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Efficient Grid-Based Parking Navigation Using Heuristic Path Planning

Pratik Godase[1], Pavan Pandit[2], Rutuja Patil[3], Prof. M. M. Zade[4]
[1,2,3]UG Students, Department of Electronics and Telecommunication Engineering,
[4]Assistant Professor, Department of Electronics and Telecommunication Engineering
SKN Sinhgad College of Engineering, Pandharpur

Abstract: *In modern urban environments, the efficient utilization of parking spaces has become a critical challenge due to rapid vehicle growth and limited infrastructure. This paper presents an intelligent path planning approach for grid-based parking lots using the A* (A-star) algorithm to determine the optimal path between a designated source and destination point. The parking lot is modelled as a two-dimensional grid where certain blocks represent obstacles corresponding to occupied or restricted spaces. The proposed system, implemented in Python, dynamically computes the shortest feasible path while avoiding obstacles, ensuring minimal traversal cost and time. The A* algorithm integrates heuristic estimation with actual movement cost to efficiently explore possible routes and identify the most cost-effective path. Simulation results demonstrate accurate and reliable path generation in complex grid configurations, validating the algorithm's capability to enhance autonomous navigation and smart parking management. This research contributes toward the development of intelligent parking systems that can be extended to autonomous vehicles and real-time traffic control applications.*

Keywords: A* Algorithm, Path Planning, Grid Parking System, Optimal Pathfinding, Python Implementation, Intelligent Transportation Systems

I. INTRODUCTION

The rapid urbanization and continuous growth of vehicle ownership have intensified the challenges of efficient traffic and parking management. With the rising number of vehicles and limited infrastructure, urban areas are facing a severe shortage of parking spaces. This not only results in traffic congestion and increased fuel consumption but also contributes to higher emissions and driver frustration. According to multiple urban mobility studies, nearly 30–40% of city traffic congestion occurs due to vehicles searching for available parking spaces. Hence, there is an urgent need for intelligent systems capable of automating and optimizing parking operations through advanced computational algorithms and real-time decision-making.

Traditional parking systems largely depend on manual searching or basic guidance indicators, which are often inefficient in handling dynamic vehicle flow or obstacle-filled environments. Modern intelligent transportation systems (ITS) are increasingly focusing on integrating computational intelligence, automation, and sensing technologies to design smart parking systems. These systems aim to minimize search time, improve vehicle movement, and ensure optimal space utilization. A core component in achieving these objectives is an efficient pathfinding algorithm that can navigate vehicles within parking lots, avoiding obstacles while ensuring the shortest route between the entry and target points.

In a structured parking lot, the environment can be modeled as a two-dimensional grid, where each cell represents a possible position. The grid may contain free cells (navigable areas) and blocked cells (representing parked vehicles, pillars, or restricted zones). The challenge lies in determining the optimal route from a given source cell (entry point) to a destination cell (available parking slot) while minimizing computational complexity and traversal cost. Gridbased modeling allows discrete representation of the environment, simplifying the implementation of pathfinding algorithms in both simulation and real-world applications.

Among the various pathfinding algorithms, the A* (A-star) algorithm has proven to be one of the most efficient and widely adopted techniques for shortest path computation in graph and grid-based environments. The algorithm combines

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the strengths of Dijkstra's Algorithm, which guarantees the shortest path based on accumulated cost, and Greedy Best-First Search, which focuses on heuristic estimations to accelerate the search. A* computes a cost function *f(n)* for each node, which is the sum of two components — *g(n)* (the exact cost from the start node to the current node) and *h(n)* (the estimated cost from the current node to the destination). By balancing these two parameters, A* effectively reduces unnecessary exploration, achieving both optimality and efficiency.

This balance between exploration and exploitation makes A* highly suitable for applications requiring real-time decision-making and precise movement control. In smart parking systems, the algorithm can dynamically generate the shortest path while accounting for static obstacles like occupied parking slots and barriers. Furthermore, A* can be extended to handle dynamic conditions such as moving vehicles or temporary obstructions by continuously updating node values and recalculating the optimal route.

