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Implementation of an AIoT-based Smart Parking System for Urban Mobility and Sustainable Infrastructure Management

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As urban populations continue to grow, conventional parking systems increasingly fail to meet demands for space efficiency, user convenience, and sustainability. In this paper, we propose an AIoT-based smart parking system that reimagines the traditional mechanical tower through a modular Rubik's Cube-inspired design stabilized by a three-axis motion control framework. IoT-enabled sensors including ultrasonic units for vehicle detection, infrared modules for alignment, and radio frequency identification tags for occupancy tracking ensure accurate and responsive operation. Cars are shifted horizontally and vertically via tray-level rollers and lateral tracks, enabling multi-directional slot movement while reducing vibration and energy use. Integrated cloud infrastructure supports real-time monitoring, dynamic pricing, and user navigation through mobile applications. An operational simulation estimated retrieval times across varying occupancy levels, showing reduced waiting periods with performance dependent on scale and load. A simulated deployment in a mixed-use urban area demonstrated improved space utilization, energy efficiency, and service accessibility. Net carbon emission reduction was calculated by balancing shorter idling times with the energy costs of tray shuffling. Finally, we outline the future application of activity-based costing to compare economic and environmental performances between traditional and AIoT-based systems, providing a comprehensive framework for evaluating feasibility, cost efficiency, and sustainability in smart mobility planning.

1. Introduction

The rapid pace of urbanization has markedly increased the demand for space-efficient, user-friendly, and environmentally sustainable infrastructure. Among the critical urban challenges, parking scarcity and inefficiencies in traditional mechanical parking systems stand out as persistent distressful in high-density metropolitan areas. These systems often rely on outdated mechanical lifts or fixed-structure towers, which suffer from limitations such as long wait times,

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high maintenance costs, rigid configurations, and poor adaptability to real-time traffic dynamics.

To address the growing challenges of urban parking inefficiency, in this paper, we propose an innovative smart parking solution that combines Artificial Intelligence of Things (AIoT) with a modular parking infrastructure inspired by the logic of a Rubik's Cube and stabilized through a three-axis motion control framework. The Rubik's Cube logic allows trays to be shifted horizontally and vertically by means of roller-driven transfer mechanisms and lateral tracks beneath each unit, enabling vehicles to move into or out of vacant slots efficiently. This architectural approach enables multi-directional slot movement, thereby enhancing the spatial flexibility and utilization rate of limited parking areas. The system operates through the integration of sensor networks that enable real-time occupancy detection, including ultrasonic sensors for vehicle presence, infrared sensors for alignment confirmation, and radio frequency identification (RFID) modules for occupancy tracking. Machine learning algorithms are employed to predict parking space availability and optimize slot allocation dynamically. Furthermore, a mobile application interface facilitates user interaction, allowing for seamless reservation, payment, and navigation experiences. These components are supported by a robust cloud infrastructure that enables dynamic pricing strategies, real-time usage analytics, and broader integration with urban transportation networks. To evaluate system practicality, operational simulations were conducted to estimate retrieval times under different occupancy levels, demonstrating performance variations with scale and load. Additionally, energy consumption and carbon emissions were analyzed by balancing shorter vehicle idling times against the electricity required for tray shuffling, providing a realistic view of environmental trade-offs. Collectively, this AIoT-driven system represents a transformative step toward intelligent urban mobility and sustainable parking management.

In this paper, we outline the architectural design, system implementation, user experience features, and performance evaluation of the smart parking system. While the current study is simulation-based, future work will include small-scale prototyping to verify feasibility and provide experimental validation of the proposed transfer and sensor mechanisms. A pilot deployment in a mixed-use commercial and residential district demonstrated significant improvements in parking accessibility, system throughput, and energy efficiency.

2. Research Motivation

The inefficiency of conventional parking systems remains a persistent urban challenge, often resulting in prolonged vehicle search times, unnecessary fuel consumption, increased traffic congestion, and elevated carbon emissions.(1) These issues are further compounded by a lack of real-time information, limited flexibility in reservation mechanisms, and insufficient integration with modern mobility platforms. As cities move toward smarter infrastructure, there is an urgent need for a more intelligent, adaptive, and sustainable parking solution that aligns with the principles of the smart city paradigm.

In response to this need, we set out to design and implement a modular smart parking system grounded in three-axis mechanical control, enabling the dynamic spatial reconfiguration of parking slots. The system incorporates AI-driven prediction and automated control mechanisms to optimize parking slot allocation and utilization. Seamless user interaction is facilitated through mobile device integration, supporting functionalities such as real-time reservations, navigation, and payments. We also include a comprehensive evaluation of system performance based on key indicators including operational efficiency, user satisfaction, and environmental sustainability. Additionally, we explore the system's scalability and its potential for integration into broader urban infrastructure networks, offering a pathway toward more responsive and sustainable urban parking management.

3. Background and System Evolution

3.1 Limitations of traditional mechanical parking systems

In many urban centers, traditional mechanical parking towers have been deployed for decades to address the growing demand for vehicle storage in limited spaces.(2) These systems typically utilize a lift-and-slide mechanism to stack cars vertically, allowing for a compact footprint. However, while space-efficient, such systems suffer from significant limitations in operational efficiency, flexibility, and user experience.

As shown in Fig. 1, conventional parking towers are generally built with fixed grid structures where vehicles are only accessible through vertical and horizontal movement sequences. This leads to sequential access delays, particularly during peak hours, as users must wait for other vehicles to be moved before theirs can be retrieved.

