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Original scientific paper

PP-US: An Optimized Ultrasonic Sensor Module for Intelligent Parking in Three-Dimensional Garages

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Abstract: Urban parking challenges are exacerbated by the increase in car ownership, which requires innovative solutions. This study presents a novel Parking Path-Ultrasonic Sensor (PP-US) start stop module for intelligent vehicle parking in three-dimensional garages. The system integrates ultrasonic sensors with a fuzzy control algorithm to optimize parking path planning and execution. Experimental results demonstrated the excellent performance of the module, with a response time of 30 ms after 140 iterations, significantly outperforming existing frameworks. The PP-US module achieved high accuracy in distance measurement, with errors ranging from 0.01 to 0.04 m within 0.5-2.4 m. In parking tests, the system maintained stable vehicle speed between 3-5 km/h, and demonstrated smooth trajectory control. The comprehensive anti-interference ability score of this module was 0.91, surpassing comparison systems. These findings highlight the potential of the PP-US module in enhancing parking efficiency and safety in complex three-dimensional garage environments.

Keywords: anti-interference ability; intelligent vehicle parking; positioning system; precision sensing; ultrasonic sensor

1 INTRODUCTION

With the acceleration of urbanization and the continuous growth of car ownership, the parking difficulties in cities are becoming increasingly prominent. Three-dimensional garages have gained attention as an effective solution to urban land scarcity [1]. However, with the increasing complexity of three-dimensional garage systems, the efficiency, accuracy, and safety of intelligent parking systems have become research hotspots. In this context, parking path planning and its execution mechanism optimization have become a hot research topic [2, 3]. Traditional parking systems often rely on manual operation or simple mechanical equipment, lacking sufficient intelligence and automation, which results in low parking efficiency and susceptibility to parking accidents. With the rapid development of sensor technology, artificial intelligence, computer vision, and other advanced technologies such as ultrasonic sensors and laser radar, intelligent parking systems that achieve automatic vehicle recognition, positioning, and path planning have received widespread attention from researchers. These technologies greatly improve parking accuracy and safety, shorten vehicle parking time, and improve the utilization efficiency of the three-dimensional garage [4-6]. Ultrasonic sensors measure the distance of objects by emitting and receiving high-frequency sound waves. Its working principle is that the transmitter emits ultrasonic waves, which are reflected back when encountering an object and received by the receiver. The sensor records the time difference between transmission and reception, and calculates the distance based on the known sound speed. However, despite some progress in research, there are still some challenges. Firstly, the existing intelligent parking systems are not yet mature enough in path planning and sensor applications, especially in complex environments where their adaptability and stability need to be improved. Secondly, ultrasonic sensors still have shortcomings in signal processing, anti-interference ability, and ranging accuracy, which limit the application effectiveness in intelligent parking systems. In addition, the particularity of the three-dimensional garage environment, such as narrow space and complex structure, poses higher requirements for parking path planning and sensor layout [7-9]. Based on the above background and existing problems, the research aims to construct an intelligent vehicle parking system for three-dimensional garages, combining the latest sensor technology and intelligent algorithms to solve the weak adaptability, low accuracy and stability of existing systems in complex environments. By optimizing the parking path design and efficiently integrating the ultrasonic sensor start stop module, a fast, accurate, safe and efficient parking path planning system is constructed to optimize the overall operational efficiency and safety of the three-dimensional garage. The research innovation lies in combining ultrasonic sensors and fuzzy control technology to improve the accuracy and safety of parking space detection and parking processes, contributing to providing a cost-effective and high-precision solution for automatic parking systems.

The first part elaborates on the automatic parking system. The second part designs the method. The third part verifies the method. The fourth part summarizes the research results and proposes prospects.

2 LITERATURE REVIEW

In the research of intelligent vehicle parking systems in three-dimensional garages, many scholars have conducted in-depth discussions on parking path planning, sensor technology, and their applications [10, 11]. Recently, influenced by artificial intelligence, the research on intelligent parking systems has gradually developed towards higher intelligence and automation.

Regarding parking path planning, some studies have simulated the parking process and used fuzzy logic controllers to simulate the driver's judgment logic to optimize the parking path. Some studies also focus on the application of neural network algorithms to continuously optimize parking path planning by simulating natural selection and genetic mechanisms, thereby reducing parking time and improving parking safety. Y. Z. et al. built a hierarchical automatic valet parking path planning method. The complete AVP path planning was divided into various layers, starting from the perspective of global decision-making. The simulation results showed that the efficiency was increased by more than 20 times. In addition, the planner overcame the unsuitability of hybrid algorithms in complex parking scenarios [12]. Y. X. et al. built a parking spot detection and path planning scheme based on basic vision IMU to solve the ignored unknown obstacles in the parking environment. The simulation results showed that this method could efficiently avoid obstacles and generate smooth paths for vehicles in dynamic parking environments, effectively meeting the safety and stability requirements of parking [13]. R. Z. et al. proposed a new geometric-based secondary path planning method for automatic parking. The sequential quadratic programming was applied to determine optimization parameters. Compared with search-based methods represented by rapidly exploring random tree variants, the designed method had higher planning performance [14].

In terms of sensor technology and its applications, ultrasonic sensors and laser radar are currently the two most commonly used sensors. Ultrasonic sensors are widely used in various detection and distance detection due to their low cost and ease of deployment. D. Q. et al. proposed a multi-terminal direct current-direct current solid-state transformer topology for bidirectional photovoltaic/battery assisted electric vehicle parking lots. The research results indicated that the system could autonomously charge and discharge a certain power based on factors such as the charging status, battery capacity, and departure time of each EV to maintain the stability of the future microgrid [15]. Z. J. et al. proposed an autonomous parallel parking scheme for front wheel steering vehicles. Combining arcs with straight lines, a collision free path was constructed to park the vehicle with one or more maneuvers. The research results showed that the model had excellent performance and good parking performance in the environmental simulation system [16]. P. K. S. et al. proposed an automatic parking system suitable for existing vehicles. This model was equipped with sensors. By programming a micro-controller, the control system achieved steering wheel control, acceleration, and braking. The simulation results showed that the proposed geometric modeling ensured accuracy and safety [17]. Kyu S. J. et al. proposed a target parking position recognition method that integrated image sensors and distance sensors to improve the accuracy and popularity of automatic parking systems. The potential application of deep learning in this field required optimization through open dataset competition. The research results indicated that this method had complementary advantages and may become mainstream in the future [18]. Ma Y. et al. explored key technologies for parking space detection in order to improve the performance of automatic parking assistance systems. The method was divided into two categories: traditional visual features and deep learning. Their respective advantages and disadvantages were analyzed. The research results indicated that the deep learning method had great potential, and benchmark datasets and evaluation criteria were crucial for driving research [19].