The proposed system, titled "Optimal Path Finding in Grid Parking Using A* Algorithm," implements the A* algorithm in a grid-modeled parking lot environment using Python programming. The system initializes a predefined grid, sets random obstacles, and allows users to select the source and destination points. The A* algorithm then traverses the grid, computes the most cost-effective path, and visually displays the optimal route while distinguishing free, blocked, and visited cells. Python is chosen due to its flexibility, open-source libraries, and extensive support for computational modeling and visualization. Libraries such as NumPy, Matplotlib, and optionally Pygame are utilized for grid generation, path visualization, and interactive simulations.

This implementation not only demonstrates the working of the A* algorithm but also highlights its potential in real-world parking automation. By simulating obstacle avoidance and costefficient movement, the system can serve as a prototype for integration with IoT-based parking systems, autonomous vehicles, or smart city frameworks. The algorithm's low computational complexity, deterministic output, and heuristic-driven adaptability make it ideal for real-time embedded applications where quick response and high accuracy are essential.

Moreover, this approach can significantly improve the operational efficiency of parking facilities. Vehicles guided by such systems can minimize time spent searching for parking spaces, reduce idle fuel consumption, and contribute to lower carbon emissions. In addition, this intelligent routing can be integrated with cloud-based management systems to enable datadriven analytics for parking demand prediction, congestion management, and urban traffic optimization.

The study presented in this paper emphasizes the role of computational intelligence and heuristic-based optimization in designing next-generation parking solutions. The results derived from simulation demonstrate that the A* algorithm provides accurate and fast convergence to the shortest path, even in dense obstacle conditions. The performance can be further enhanced by adapting heuristic functions or incorporating dynamic obstacle detection mechanisms using sensors or computer vision modules.

II. LITERATURE REVIEW

R. K. Sharma et al. [1] proposed a grid-based parking management system that employs the Dijkstra algorithm to find the shortest path between entry and parking slots. The system models the parking lot as a two-dimensional grid where occupied slots are treated as obstacles. While the approach successfully identifies the shortest route, it demonstrates higher computational complexity in large grids due to exhaustive node exploration, which can lead to delays in realtime applications.

M. Gupta and S. Verma et al. [2] presented a smart parking navigation system using the Breadth-First Search (BFS) algorithm. The study focused on dynamically updating available parking spaces and providing drivers with the shortest path in real time. Although BFS ensures path completeness, the method does not incorporate heuristics and therefore may explore unnecessary nodes, resulting in increased execution time for larger parking lots.

J. Lee et al. [3] introduced an intelligent parking guidance system based on A* pathfinding for autonomous vehicle navigation. The authors demonstrated that integrating heuristic cost estimation with actual travel distance enables faster computation of the optimal route compared to traditional exhaustive search algorithms. The system also accounted for dynamic obstacles by recalculating the path when temporary blockages were detected, enhancing real-time adaptability.

S. Chen and H. Wang et al. [4] explored an IoT-enabled parking framework that combines occupancy sensing with A* algorithm-based path planning. In their approach, parking lot sensors continuously monitor slot availability, while the A*

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algorithm computes the most efficient route to a free parking space. The study highlighted the benefits of heuristic-guided search, including reduced computation time and improved parking efficiency, particularly in complex or large-scale parking environments.

P. Kumar et al. [5] developed an autonomous parking system using a combination of grid mapping and A* pathfinding. Their study emphasized reducing the computational load by limiting the search space to relevant sub grids near the source and destination. Results demonstrated that path computation time decreased significantly compared to full-grid searches, making the approach suitable for real-time applications in constrained parking environments.

L. Zhang and Y. Li et al. [6] proposed a hybrid pathfinding algorithm that combines A* and Dijkstra to improve path optimality in dynamic parking lots. The system uses Dijkstra's exhaustive search for smaller sections of the grid while A* guides the overall path planning. This hybrid approach balances computational efficiency and shortest-path accuracy, particularly in scenarios with multiple temporary obstacles.

A. Fernandez et al. [7] investigated robotic navigation in indoor parking scenarios using A* with dynamic obstacle avoidance. Their model integrated sensor inputs to detect moving obstacles, such as pedestrians or other vehicles, and recalculated paths in real-time. The study highlighted the algorithm's adaptability, demonstrating successful navigation in unpredictable environments while maintaining optimal path length.