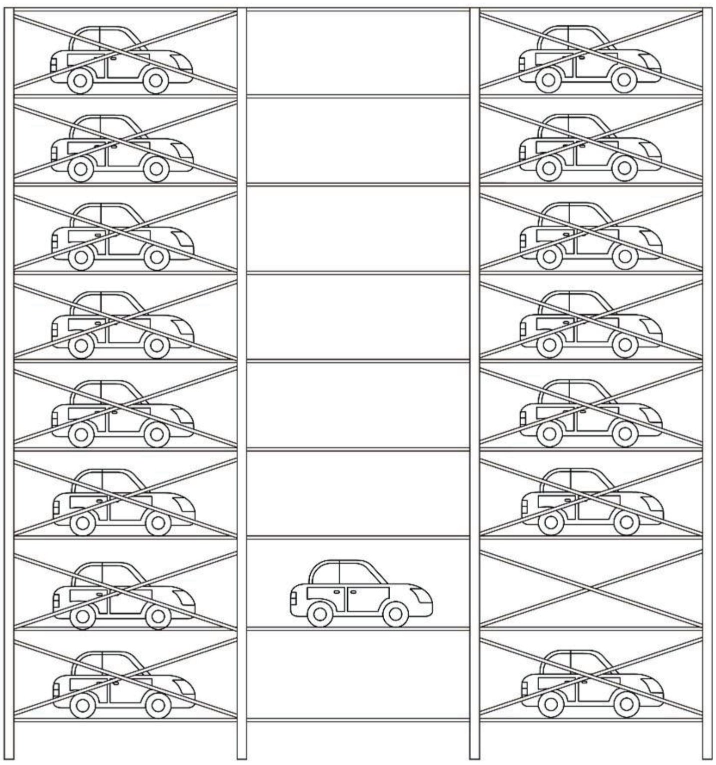

Fig. 1. Traditional mechanical parking tower.

Moreover, most traditional systems operate using basic programmable logic controllers, lacking real-time responsiveness, adaptive path planning, or predictive analytics.(3) Maintenance requirements are also high owing to mechanical wear, and user interfaces are often outdated or non-intuitive. Energy consumption tends to be inefficient, with elevators and lighting systems running continuously without adaptive control.

Figure 1 presents a traditional mechanical parking tower characterized by a vertically stacked design with fixed slots and limited motion paths. This configuration typically relies on linear elevator mechanisms to move vehicles vertically, without the capacity for lateral or multidirectional repositioning. While such systems have historically offered a compact solution for dense urban settings, they remain constrained by their mechanical rigidity, low adaptability, and inability to dynamically respond to fluctuating user demand or spatial conditions.

The limitations inherent in this traditional setup such as prolonged retrieval times, underutilized vertical space, and inflexible access patterns highlight the urgent need for smarter, more responsive infrastructure. As urban populations grow and mobility patterns become increasingly dynamic, conventional parking models struggle to meet sustainability, efficiency, and user-experience expectations. Moreover, the lack of real-time integration with digital services such as occupancy detection, predictive allocation, and mobile-enabled interaction further diminishes their utility in the context of emerging smart city ecosystems.

Considering these challenges, the traditional mechanical tower serves as a critical baseline from which we can evaluate and contrast more advanced, AIoT-integrated parking solutions that prioritize modularity, adaptability, and system intelligence.

3.2 Emergence of AIoT-driven smart parking solutions

The convergence of AI and IoT, collectively referred to as AIoT, has fundamentally redefined the landscape of urban parking infrastructure. Traditional parking systems, which primarily function as passive storage spaces for vehicles, are increasingly being replaced by intelligent solutions that offer real-time, data-driven, and user-centric services. Modern smart parking systems are no longer limited to basic occupancy detection or mechanical operation; instead, they incorporate adaptive architectures and algorithmic intelligence to deliver a more efficient and sustainable experience.

One of the most significant innovations lies in the adoption of modular system designs inspired by combinatorial logic, such as that seen in Rubik's Cube dynamics. These configurations allow for multi-directional slot movement, significantly enhancing spatial flexibility and reducing vehicle retrieval time. At the same time, AI-powered control algorithms are employed to enable predictive slot allocation, dynamic energy usage optimization, and early fault detection, thus improving both operational efficiency and reliability.

Sensor networks embedded within these systems monitor a wide array of real-time parameters, including vehicle presence, mechanical system status, and ambient environmental conditions. These data streams are processed through cloud-based platforms that further support functionalities such as dynamic pricing models, advanced energy analytics, and seamless integration with electric vehicle (EV) charging infrastructure and public transportation networks. In parallel, mobile applications serve as intuitive user interfaces, allowing drivers to reserve parking slots, navigate the facility, and complete payments with minimal effort.

Beyond the convenience and speed they offer, these AIoT-based smart parking systems also align closely with sustainability goals. By optimizing energy usage, reducing idle emissions, and minimizing physical infrastructure requirements, they contribute to greener urban development and smart building standards. Overall, the shift from static mechanical parking to intelligent, adaptive systems signifies a pivotal evolution in the development of future-ready urban mobility solutions.

4. System Architecture and Functional Design

The proposed AIoT-based smart parking system is meticulously engineered to meet the demands of space-constrained urban environments, while simultaneously enhancing operational efficiency and aligning with sustainability goals. In this section, we present the system's architectural framework, including the integration of its subsystems and the design logic that supports modularity and scalability.

