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# A Comprehensive Survey on Infrastructure-Independent and Adaptive Ultrasonic Parking Slot Detection Systems

Akshath V Nadig[1], Ajay Jayaram[2], Hruthik S[3], Pavan Kumar MK[4]
*Dept. of CSE, Sapthagiri College of Engineering*

***Abstract: Urban infrastructure frequently demonstrates vulnerability during extreme conditions and complicated parking scenarios, where depending on expensive LiDAR or vision-centric modules results in operational failures during severe weather or network blackouts. This study introduces an innovative, software-oriented framework formulated to close the divide between economical consumer hardware and highly accurate spatial recognition.***

***The proposed model is driven by the Adaptive Spatial Positioning (ASP) algorithm, employing conventional ultrasonic transducers to secure exact boundary localization by evaluating multiple sound wave reflections. To counteract the "ghost" signals and acoustic interference common in ultrasonic devices, the architecture integrates an adaptive filtering protocol and a decision-tree fusion mechanism analyzing inputs from ipsilateral sensors. Engineered for maximum computational brevity, the ASP logic functions on a highly restricted memory footprint, rendering it exceptionally appropriate for standard microcontrollers.***

***To corroborate the proposed architecture, a physical prototype encompassing four parking bays serves as a scaled proof-of-concept. It processes a variety of ultrasonic metrics to pinpoint physical obstacles alongside the intervening vacant areas. Final quantitative metrics concerning processing speed, memory utilization, and boundary detection precision will be explicitly measured following the conclusion of the hardware trials. By combining a localized ESP32 processor with Wi-Fi connectivity, a Backend API, a MySQL Database, and a live Web Dashboard, the system guarantees uninterrupted remote tracking and data archiving. This bypasses the need for resource-heavy, cloud-dependent control units for essential detection tasks. Ultimately, this inquiry provides a highly scalable, infrastructure-agnostic strategy for automated parking using widely available components.***

***Keywords: Adaptive Spatial Positioning (ASP), ultrasonic sensors, infrastructure-independent architecture, IoT, Web Dashboard, edge localization, and Automated Parking Systems.***

## I. INTRODUCTION

The ongoing challenge of urban parking is heavily compounded by the operational constraints of modern automated sensors. Contemporary parking solutions largely depend on computer vision—leveraging high-definition cameras and neural networks—or LiDAR setups that construct 3D environments via laser emission. Although technologically sophisticated, these methods possess notable disadvantages: they are cost-prohibitive, require substantial processing power (often necessitating GPUs), and remain highly fragile in shifting environmental conditions. In scenarios lacking adequate visibility—such as intense rain, dense fog, or blinding sunlight—both camera and LiDAR mechanisms frequently malfunction. Additionally, optical devices are prone to errors caused by surface reflectivity, where vehicles with matte or dark finishes absorb light, generating inaccurate occupancy evaluations. To navigate these obstacles, developers often turn to ultrasonic sensors as a pragmatic substitute; nevertheless, deploying a purely ultrasonic framework introduces distinct scientific hurdles. Because sound waves propagate spherically and typical ultrasonic components feature wide beam angles, a singular physical boundary can reflect multiple overlapping echoes. When attached to a moving vehicle, this physical trait yields deceptive boundary readings, heavily disrupting the accurate mapping of parking slot perimeters. To bridge the operational divide between cost-intensive visual arrays and imprecise sonar interpretations, this initiative proposes "Smart Sonar Parking: Adaptive Ultrasonic Parking Slot Detection." This budget-friendly, microcontroller-driven system operates with full autonomy onboard the vehicle, eliminating the necessity for external smart-city networks or web-linked camera grids.

The cornerstone of this model is the Adaptive Spatial Positioning (ASP) algorithm. This algorithmic engine translates raw Time-of-Flight (ToF) metrics gathered by standard HC-SR04 sonar units into exact spatial geometries. By applying an adaptive filter and scrutinizing echo behaviors, the software actively discards erroneous data points and non-perpendicular surface reflections. Consequently, the primary detection phase executes entirely within the local ESP32 hardware, reserving the robust IoT infrastructure exclusively for remote data visualization and historical storage.