K. R. Singh and M. Bansal et al. [8] explored a smart parking assistant that uses heuristicdriven pathfinding for electric vehicles. The system factors in not only distance but also energy consumption while navigating to a free parking slot. By applying A* with a weighted cost function, the algorithm selects routes that minimize both travel distance and energy usage, demonstrating the versatility of heuristic-based path planning.

T. Y. Kim et al. [9] presented a simulation-based analysis of A* and its variants in urban parking grids. The research compared traditional A* with Weighted A* and Adaptive A* algorithms, showing that heuristic weighting can significantly reduce node expansion and computational time, particularly in large-scale parking lots with multiple obstacle clusters.

S. R. Mishra and P. K. Das et al. [10] developed a Python-implemented parking navigation system that simulates various grid configurations with static and dynamic obstacles. The system validates the A* algorithm's efficiency by measuring path cost, execution time, and number of explored nodes across multiple test scenarios. The results confirmed that A* consistently identifies the shortest feasible path while maintaining low computational overhead, supporting its use in intelligent parking and autonomous navigation applications.

III. METHODOLOGY

A. Parking Lot Modeling

The parking lot is represented as a two-dimensional grid, where each cell corresponds to a parking space or pathway. The grid provides a discrete representation of the environment, enabling systematic exploration for pathfinding algorithms. Each cell is assigned a status:

Free Cell (0): Traversable space where the vehicle can move.

Obstacle Cell (1): Occupied or restricted space representing parked vehicles or barriers.

The grid can be of any size depending on the parking lot dimensions, e.g., a 10×10 or 20×20 matrix, allowing scalability for real-world scenarios.

B. Source and Destination Definition

The system requires a source point (entry location) and a destination point (target parking slot). These points are specified as grid coordinates, e.g., (x_s, y_s) for the source and (x_d, y_d) for the destination. The algorithm computes the shortest feasible path between these points while avoiding obstacles.

C. Path Planning Using A*

The A* algorithm is selected due to its efficiency in computing the shortest path in a grid with obstacles. The algorithm evaluates nodes using a cost function:

$$f(n) = g(n) + h(n)$$

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Where:
$g(n)$is the cost to reach node $n$from the source.
$h(n)$is the heuristic estimate of the cost from node $n$to the destination.
For grid-based parking, the Manhattan distance is used as the heuristic:
$h(n) = | x_n - x_d | + | y_n - y_d |$
A* maintains two sets:
Open List: Nodes to be evaluated.
Closed List: Nodes already evaluated.
The algorithm iteratively selects the node with the lowest f(n) value, explores its neighbors, updates costs, and continues until the destination is reached.

D. Neighbour Exploration and Obstacle Handling

Each node considers up to four neighbours (up, down, left, right) for movement. Diagonal movement can be added if required. Neighbour cells are evaluated only if they are free cells and not already in the closed list. Obstacle cells are automatically skipped to prevent collision.

E. Python Implementation

The system is implemented in Python, using standard data structures:
Lists/Queues: For open and closed sets.
2D Arrays: For grid representation.
Matplotlib: For visualization of the grid and path.
The Python code generates a visual output where:
Free cells are shown in white. • Obstacles are shown in black.
The computed path is highlighted in green.
Source and destination points are marked in distinct colors.

F. Workflow Summary

The methodology follows these steps:
Initialize the grid and mark obstacles.
Define the source and destination coordinates.
Initialize the open and closed lists for A*.
While the destination is not reached:
Select the node with minimum f(n) from the open list.
Explore valid neighbours and update costs.
Move the current node to the closed list.
Reconstruct the path from destination to source once the algorithm terminates.
Display the computed path visually on the grid.

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Block Diagram

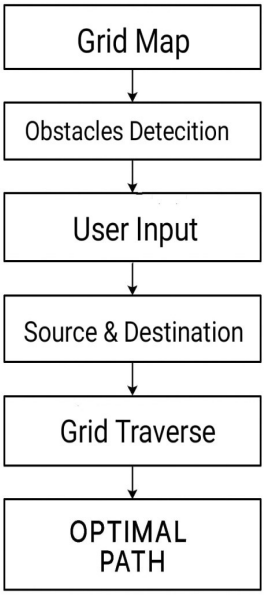

Fig. Block Diagram

The proposed system architecture illustrated in the block diagram represents the sequential process for optimal path determination in a grid-based environment. The system is designed to ensure efficient navigation by identifying the most suitable route between a defined source and destination while avoiding obstacles within the grid.