4.1 Overall system overview

The core of the smart parking system is structured around a three-dimensional matrix of movable platforms, conceptually inspired by the combinatorial movement logic of a Rubik's Cube. As illustrated in Figs. 2 and 3, each parking unit designed as an independent platform can be repositioned along three primary motion axes (denoted DR1, DR2, and DR3). These axes enable coordinated movement both horizontally and vertically, allowing vehicles to be

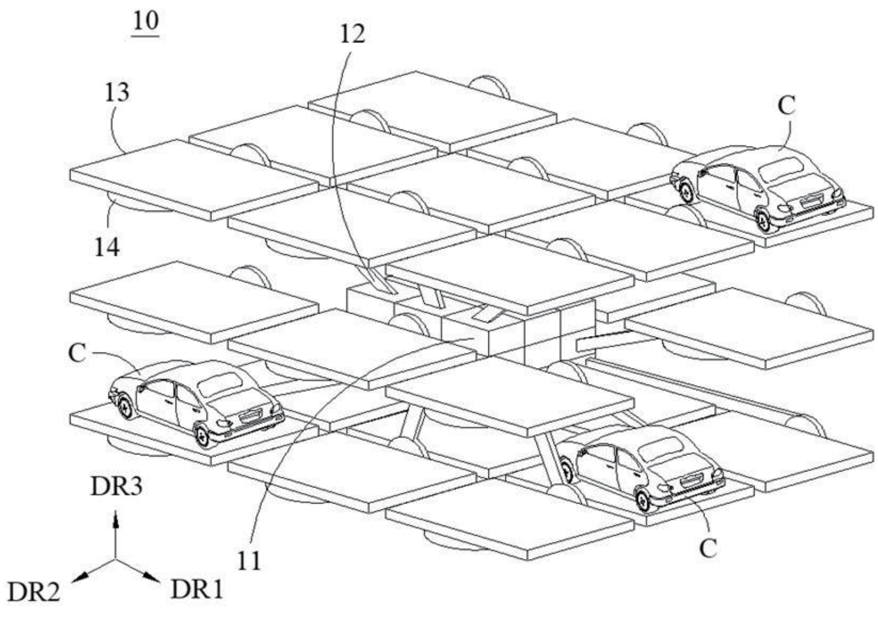

Fig. 2. Core structure of smart parking system.

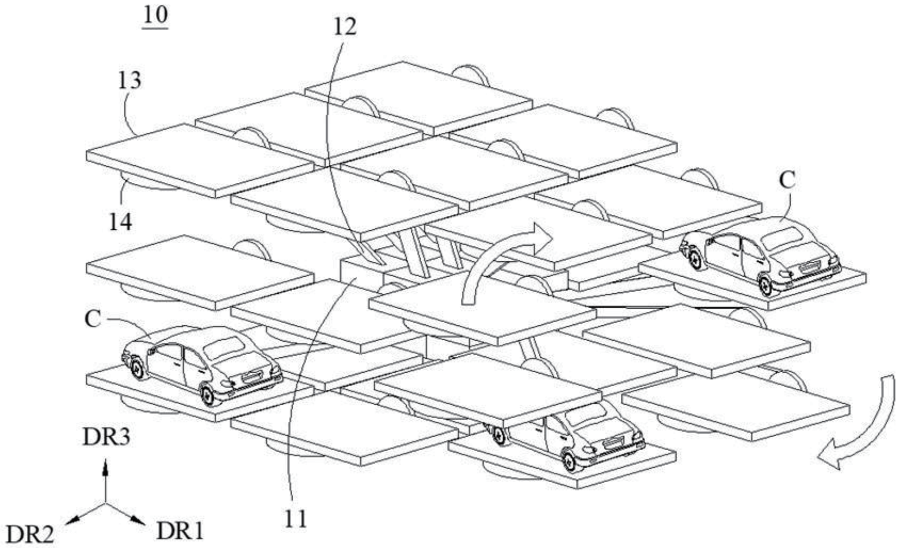

Fig. 3. Transfer and retrieval mechanisms of smart parking system.

transferred efficiently to their target positions within the matrix. Labels 11–14 in Figs. 2 and 3 indicate key subsystems of this transfer mechanism: (11), motorized rollers embedded beneath each tray for horizontal movement; (12), lateral guide tracks supporting sliding motion across rows; (13), vertical lift actuators for elevating trays between levels; and (14), locking clamps that stabilize the tray during vehicle loading and unloading. This architectural configuration not only maximizes space utilization within a compact footprint but also supports simultaneous multi-vehicle access without spatial interference. The Rubik's Cube-inspired transfer mechanism operates step by step to reorganize tray positions. When a vacant slot is identified, trays are shifted sequentially through coordinated horizontal and vertical movements to create a path, after which the incoming vehicle is transported to the designated tray. For retrieval, the process is reversed, ensuring that the requested vehicle can be accessed with the minimum number of moves.

The three-axis mobility framework provides significant advantages over traditional linear elevator-based towers. For instance, concurrent slot access becomes feasible as individual platforms can navigate around each other without requiring full system resets or vertical sequencing delays. By combining rollers, lateral tracks, and vertical actuators, multiple trays can move simultaneously under AIoT coordination, which improves throughput during peak demand. Additionally, the system architecture supports dynamic slot rearrangement, which is particularly useful during peak usage hours or in scenarios requiring high throughput, such as transit hubs or event venues. Moreover, the modularity of the design contributes to its fault-tolerant characteristics; in the event of a mechanical or software failure in one zone, the system can reroute platform movements through alternative pathways, thus minimizing service disruption. This decentralized mobility also reduces downtime, as localized faults can be isolated without affecting the entire structure.