In summary, although the research on intelligent vehicle parking systems has made some progress, there are still challenges in optimizing path planning, improving the accuracy of sensor data processing, and reducing system cost. Path planning algorithms need to adapt to constantly changing parking environments, such as other vehicles, pedestrian movements, and obstacles. Implementing real-time path planning in complex environments requires efficient algorithms to optimize computation time and resource utilization. In addition to the shortest path, path planning also needs to consider multiple objectives such as safety, energy consumption, and time, which increases the algorithm complexity. Intelligent vehicle parking systems typically rely on multiple sensors. How to fuse data from different sensors to obtain more accurate environmental awareness is a key issue. Sensor data may contain noise and interference, especially in complex urban environments, requiring effective algorithms to filter out these interferences. Realizing high-precision vehicle positioning is the foundation of parking systems, which requires addressing error accumulation, especially in environments with poor GPS signals. Therefore, the research on intelligent vehicle parking systems for three-dimensional garages, especially the optimization of parking path planning and ultrasonic sensor application, has important theoretical significance and application value for solving the urban parking difficulties, improving the efficiency and safety of three-dimensional garages.

3 RESEARCH METHODOLOGY

3.1 Construction of the US-Based Parking Detection System

In modern three-dimensional garage automatic parking systems, the parking space detection systems rely on high-precision and reliable sensing technology. Ultrasonic sensors measure the distance of objects by emitting and receiving high-frequency sound waves. Its working principle is that the transmitter emits ultrasonic waves, which are reflected back when encountering an object and received by the receiver [20]. The sensor records the time difference between transmission and reception, and calculates the distance based on the known sound speed. Ultrasonic sensors are widely used for parking space detection due to their cost-effectiveness and broad detection range. Compared with sensors such as LiDAR and cameras, ultrasonic sensors have lower cost, which are suitable for large-scale applications. Ultrasonic sensors can cover a large detection range and are suitable for various parking environments, such as side parking and vertical parking. Through data fusion technology, the proposed method can significantly improve the accuracy of parking space detection, reduce errors, and ensure that vehicles can accurately park in parking spaces [21-23]. Ultrasonic sensors exhibit stable performance under different environmental conditions, which can effectively work in complex parking environments, with strong anti-interference capabilities. The Parking path-Ultrasonic Sensor (PP-US) system can detect the surrounding environment in real time and provide immediate feedback, ensuring the safety and accuracy of the parking process. Combined with fuzzy control systems, the PP-US method can achieve full process control of automatic parking, including parking space detection, path planning, and parking execution, improving the automation and user experience of the system. Ultrasonic sensors are small in size, easy to install, and can be integrated with others in vehicle systems, enhancing the intelligence level of the entire vehicle [24, 25]. Ultrasonic sensors are not affected by environmental factors such as light and weather, which can work stably under various conditions with strong adaptability. The ultrasonic ranging is displayed in Fig. 1.

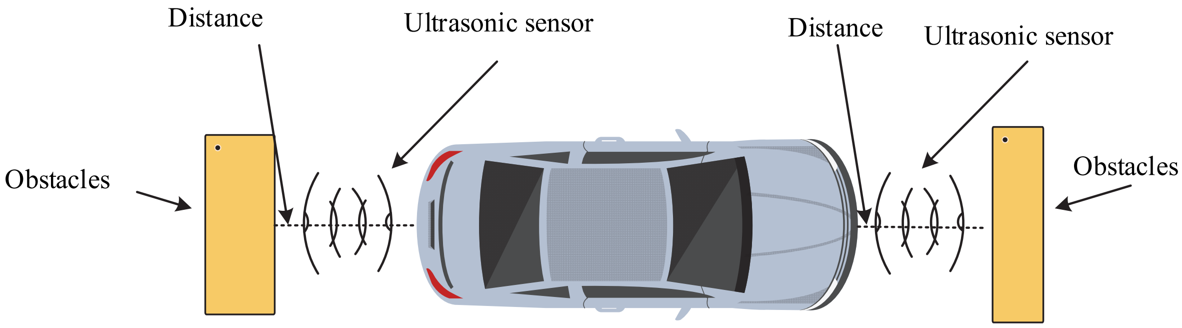


Figure 1 Ultrasonic sensor ranging diagram

From Fig. 1, the ultrasonic sensor emits and receives ultrasonic waves. The reflection time of ultrasonic waves is used to determine the distance of obstacles. When ultrasonic waves encounter obstacles, they will reflect and return to the sensor, thereby calculating the obstacle's position and size [26, 27]. In the parking space detection system, the ultrasonic wave is used to identify and measure the size of the parking space, ensuring that the vehicle can safely and accurately park in the parking space. Among them, the propagation distance of ultrasonic waves can be calculated, as shown in Eq. (1).

$$S = \frac{v \times t}{2} \tag{1}$$

In Eq. (1), v is the propagation speed of ultrasonic wave at room temperature. t represents the time difference between ultrasonic emission and reception. The spatial distance covered by ultrasonic wave is s. The propagation speed of ultrasonic wave is shown in Eq. (2).

$$v = 331.4\sqrt{\frac{c + 273.16}{273.16}} \tag{2}$$

In Eq. (2), the temperature of the air is represented by c, and the temperature is measured in degrees Celsius. When the vehicle speed meets the conditions, the ultrasonic sensor automatically starts to detect the surrounding area [28-29]. When a suitable parking space is detected, the ultrasonic sensor prompts the driver to have a parking environment, which contains side and vertical parking. The former is shown in Fig. 2.

The side parking in Fig. 2 is a common parking method at the edge of urban streets. The vehicle is parked parallel to the roadside [30-31]. The automatic parking system requires highly accurate parking detection technology and complex control algorithms to simulate the judgment and operation of drivers when handling side parking, ensuring the safety and accuracy of the parking process. The vertical parking is shown in Fig. 3.