## II. LITERATURE SURVEY

1) Nupur Kulkarni et al. (2026): Detailed an IoT-centric Smart Parking architecture employing infrared (IR) sensors paired with an ESP32 for instantaneous slot reservations. The primary benefit is a 94% accuracy rate coupled with a dynamic user map intended to decrease transit time. Conversely, the model is constrained by the environmental fragility of IR technology, which is easily disrupted by ambient sunlight or obscured by highly reflective vehicle surfaces.
2) Khairun Nesa et al. (2025): Authored a study on an Image Processing and IoT-driven parking recognition model leveraging YOLOv11 and a LoRa-equipped Raspberry Pi. The setup boasts an impressive detection rate of 99.98% alongside steadfast data routing. However, it suffers from heavy computational demands that mandate advanced processing hardware, alongside the inherent instability of optical systems during inclement weather.
3) N. Srivani et al. (2025): Introduced an automated allocation protocol utilizing an Arduino-driven Optical Character Recognition (OCR) module for license plate extraction. The strength of this approach lies in the frictionless automation of slot assignments, minimizing manual oversight. Its critical weakness is an absolute reliance on unobstructed optical clarity, making it virtually useless during fog, heavy downpours, or nighttime operations.
4) Hanouf Albatati et al. (2025): Developed a unified sensor network for parking that features an integrated chatbot to streamline urban traffic flow. The chief advantage is its capacity to pinpoint empty spaces instantaneously, thereby alleviating driver fatigue and lowering fuel consumption. While explicit vulnerabilities were not thoroughly dissected in the text, such standard sensor systems inherently inherit the environmental susceptibilities highlighted across similar studies.
5) Balaram Reddy et al. (2024): Designed an automated parking model infused with AI and IoT that merges computer vision with ultrasonic data. The framework effectively aids in vehicle alignment, registering an AUC performance metric of 0.82. The drawback remains the substantial bandwidth and processing latency intrinsic to video-centric perception models.
6) M. C. Chinnaiah et al. (2024): Formulated a geometry-focused parking aid that utilizes ultrasonic sensor fusion tailored for robotic deployment. Its primary asset is the exact synchronization of parking voids to the specific volumetric dimensions of the robot. The limitation is its dependence on bespoke FPGA hardware accelerators, which strays from the objective of utilizing economical, off-the-shelf microcontrollers.

## III. METHODOLOGY

To bypass the fundamental weaknesses inherent to optical and LiDAR infrastructures, the "Smart Sonar Parking" model employs a decentralized, self-sustaining methodology. The framework operates through a multi-tiered architecture, funneling data across sequentially optimized phases.

### A. *System Architecture and Physical Demonstration*

The structural and networking blueprint is tailored for economical, edge-computing scenarios. The hardware tier incorporates several HC-SR04 ultrasonic devices orchestrated by an ESP32 chip. The experimental prototype simulates four parking spots as a proportional physical demonstration. Rather than relying on a rudimentary "one sensor per vehicle" methodology, the system aggregates multiple sonar readings to map physical perimeters and calculate the intermediate empty zones. For external monitoring, the setup transmits metrics over Wi-Fi to a Backend API, subsequently interfacing with a MySQL Database and a graphical Web Dashboard.

### B. *Data Acquisition & Signal Conditioning*

The hardware emits 40kHz acoustic pulses that bounce back as echoes to the HC-SR04 receivers. The ESP32 functions as the primary processing node, tasked with:

1) Continuously broadcasting 40kHz ultrasonic frequencies.
2) Logging the raw Time-of-Flight (ToF) metrics from the returning acoustic waves.
3) Translating these ToF figures into preliminary spatial coordinates relative to the vehicle's position.

### C. *Adaptive Filtering*

Following the initial data capture, localized algorithms scrub the dataset to remove inconsistencies:

1) Signal Smoothing: Employs a moving average mathematical filter to neutralize hardware jitter and physical vibrations.
2) Outlier Rejection: Activates a threshold-dependent "Reflection Guard" designed to purge phantom boundaries generated by non-orthogonal surface echoes.

### D. *Adaptive Spatial Positioning (ASP) & Mapping*

Post-filtration, the central ASP algorithm converts the isolated data points into a cohesive spatial diagram.

1) Spatial Transformation: Shifts the vehicle-centric data points into fixed, absolute environmental coordinates.
2) Void Identification: Scans the resulting topographical map to locate structural voids (available parking bays) amidst physical barriers.
3) Dimension Calculation: Computes the precise geometric length and width of the located voids to ascertain parking compatibility.