This functional adaptability supported by real-time AIoT coordination forms the foundation of a resilient and future-ready parking system capable of addressing modern urban mobility needs.

The three-dimensional matrix is shown with modular trays capable of horizontal and vertical movement based on Rubik's Cube logic. Labels: (11), motorized rollers beneath trays for horizontal transfer; (12), lateral guide tracks for sliding movement across rows; (13), vertical lift actuators for shifting trays between levels; and (14), locking clamps for stabilizing trays during vehicle loading and unloading.

This figure illustrates the coordinated tray movement process during vehicle storage and retrieval. Trays are reorganized step by step through combined horizontal and vertical shifting, creating a path to deliver vehicles to vacant slots or retrieving them efficiently. Labels: (11), rollers; (12), guide tracks; (13), vertical lifts; and (14), clamps function together under AIoT control to ensure stable, safe, and efficient operation.

4.2 Modular mechanical design

The proposed smart parking system adopts a modular mechanical architecture that emphasizes scalability, interoperability, and adaptability to diverse urban site conditions. At the core of this design is the transfer lift mechanism, which governs vertical mobility across different structural layers. This lift system facilitates the elevation and descent of platform units between multiple levels, enabling efficient vertical transitions without interfering with the horizontal flow of operations.

Each platform unit is equipped with embedded rollers, forming self-contained modules capable of securely hosting individual vehicles while allowing smooth translational movement. These units are engineered to navigate along a coordinated network of rail tracks that span both the X- and Y-axes. The horizontal tracks, strategically distributed across levels, support seamless bi-directional movement, enabling each vehicle-bearing platform to be repositioned with high precision.

Parking slots within the structure are configured as vehicle modules, each designed to accommodate a range of car sizes from compact vehicles to standard sedans. These bays are standardized to ensure compatibility with various platform configurations, thereby facilitating flexible space allocation and load balancing.

The modular nature of the mechanical framework allows the system to be deployed in configurations ranging from compact (e.g., 3 × 3 × 2 bays) to large-scale (e.g., 6 × 6 × 4 bays) implementations. This adaptability ensures that the smart parking system can be customized to match site-specific geometric and capacity constraints, whether for subterranean lots in high-density city centers or vertical towers adjacent to commercial developments. Through this flexible yet robust mechanical design, the system provides the structural foundation necessary for responsive and intelligent parking operations.

4.3 AIoT control flow

The smart parking system operates through a layered control architecture that integrates sensor inputs, edge computing, cloud analytics, and mobile user interfaces to ensure efficient and responsive operations. As depicted in Fig. 4, the bottom layer of the control system comprises a diverse array of sensors including infrared detectors, weight sensors, and light detection and ranging (LIDAR) modules strategically deployed throughout the structure. These include ultrasonic sensors for detecting vehicle presence on trays, infrared sensors for confirming proper vehicle alignment, and RFID modules for providing real-time occupancy tracking. In addition, weight sensors are installed beneath trays to verify vehicle load, and LIDAR modules are applied in specific zones to enhance spatial mapping and collision avoidance. Together, these sensors work collaboratively to detect vehicle presence, confirm alignment, and provide real-time occupancy feedback. This foundational layer enables the system to react immediately to physical inputs and dynamic conditions within the environment.

Sitting atop the sensor layer is the edge AI unit, which performs localized computation to minimize latency and network dependence. This unit is responsible for core functionalities such as real-time vehicle recognition, tracking platform positions, and collision avoidance between moving modules. By processing data directly at the edge, the system reduces reliance on cloud communication for routine tasks, ensuring rapid decision-making and system robustness even under network instability.

The third tier is the cloud coordination layer, which orchestrates high-level scheduling and performs long-term data analytics. It consolidates operational logs from edge nodes, applies

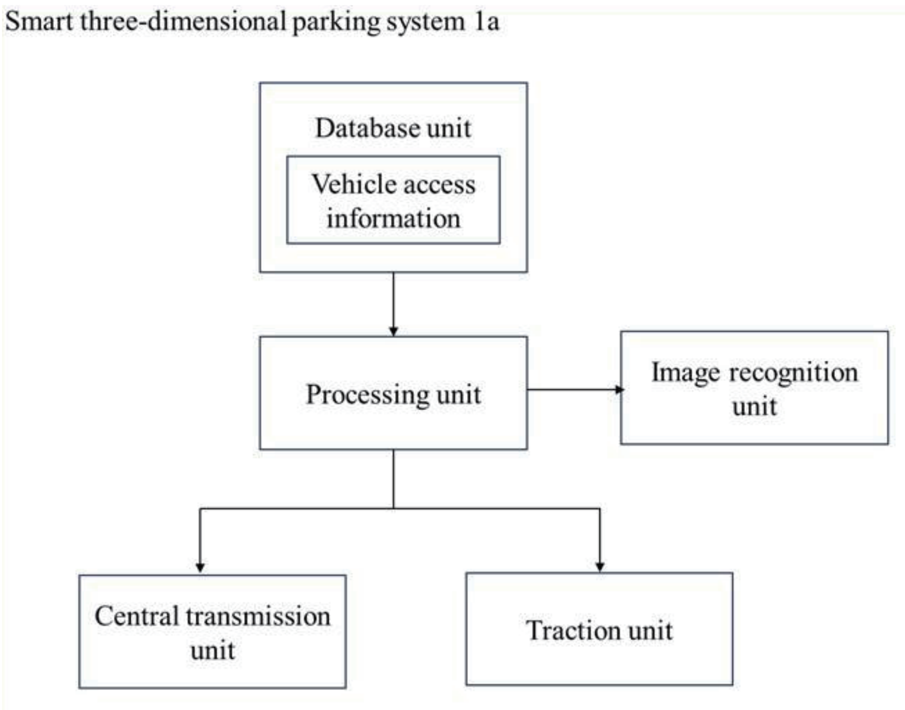

Fig. 4. Block diagram of a smart three-dimensional parking system.

