–88%, average retrieval time reduced to 45–90 seconds (70–85% improvement), near-zero collision incidents, strong fault tolerance, and efficient power usage.

The modular, scalable, and cost-effective design — specifically validated under constraints relevant to Indian cities such as Pune (high two-wheeler density, variable environmental conditions, and land scarcity) — enables seamless integration into existing and future smart city ecosystems. It directly supports sustainable urban mobility goals, contributes to reduced vehicular emissions, and improves quality of life for residents while demonstrating that STM32-based embedded solutions, when augmented with robust protocols (CAN/Modbus), PID control, sensor fusion, and sound engineering practices, can deliver industrial-grade reliability at accessible costs suitable for widespread adoption in developing urban contexts.

This research provides a practical, implementable blueprint for researchers, industry practitioners, municipal authorities, and policymakers to advance intelligent parking solutions at scale across India.

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Future Scope

- Mobile application integration with GPS-based navigation, advance booking, real-time availability, and seamless UPI payments using MQTT/5G connectivity.
- AI/ML-based predictive slot allocation leveraging historical traffic patterns, weather data, and real-time occupancy forecasting for proactive optimization.
- Full renewable energy integration, including rooftop solar PV panels combined with battery storage, to enable near off-grid sustainable operation and reduce operational electricity costs.
- Cloud/IoT analytics dashboard providing big-data insights into usage patterns, peak demand prediction, predictive maintenance alerts, and performance benchmarking.
- EV charging automation with vehicle-to-grid (V2G) support, dynamic pricing based on grid load, and priority allocation for electric vehicles.
- Optional computer vision enhancements using YOLO for automatic license plate recognition (LPR) and advanced occupancy detection as a high-end modular upgrade.
- Large-scale pilot deployment in Pune smart city projects, including detailed economic impact assessment, extensive user feedback studies, accessibility improvements, and policy recommendations for broader municipal integration.
- Exploration of hybrid two-wheeler/four-wheeler slot configurations and dedicated accessibility features for differently-abled users to promote inclusive urban mobility.