### E. *Decision Tree Fusion and IoT Integration*

To conclude the detection cycle, the framework merges sensor data and synchronizes with the web layer:

1) Data Fusion: Implements a decision tree logic to synthesize perimeter data gathered by sensors on identical sides, filtering out residual acoustic noise.
2) Remote Storage & Display: Broadcasts the validated vacancy status over Wi-Fi to the Backend API. The MySQL architecture logs the specific bay, dimensions, suitability status, raw sensor metrics, timestamps, and real-time occupancy. The Web Dashboard then renders this data visually for remote users.

### F. *Advantages of the Proposed Method*

1) High reliability during adverse weather and poor lighting.
2) Self-contained mapping via localized edge processing.
3) Utilization of highly affordable, commercially available hardware.
4) Extensive database tracking for dynamic web visualization.
5) Algorithmic geometry filtering that actively suppresses false sonar readings.

### G. *Expected Outcome & Core Flow*

The system strictly follows this operational sequence: HC-SR04 -> ESP32 -> ToF -> filtering -> ASP -> spatial mapping -> void detection -> dimension calculation -> sensor fusion -> parking decision. While the conceptual design prioritizes maximum computational efficiency, the precise statistics regarding edge localization accuracy, execution latency, memory limits, and exact positioning drift will be thoroughly documented upon the completion of the physical scaled-model testing.

## IV. DISCUSSION

An evaluation of current literature alongside the newly engineered ASP parking framework illustrates a clear paradigm shift from manual space estimation toward responsive, automated algorithms. Historical approaches leaned heavily on visual confirmation or capital-intensive smart-city grids, both of which proved financially and operationally unstable. Merging localized edge computation with contemporary web frameworks now facilitates the rapid and resilient identification of urban parking availability.

A recurrent theme within the analyzed literature is the realization that no singular sensor type remains infallible across all environments. Optical and camera-based architectures experience catastrophic drop-offs in accuracy within "visual dead zones" or when scanning vehicles with light-absorbing paint. Conversely, LiDAR networks provide exceptional precision but demand exorbitant financial and computational investments.

The advanced "Smart Sonar Parking" structure resolves these friction points by uniting economical ultrasonic devices (HC-SR04) with the bespoke Adaptive Spatial Positioning (ASP) software, executed directly on an ESP32 module. Acoustic measurements yield stable ToF metrics independent of ambient light or precipitation, while the ASP logic decodes the shifting geometric boundaries of available slots. By funneling these readings through a decision tree fusion protocol, the likelihood of logging false positives is dramatically diminished.

1A pivotal aspect of this research is the deliberate separation between the edge processing unit and the overarching web database. Running the complex spatial math and adaptive filters natively on the ESP32 guarantees that the core detection capabilities remain completely unreliant on external infrastructure. Concurrently, transmitting the finalized parking verdicts via Wi-Fi to a Backend API and MySQL Database allows for centralized tracking and live rendering on a Web Dashboard. This dual-pronged strategy ensures a vehicle can autonomously navigate and map its surroundings while seamlessly feeding valuable spatial metrics back to a larger surveillance network.

The true viability of automated parking technologies must be evaluated against practical implementation metrics, including execution speed, hardware costs, and scalability. The trajectory of intelligent slot detection is decisively pointing toward decentralized edge processing coupled with data-rich web portals. The exact quantitative benchmarks for this specific ASP architecture will be rigorously evaluated and published following the imminent prototype trials.

## V. CONCLUSION

Mitigating urban parking congestion and deploying dependable automated assistance are critical for the evolution of modern smart cities. Traditional spatial mapping and infrastructure-reliant sensor arrays are frequently cost-prohibitive, sensitive to environmental shifts, and vulnerable to systemic failure. While camera modules supply detailed visual data under perfect conditions and LiDAR maps highly accurate 3D topographies, both suffer from severe weaknesses tied to weather interference and massive processing requirements.