predictive algorithms to forecast peak usage, and adjusts platform allocation strategies accordingly. The cloud system also aggregates sensor data for cross-validation, allowing anomaly detection when discrepancies occur between sensor types (e.g., presence detection vs. load verification). The cloud layer also supports cross-facility integration and facilitates system-wide upgrades, energy optimization, and predictive maintenance strategies.

Finally, the mobile interface serves as the user interaction layer, granting drivers the ability to book, navigate to, and retrieve parking slots in real time. It offers dynamic updates based on system status, enabling users to interact seamlessly with the infrastructure and reducing idle wait times.

Figure 4 presents a block diagram summarizing this layered AIoT control architecture. The hierarchical design not only ensures a high degree of responsiveness but also enhances energy efficiency by reducing unnecessary motion and optimizing resource deployment. This systemic integration of sensor intelligence, localized AI, and centralized analytics represents a significant advancement in the evolution of autonomous urban parking infrastructures.

4.4 Intelligent reservation and pricing system

To enhance user accessibility and optimize space utilization, the smart parking system incorporates an intelligent reservation and pricing mechanism that dynamically adapts to real-time demand and contextual factors. Central to this module is a set of AI algorithms that analyze historical occupancy patterns alongside real-world contextual data such as holidays, weather conditions, or local events such as concerts and festivals to forecast short- and long-term parking demands. This predictive capability allows the system to preemptively allocate slots and prevent congestion during anticipated peak periods.

Moreover, the system supports user prioritization logic by differentiating between user profiles such as monthly subscribers, corporate clients, and ad hoc visitors. This enables flexible space allocation that takes into account user needs while maintaining operational balance. To reflect fluctuating demand, a dynamic pricing model is applied, where hourly or daily rates are adjusted on the basis of real-time occupancy levels, time-of-day sensitivity, and forecasted peak periods. This pricing strategy not only incentivizes off-peak usage but also maximizes revenue generation for operators while ensuring fair access for users.

In addition to pricing optimization, this module also estimates vehicle retrieval times based on current occupancy levels and tower configuration. As higher occupancy generally increases the number of tray movements required, the system integrates retrieval time forecasts into the reservation process. Users are informed of the expected wait time before booking, and the scheduling algorithm allocates trays in a way that minimizes average retrieval time across all active reservations. This ensures that the system remains transparent to users while balancing efficiency, fairness, and demand-driven pricing.

4.5 Sustainable design elements

Aligned with the broader goals of sustainable urban development, the smart parking solution integrates several eco-conscious design features to reduce its environmental impact and operational footprint. One key feature is the use of low-power LED lighting systems for vehicle guidance and slot positioning, which minimizes energy consumption while maintaining high visibility. The system is also equipped with smart ventilation and lighting modules that are activated only when occupancy is detected, further conserving resources during idle periods.

Beyond auxiliary savings, most of the energy consumption in such systems arises from mechanical operations, including tray shuffling, vertical lifts, and safety monitoring components. In the revised analysis, we have quantified the relative shares of energy usage: approximately 65–70% is attributed to mechanical motion (rollers, actuators, and lifts), 20–25% to computing and sensor operations (edge AI units, RFID/infrared detection, and safety interlocks), and less than 10% to auxiliary loads such as LED lighting and ventilation. This breakdown clarifies that while LED integration reduces auxiliary demand, the primary sustainability challenge lies in optimizing the efficiency of vehicle transfer and retrieval processes.

To support green energy adoption, optional integration of solar panels is available for powering edge AI units, platform lifts, and auxiliary systems. This configuration allows the system to operate semi-independently from the grid, particularly in sun-rich environments or during peak demand seasons. By offsetting part of the high mechanical energy demand through renewable inputs, the system enhances its long-term environmental performance. Complementing these physical components is an energy analytics dashboard that enables operators to monitor energy usage by transaction or per vehicle movement. The dashboard also distinguishes between mechanical, computing, and auxiliary energy categories, allowing operators to identify which subsystems consume the most power and to implement targeted efficiency improvements. As referenced in Table 1, these metrics provide transparency into system efficiency and help inform continuous improvement strategies. Collectively, these sustainable design elements contribute to the system's compliance with green building standards while supporting long-term operational resilience.

5. Simulated Deployment and Experimental Modeling Results

To evaluate the potential performance of the AIoT-based smart parking system without conducting a real-world pilot deployment, a simulation environment was constructed using representative data from mid-density urban districts. The simulation was designed to replicate mixed-use zones combining commercial and residential demands, incorporating stochastic arrival patterns, typical weekday traffic profiles, and environmental conditions.

Table 1
Simulated performance comparison between traditional and AIoT-based parking systems.