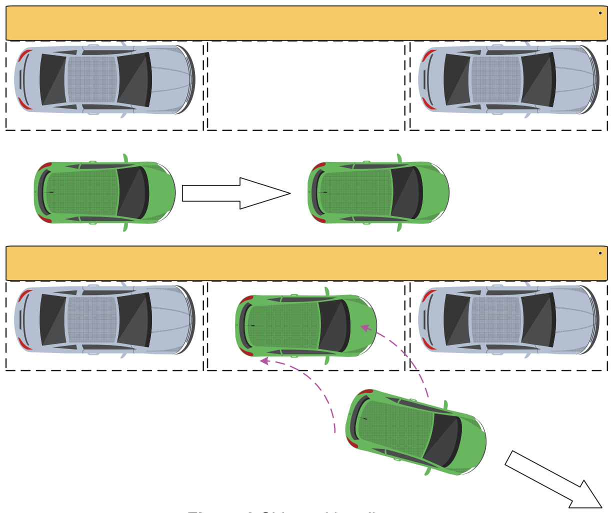


Figure 2 Side parking diagram

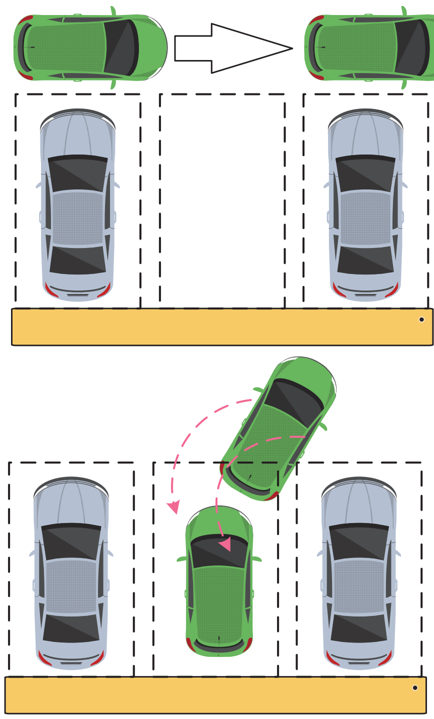


Figure 3 Vertical parking diagram

The vertical parking in Fig. 3 is commonly found in enclosed or semi-enclosed parking environments such as parking lots and shopping centers. When handling vertical parking, the automatic parking system needs to accurately identify the size and location of the parking space, and calculate the optimal entry path. Therefore, the research integrates the data synthesis technology of ultrasonic sensors into a parking detection system. The most reliable data measured by two sensors in the same direction are adjusted to reduce data bias. The basis for adjustment is to compare the difference between the first measurement of the front sensor and the last measurement of the rear sensor relative to the vehicle position. Then data fusion is performed.

3.2 Construction of PP-US Start Stop Module

After determining the sensors, a PP-US start stop module is constructed. Therefore, a parking coordinate system needs to be constructed. In vehicle parking, the parking coordinate system is shown in Fig. 4.

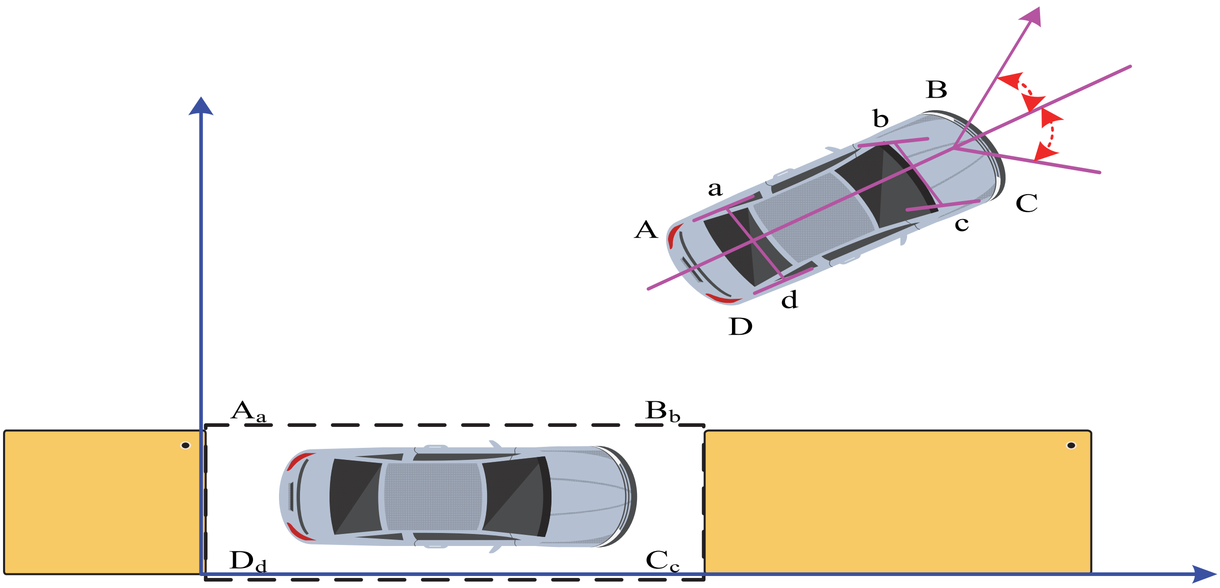


Figure 4 Vehicle parking coordinate system

In Fig. 4, the vehicle is geometrized and the vertices are divided into four points *A*, *B*, *C*, and *D*. The projection of the *A* can be represented by Eq. (3).

$$\begin{cases} x_A = x - \frac{L}{2}\cos\theta - \frac{W}{2}\sin\theta \\ y_A = y - \frac{L}{2}\sin\theta + \frac{W}{2}\cos\theta \end{cases} \quad (3)$$

In Eq. (3), θ is the yaw angle of the vehicle body. x and y are projection coordinates. L is the vehicle length. W is the width. The vertex B is shown in Eq. (4).

$$\begin{cases} x_B = x + \frac{L}{2}\cos\theta - \frac{W}{2}\sin\theta \\ y_B = y + \frac{L}{2}\sin\theta + \frac{W}{2}\cos\theta \end{cases} \quad (4)$$

The vertex C is shown in Eq. (5).

$$\begin{cases} x_C = x + \frac{L}{2}\cos\theta + \frac{W}{2}\sin\theta \\ y_C = y + \frac{L}{2}\sin\theta - \frac{W}{2}\cos\theta \end{cases} \quad (5)$$

The vertex D is shown in Eq. (5).

$$\begin{cases} x_D = x - \frac{L}{2}\cos\theta + \frac{W}{2}\sin\theta \\ y_D = y - \frac{L}{2}\sin\theta - \frac{W}{2}\cos\theta \end{cases} \quad (6)$$

The coordinate system for vertical parking is similar to the coordinate system for side parking. Therefore, the geometric coordinates of the front and rear wheels of the vehicle are *a*, *b*, *c*, and *d*. The coordinates of point *a* are represented by Eq. (7).

$$\begin{cases} x_a = x - \frac{l}{2}\cos\theta - \frac{L_{rw}}{2}\sin\theta \\ y_a = y - \frac{l}{2}\cos\theta + \frac{L_{rw}}{2}\sin\theta \end{cases} \quad (7)$$

In Eq. (7), l is the wheel base. L_{rw} is the distance between the front and rear wheels of the vehicle. The other three rounds of calculation formulas are the same. The vehicle speed is often below 5km/h during parking and has slow turning characteristic at low speeds. Therefore, the left rear wheel is expressed as Eq. (8).

$$x_a^2 + (y_a - l\cot\varphi)^2 = (L\cot\varphi - \frac{L_{rw}}{2})^2 \quad (8)$$