To overcome these barriers, the proposed Smart Sonar Parking framework capitalizes on affordable ultrasonic sensors, the Adaptive Spatial Positioning (ASP) algorithm, decentralized local computing via an ESP32 chip, and a resilient Web/Database networking layer. By evaluating overlapping ultrasonic echoes onboard the vehicle, the model successfully isolates physical boundaries and available spaces without requiring supplementary visual inputs. Additionally, by recording detected bays, exact dimensions, viability statuses, and timestamps within a MySQL ecosystem, the architecture effectively links self-sufficient detection with comprehensive remote tracking. Finalized metrics regarding precision, processing speed, and network latency will be systematically extracted during the forthcoming experimental phase. Through persistent innovations in edge computing, vehicle-centric parking models are poised to become significantly more robust, accessible, and proactive.

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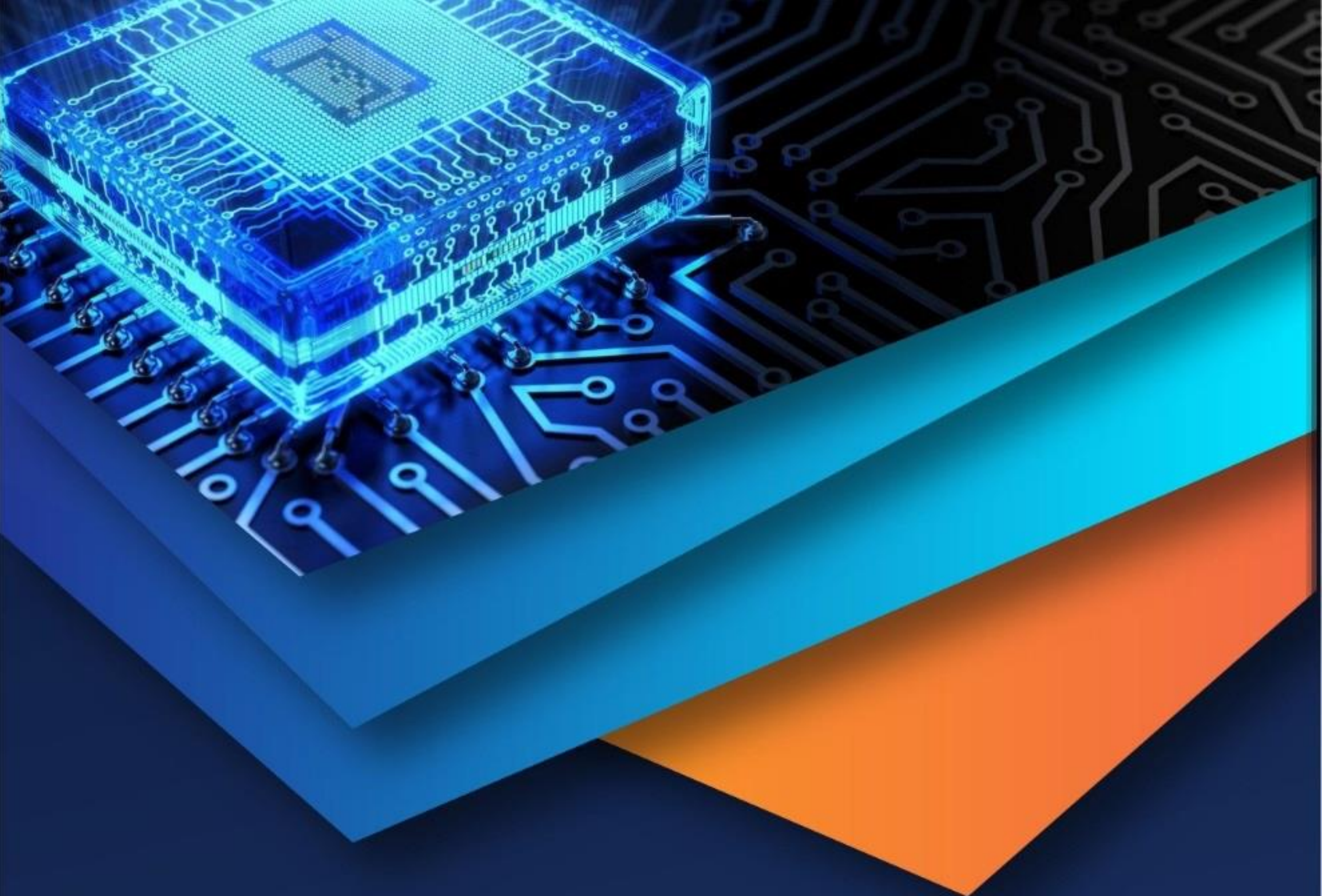

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