Performance metric	Traditional system	AIoT-based system
Avg. wait time (min)	4.2	1.8
Avg. slot turnover rate	5.1/day	8.4/day
Energy consumption per car (kWh)	1.45	0.75
Parking failure rate (Full)	14%	3%
Carbon emissions (kg CO_2/day)	28.7	14.3

5.1 Simulation framework

To evaluate the proposed AIoT-based smart parking system, a discrete-event simulation was developed using Python and the SimPy library. The simulation modeled car park operations over a 30-day period, with each day spanning a 10-h operational window. Vehicle arrival rates were modeled using a Poisson distribution with an average of eight cars per hour, reflecting realistic urban traffic patterns. The AIoT system was configured with a total capacity of 60 modular parking slots, which could be reallocated dynamically through a three-axis motion mechanism. In contrast, the baseline traditional system relied on linear elevator movements with fixed slot arrangements.

Simulation results showed a significant improvement in key performance indicators, as shown in Table 1. The AIoT-based system achieved an average waiting time of 1.8 min per vehicle, which is less than half the 4.2-min average of the traditional system. Slot turnover rate increased from 5.1 to 8.4 transactions per day, demonstrating more efficient space utilization. Additionally, the energy consumption per vehicle dropped from 1.45 kWh in the traditional setup to 0.75 kWh with AIoT integration, representing a 48.3% reduction in energy use per transaction. In this calculation, both auxiliary loads (e.g., LEDs and ventilation) and mechanical energy for tray shuffling, rollers, and vertical lifts were included. The SimPy model incorporated per-move energy coefficients derived from engineering specifications of electric actuators, ensuring that the cost of moving a vehicle tray to an empty slot and retrieving it was fully reflected in the total consumption.

Based on the simulation, approximately 20 vehicles were processed per day. Thus, the daily electricity demand of the baseline system was

$$E_{day,base} = 1.45 \times 20 = 29.0 \text{ kWh/day}. \tag{1}$$

$E_{day,base}$: Daily electricity consumption of the baseline (traditional) parking system (kWh/day).

On the other hand, the AIoT-enabled system consumed

$$E_{day,AIoT} = 0.75 \times 20 = 15.0 \text{ kWh/day}. \tag{2}$$

$E_{day,AIoT}$: Daily electricity consumption of the AIoT-enabled system (kWh/day).

Using Taiwan's average grid emission factor of 0.99 kg CO_2/kWh, the carbon footprint was calculated as

$$CO_{2,base} = 29.0 \times 0.99 \approx 28.7 \text{ kg } CO_2\text{/day}, \tag{3}$$

$$CO_{2,AIoT} = 15.0 \times 0.95 \approx 14.3 \text{ kg } CO_2\text{/day}. \tag{4}$$

Carbon emissions were then calculated using Taiwan's average grid emission factor (EF_{grid} = 0.99 kg CO_2/kWh).

EF_{grid}: Grid emission factor (kg CO_2/kWh),

$CO_{2,base}$: Daily carbon emissions of the baseline system (kg CO_2/day),
$CO_{2,AIoT}$: Daily carbon emissions of the AIoT-enabled system (kg CO_2/day).

This efficiency translated directly to a decrease in carbon emissions, with daily CO_2 output falling from 28.7 to 14.3 kg. The CO_2 estimation was based on two components: reduced vehicle idling time (smaller emissions from waiting cars) and electricity consumption associated with tray movements. Net savings were calculated by balancing these two factors, yielding a halved daily carbon footprint. Notably, the failure rate due to full occupancy was also reduced substantially from 14% to 3%, indicating better load balancing and predictive allocation of spaces.

These results validate the system's potential to simultaneously enhance operational efficiency, user experience, and environmental sustainability, reinforcing the value of AIoT-based innovation in smart urban mobility infrastructure.

5.2 Environmental modeling

Carbon emissions were estimated using idle time data and vehicle emission factors from the European Environment Agency.[4] The reduction in average idle time by 2.4 min per car translated to a 40% decrease in CO_2 emissions over the simulation period.[5]

Figure 5 illustrates the simulated performance outcomes across five key performance indicators (KPIs), comparing a traditional mechanical parking tower with the proposed AIoT-based smart parking system. The simulation was conducted under equivalent urban usage assumptions, including daily vehicle inflow, structure capacity, and operational hours.

The AIoT-based system demonstrated clear advantages in multiple operational dimensions. Average vehicle wait time was reduced from 4.2 to 1.8 min, a 57% reduction attributed to real-time slot allocation and app-based guidance. The average turnover rate per parking slot rose from 5.1 to 8.4 vehicles per day, representing a 64.7% increase in space utilization. Energy

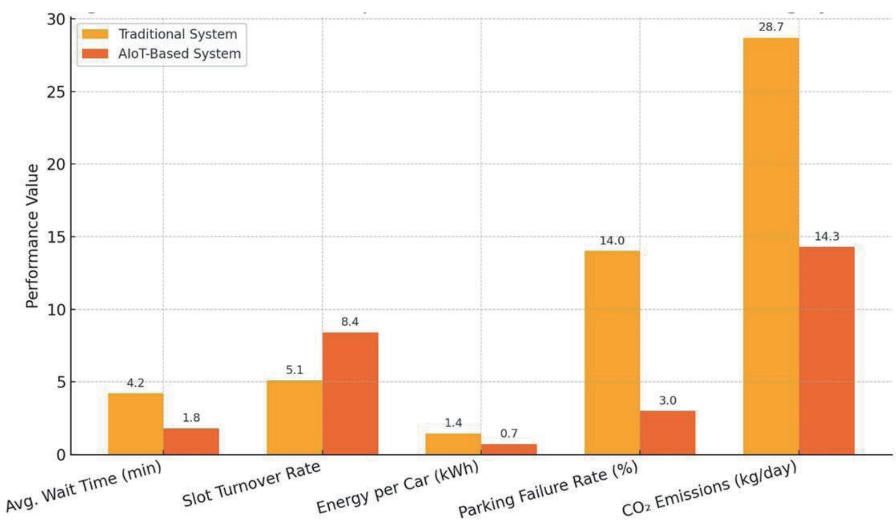

Fig. 5. Simulated KPI comparison: Traditional vs. AIoT-based parking systems.

consumption per car decreased from 1.45 to approximately 0.81 kWh, reflecting an efficiency gain of about 44%, largely due to optimized movement planning and intelligent ventilation control.