The process begins with the Grid Map generation. In this stage, the entire environment is represented as a structured grid, where each cell corresponds to a discrete spatial unit. This grid-based representation facilitates the mapping of free and obstructed areas, simplifying the computational process for pathfinding algorithms.

The next stage, Obstacle Detection, is responsible for identifying and marking cells that contain obstacles or restricted regions. These detected obstacles are then excluded from possible traversal paths. The detection process can be based on sensor inputs or pre-loaded environmental data, ensuring accurate modeling of the navigational space.

Following this, the User Input module allows the user to interact with the system by defining the operational parameters. The user specifies the source and destination points within the grid, which serve as the initial and target positions for the pathfinding operation. This input acts as a crucial control stage, linking human decision-making with automated computation.

The Source and Destination block stores and validates these user-defined coordinates, ensuring they fall within the permissible boundaries of the grid and are not located within obstructed regions. This validation step enhances system reliability and prevents computational errors during traversal.

Once the map and parameters are defined, the Grid Traverse phase begins. In this stage, the pathfinding algorithm explores possible routes from the source to the destination by systematically traversing the grid. Various algorithms, such as Dijkstra's algorithm, A*, or BFS/DFS methods, can be implemented depending on the system's design objectives. The traversal process involves analyzing each node's cost, heuristic value, and connectivity to determine the most efficient movement sequence.

Finally, the Optimal Path stage computes and outputs the shortest and most efficient route between the given points. This path minimizes travel distance, time, or energy consumption while ensuring obstacle avoidance. The resulting optimal path can be visualized on the grid map or transmitted to a robotic or autonomous navigation system for execution.

Overall, this structured process ensures that the system achieves accurate, reliable, and computationally efficient path planning suitable for real-world robotic, autonomous vehicle, or AI navigation applications.