In Eq. (8), φ is the turning angle. L_{rw} is the rear wheel track width. The same goes for the right rear wheel. After constructing the coordinate system, the minimum turning radius is obtained. The Ackermann criterion states that anti-slip turning requires the wheels to follow their natural trajectory, that is, all wheels to rotate around a common turning center. Therefore, the angle relationship of the inner steering wheel is shown in Eq. (9).

$$\cot\alpha - \cot\beta = \frac{K}{l} \tag{9}$$

In Eq. (9), α and β signify the angles of the front inner and outer wheels. K represents the extension distance of the main centerline and the ground intersection point. The angle relationship of the outer steering wheel is shown in Eq. (10).

$$\frac{\alpha + \beta}{2} = \varphi \tag{10}$$

In Eq. (10), φ is the turning angle, as shown in Eq. (11).

$$\varphi = \arctan\frac{1}{R} \tag{11}$$

In Eq. (11), R is the turning radius. The minimum turning radius is represented by Eq. (12).

$$R_{\min} = \frac{1}{\sin\gamma_{\max}} + \gamma \tag{12}$$

In Eq. (12), γ is the wheel turning arm. After determining the minimum turning radius, the size of the parking space is determined. To consider space utilization, the minimum lateral parking space needs to be determined. The minimum parking space requirements are presented in Eq. (13).

$$\begin{cases} l_{ad} \ge l_r + \sqrt{R_B^2 - \left(R - \frac{W}{2}\right)^2} \\ l_{ab} \ge \frac{W}{2} + R_C - R \end{cases} \tag{13}$$

In Eq. (13), R_B and R_C are the radius of the arc corresponding to the vertex. l_{ad} is the minimum length of lateral parking space. l_{ab} signifies the minimum width. R_B is shown in Eq. (14).

$$R_B = \sqrt{(l + L_f)^2 + \left(R + \frac{W}{2}\right)^2} \tag{14}$$

In formula (14), L_f represents the front overhang. R_C is calculated in Eq. (15).

$$R_C = \sqrt{L_r^2 + \left(R + \frac{W}{2}\right)^2} \tag{15}$$

In Eq. (15), L_r is the rear overhang of the vehicle. The minimum parking space for vertical parking can be obtained similarly. Fuzzy control can handle the uncertainty and fuzziness present in the system, and does not require precise mathematical models. It can be designed based on empirical rules. Even in situations where the model is difficult to establish or not fully understood, it can still work effectively. By adjusting fuzzy rules and membership functions, fuzzy control systems can adapt to different system requirements and environmental changes, with good flexibility. It has strong robustness to changes in system parameters and external disturbances, and can maintain good control performance even when system conditions change. After establishing relevant indicators and coordinate systems, the PP-US system is designed based on the fuzzy control system. For parallel and vertical parking, membership functions are established based on the vehicle's dynamic characteristics and parking requirements. The yaw angle, lateral and longitudinal distance of the vehicle are used as input variables, and the steering wheel angle is used as output variables. The variables are defined through triangle and trapezoidal membership functions. The specific process is shown in Fig. 5.

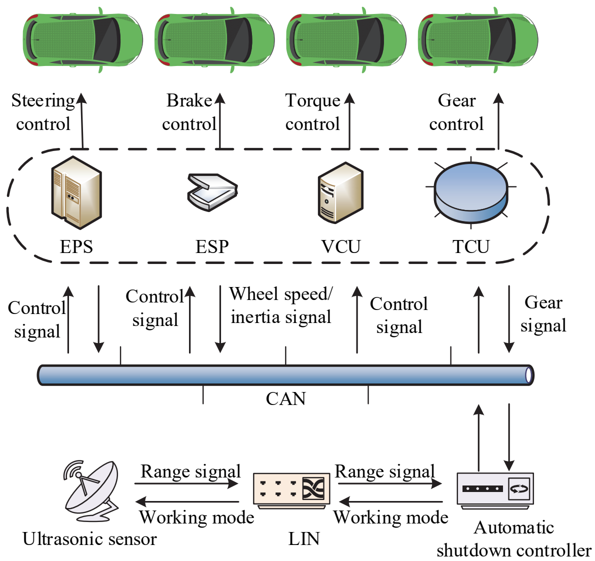


Figure 5 Automatic parking system hardware process

In Fig. 5, a fuzzy rule set is constructed. Based on parking experience and vehicle motion, an Electric Power Steering System (EPS) is equipped to achieve steering control. The Transmission Control Unit (TCU) is used to adjust gears. The Body Electronic Stability Program (ESP) is used to adjust brake pressure and provide necessary vehicle speed and dynamic data. The Vehicle Control Unit (VCU) is used to control the electric motor to provide acceleration. The Local Interconnect Network (LIN) is used to manage 12 ultrasonic sensors for environmental detection, and receive sensing data through the Controller Area Network (CAN) bus to execute parking commands.

The PP-US module uses ultrasonic sensors for parking space detection and integrates them with the vehicle control system for automated parking. Firstly, the ultrasonic sensors measure the distance between the parking space and surrounding obstacles in real time. These data are processed by data fusion techniques to improve the measurement accuracy. The processed data are fed into a fuzzy control system, which generates parking commands based on preset control rules. Next, the fuzzy control system sends the commands to vehicle control units, such as the electric power steering system, the transmission control unit, and the body electronic stability program, to adjust the direction and speed of the vehicle. Finally, the vehicle automatically completes the parking operation according to the generated instructions.

To develop and optimize a fuzzy rule set, firstly, the fuzzy rule base is defined and the input variables and output variables are determined. Then, an affiliation function is designed for each input variable. A triangular or trapezoidal function is used to describe the fuzzy degree of the variable. Next, the rule base is established based on the actual parking experience, such as generating larger steering commands when the vehicle distance is small and the yaw angle is large. The system is tested in real parking scenarios to evaluate the effectiveness of the rule set. Based on the test feedback, the rules and the affiliation function are adjusted to optimize the accuracy and reliability of the system. Through repeated testing and optimization, the adaptability and performance of the fuzzy control system in different parking environments are improved.

4 RESULTS AND DISCUSSION

4.1 Performance Testing and Analysis of PP-US Start Stop Module

Various testing and analysis methods are comprehensively applied to evaluate the effectiveness and reliability of the PP-US start stop module in the 3D garage intelligent parking system. Among them, Tab. 1 displays the main parameters.