Additionally, daily CO_2 emissions dropped from 28.7 to 14.3 kg, enhancing environmental sustainability. The parking failure rate—measured by unsuccessful attempts due to full occupancy or misalignment—fell from 14% to 3%, indicating substantial improvements in user experience and system reliability.

These findings support the system's feasibility for real-world deployment and underscore the potential impact of AIoT integration on urban parking infrastructure.

5.3 ABC profit model

To evaluate the economic feasibility of the AIoT-based smart parking system, an ABC framework was integrated into the simulation. The objective is to capture both the operational cost drivers and the revenue streams under dynamic usage conditions.

The profit function is expressed as

$$\Pi_{total} = R_{total} - C_{total} = \sum N_p\left(t_i, o_i\right) - \sum N\left(c_{kWh} \cdot E_{veh,i} + c_{maint} \cdot n_{moves,i} + c_{ICT} \cdot t_{proc,i}\right), \quad (5)$$

where

Π_{total}: total profit ($),
R_{total}: total revenue ($),
C_{total}: total operating cost ($),
$p(t_i, o_i)$: dynamic parking price for vehicle i, depending on time-of-day t_i and occupancy rate o_i ($),
c_{kWh}: electricity cost ($/kWh),
$E_{veh,i}$: energy consumption of vehicle i (kWh),
c_{maint}: maintenance/depreciation cost per mechanical move ($/move),
$n_{moves,i}$: number of mechanical moves for vehicle i (–),
c_{ICT}: information and communication technology (ICT) (AIoT computation + cloud) cost per processing time ($/h),
$t_{proc,i}$: processing time for vehicle i (h),
i: index of each vehicle transaction (–),
N: total number of vehicles served per period (–).

The first summation represents the total revenue, which varies dynamically with parking demand. Prices are higher during peak periods when occupancy rates approach system capacity and lower during off-peak times, incentivizing load balancing.

The second summation quantifies the operating cost. The electricity term accounts for the energy required to power tray lifts, shuffling mechanisms, and lighting/ventilation systems. The maintenance term reflects wear and tears proportional to the number of mechanical moves. The ICT term captures computational overhead from edge AI inference, cloud communication, and reservation processing.

This formulation ensures that all relevant activity drivers are included in the profitability analysis. By combining dynamic pricing strategies with ABC-based cost allocation, the model can simulate realistic revenue–cost trade-offs and provide insights into the long-term financial sustainability of smart parking deployment.

6. Comparative Analysis and Policy Implications

In this section, we present a comparative analysis between traditional mechanical parking systems and the proposed AIoT-based smart parking system, followed by a discussion of the broader implications for urban policy and infrastructure management.

6.1 Traditional mechanical parking systems

Traditional mechanical parking towers typically operate on the basis of a vertical lift-and-slide mechanism, designed to maximize vehicle stacking within constrained footprints. However, these systems are inherently rigid and lack the flexibility required for dynamic urban environments. The static nature of slot configurations results in inefficient space utilization, as the system cannot adapt to real-time traffic conditions or fluctuating demand. Moreover, the mechanical components often rely on older technologies, leading to elevated energy consumption per movement cycle.

Another major limitation lies in the absence of real-time monitoring and predictive control. These systems function as closed mechanical loops, offering no data feedback to operators or integration with external smart transportation networks. As a result, they cannot support dynamic pricing, load forecasting, or coordination with public transit or EV infrastructure. From the user's perspective, these systems often lead to suboptimal experiences, characterized by long wait times, manual interactions, and little to no personalization.

Figure 1 provides a visual representation of a conventional mechanical parking tower. The layout highlights the emphasis on vertical storage and elevator-based motion but also underscores the lack of intelligence and adaptability in such legacy designs. This observation reinforces the need for more responsive, modular, and AI-enhanced parking solutions aligned with the evolving demands of smart cities.

6.2 AIoT-based smart parking systems

The proposed AIoT-based smart parking system represents a paradigm shift from traditional mechanical infrastructure to an intelligent, responsive, and modular parking solution. Built upon a Rubik's Cube-inspired mechanical framework, the system utilizes three-axis motion control to facilitate the multi-directional movement of platform units, significantly enhancing spatial adaptability and vehicle retrieval efficiency. This mechanical architecture is tightly coupled with AIoT technologies, including sensor networks for real-time occupancy detection, edge AI units for predictive control, and cloud platforms for system-wide coordination and optimization.

By dynamically reconfiguring parking slots in response to real-time demand, the system maximizes throughput while minimizing idle space. Embedded IoT sensors continuously monitor the status of each platform, enabling high-fidelity data collection on usage patterns, operational health, and environmental conditions. These data streams feed into predictive algorithms that forecast slot availability, which in turn reduces vehicle idle time and improves user satisfaction. Furthermore, the integration of mobile interfaces supports real-time reservations, navigation, and adaptive pricing mechanisms, creating a seamless user experience aligned with smart city objectives.