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IV. RESULTS

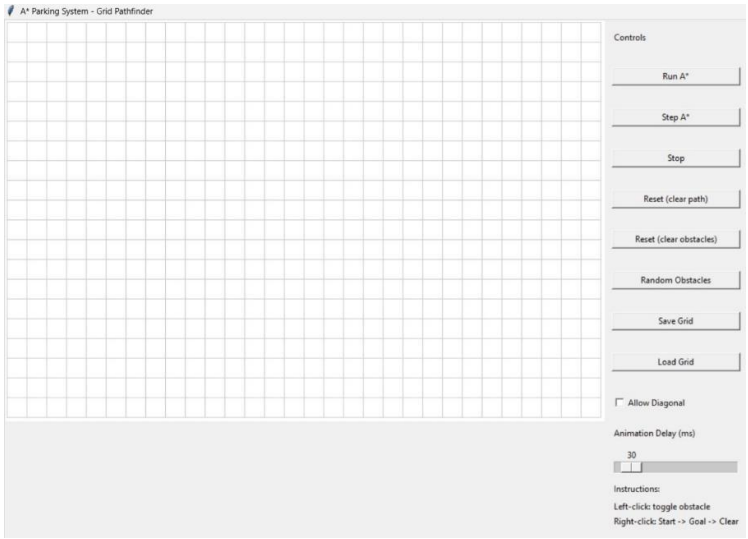

Fig2.Result 1

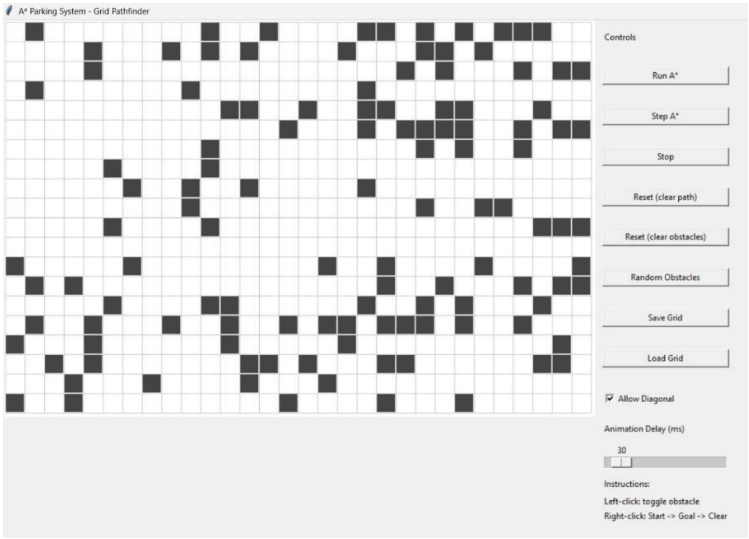

Fig3. Result2

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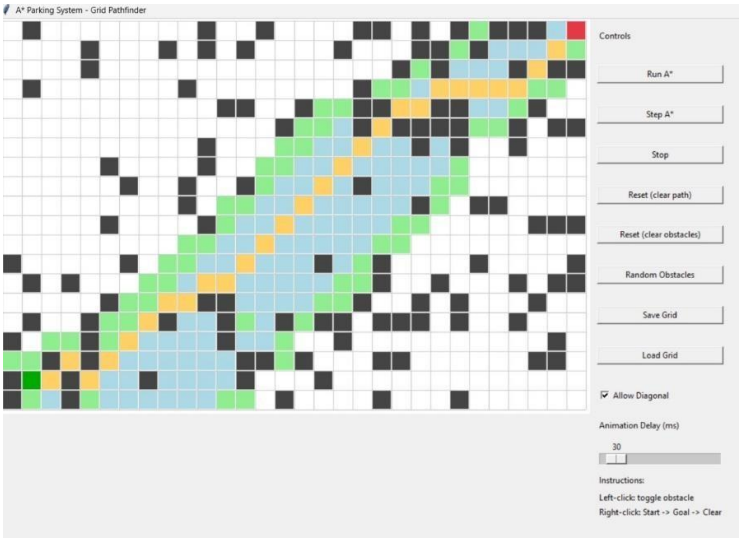

Fig4. Result 3

V. DISCUSSIONS

The above figure represents the implementation of the A* (A-star) algorithm in a grid-based pathfinding system designed for intelligent parking management. Each cell in the grid acts as a node in the search space, where black cells denote obstacles, green and blue regions represent explored paths, and the yellow path indicates the final optimized route from the start point (green) to the destination (red). The system dynamically computes the shortest and most efficient path while avoiding obstacles, ensuring smooth navigation within a complex parking layout.

The visualization demonstrates how the A* algorithm combines heuristic estimation and actual cost values ($f = g + h$) to identify the most feasible path. The algorithm explores multiple routes simultaneously and prioritizes nodes with the lowest estimated total cost. Allowing diagonal movement, as shown, enhances the system's flexibility and reduces travel distance compared to strictly horizontal or vertical motion.

This simulation effectively illustrates the practical application of artificial intelligence in smart parking systems, where vehicles can autonomously locate and reach available parking spaces with minimal delay. It also highlights how A* can adapt to dynamic environments by recalculating optimal routes in real time if obstacles appear or parking slots change. The colorcoded grid and real-time animation provide a clear representation of the decision-making process, contributing to better understanding and analysis of algorithmic efficiency in intelligent transport systems.

VI. CONCLUSION

This paper presents an optimal pathfinding system for grid-based parking lots using the A* algorithm, implemented in Python. By representing the parking area as a two-dimensional grid, where occupied cells act as obstacles, the system efficiently computes the shortest feasible path between a specified source and destination. The proposed methodology leverages the heuristicdriven A* algorithm to minimize traversal cost while avoiding obstacles, ensuring both accuracy and computational efficiency.

Simulation results demonstrate that the algorithm can reliably generate optimal paths in various grid configurations, highlighting its applicability for intelligent parking systems and autonomous vehicle navigation. The visual output provides clear representation of the path, obstacles, and start/destination points, making it suitable for practical implementations and testing.

Future work may include extending the system to handle dynamic obstacles, incorporating multi-level parking structures, and integrating real-time sensor data for live parking guidance. Additionally, combining A* with other optimization

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techniques or machine learning-based predictive models can further improve efficiency and scalability in large-scale or highly dynamic parking environments.

Overall, the research demonstrates that heuristic-based path planning in structured parking environments is a viable and effective solution for enhancing parking efficiency, reducing driver search time, and contributing to the development of smart and autonomous transportation systems.

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