Table 1 Vehicle parameter

Argument	Unit	Numerical value
Vehicle length	m	4.510
Vehicle width	m	1.860
Wheelbase	m	2.730
Front overhang	m	0.920
Rear overhang	m	1.020
Front track	m	1.590
Rear track	m	1.600
Minimum turning radius of rear axle	m	5.000
Maximum equivalent Angle of front axle	rad	0.482
Maximum front axle rotation speed	rad/s	0.482

Tab. 1 shows the relevant parameters of a certain vehicle model from China Great Wall Motors Co., Ltd. The parameters include vehicle length, width, wheelbase, front overhang, rear overhang, etc. These parameters are expressed in international standard units, ensuring the data accuracy and comparability. The comparison of response time between PP-US and other models is shown in Fig. 6.

From Fig. 6, the PP-US system exhibited significant performance advantages. When the iteration increased to 140, the response time of PP-US decreased from the initial 45 ms to 30 ms, demonstrating significant performance advantages. In contrast, other frameworks such as TensorFlow and PyTorch had a smaller decrease in response time. The former decreased from 75 ms to 60 ms, and the latter decreased from 85 ms to 70 ms. Caffe decreased from 65 ms to 50 ms, and MXNet decreased from 60 ms to 45 ms.

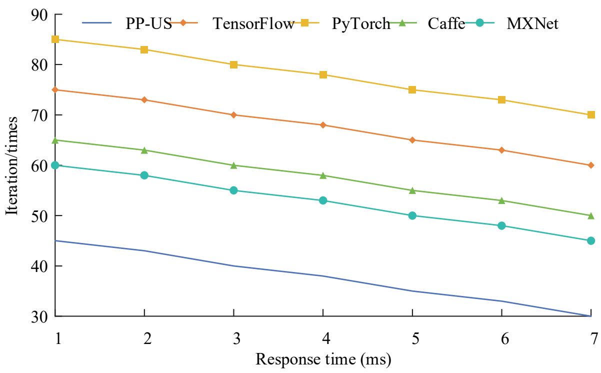
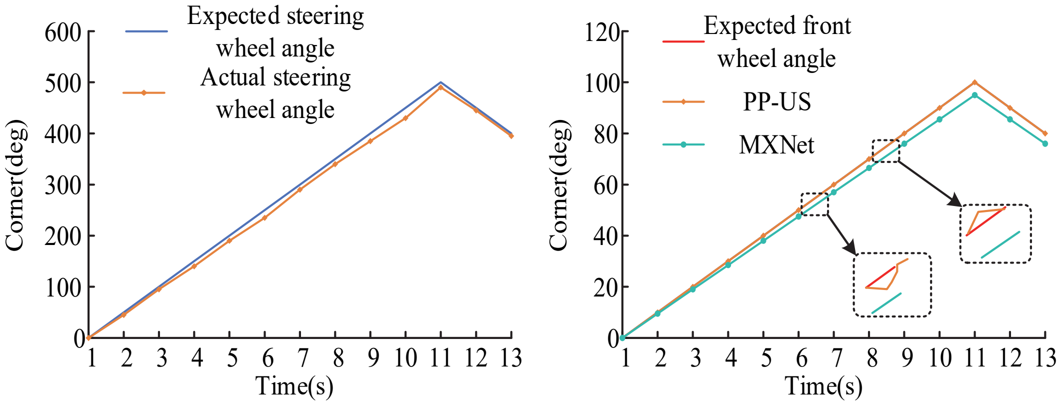


Figure 6 Response time comparison

Fig. 7a shows the comparison between the expected steering angle and the actual steering angle. At 1s, the deviation was 5°. Subsequently, this deviation was maintained at around 10° as it increased to the maximum expected steering angle of 500°. Afterwards, during the period of reducing the steering angle, the deviation slightly decreased to 5° by 12 s. As a whole, the tracking performance of the actual steering angle showed consistency in dynamic changes, and there was also a slight lag. When reaching the expected maximum point of 500°, the actual steering angle was 490°. During the entire observation period, the average deviation of the actual steering wheel angle was 7.5°, with a standard deviation of 1.58°. The maximum and minimum deviations were 10° and 5°. The performance of the system remained within a relatively stable range. In the comparison of the relationship between front wheel steering angle and time in Fig. 7b, the actual front wheel steering angle of the PP-US system almost matched the expected value within 0 to 12 s, without any deviation. On the contrary, the actual front wheel steering angle of the MXNet system was lower than that of the expected value at all time points, with an average deviation of 0.5°. Compared with the low error performance of the PP-US system, its accuracy was significantly lower. When reaching the midpoint of the desired steering angle (50°), the actual steering angle of the MXNet system averaged 47.5°, while the PP-US system achieved an accurate steering angle of 50°. In the test at the highest point of 100°, the actual steering angle of the PP-US system perfectly matched the expected value. In contrast, the average actual steering angle of the MXNet system was 95°. The distance measurement accuracy of the sensor is shown in Tab. 2.

Tab. 2 shows the performance differences of sensors at different distance stages. All sensors can provide measurement data that are closer to the true value within 0.5 m to 2.4 m. Within 0.5 m, the data recorded by the sensors were slightly lower than the true distance, with an error range of 0.01 m to 0.04 m. When the measurement distance increased to 1.0 m and 1.5 m, these sensors accurately reflected the true distance with minimal error. Within 2.0 m and 2.4 m, the data showed slight fluctuations, but overall maintained high accuracy. Sensors that can obtain data continue to demonstrate effective measurement capabilities for longer distances. At the farthest measurement point of 4.9 m, the recorded data were not significantly different from the actual distance. Overall, from the perspective of distance measurement accuracy, compared with actual measurement values, the PP-US start stop module's distance measurement error is controlled within a small range, with high accuracy. This module can effectively identify and locate the distance between vehicles and obstacles, providing reliable data support for parking path planning. The comparison results of parking condition tests are shown in Fig. 8.