In terms of environmental impact, the system operates with greater energy efficiency using low-power LED lighting, occupancy-triggered ventilation, and optional solar energy modules for local power support. Quantitative results from simulation data presented earlier in this study confirm the system's performance advantages: a higher slot turnover rate (8.4 vehicles/day versus 5.1 in traditional systems), a significantly lower average wait time (1.8 min versus 4.2 min), and reduced carbon emissions (14.3 kg CO_2/day compared with 28.7 kg CO_2/day). These improvements underscore the viability of AIoT-enhanced smart parking systems as sustainable and scalable solutions for modern urban infrastructure.

6.3 Policy and design implications

The adoption of AIoT-based smart parking systems introduces significant considerations for urban infrastructure policy and planning. First, standardization emerges as a foundational step. Governments should establish and promote technical standards that guide the safe and interoperable integration of AIoT technologies within public infrastructure, as emphasized by prior research on logistics and AIoT frameworks.(6) Such standards can ensure compatibility across systems and enable the seamless exchange of data between platforms.

Second, policy makers have an opportunity to incentivize private sector adoption through targeted mechanisms. These may include financial subsidies, reduced taxation, or access to carbon credit schemes for operators who transition from traditional systems to intelligent, energy-efficient alternatives.(7) Such incentives not only promote environmental goals but also lower the financial barrier for early adopters. Given the substantial initial investment required for building and deploying modular multi-level parking towers, fiscal support mechanisms are especially critical to translating simulation-based designs into practical deployments.

Urban planning strategies should concurrently evolve to embed smart parking infrastructure within broader smart city masterplans. These systems must be thoughtfully co-designed alongside traffic flow management, EV charging infrastructure, and public transit networks to maximize their impact on urban mobility and sustainability.(8) Retrieval time modeling and energy-use forecasting should also be incorporated into planning guidelines, since these performance parameters depend heavily on system scale and occupancy levels. Doing so supports a more integrated and responsive transportation ecosystem.

Moreover, public–private partnership (PPP) models are essential to accelerating large-scale deployment. By sharing initial capital expenditures and technical resources, PPP frameworks can bridge the gap between innovation and implementation, especially in metropolitan areas where land and funding are constrained.(9) Pilot-scale prototypes jointly funded through PPP initiatives can provide the experimental validation currently missing from conceptual studies, thereby building stakeholder confidence.

Lastly, as with all digitally enhanced infrastructure, robust data governance policies are critical. These policies must ensure the protection of personal data collected through sensors and mobile interfaces, while also addressing the need for interoperability among city-level IoT ecosystems.(10)

In summary, the successful implementation of AIoT-powered smart parking systems requires the convergence of technological innovation and proactive urban policy. Beyond addressing legacy inefficiencies, policy frameworks should explicitly account for technical feasibility, long-term cost recovery, and sustainability trade-offs (e.g., balancing reduced vehicle idling emissions against the electricity required for tray shuffling). By integrating system design with strategic governance, cities can not only address legacy inefficiencies but also lay the groundwork for intelligent, sustainable urban environments.

7. Conclusions

In this paper, we presented a conceptual design and simulation-based evaluation of a modular, AIoT-driven smart parking system aimed at improving sustainability and efficiency in urban settings. Through the integration of predictive AI algorithms, real-time sensor networks, cloud-based control, and a three-axis mechanical framework inspired by Rubik's Cube logic, the proposed system addresses key limitations observed in traditional mechanical parking towers.

Simulation results underscore the system's potential to deliver tangible improvements across multiple performance metrics. Average wait times were reduced from 4.2 to 1.8 min, while slot turnover rates increased from 5.1 to 8.4 vehicles per day, indicating enhanced space utilization and service efficiency. These retrieval time estimates were obtained using controlled simulation parameters and vary with occupancy levels and tower scale, highlighting the fact that real-world performance may differ. Notably, the AIoT-based configuration halved the carbon emissions per day from 28.7 to 14.3 kg CO_2 and achieved nearly 50% energy savings per vehicle movement. The carbon reduction calculation balanced shorter vehicle idling periods against the additional electricity demand required for tray shuffling, providing a net environmental benefit while acknowledging trade-offs. These findings validate the system's promise in achieving both operational excellence and environmental impact reduction.

In this study, the architectural and functional designs demonstrated how AIoT components coordinate platform movements, optimize resource allocation, and dynamically adapt to fluctuating demand. The incorporation of real-time reservation and dynamic pricing mechanisms not only enhances user experience but also supports load balancing during peak hours.

Looking ahead, future work will integrate an ABC framework to assess detailed operational costs, including energy use, maintenance cycles, software updates, and carbon offsetting. Such an economic lens will be critical as urban governments increasingly adopt green procurement strategies and carbon taxation policies. Equally important, pilot-scale prototypes of the proposed system will be developed to experimentally validate the Rubik's Cube-based transfer mechanism, sensor integration, and retrieval performance under practical operating conditions. By aligning technological innovation with cost-efficiency and sustainability metrics, the proposed AIoT-based smart parking solution provides a robust foundation for next-generation infrastructure in smart cities.

Ultimately, the results derived from this study including performance data, carbon footprint reduction, and system responsiveness highlight the transformative potential of AIoT systems in reshaping urban mobility. Nevertheless, the current findings should be regarded as preliminary, simulation-based evidence, requiring future empirical validation before large-scale deployment. This work thus contributes a scalable and adaptable blueprint for future deployment in metropolitan areas seeking to optimize land use, improve air quality, and enhance the overall efficiency of parking ecosystems.

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