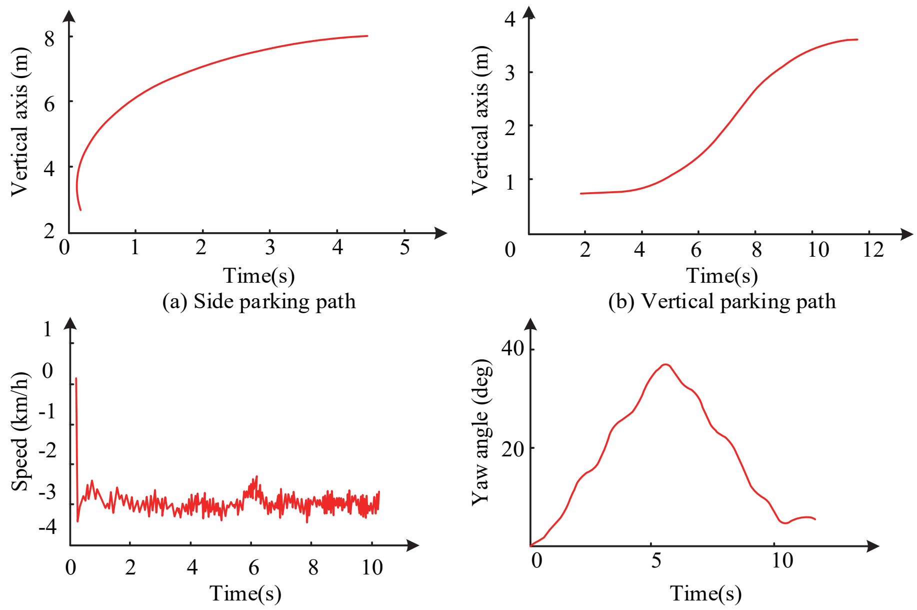


(a) Expected angle versus actual angle (b) Front wheel angle versus time

Figure 7 Angle comparison

Table 2 Sensor ranging accuracy

True distance	F1	F2	F3	F4	F5	F6	R1	R2	R3	R4
0.5 m	0.49	0.49	0.47	0.48	0.50	0.47	0.48	0.47	0.50	0.46
1.0 m	1.00	0.99	0.96	0.99	0.98	0.95	0.98	1.00	1.03	0.98
1.5 m	1.48	1.49	1.46	1.50	1.46	1.50	1.45	1.50	1.51	1.5
2.0 m	1.98	1.95	1.98	2.02	1.95	1.98	1.96	1.99	2.05	1.95
2.4 m	2.42	2.37	2.36	2.45	2.37	2.4	2.38	2.42	2.37	2.36
3.0 m	3.02	\	\	\	\	2.99	3.04	\	\	\
3.5 m	3.49	\	\	\	\	3.52	3.46	\	\	\
4.0 m	4.03	\	\	\	\	3.98	4.04	\	\	\
4.5 m	4.57	\	\	\	\	4.56	4.55	\	\	\
4.9 m	4.94	\	\	\	\	4.87	4.93	\	\	\



(a) Side parking path (b) Vertical parking path

(c) Speed of vehicle (d) Yaw angle effect

Figure 8 The change of vertical parking vehicles over time

Fig. 8a shows the variation of the vehicle over time during side parking. The vehicle had a good posture. Fig. 8b shows the variation of the vehicle over time during vertical parking. The vehicle traveled along a smooth curve over time during the parking process. Fig. 8c shows the vehicle speed condition for side parking. The vehicle speed remained stable between 3-5 km/h over time, with a reasonable fluctuation range. Fig. 8d shows the change in side parking yaw angle. The yaw angle of the test vehicle reached its maximum at 5 s and finally reached a stable state after 10 s. The overall yaw angle first increased and then decreased, and the overall vehicle condition was stable throughout the test. Further analysis is conducted on vertical parking, as shown in Fig. 9.

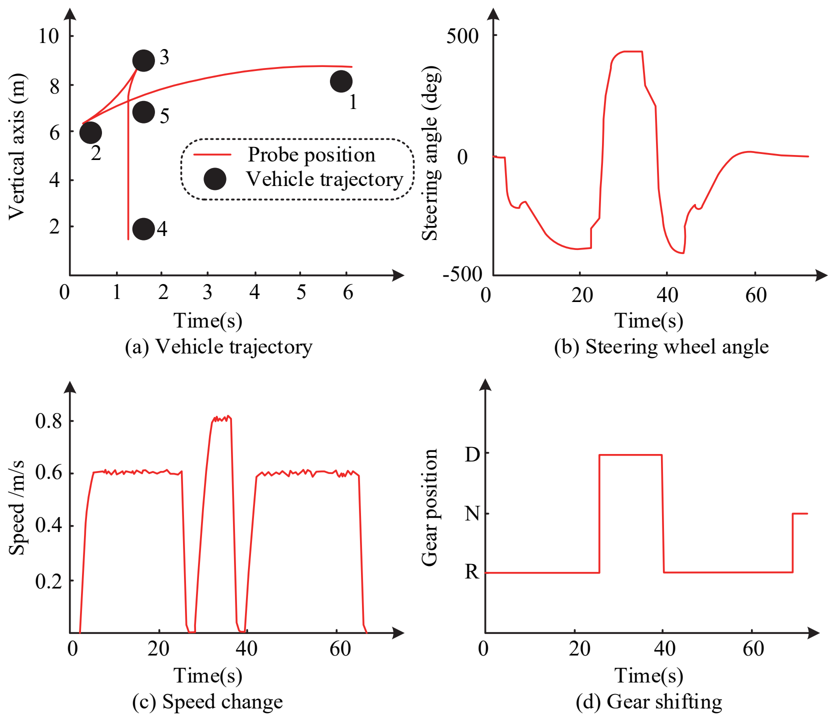


Figure 9 Vertical parking vehicle condition

Fig. 9a shows the motion trajectory of the test vehicle during vertical parking. The vehicle started from 1. After detecting a parking spot at 2, it started the automatic parking program. After passing through the predetermined path from 3 to 5, it smoothly entered the parking spot. The vehicle has good path tracking performance during driving, with a final lateral position deviation of 12.3 cm and a directional deviation controlled within 3.2°. In addition, Fig. 9b shows the vehicle steering during vertical parking. The overall adjustment of the vehicle ran smoothly. Fig. 9d shows the gear shifting during the parking process. At 23 s, the gear shifting was carried out. At 40 s, the last gear shifting was performed, effectively avoiding the possible vehicle impact caused by the speed not returning to zero during gear shifting, thereby maintaining the stability and comfort throughout the entire automatic parking process. The anti-interference ability test results are displayed in Tab. 3.

Table 3 Anti-interference test

Model/interference type	Electromagnetic interference	Temperature change	Humidity change	Sound interference	Light interference	Comprehensive anti-interference ability score
PP-US	0.950***	0.900***	0.880***	0.920***	0.900***	0.910***
Laser radar	0.900	0.850	0.820	0.880	0.850	0.860
BP-SVM	0.850	0.800	0.850	0.800	0.820	0.824
GA-RNN	0.880	0.830	0.800	0.840	0.880	0.846
Wireless cloud parking	0.820	0.780	0.790	0.810	0.800	0.800

Tab. 3 shows the test results of the anti-interference capability of different technology models under various interference conditions. Among them, PP-US model showed high stability in electromagnetic interference, temperature change, humidity change, sound interference, and light interference. Its comprehensive anti-interference ability score reached 0.91, with excellent overall performance. Laser radar technology had excellent performance, but it was a little bit inferior in all the tests, with a comprehensive score of 0.86. BP-SVM model was slightly insufficient in handling sound interference and humidity change, with a comprehensive score of 0.824. BP-SVM model was a bit weak in dealing with sound interference and humidity changes, with a composite score of 0.824. GA-RNN had a composite score of 0.846, while the wireless cloud parking system had the weakest performance among the interference types, with a composite score of 0.8. Overall, the designed PP-US model has significant advantages in complex interference environments, with a good overall interference resistance, which can be applied to various situations.

4.2 Discussion

The PP-US start stop module in the intelligent vehicle parking system for three-dimensional garages is comprehensively evaluated. According to the test results, the system has significant advantages in achieving fast and accurate vehicle positioning and parking path planning. Compared with other technical models, the PP-US module not only demonstrates excellent performance in response time, but also presents high stability and reliability in various aspects such as vehicle control accuracy, sensor ranging accuracy, and anti-interference ability. It can effectively improve the scheduling performance of large-scale high-density parking lots, which is consistent with the research results of C. G. et al. [31].

The PP-US module exhibits good dynamic tracking performance in handling the deviation between the expected and the actual steering wheel angles of the vehicle. It can reflect the module's ability to accurately control vehicle movement and its adaptability to complex operating environments. Meanwhile, accurately controlling the front wheel steering angle further ensures that the vehicle can smoothly travel along the predetermined path during parking, reducing parking errors and improving the safety of the parking process. In terms of sensor ranging accuracy, the ultrasonic sensor of the PP-US module can effectively identify the distance between vehicles and obstacles. The distance measurement accuracy indicates that the module can maintain high measurement accuracy at different distance stages and has excellent performance in narrow or complex three-dimensional garage environments. From the anti-interference ability test results, the PP-US module exhibits strong stability and reliability in the face of electromagnetic interference, temperature changes, humidity changes, sound interference, and light interference]. The PP-US module has excellent environmental adaptability, which can maintain efficient and accurate performance in ever-changing practical application environments. This is also similar to the research results of L. Y. et al., which meet continuous safety, and curvature constraints, thereby improving the parallel parking capacity of small parking spaces [32].

Although the PP-US start stop module has demonstrated its advantages in multiple aspects, it is crucial to optimize the energy consumption management of the module in future application expansion to meet energy conservation and emission reduction. The measurement accuracy of ultrasonic sensors is limited by their frequency and resolution. Although it performs well in many scenarios, errors may occur in high-precision environments such as narrow parking spaces or complex obstacle layouts, which can affect parking accuracy. Although data fusion technology can improve detection accuracy, data inconsistency or processing delay may occur during the fusion process, affecting the real-time performance and stability of the system. Data fusion of different sensors may also introduce additional computational complexity and cost. Implementing PP-US systems in real-world three-dimensional garages faces several potential challenges, as three-dimensional garages typically have multi-layered structures and complex spatial layouts. Ultrasonic sensors may be difficult to accurately detect all parking spaces in complex three-dimensional environments, especially in corners or inter story spaces of garages. Due to the three-dimensional structure and multi-faceted reflection of the garage, ultrasonic signals may reflect and refract along multiple paths, resulting in inaccurate measurement results. This multi-path interference is particularly significant in complex garage environments.

In summary, the performance testing results of the PP-US start stop module indicate that the system has significant advantages in achieving fast and accurate parking in three-dimensional garages. Through continuous optimization and innovation of key technologies, it is expected to further enhance the application value of intelligent parking systems and provide effective technical support for solving urban parking problems.

5 CONCLUSION

This study demonstrates the effectiveness of the PP-US module for intelligent vehicle parking in three-dimensional garages. The excellent response time of the system was 30 ms, the sensor accuracy was high, the error was between 0.01-0.04 m, and the comprehensive anti-interference ability score was 0.91, highlighting its potential to significantly improve parking efficiency and safety. The module's performance in maintaining stable vehicle speed and smooth trajectory control during parking maneuvers further emphasized its practical applicability. However, limitations such as the need for further verification in extreme environments and potential challenges in real-world implementation remain. Future research should focus on enhancing the module's performance under varied environmental conditions, integrating with other sensor technologies, and conducting extensive real-world trials in diverse three-dimensional garage settings. The findings of this study provide a strong foundation for advancing intelligent parking systems, potentially alleviating urban parking challenges and improving overall urban mobility.

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6 REFERENCES

[1] Jhang, J. H., Lian, F. L., & Hao, Y. H. (2021). Human-like motion planning for autonomous parking based on revised

bidirectional rapidly-exploring random tree* with Reeds-Shepp curve. *Asian Journal of Control*, *3*(23), 1146-1160. https://doi.org/10.1002/asjc.2439

[2] Meng, J. & Song, S. (2020). Parking Path Tracking Method Based on Kalman Filter and Fuzzy Control. *International Core Journal of Engineering*, *6*(1),77-85.

[3] Manav, A. C. & Lazoglu, I. (2021). A Novel Cascade Path Planning Algorithm for Autonomous Truck-Trailer Parking. *IEEE Transactions on Intelligent Transportation Systems*, *7*(23),6821-6835. https://doi.org/10.1109/TITS.2021.3062701

[4] Chinthamu, N. & Karukuri, M. (2023). Data Science and Applications. *Journal of Data Science and Intelligent Systems*, *1*(1), 83-91. https://doi.org/10.47852/bonviewJDSIS3202837

[5] Kim, D. J. & Chung, C. C. (2020). Automated Perpendicular Parking System with Approximated Clothoid-Based Local Path Planning. *IEEE Control Systems Letters*, *6*(5), 1940-1945.

[6] Diachuk, M., Easa, S., & Bannis, J. (2020). Path and Control Planning for Autonomous Vehicles in Restricted Space and Low Speed (Special Issue Cover). *Infrastructures*, *5*(5), 42-69. https://doi.org/10.3390/infrastructures5050042

[7] Sidra, A. & Mrissa, M. (2023). A Framework for Privacy-aware and Secure Decentralized Data Storage. *Computer Science and Information Systems*, *20*(3), 1235-1261. https://doi.org/10.2298/CSIS220110007A

[8] Wu, B., Qian, L., Lu, M., Qiu, D., & Liang, H. (2020). Optimal control problem of multi-vehicle cooperative autonomous parking trajectory planning in a connected vehicle environment. *IET Intelligent Transport Systems*, *13*(11), 1677-1685. https://doi.org/10.1049/iet-its.2019.0119

[9] Chen, S., Leng, Y., & Labi, S. (2020). A deep learning algorithm for simulating autonomous driving considering prior knowledge and temporal information. *Computer-Aided Civil and Infrastructure Engineering*, *35*(4), 305-321. https://doi.org/10.1111/mice.12495

[10] Bukya, R., Madhu Mohan, G., & Kumar Swamy, M. (2025). Artificial intelligence role in optimizing electric vehicle charging patterns, reduce costs, and improve overall efficiency: A review. *Journal of Engineering, Management and Information Technology,* *2*(3), 129-138. https://doi.org/10.61552/JEMIT.2024.03.004

[11] Erić, M., Stefanović, M., Zahar Djordjević, M., Kokić Arsić, A., & Đorđević, A. (2023). Smart cloud based ecological system for contactless vehicle cleaning. *Journal of Innovations in Business and Industry*, *2*(1), 1-6. https://doi.org/10.61552/JIBI.2024.01.001

[12] Zhang, Y., Chen, G., Hu, H., & Gao, Z. (2023). Hierarchical Parking Path Planning Based on Optimal Parking Positions. *Automotive Innovation*, *2*(6), 220-230. https://doi.org/10.1007/s42154-022-00214-z

[13] Xu, Y., Gao, S., Jiang, G., Gong, X., Li, H., Sang, X., Wang, L., Zhu, R., & Wang, Y. (2021). Parking Space Detection and Path Planning Based on VIDAR. *Journal of Robotics*, *1*(21), 1-15. https://doi.org/10.1155/2021/4943316

[14] Zhou, R. F., Liu, X. F., & Cai, G. P. (2020). A new geometry-based secondary path planning for automatic parking. *International Journal of Advanced Robotic Systems*, *17*(3), 1-17. https://doi.org/10.1177/1729881420930575

[15] Qin, D., Sun, Q., Wang, R., Ma, D., & Liu, M. (2020). Adaptive Bidirectional Droop Control for Electric Vehicles Parking with Vehicle-to-grid Service in Microgrid. *CSEE Journal of Power and Energy Systems*, *6*(4), 793-805.

[16] Zhang, J., Shi, Z., Yang, X., & Zhao, J. (2020). Trajectory planning and tracking control for autonomous parallel parking of a non-holonomic vehicle. *Measurement and Control -London- Institute of Measurement and Control*, *53*(2),100-1816. https://doi.org/10.1177/0020294020944961

[17] Shyamshankar, P. K., Rajendraboopathy, S., & Bhuvaneswaran, R. S. (2019). Design of Working Model of Steering, Accelerating and Braking Control for Autonomous Parking Vehicle. *Computers, Materials and Continua*, *61*(1), 55-68. https://doi.org/10.32604/cmc.2019.07761

[18] Kyu, S. J. & Gi, J. H. (2023). Survey of Target Parking Position Designation for Automatic Parking Systems. *International Journal of Automotive Technology*, *24*(1), 287-303. https://doi.org/10.1007/s12239-023-0025-6

[19] Ma, Y., Liu, Y., Shao, S., Zhao, J., & Tang, J. (2022). Review of Research on Vision-Based Parking Space Detection Method. *International journal of web services research*, *19*(21),270-293. https://doi.org/10.4018/IJWSR.304061

[20] Zhang, R., Li, K., Wu, Y., Zhao, D., Lv, Z., Li, F., Chen, X., Qiu, Z., & Yu, F. (2022). A Multi-Vehicle Longitudinal Trajectory Collision Avoidance Strategy Using AEBS With Vehicle-Infrastructure Communication. *IEEE Transactions on Vehicular Technology*, *71*(2), 1253-1266. https://doi.org//10.1109/TVT.2021.3132558

[21] Chen, X., Qin, Z., & Chen, Z. L. (2020). An Efficient Path Planning Methodology Based on the Starting Region Selection. *SAE International Journal of Advances and Current Practices in Mobility*, *2*(6), 3072-3082. https://doi.org/10.4271/2020-01-0118

[22] Yu, L., Wang, X., Hou, Z., Du，Z., & Mu, Z. (2021). Path Planning Optimization for Driverless Vehicle in Parallel Parking Integrating Radial Basis Function Neural Network. *Applied Sciences*, *11*(17), 8178-8195. https://doi.org/ 10.3390/app11178178

[23] Kyu, S. J. & Gi, J. H. (2023). Survey of Target Parking Position Designation for Automatic Parking Systems. *International Journal of Automotive Technology*, *24*(1), 287-303. https://doi.org/10.1007/s12239-023-0025-6

[24] Wang, X., Zhou, M., & Liu, Z. (2022). On Minimum Parking Space Required by Automatic Parallel Parking. *Sensors (Basel, Switzerland)*, *2*(3), 154-274. https://doi.org/10.3390/s22030795

[25] Yuan, Z., Wang, Z., & Li, L. Z. L. (2023). Hierarchical Trajectory Planning for Narrow-Space Automated Parking with Deep Reinforcement Learning: A Federated Learning Scheme. *Sensors (Basel, Switzerland)*, *8*(23), 142-161. https://doi.org/10.3390/s23084087

[26] Nkounga, W. M., Ndiaye, M. F., & Cisse. O. (2022). Automatic control and dispatching of charging currents to a charging station for power-assisted bikes. *Energy*, *246*(5), 123415.1-12345.17. https://doi.org/10.1016/j.energy.2022.123415

[27] Qiping, C., Lu, G., & Bo, C. (2023). Parallel Parking Path Planning Based on Improved Arctangent Function Optimization. *International Journal of Automotive Technology*, *4*(1), 23-33. https://doi.org/10.1007/s12239-023-0003-z

[28] Yu, L., Cai, Y., & Feng, X. (2024). Parallel Parking Path Planning and Tracking Control Based on Simulated Annealing Algorithm. *International Journal of Automotive Technology*, *25*(4), 867-880. https://doi.org//10.1007/s12239-024-00087-7

[29] Wang, M., Li, Q., Gu, Y., Fang, L., & Zhu, X. (2022). SCAF-Net: Scene Context Attention-Based Fusion Network for Vehicle Detection in Aerial Imagery. *IEEE geoscience and remote sensing letters*, *19*(3),1-5. https://doi.org/10.1109/LGRS.2021.3107281

[30] Han, Z., Wang, C., & Fu, Q. (2021). M 2 R-Net: deep network for arbitrary oriented vehicle detection in MiniSAR images. *Engineering Computations*, *38*(7), 2969-2995. https://doi.org/10.1108/EC-08-2020-0428

[31] Chen, G., Hou, J., Dong, J., Li Z., & Chung, H. T. (2020). Multi-Objective Scheduling Strategy with Genetic Algorithm and Time Enhanced A* Planning for Autonomous Parking Robotics in High-Density Unmanned Parking Lots. *IEEE/ASME Transactions on Mechatronics*, *3*(26),1547-1557. https://doi.org/10.1109/TMECH.2020.3023261

[32] Arsalan, M. & Akbar, F. (2021). An ultrasonic sensor based automatic braking system to mitigate driving exhaustion during traffic congestion. *Proceedings of the Institution of Mechanical Engineers, Part D: Journal of Automobile Engineering*, *235*(12), 3026-3035. https://doi.org/10.1177/09544070211009076

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